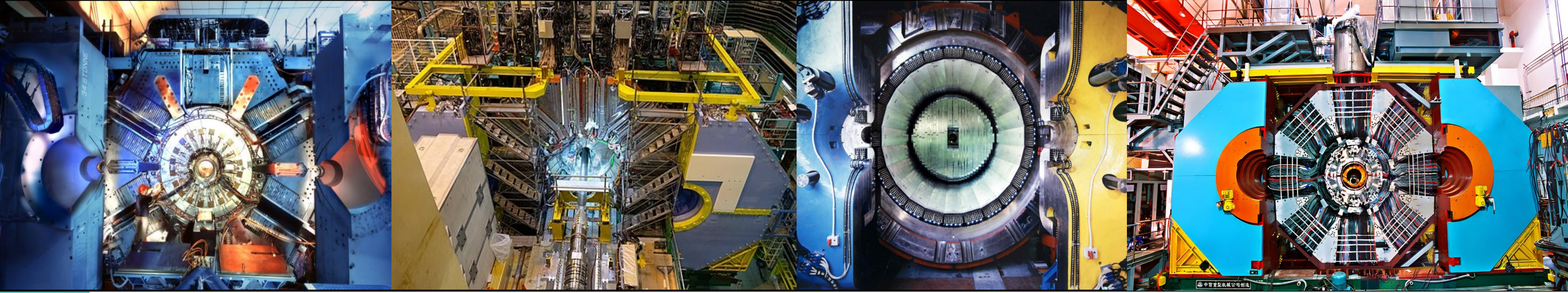


Dark sector searches at e^+e^- colliders

Neutrino and Flavour: a stairway to New Physics - Workshop

April 2-3, 2025, INFN Pisa– Pisa, Italy

Luigi Corona - University and INFN of Pisa

luigi.corona@pi.infn.it

INFN Istituto Nazionale di Fisica Nucleare

Belle II

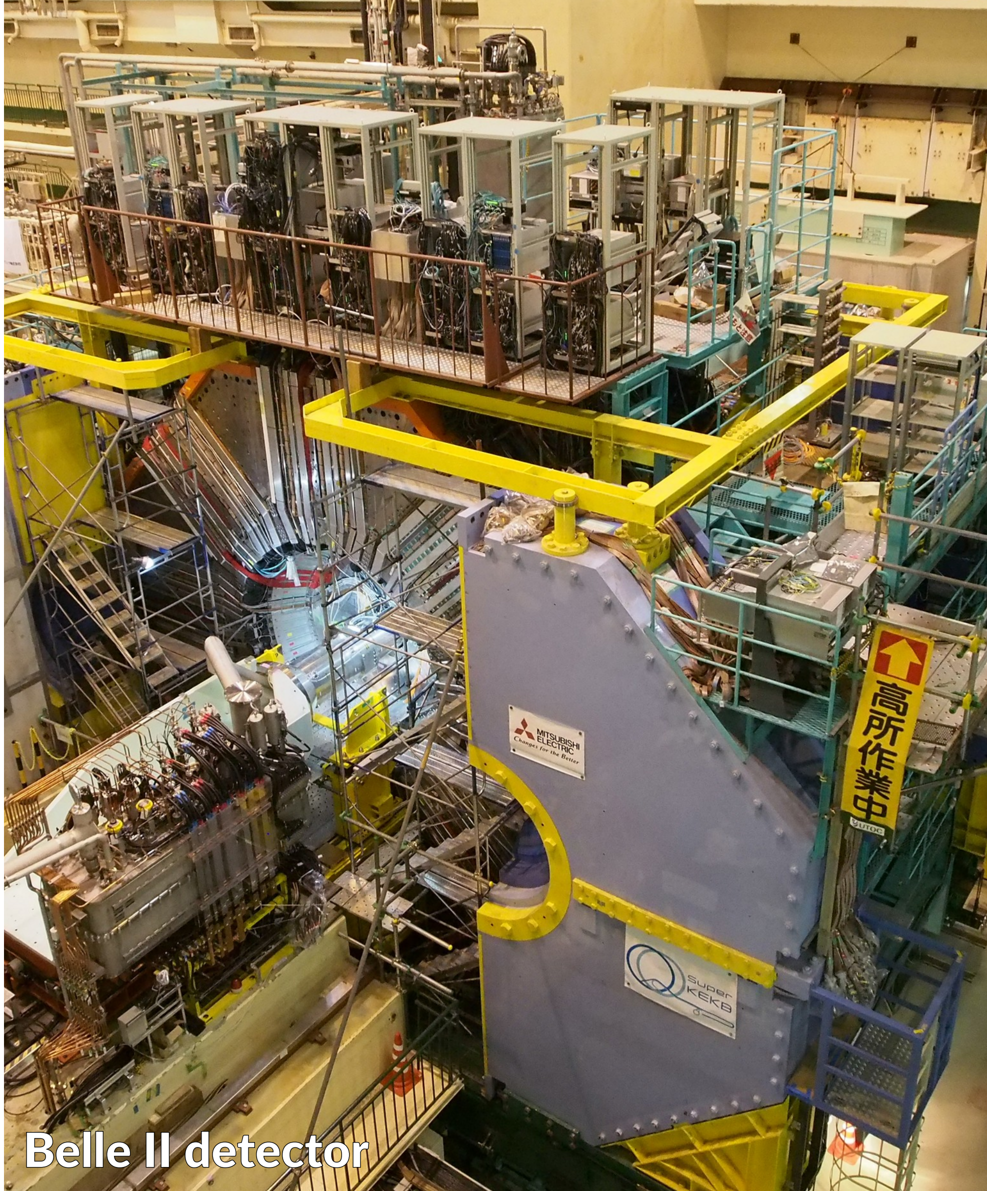
Outline

- Introduction to dark sectors

- Introduction to the experiments at e^+e^- colliders

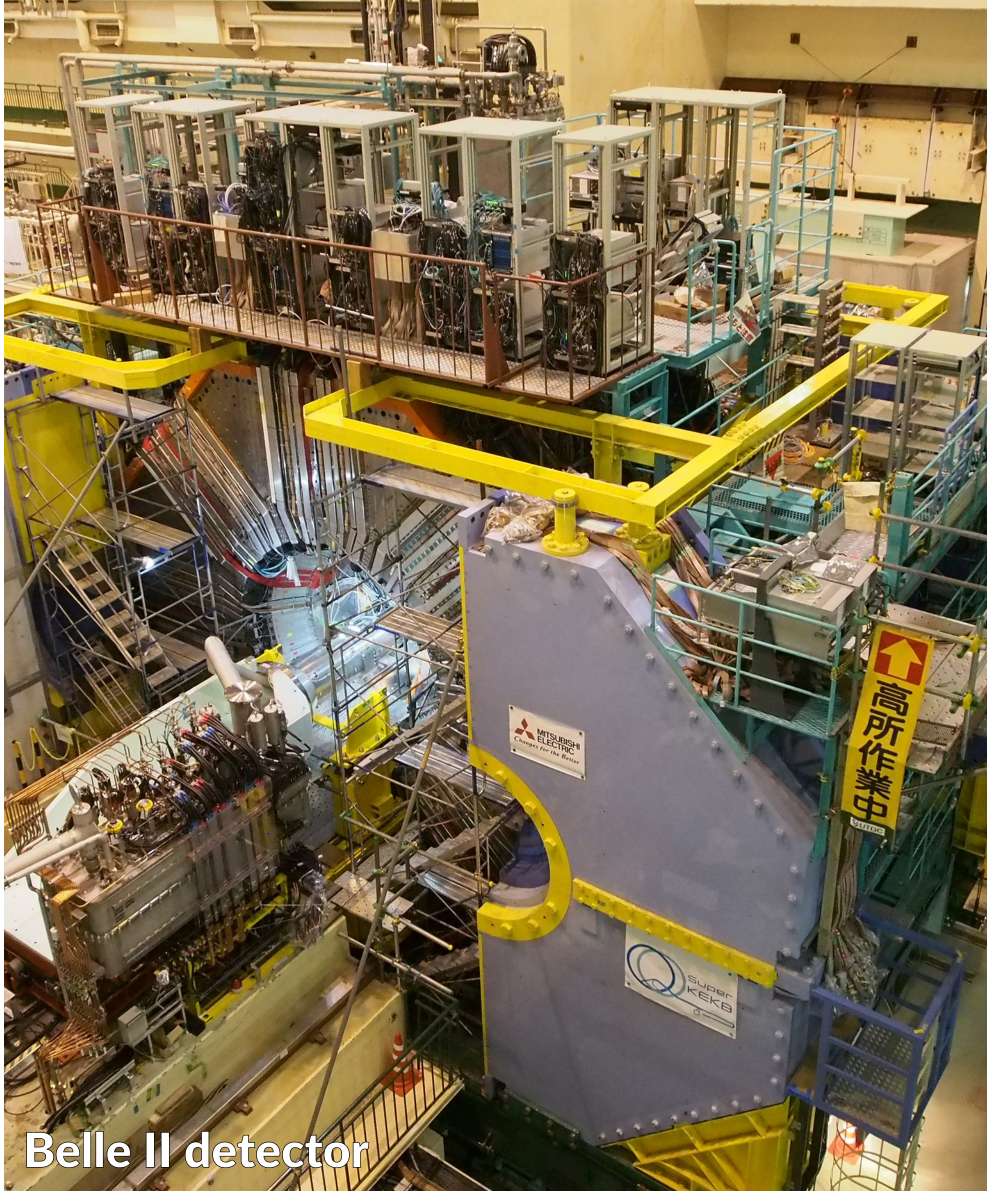
- Overview of dark sector searches (Belle II, Belle, BaBar, KLOE, BES III)

- Summary and Conclusions



Belle II detector

Introduction to dark sectors



Belle II detector

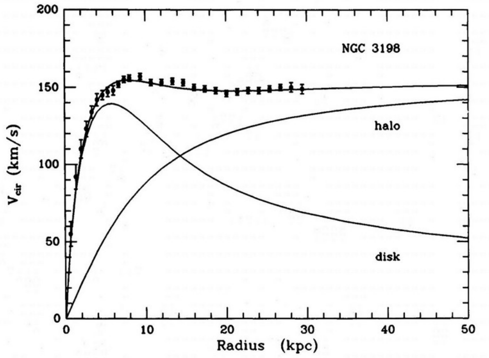
Evidences of dark matter

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

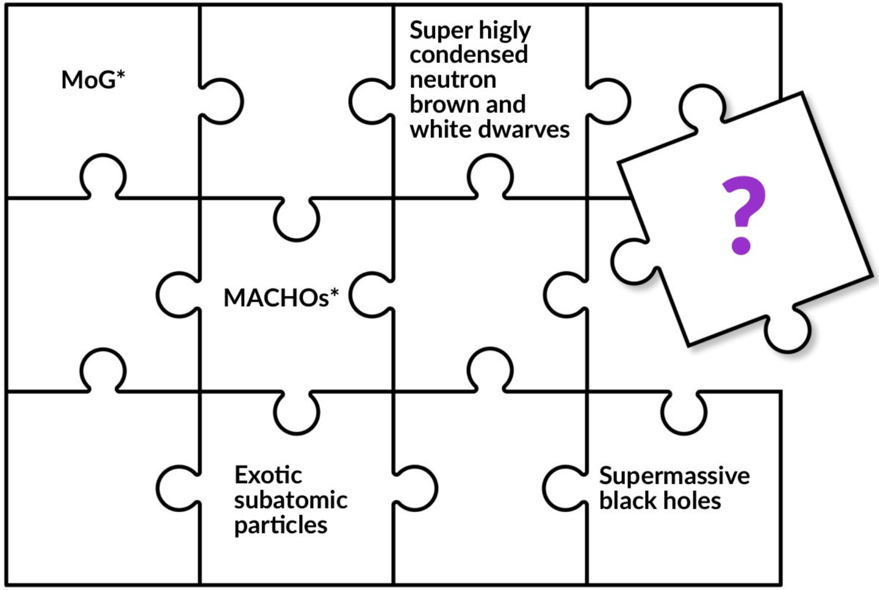

F. Zwicky in 1930s


V. Rubin in 1970s



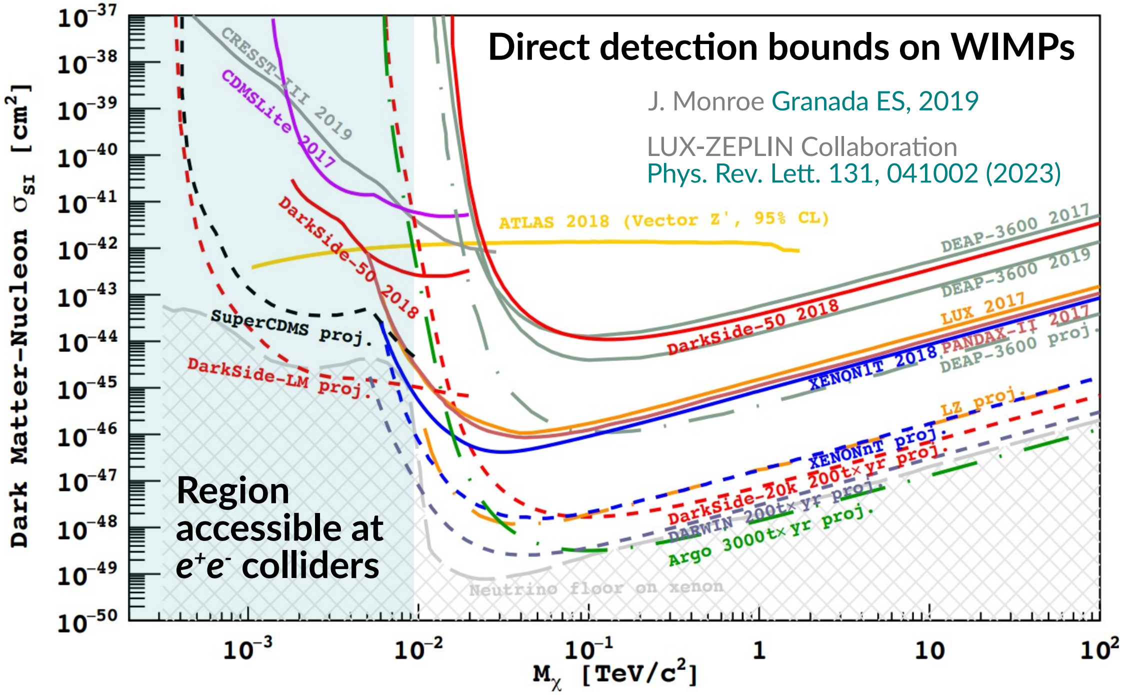
DM nature is unknown

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

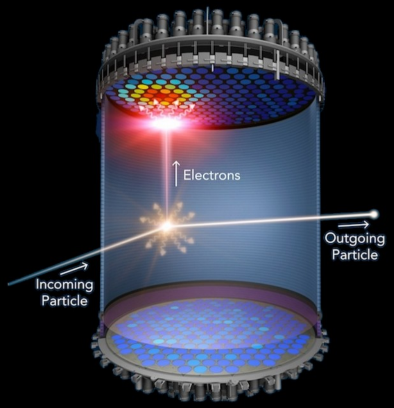


Dark matter searches

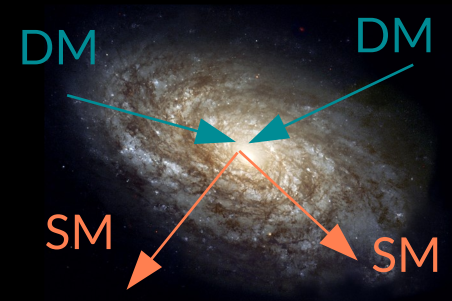
If DM weakly couples to SM particles, it can be produced in SM particles annihilation at accelerators → Involve dark sector mediators



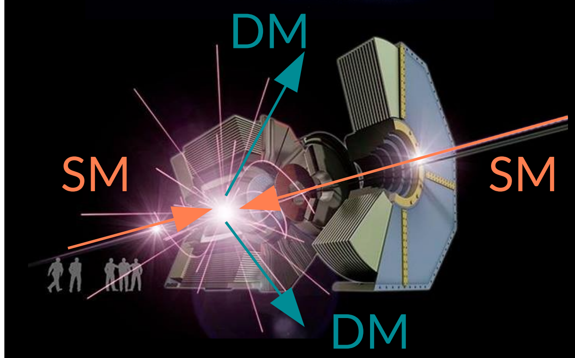
Direct detection



Indirect detection



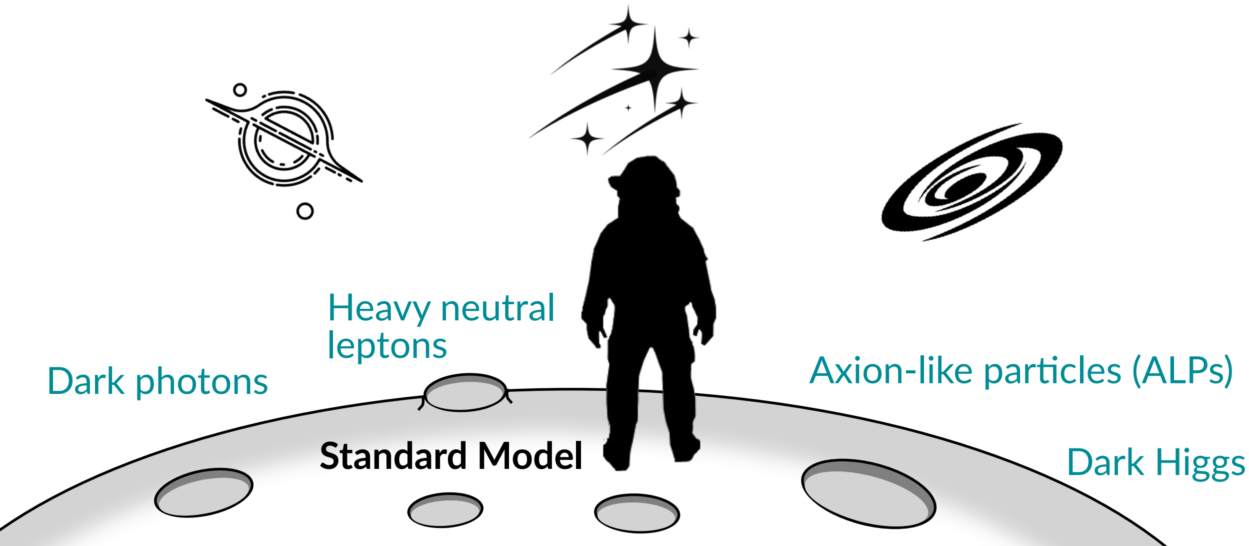
Colliders



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

S. Gori et al., arXiv:2209.04671 [hep-ph] (2022)



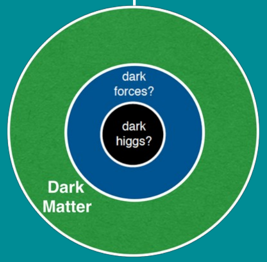
"Portals" of interaction

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

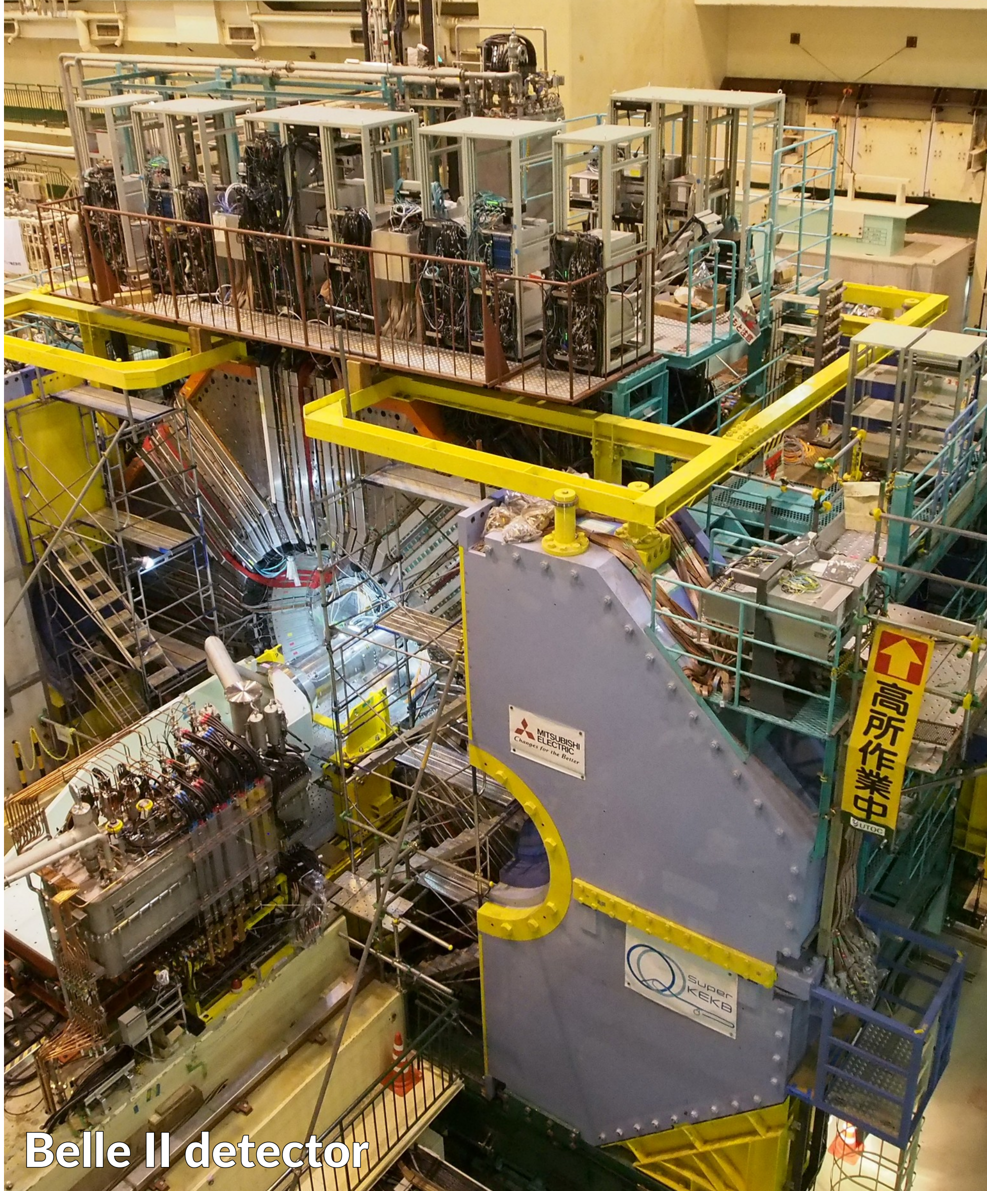
$$\mathcal{L}_{\text{scalar}} \sim |H|^2 \left(\kappa S + \lambda S^2\right)$$

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

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



Experiments at e^+e^- colliders



Belle II detector

What we can do at e^+e^- colliders?

[1] T. Keck et al., Comput. Softw. Big. Sci. 3, 6 (2019)

e^+e^- collisions

- Clean, low background, energy conserving environment
- Closed kinematics, 3D momentum conservation
- Full Event Interpretation[1]

Capabilities for the following signatures

- Low multiplicity signatures
- Fully neutral final states
- Missing energy signatures
- Dark sector signatures in B, D, τ, ϕ, J/ψ and Υ decays

Energies

- **DAΦNE** $\simeq$ 1 GeV (ϕ resonance)
- **BEPC** $\simeq$ 2 – 5 GeV
- **PEP-II, KEKB, SuperKEKB** $\simeq$ 10 – 11 GeV (Υ(nS) resonances)
- Most of the interesting cross sections scale with 1/s

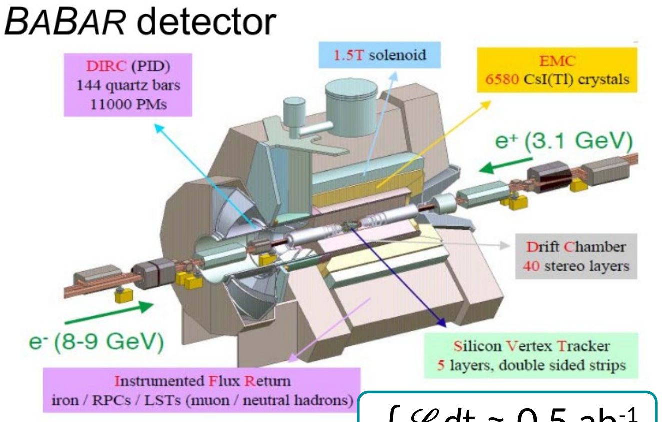
Cross sections at Belle II – SuperKEKB

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

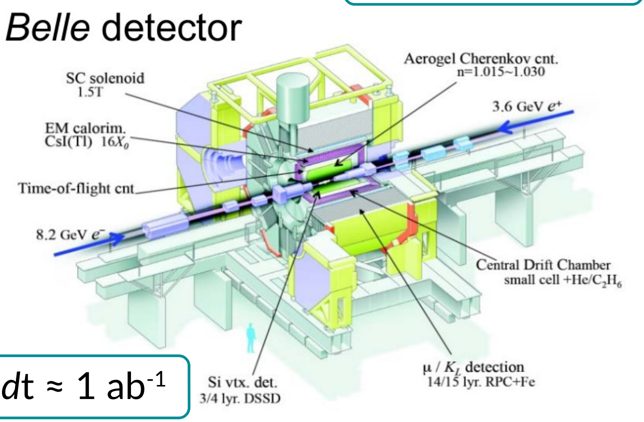
- **Cleanliness and luminosity compensate for cross section**
- **Probe dark sector at the MeV – GeV scale,**
- **Unique places to study some rare light meson decays**
  - → ***B*, *D*, τ, ϕ, *J*/ψ and Υ factories**

Experiments at e^+e^- colliders

- Many **experiments at e^+e^- colliders** have been providing **important contribution to dark sector searches**



$\int \mathscr{L} dt \approx 0.5\ ab^{-1}$



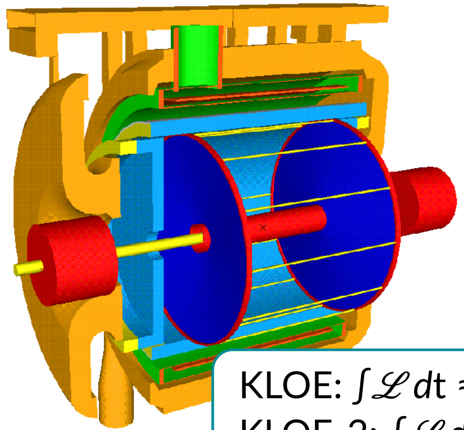
$\int \mathscr{L} dt \approx 1\ ab^{-1}$

- Experiments at ***B*-factories**
  - BaBar at PEP-II (2000-2008)
  - Belle at KEKB (1999 - 2010)
  - Belle II at SuperKEKB (2018 -)
  - ➔ $\sqrt{s} \simeq 10 - 11$ GeV

- KLOE (2001 – 2006)
  KLOE-2 (2014 – 2018)
  at DAΦNE
  - ➔ $\sqrt{s} \simeq 1$ GeV

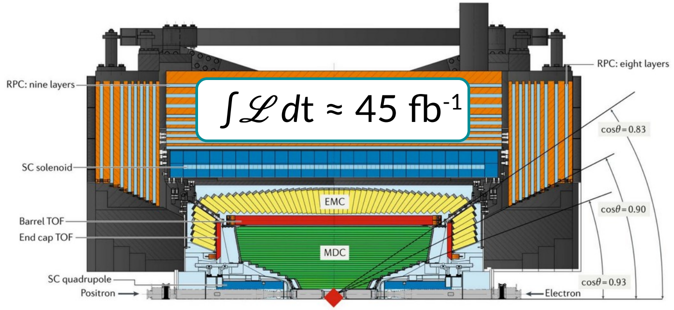
- BES III (2009 -) at BEPC II
  - ➔ $\sqrt{s} \simeq 2 - 5$ GeV

KLOE detector



KLOE: $\int \mathscr{L} dt \approx 2\ fb^{-1}$
KLOE-2: $\int \mathscr{L} dt \approx 6\ fb^{-1}$

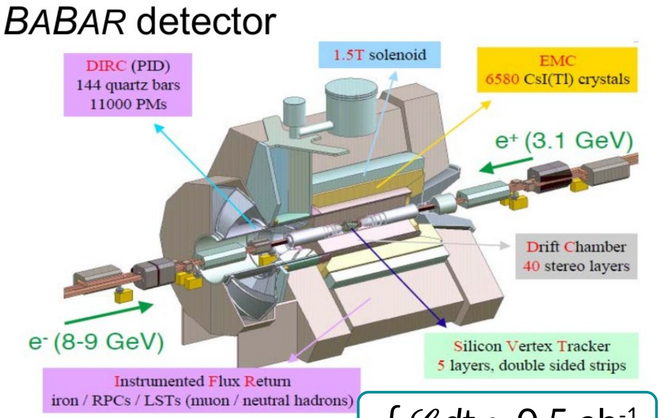
BESIII detector



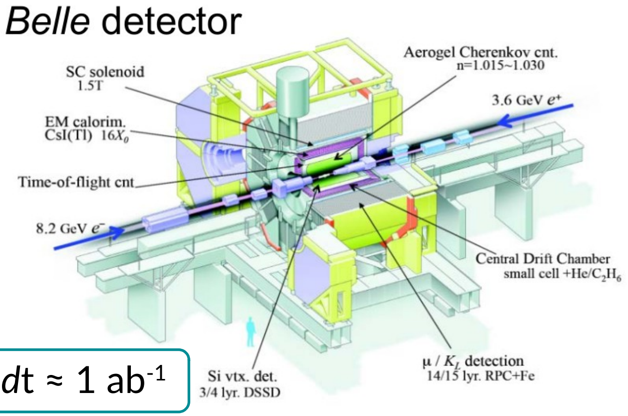
$\int \mathscr{L} dt \approx 45\ fb^{-1}$

Experiments at e^+e^- colliders: *B*-factories

- Many **experiments at e^+e^- colliders** have been providing **important contribution to dark sector searches**

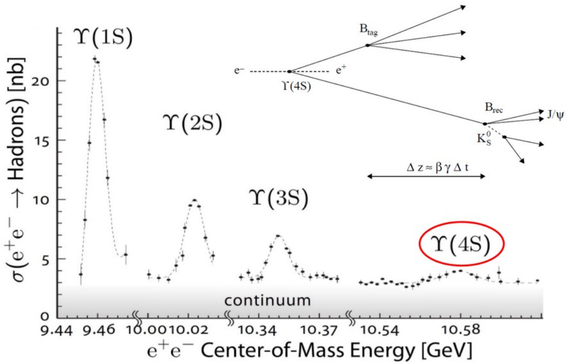


$\int \mathscr{L}\, dt \approx 0.5$ ab^{-1}



$\int \mathscr{L}\, dt \approx 1$ ab^{-1}

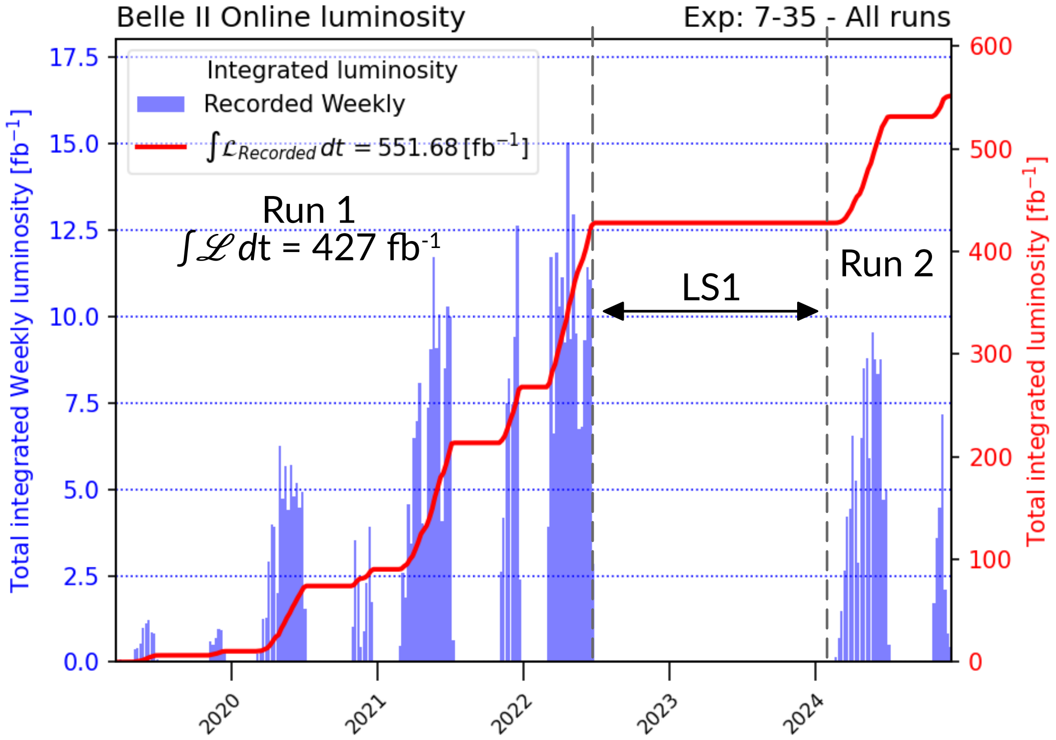
- Experiments at ***B*-factories**
  - BaBar at PEP-II (2000-2008)
  - Belle at KEKB (1999 - 2010)
  - Belle II at SuperKEKB (2018 -)
  - ➔ $\sqrt{s} \simeq 10 - 11$ GeV

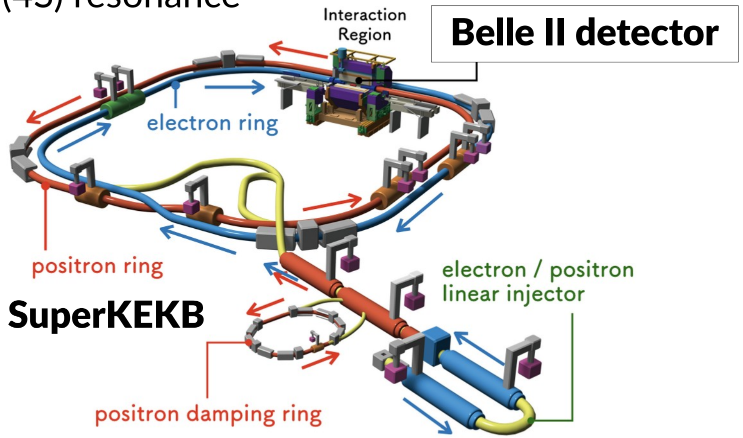


- **Asymmetric e^+e^- colliders** optimized for the production of *B* meson pairs, but also *D* mesons, *τ* leptons, …
- **Collisions occur at Y(nS) resonances**
  - ➔ Mainly at Y(4S): $\sqrt{s}$ = 10.58 GeV, just above the production threshold of $B\bar{B}$, $BR(\Upsilon(4S) \to B\bar{B}) > 96\%$
-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

The Belle II experiment at SuperKEKB

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





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

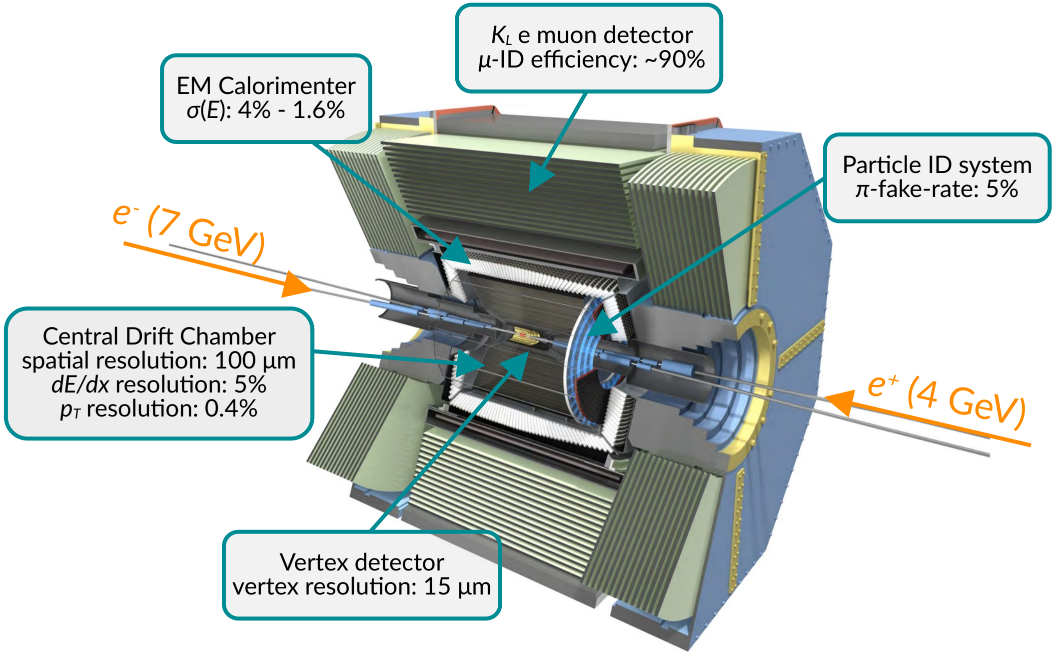
High luminosity

Target	Achieved
$\int \mathscr{L} dt = 50\ \mathrm{ab}^{-1}$	$\int \mathscr{L} dt = 575\ \mathrm{fb}^{-1}$
$\mathscr{L}_{peak} = 6 \times 10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$	$\mathscr{L}_{peak} = 5.1 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

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)

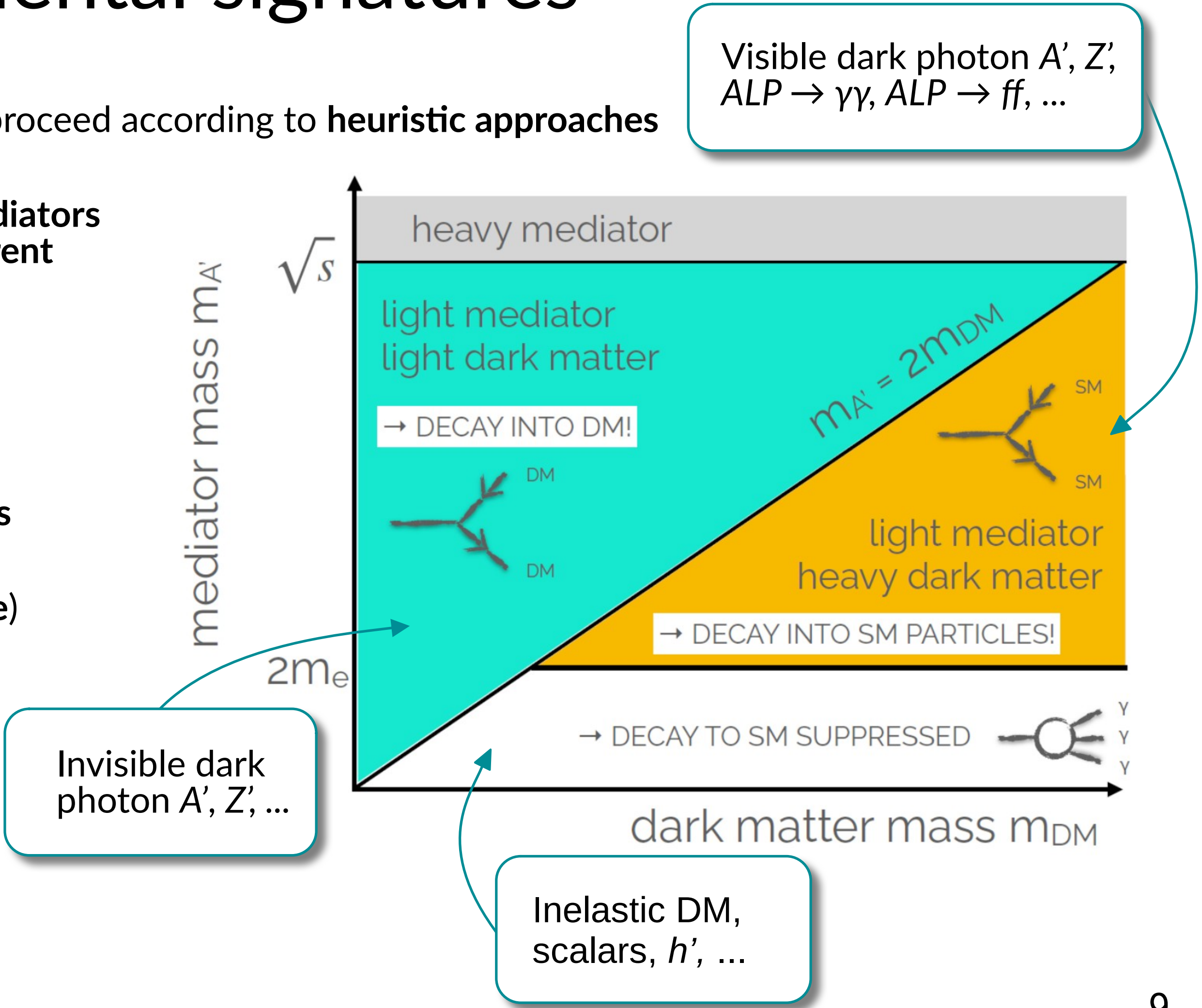
Dark sector experimental signatures

- **Searches** are usually **driven by models** or proceed according to **heuristic approaches**

- The **relationship between mass of the mediators** and **mass of DM candidates** leads to **different topologies**

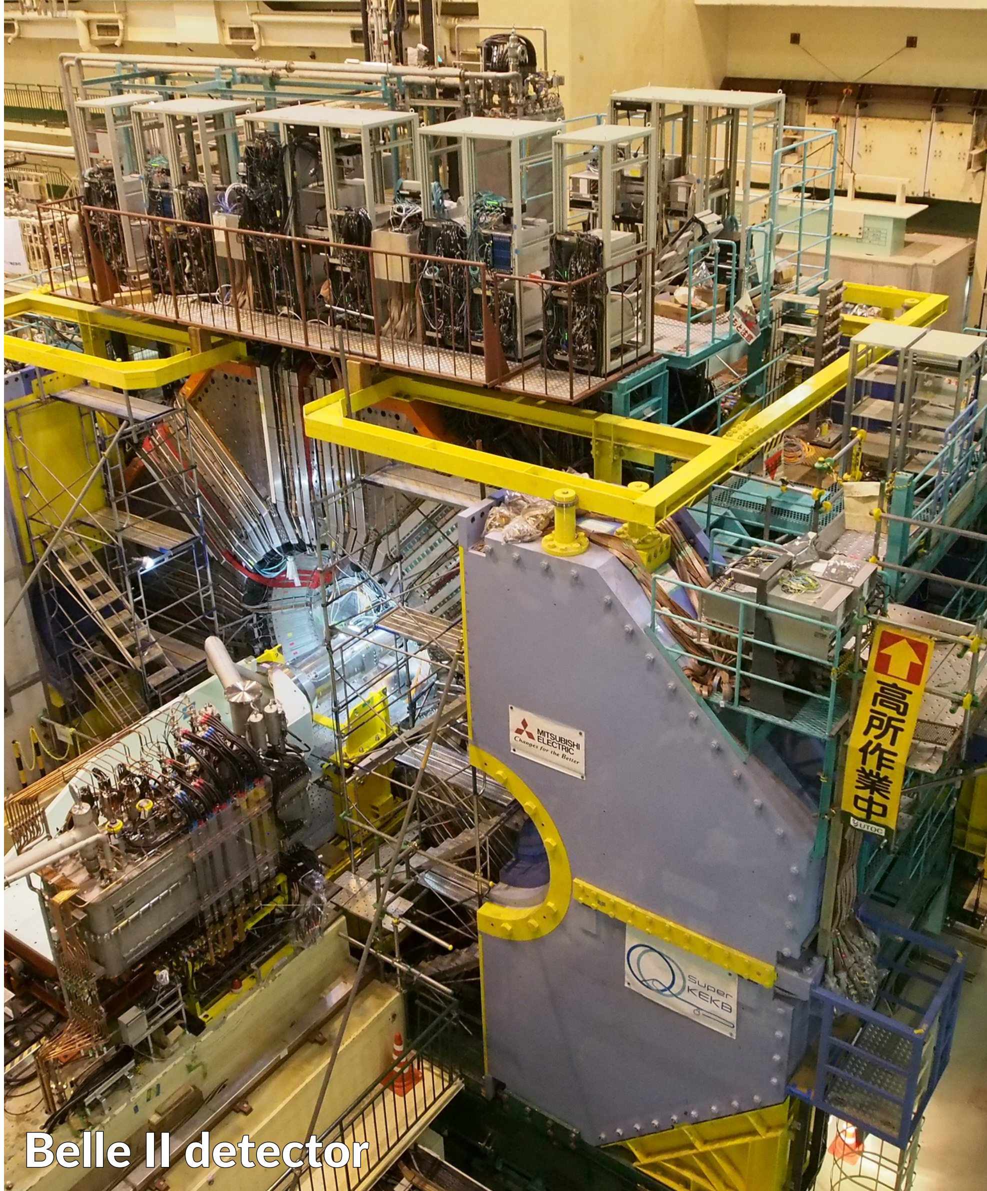
- **Negligible interaction probability of DM** with the detector
  - Search for final states with **missing mass**
  - Search for **mediators** (**visible** or **invisible**)
  - Search for both

- In models where decay to SM is suppressed
  - **Long-lived mediators**



Invisible decays
Decays to SM particles
ALPs $\rightarrow \gamma\gamma$
Dark Higgs

Exploring the dark sectors at experiments at e^+e^- colliders



Belle II detector

Invisible decays
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ALPs $\rightarrow \gamma\gamma$
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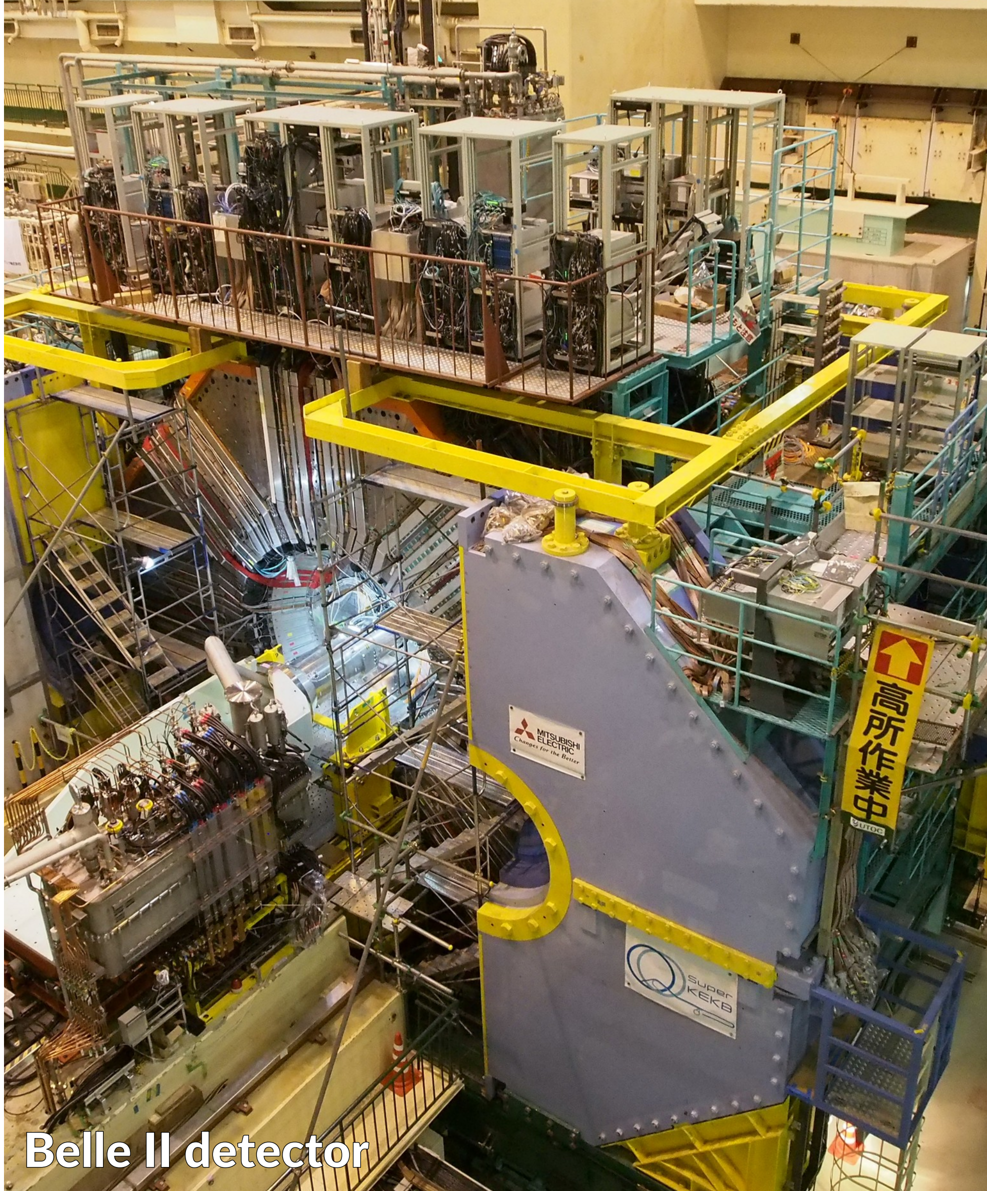
Exploring the dark sectors at experiments at e^+e^- colliders



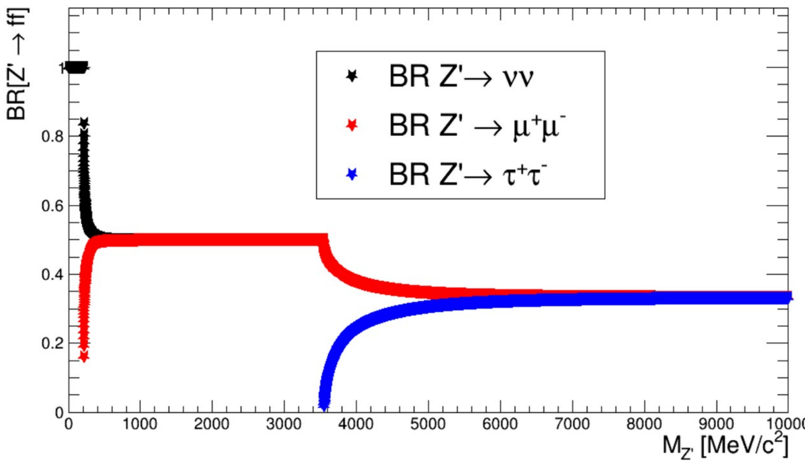
Belle II detector

Search for Z' bosons

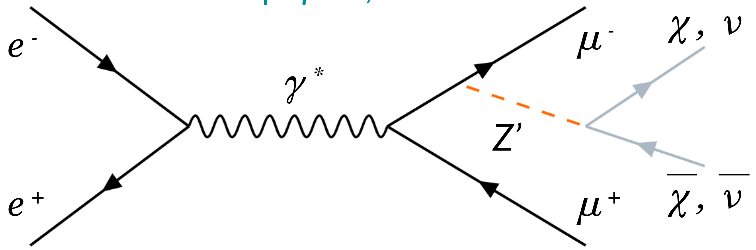
Shuve et al., Phys. Rev. D 89 , 113004 (2014)
D. Curtin et al., JHEP 02 (2015) 157
Altmannshofer et al., JHEP 106 (2016)

- **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'* → invisible** ($Z' \to \nu\bar{\nu}/\chi\bar{\chi}$)
  - If light **DM χ kinematically accessible** exists, ***BR*(Z' → 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 at Belle II

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**

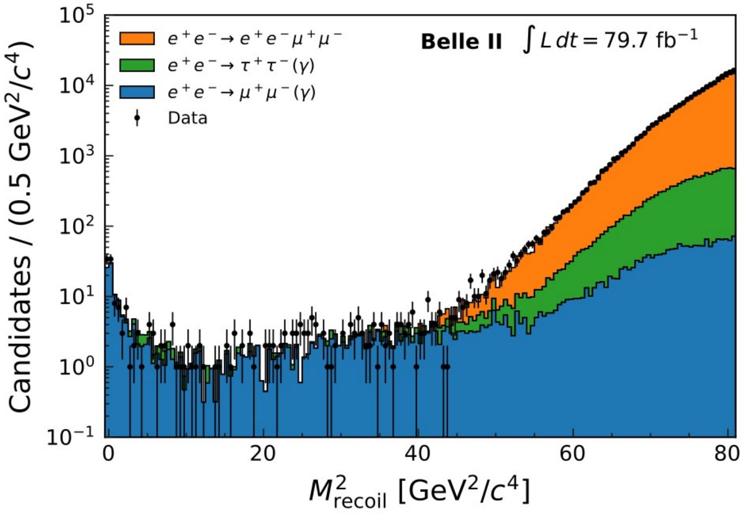
- Challenging **$e^+e^- \to \tau^+\tau^- (\gamma)$** suppression tackled with **neural network** trained simultaneously on all Z' mass hypotheses

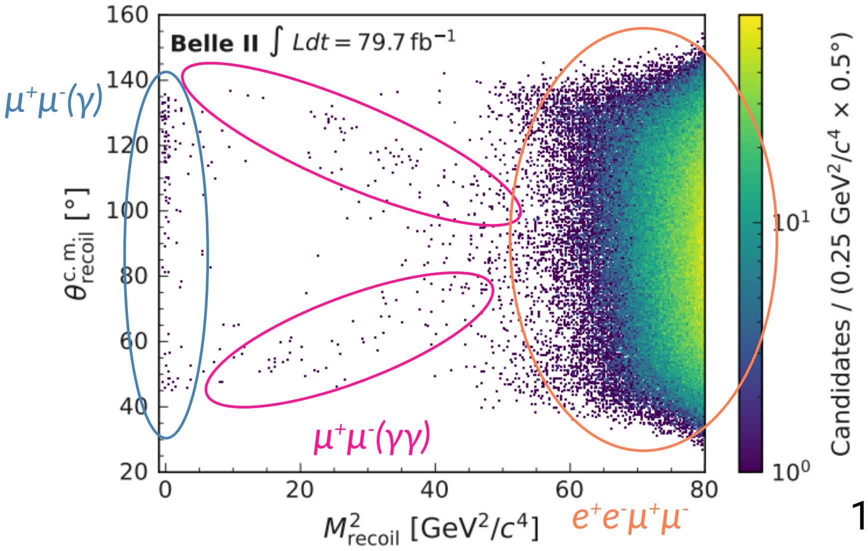
  F. Abudinén et al., Eur. Phys. J. C 82, 121 (2022)

  - 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}**

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



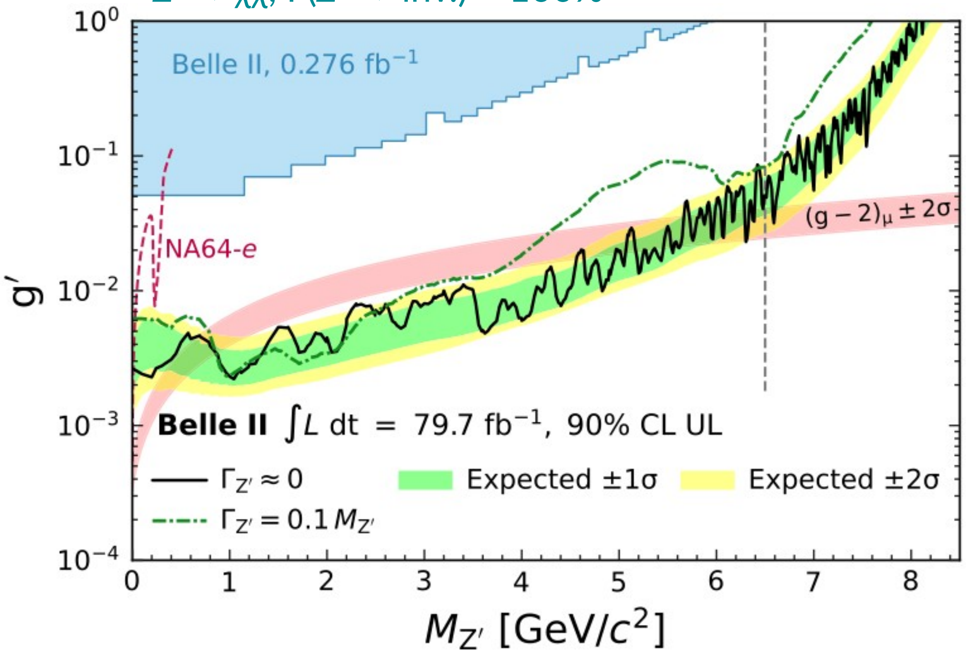


Z' → invisible at Belle II

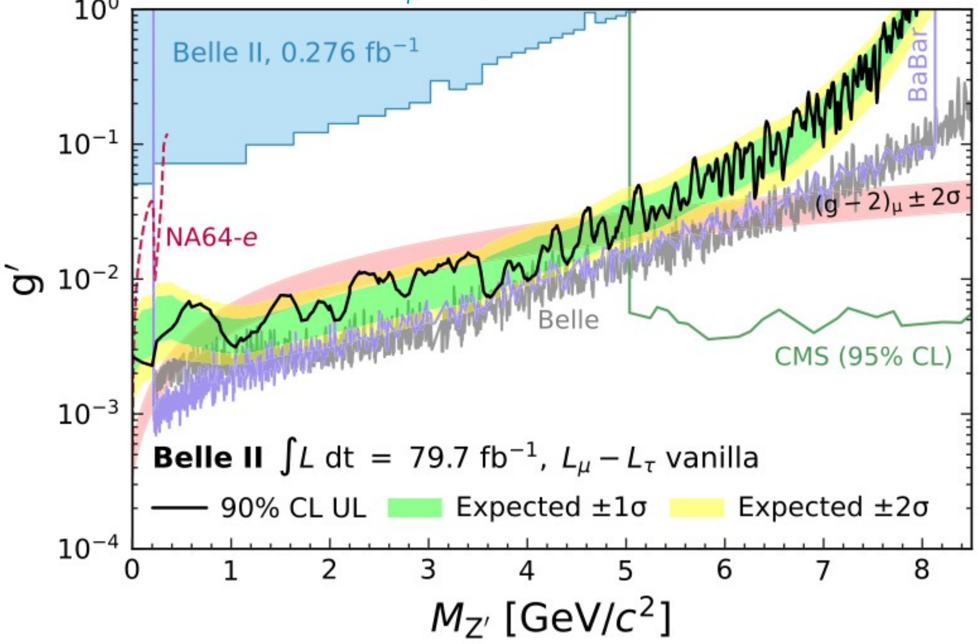
I. Adachi et al., Phys. Rev. Lett. 130, 231801 (2023)

- **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 $\Gamma(Z' \to \text{inv.}) = 100\%$**

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

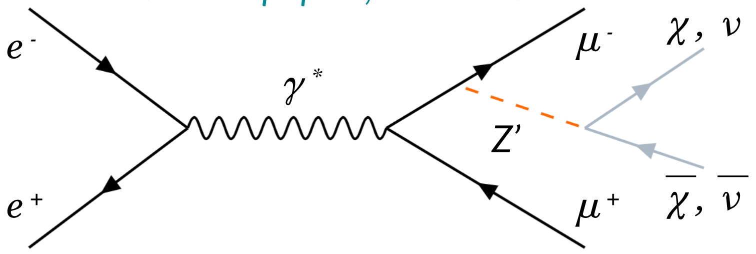


$Z' \to \nu\bar{\nu}$ in the $L_\mu - L_\tau$ model

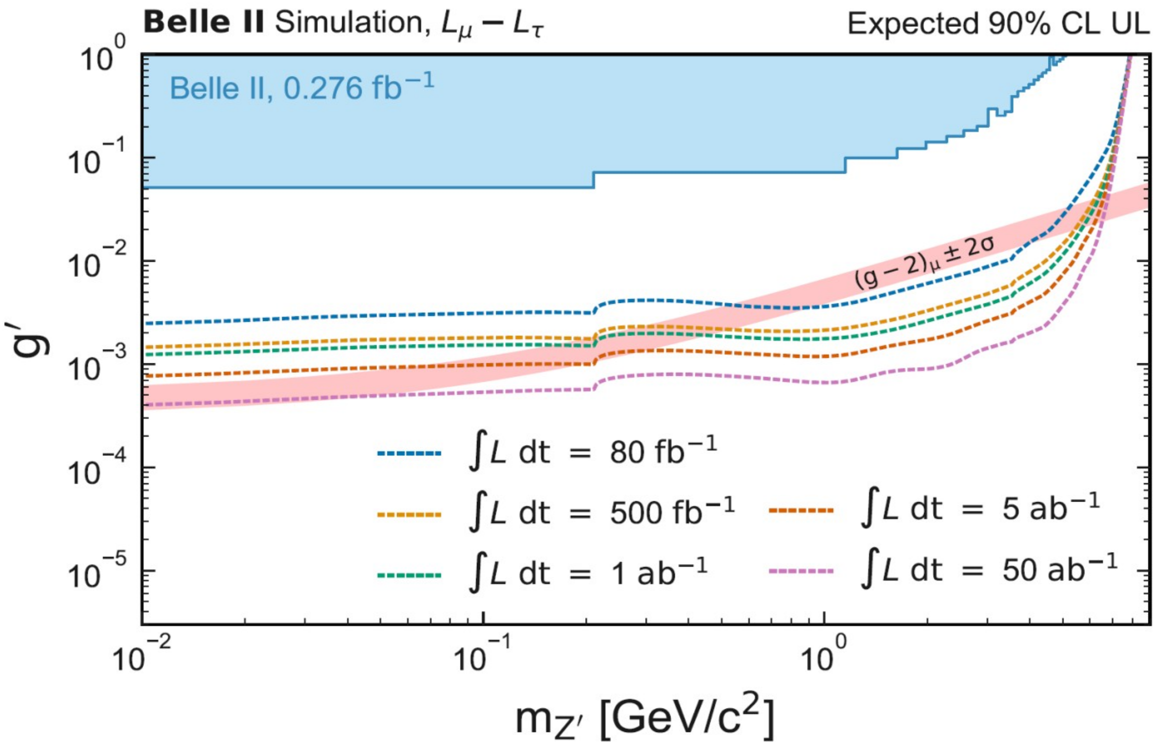


Z' → invisible prospects at Belle II

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



Snowmass White Paper Belle II, arXiv:2207.06307 [hep-ex] (2022)



- Next update based on Belle II Run 1 luminosity in progress

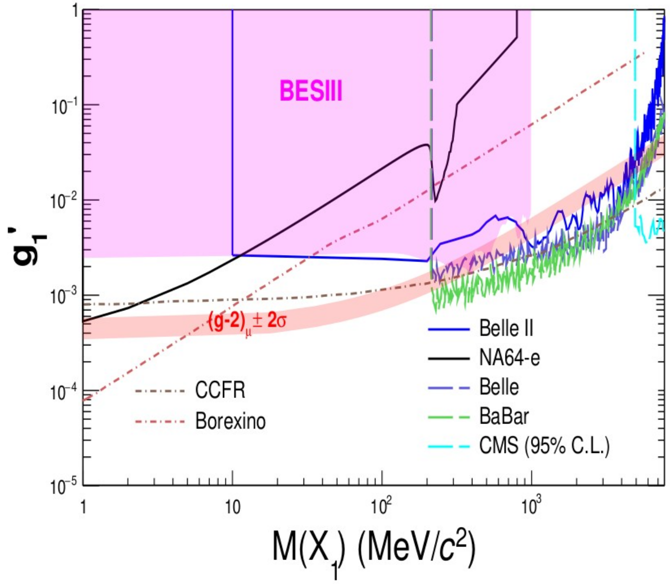
$J/\psi \to \mu\mu X_{0,1}$ at BES III

M. Ablikim et al., Phys. Rev. D 109, L031102 (2024)

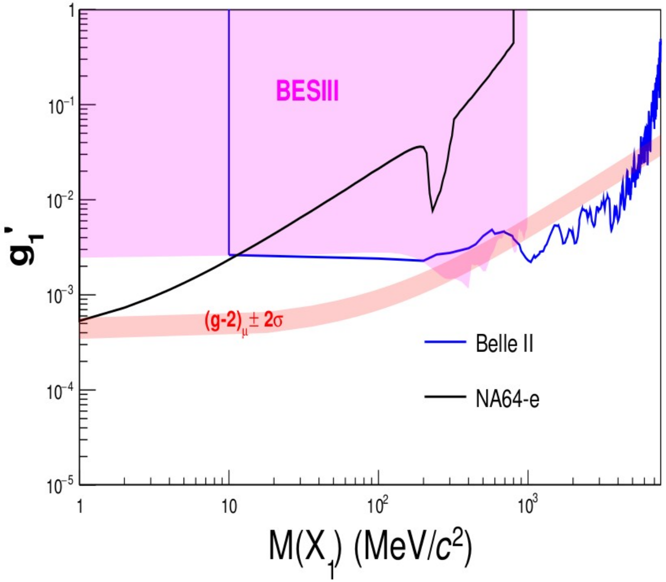
SM Backgrounds
$J/\psi \to \mu^+\mu^-$,
$e^+e^- \to \mu^+\mu^-$,
$J/\psi \to$ hadrons

- (8.998 ± 0.039) x 10^9 ***J/ψ***
- X_0 and X_1 are a light scalar and vector particles respectively
- **Signal: narrow peak in the recoil mass distribution of the *μμ* system, extracted through fits**
- **Best 90% CL upper limits to g'_1 for 200 < $m(X_1)$ < 860 MeV/c^2 in the invisible $L_\mu - L_\tau$**

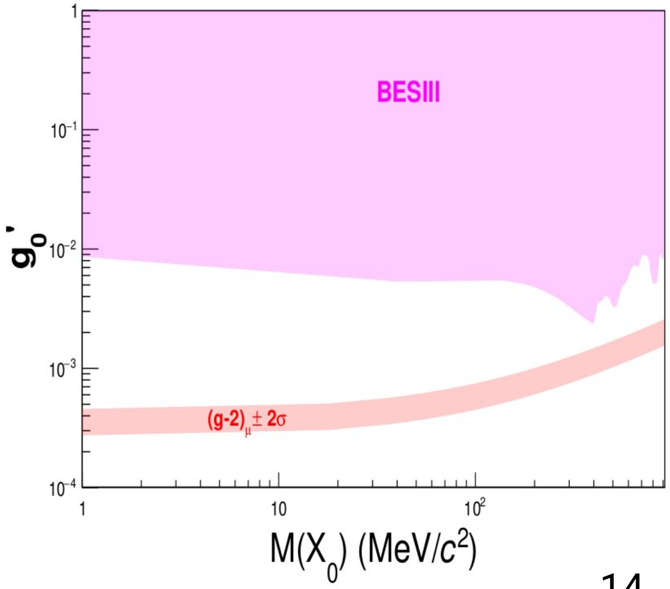
$L_\mu - L_\tau$ model



Fully invisible

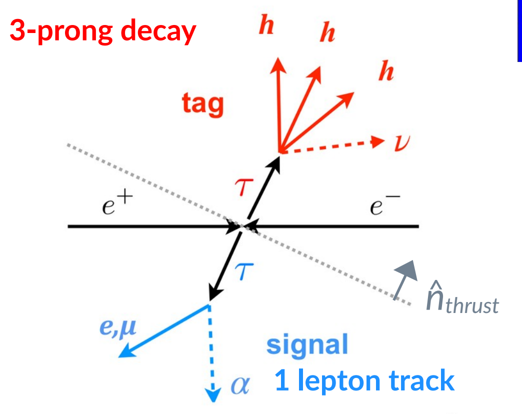


Dark scalar



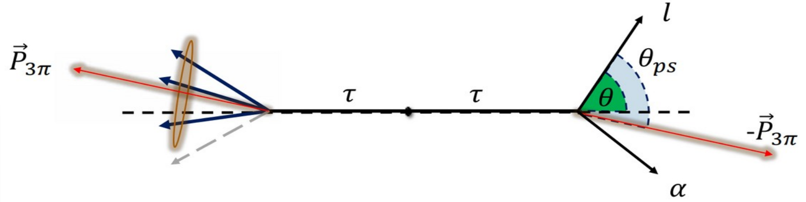
$\tau \to l\,\alpha$ (invisible) decay at Belle II

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 $e^+e^- \to \tau_{sig}\,\tau_{tag}$, $\tau_{tag} \to 3\pi\,\nu$

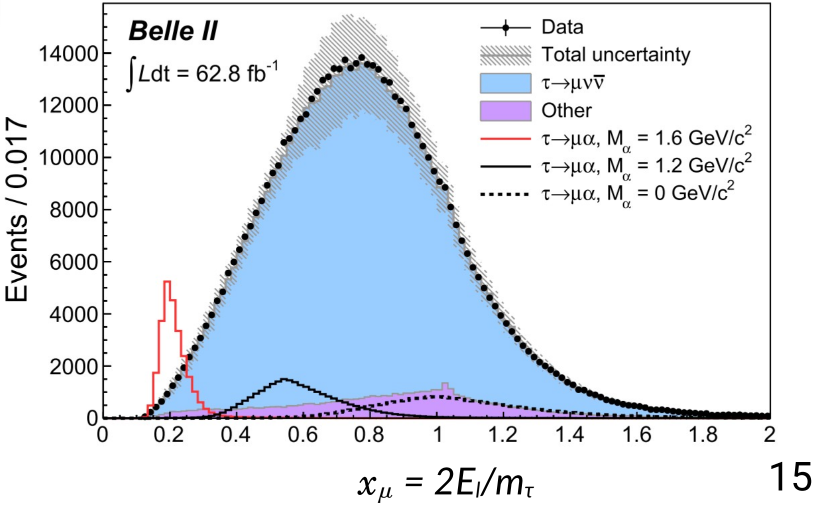
$$\hat{p}_\tau \approx -\frac{\vec{p}_{tag}}{|\vec{p}_{tag}|}$$

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

- 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**

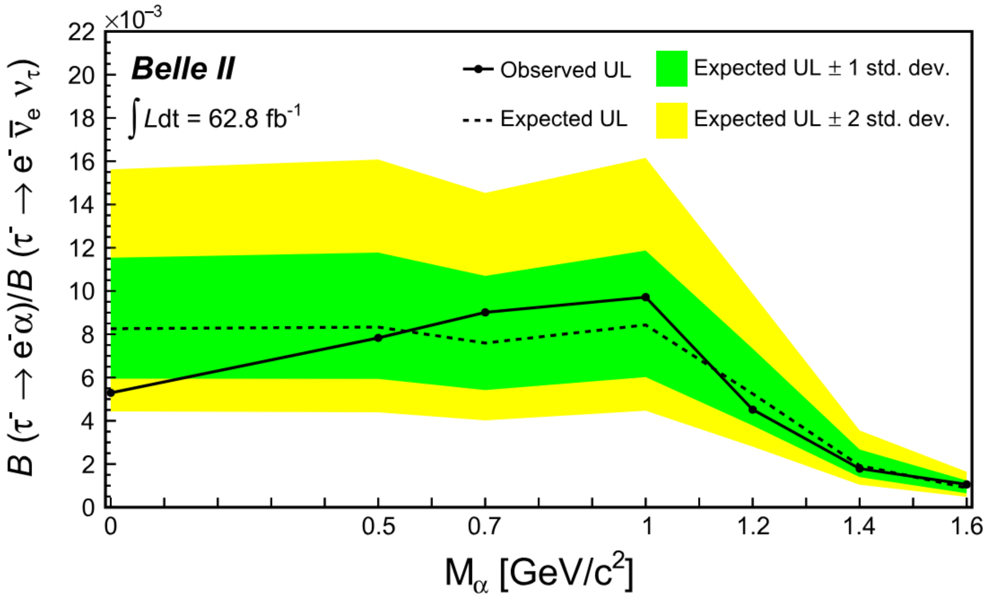


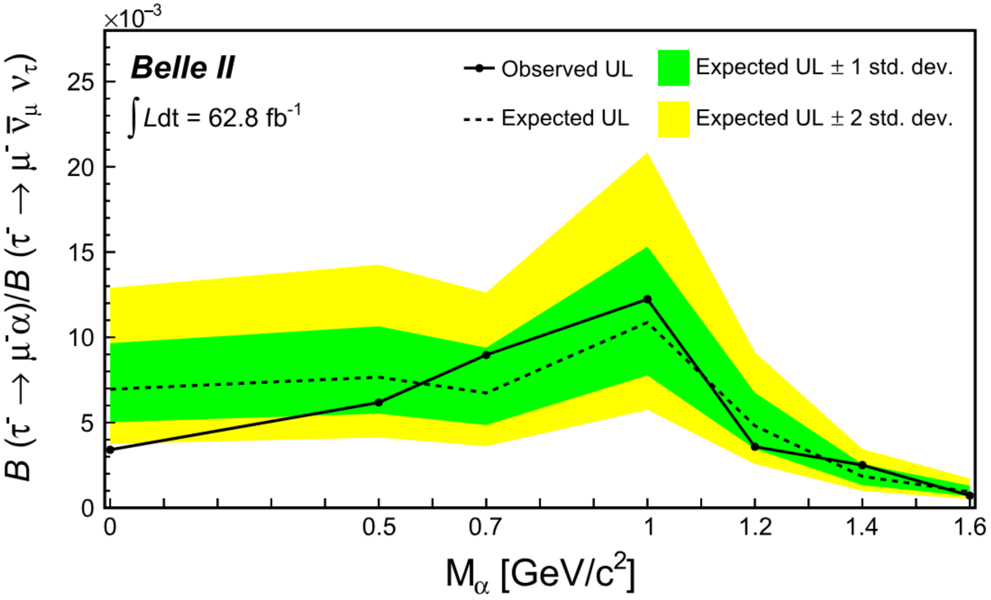
$\tau \to l\,\alpha$ (invisible) decay at Belle II

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

- **No excess observed in 62.8 fb^{-1}**
  - **95% CL most stringent limits**
  - Previous existing limits from ARGUS[1]

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





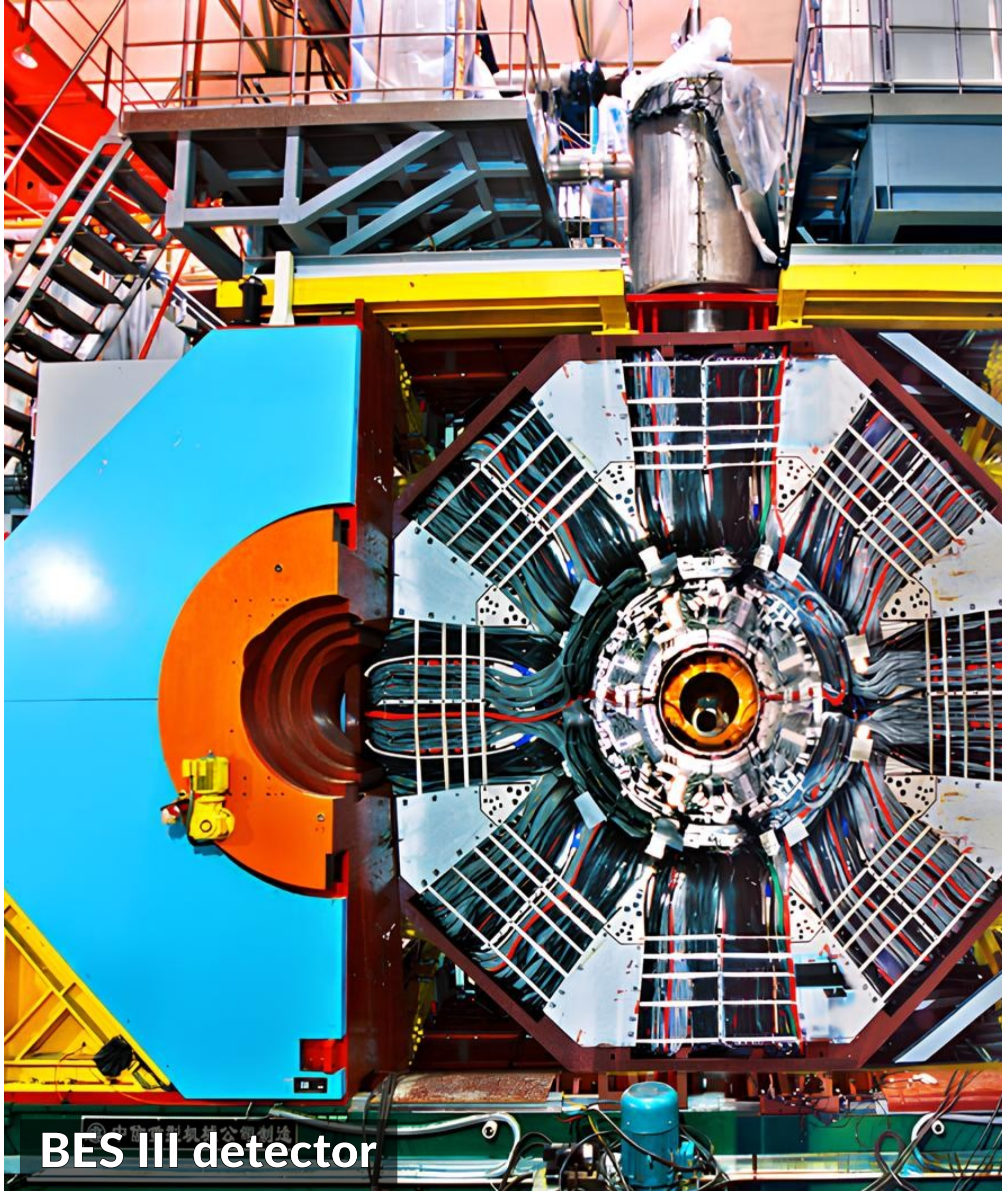
Invisible decays

Decays to SM particles

ALPs $\rightarrow \gamma\gamma$

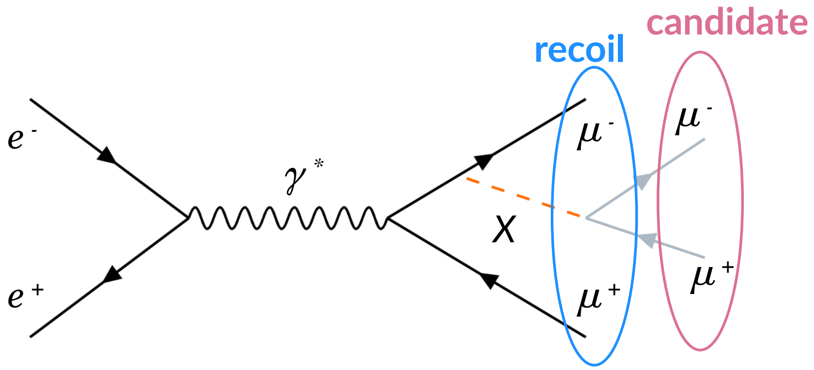
Dark Higgs

Exploring the dark sectors at experiments at e^+e^- colliders

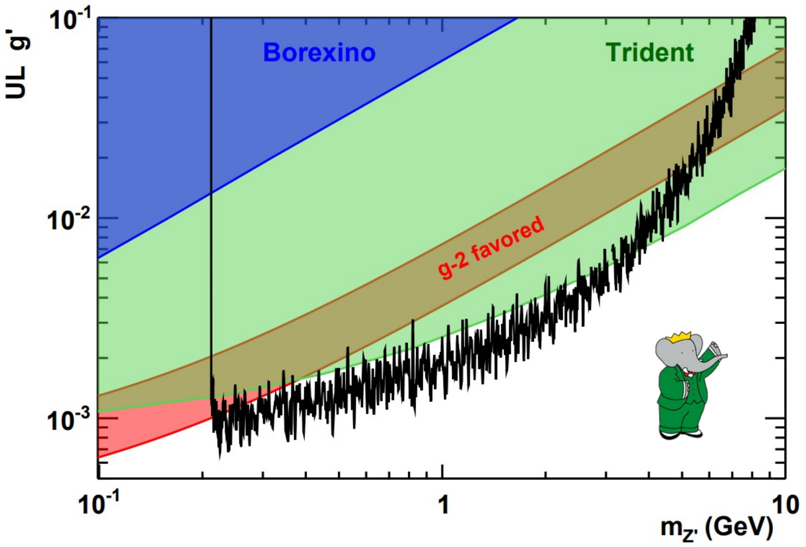


$Z' \to \mu\mu$ at BaBar and Belle

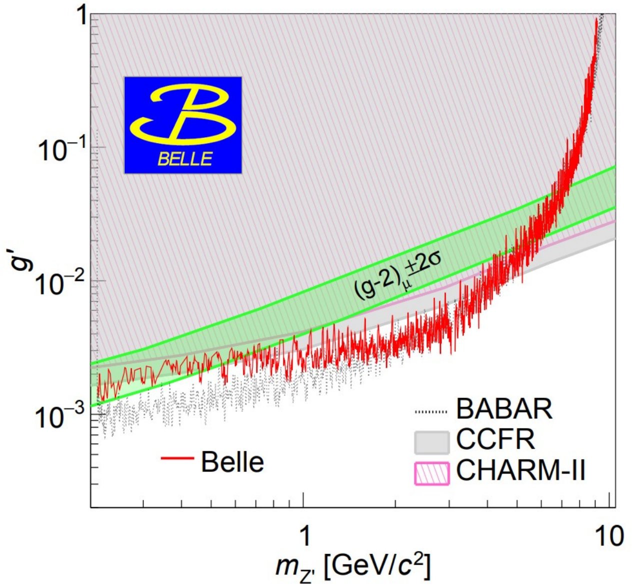
- $e^+e^- \to \mu^+\mu^- Z'(\to \mu^+\mu^-)$
  - Four-track invariant mass compatible with collision $\sqrt{s}$
  - No extra energy
- Signal signature is a **narrow peak in the opposite-charge dimuon mass $M(\mu\mu)$**
- BaBar used 514 fb^{-1}, Belle used 643 fb^{-1}



J. P. Lees et al., Phys. Rev. D 94, 011102(R) (2016)



T. Czank et al., Phys. Rev. D 106, 012003 (2022)

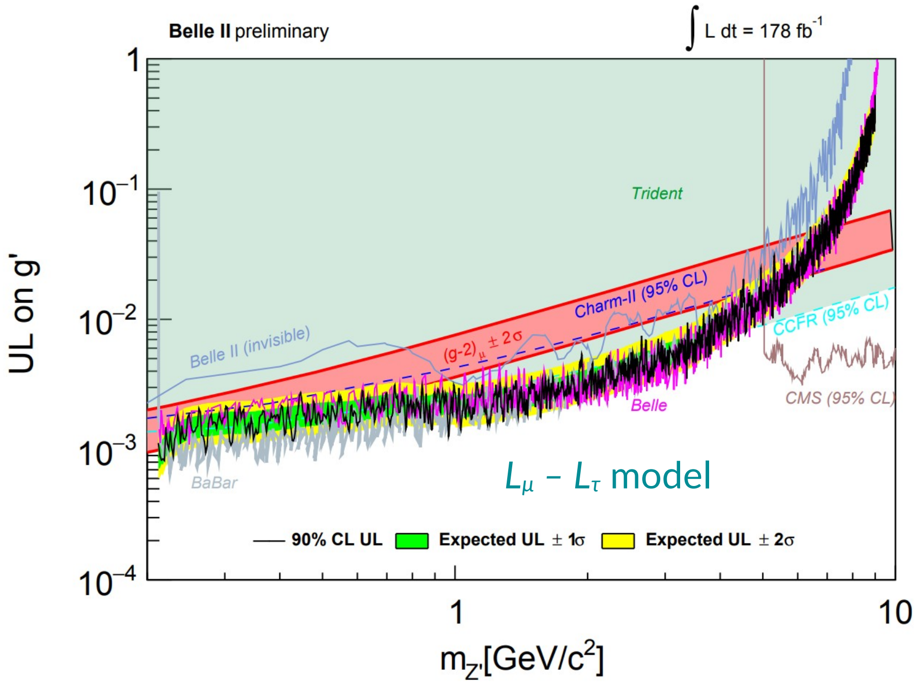


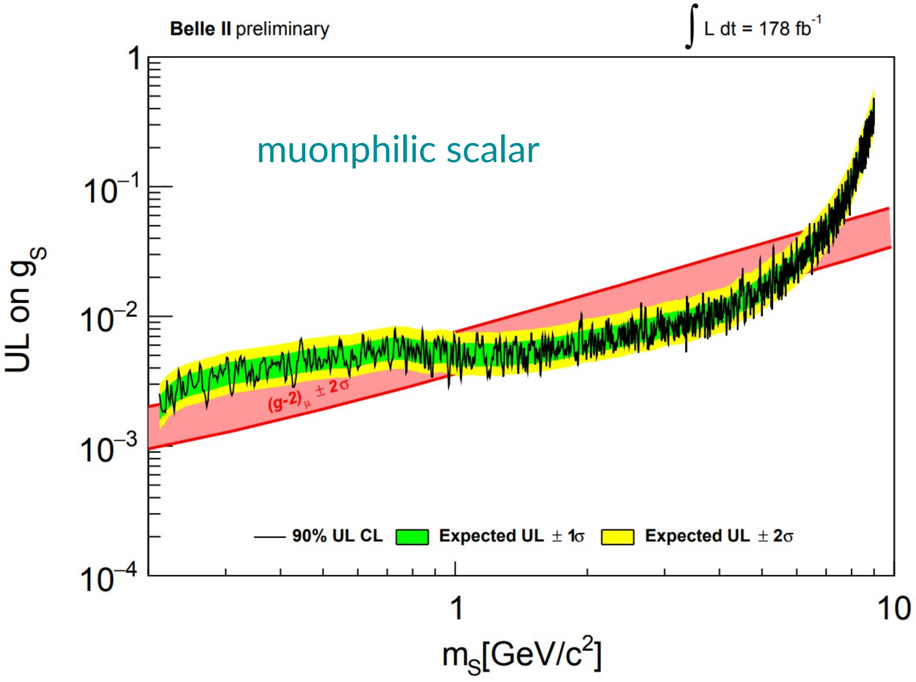
$Z' \to \mu\mu$ at Belle II

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

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 → **agressive background suppression through neural networks**
  - First 90% CL upper limits for the **muonphilic scalar model** from a dedicated search

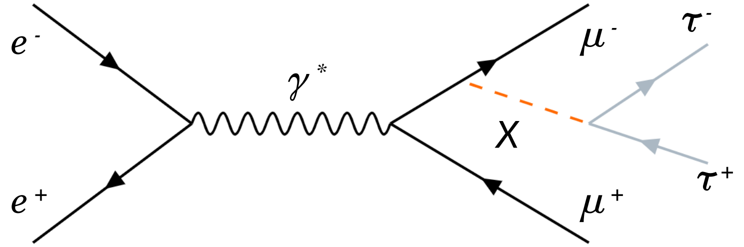




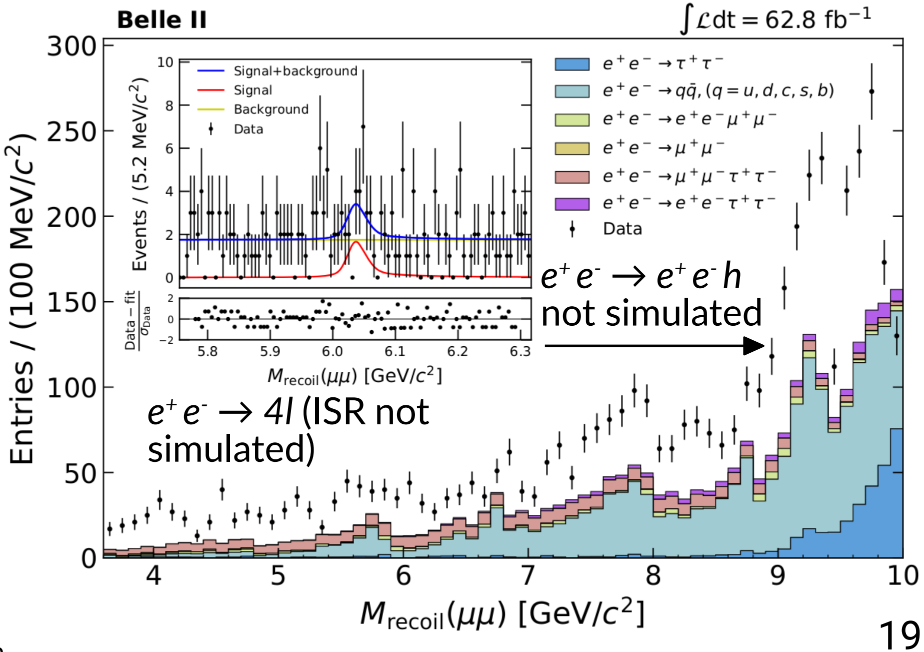
$\tau\tau$-resonance in $e^+e^- \rightarrow \mu^+\mu^-\tau^+\tau^-$ at Belle II

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** through **neural networks**
  - 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



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

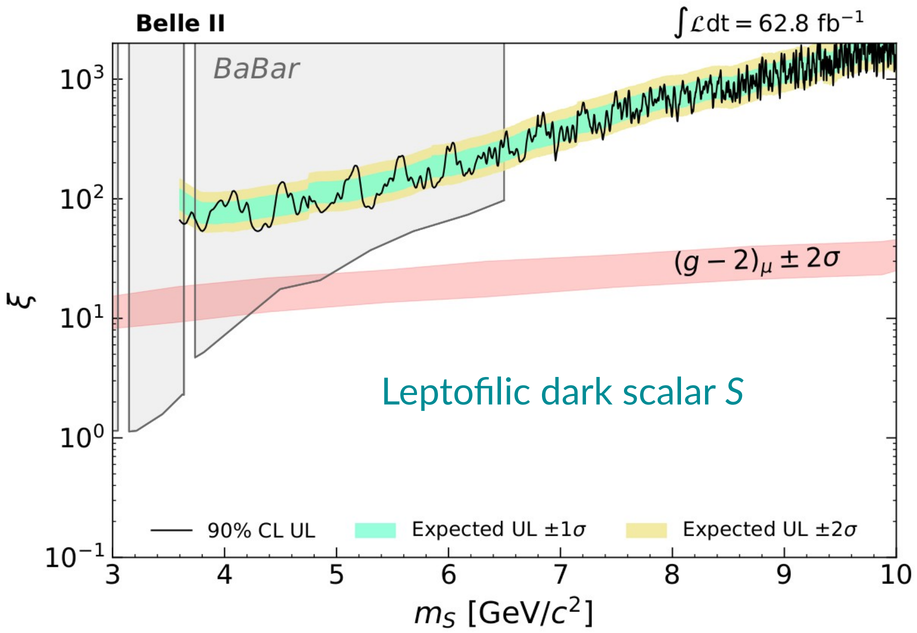


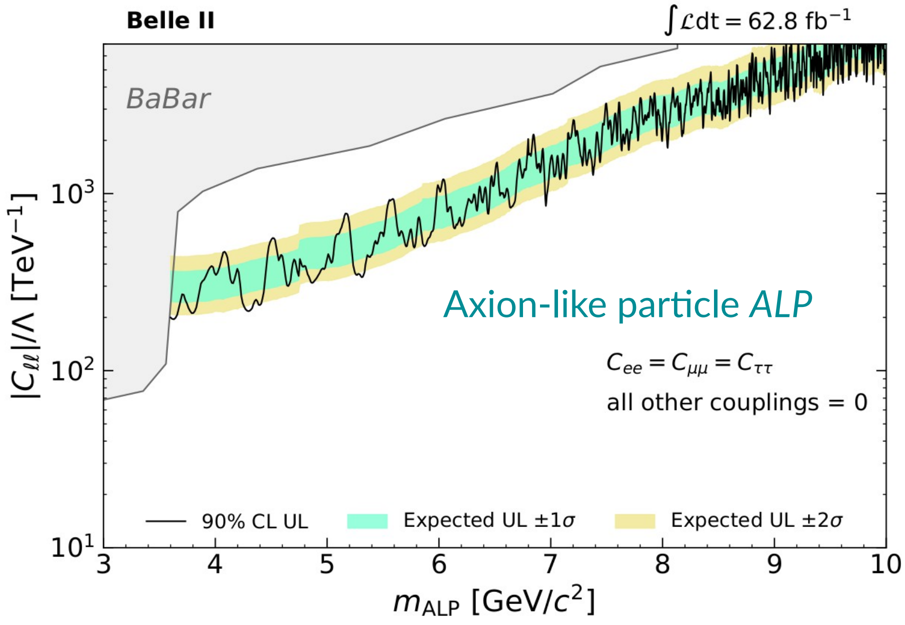
$\tau\tau$-resonance in $e^+e^- \to \mu^+\mu^-\tau^+\tau^-$ at Belle II

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* → $\tau\tau$**

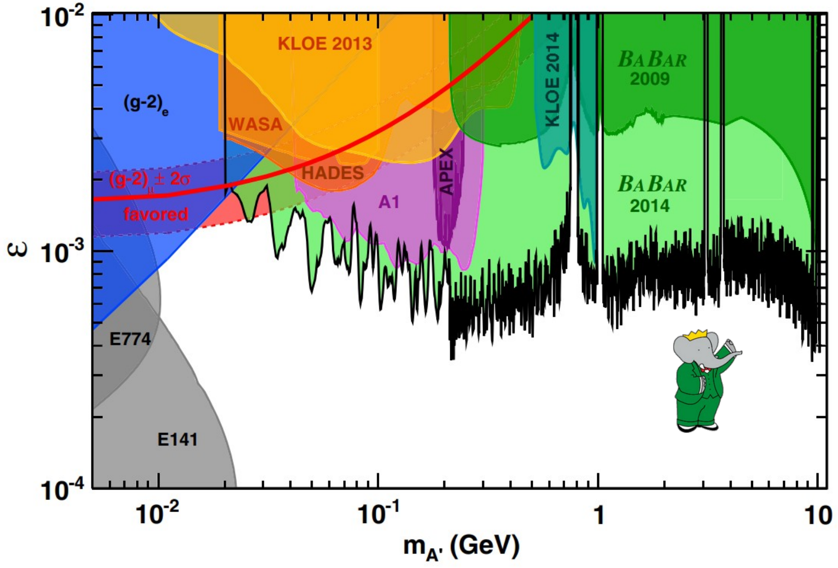




Dark photon (A') at BaBar and LHCb

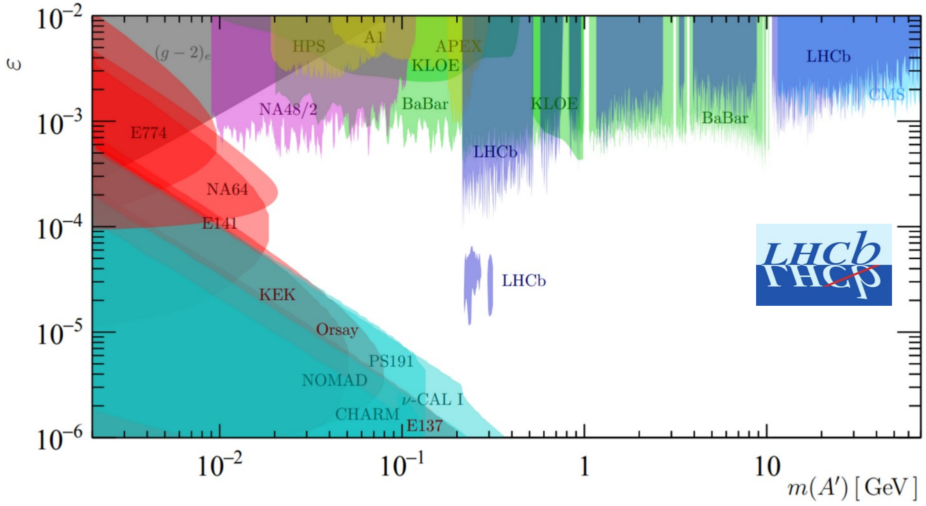
- A' mixes with SM through **mixing strenght ε**
- **BaBar** with 514 fb^{-1}
  - $e^+e^- \rightarrow \gamma_{ISR} A' (\rightarrow e^+e^-/\mu^+\mu^-)$
  - Signature: bump in the di-lepton invariant mass
  - **Set 90% CL upper limit on ε at level of O(10^{-3})**

J.P. Lees et al., Phys. Rev. Lett. 113, 201801 (2014)



- **LHCb** with 5.5 fb^{-1}
  - ***A'* → *μ⁺μ⁻*** in *p-p* collisions at 13 TeV
  - In the **~ 200 -700 MeV range better results**
  - **First displaced exclusion not from beam dump experiments**

R. Aaij et al., Phys. Rev. Lett. 124, 041801 (2020)

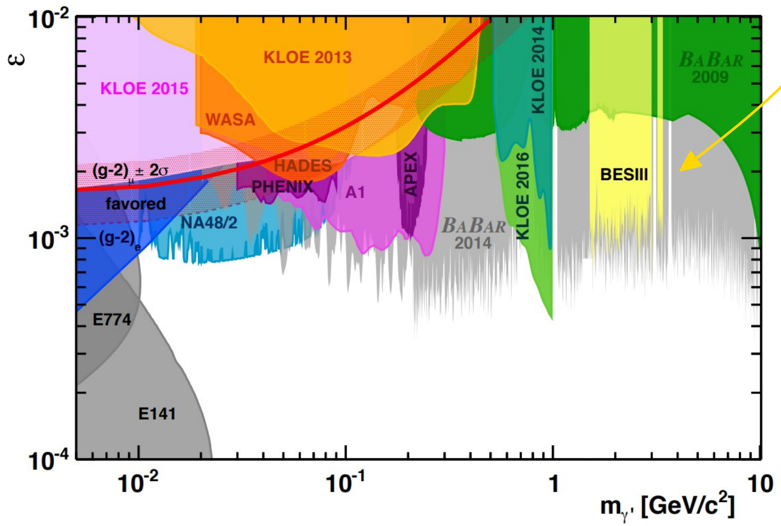


Dark photon (A') at BES III

$e^+e^- \to \gamma_{ISR} A', A' \to l^+l^- \ (l = e, \mu)$

- 2.93 fb^{-1} at $\sqrt{s}$ = 3.773 GeV
- Untagged photon method to increase statistics
- Search for a narrow peak in $m_{l^+l^-}$ spectrum
- **90% CL UL on $\varepsilon \sim O(10^{-4} - 10^{-3})$, $1.5 < m_{A'} < 3.4$ GeV/c^2**

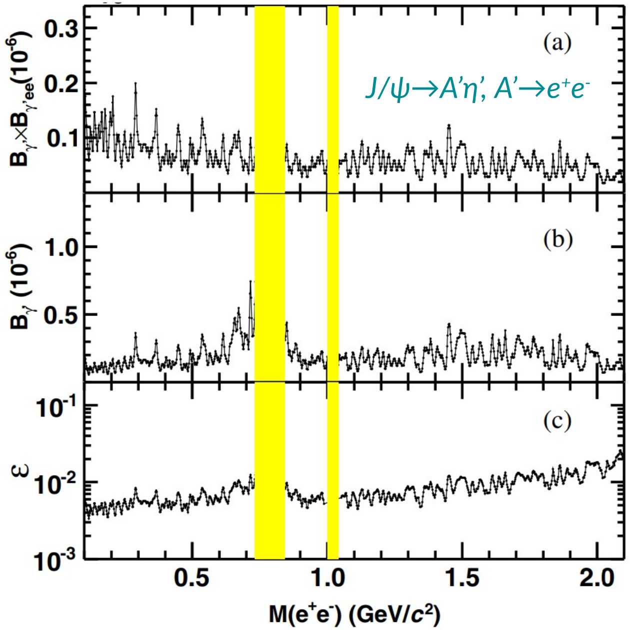
M. Ablikim et al., Phys. Lett. B 774, 252 (2017)



$J/\psi \to A' \eta/\eta', A' \to e^+e^-$

- First search for dark photon via electromagnetic Dalitz decays with **1.3 billion J/ψ**
- **90% CL limits on $\varepsilon \sim O(10^{-3} - 10^{-2})$ for $0.1 < m_{A'} < 2.$ GeV/c^2**

M. Ablikim et al., Phys. Rev. D 104, 099901 (2021)

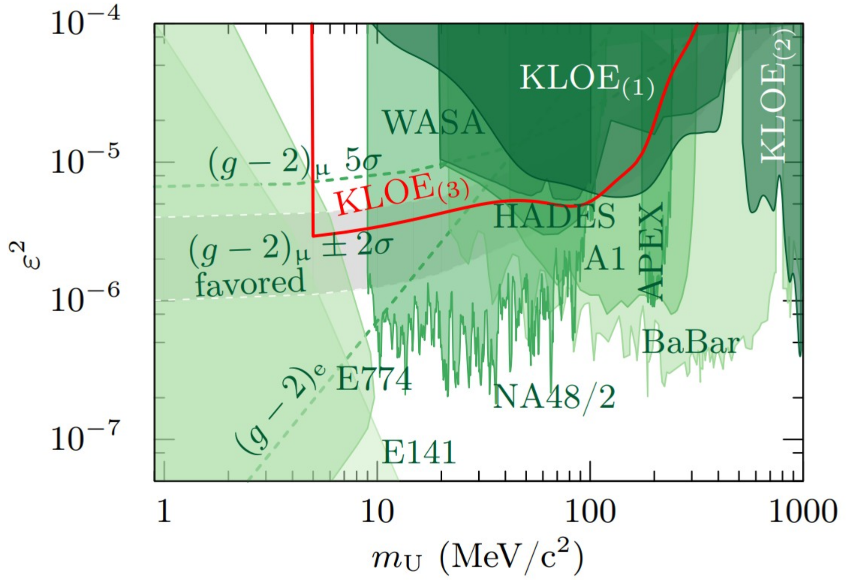


Dark photon (A') at KLOE/KLOE-2

$e^+e^- \rightarrow \gamma_{ISR} A', A' \rightarrow e^+e^-$

- 1.54 fb^{-1} at $\sqrt{s}$ = 1.019 GeV
- Search for a narrow peak in m_{e+e-} spectrum
- **90% CL UL on ε^2 ~ O(10^{-6} – 10^{-4}) in the mass range 5 – 520 MeV/c^2**

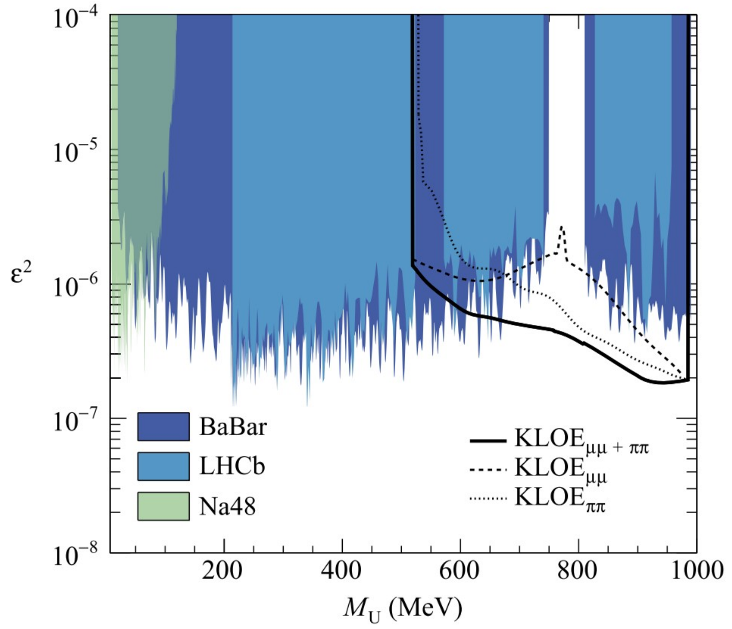
A. Anastasi et al., Phys. Lett. B 750 633-637 (2015)



$e^+e^- \rightarrow \gamma_{ISR} A', A' \rightarrow \mu^+\mu^-/\pi^+\pi^-$

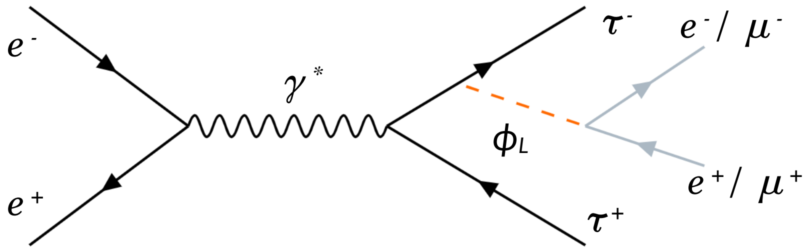
- 1.93 fb^{-1} at $\sqrt{s}$ = 1.019 GeV
- Search for a narrow peak in $m_{\mu+\mu-/\pi+\pi-}$ spectrum
- **90% CL UL on ε^2 ~ O(10^{-7}) in the mass range 519–987 MeV/c^2**

A. Anastasi et al., Phys. Lett. B 784 336-341 (2018)



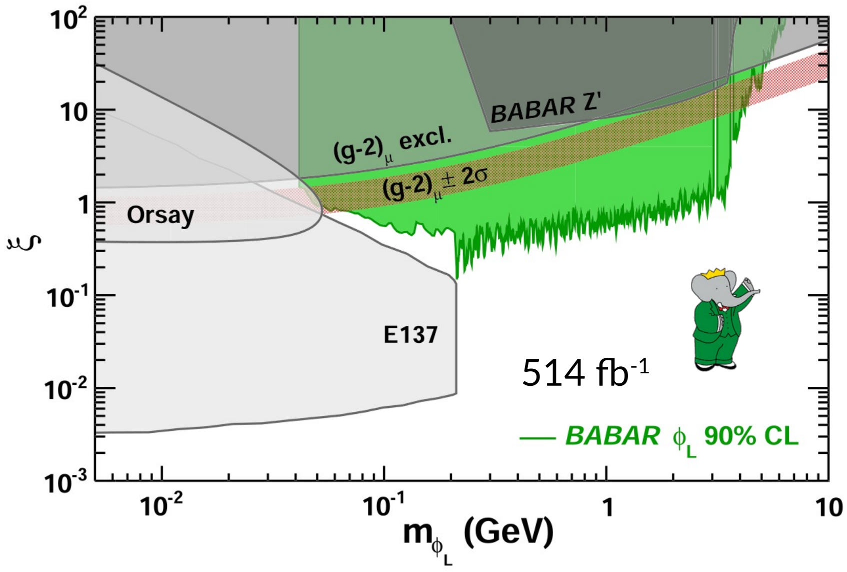
Dark scalar at BaBar and Belle

$e^+e^- \to \tau^+\tau^- \phi_L (\to l^+l^-), l = e, \mu$

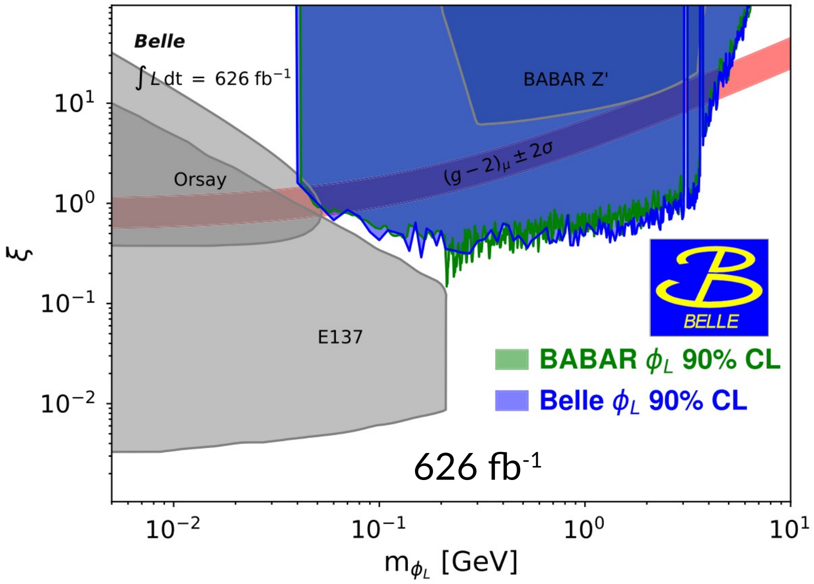


- ϕ_L is a **leptophlic scalar**
  - It would be produced predominantly through radiation from a τ lepton
- ϕ_L reconstructed as invariant mass of the l^+l^- system
- Results exclude ϕ_L as explanation for $(g\text{-}2)_\mu$ for masses below 4 GeV/c^2, at 90% CL

J. P. Lees et al., Phys. Rev. Lett. 125, 181801 (2020)



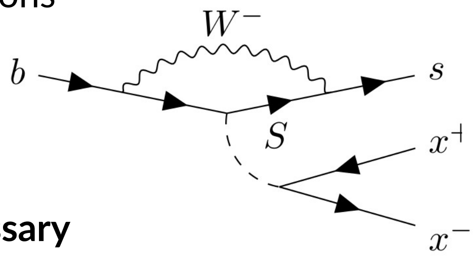
D. Biswas et al., Phys. Rev. D 109, 032002 (2024)

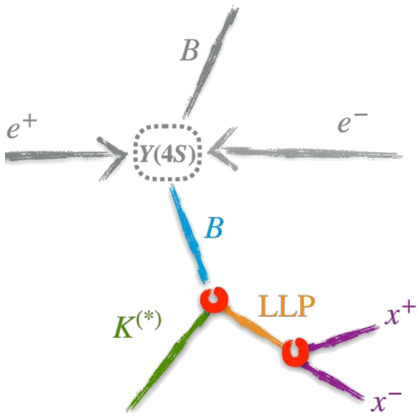


LLP in $b \to s$ transitions at Belle II

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**



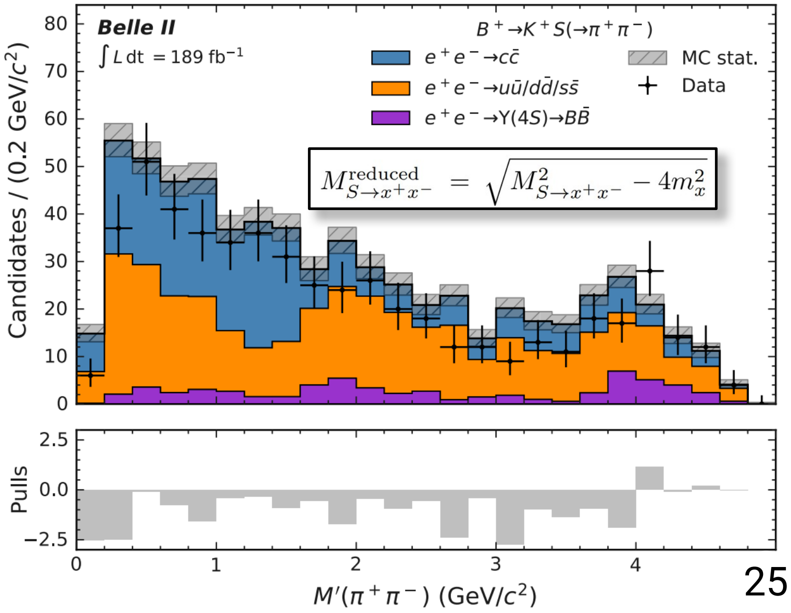


- **First Belle II dark sector search in *B*-meson decays with LLP signature**

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

- B meson decays
  - Eight exclusive “visible” channels reconstructed
  - Prompt decay of K or K^* + opposite-charged tracks that make a **displaced vertex**

- Signal extracted through **fit to the *LLP* reduced mass, separately for each channel and lifetime**

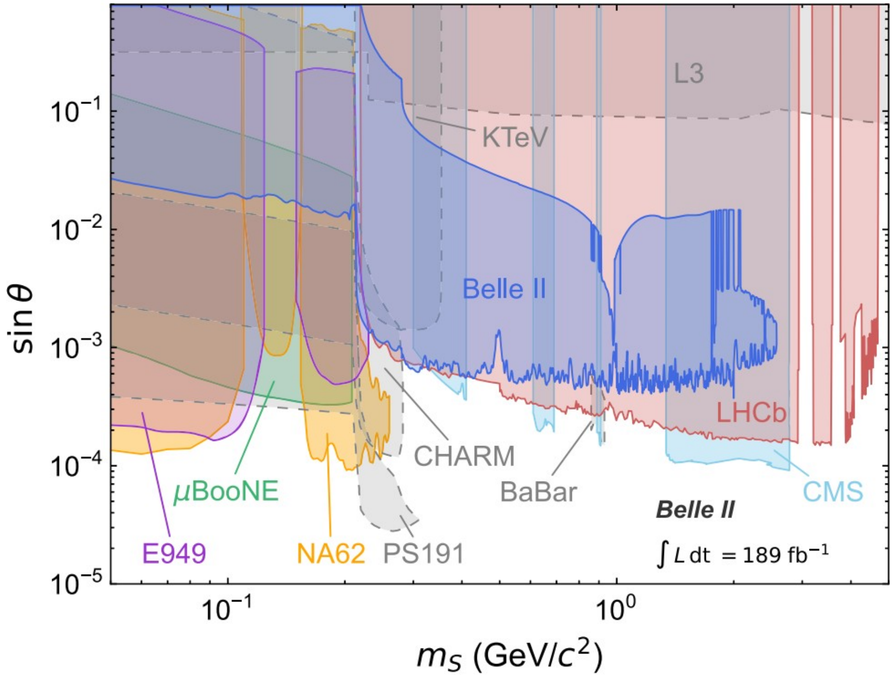


LLP in $b \to s$ transitions at Belle II

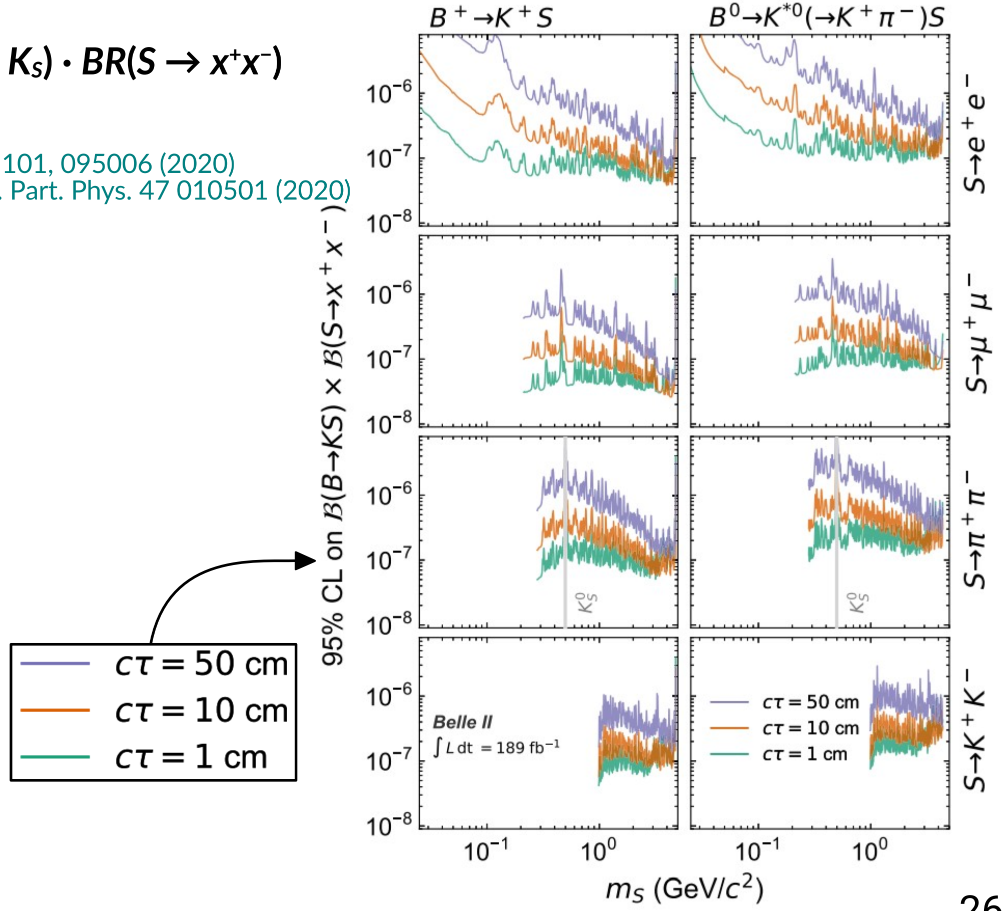
I. Adachi et al., Phys. Rev. D 108, L111104 (2023)

- 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



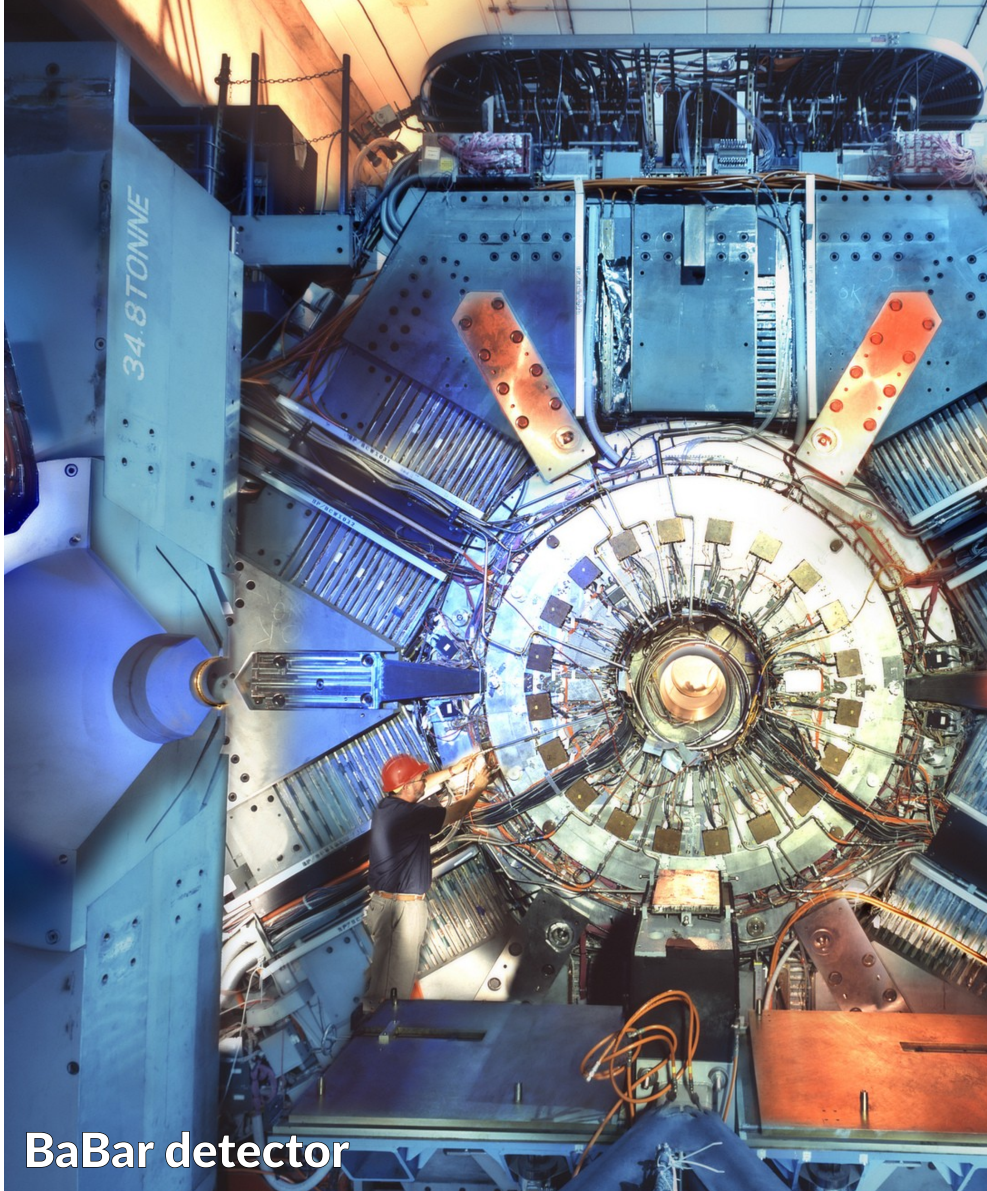
Invisible decays

Decays to SM particles

ALPs $\to \gamma\gamma$

Dark Higgs

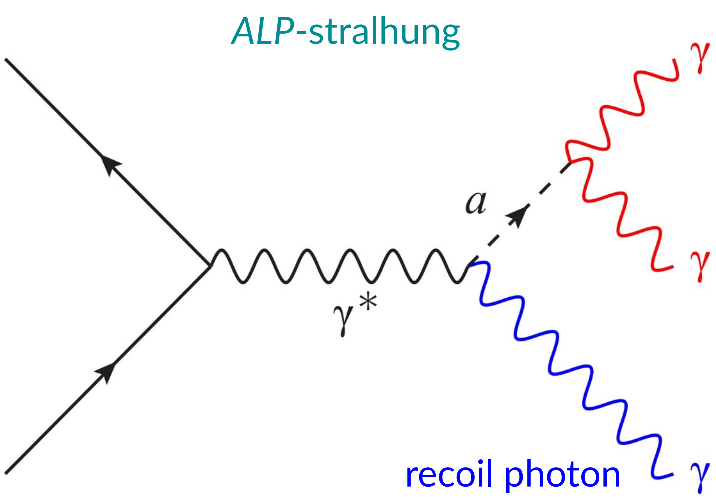
Exploring the dark sectors at experiments at $e^{+}e^{-}$ colliders

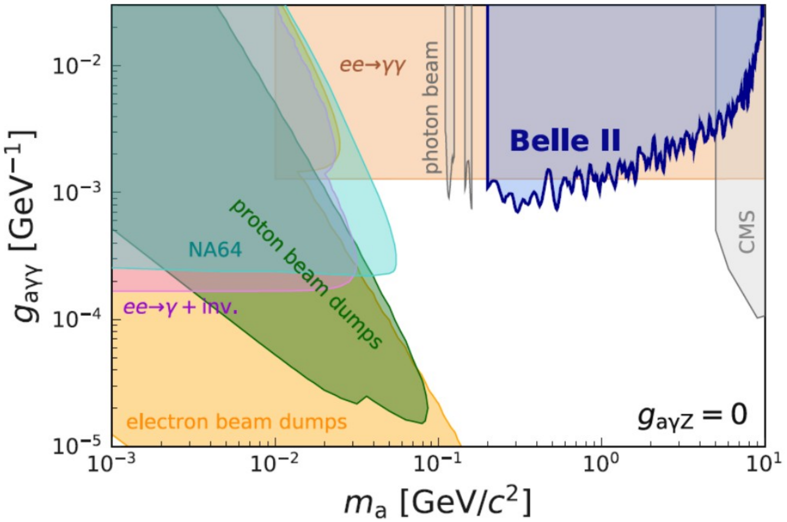


ALP → γγ at Belle II

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

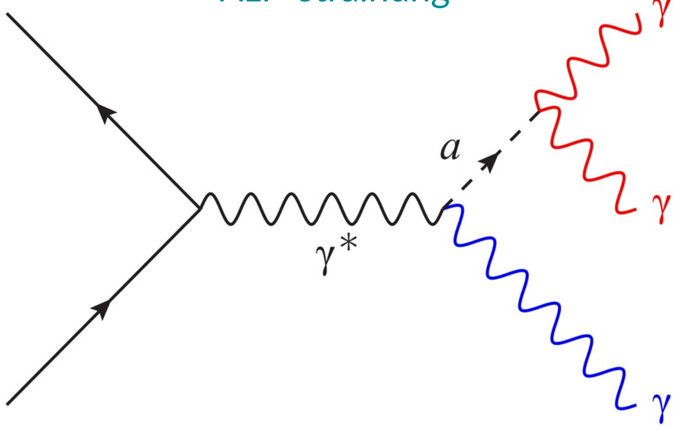
- *ALP*-photon coupling ($g_{a\gamma\gamma}$) dominates: *BR*($ALP \to \gamma\gamma$) ~ 100%
- $e^+e^- \to \gamma\, ALP\, (\to \gamma\gamma)$
  - electromagnetic calorimeter trigger (efficiency ~100%)
  - three-γ invariant mass compatible with collision √s
- Signal signature is a **narrow peak in $M^2_{\gamma\gamma}$ 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}** (Belle II commissioning run)
  - Upper limits at 95% CL on $g_{a\gamma\gamma}$
  - **World-leading limits for m_a ~ 0.5 GeV/c^2**



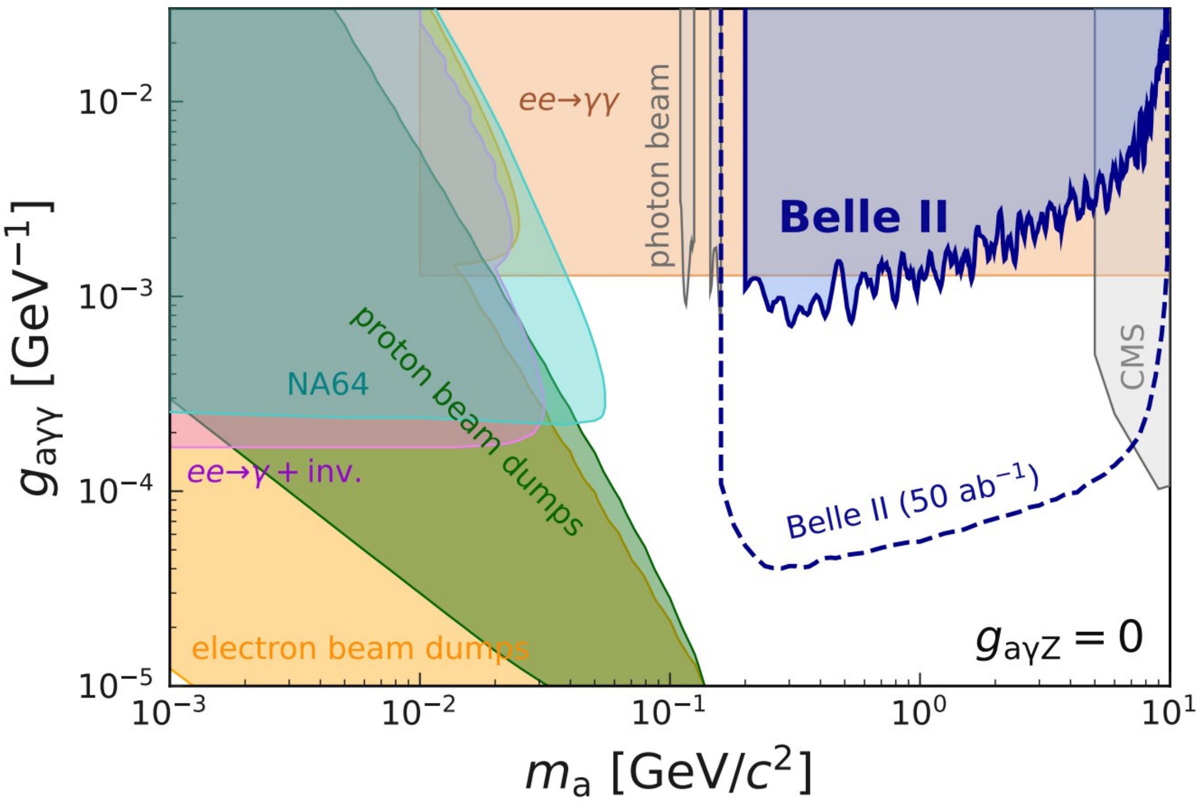


ALP → γγ prospects at Belle II

ALP-stralhung

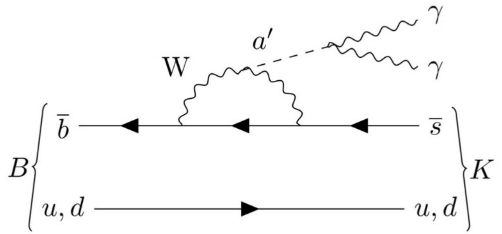


Snowmass White Paper Belle II, arXiv:2207.06307 [hep-ex] (2022)



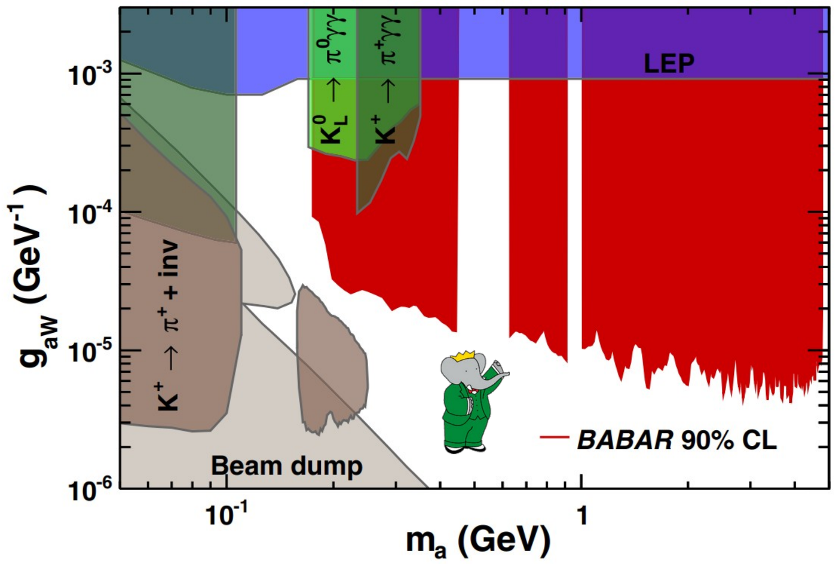
- Next update based on Belle II Run 1 luminosity in progress

$B \to K^{(*)}\, a\, (\to \gamma\gamma)$ at BaBar and Belle



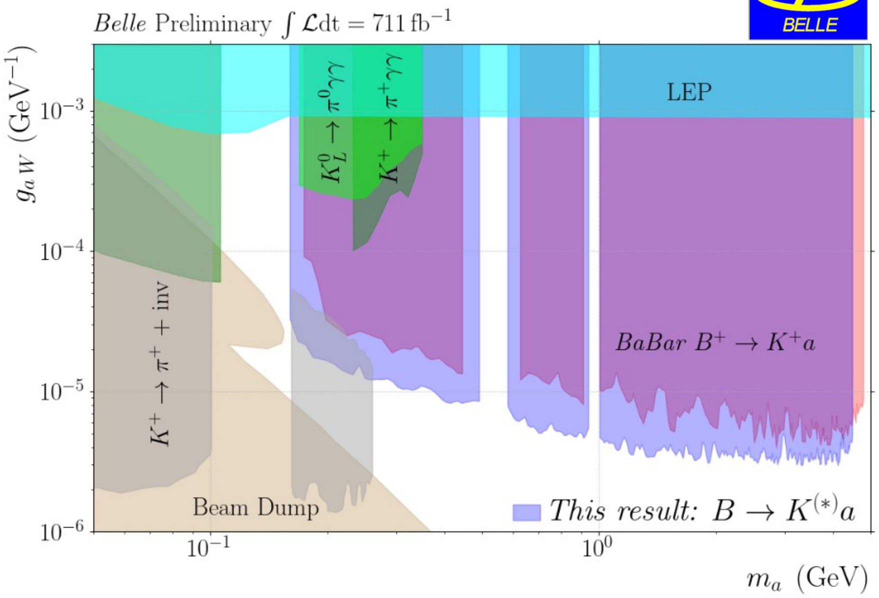
- Axion-like particles in B decays
  - ***ALP* decaying 100% to $\gamma\gamma$**
- Probe **ALP-W** coupling in **$b \to s$ transitions**
- ***$B \to K^{\pm}a\ (\to \gamma\gamma)$*** at **BaBar** with 424 fb^{-1}

J. P. Lees et al., Phys. Rev. Lett. 128, 131802 (2022)



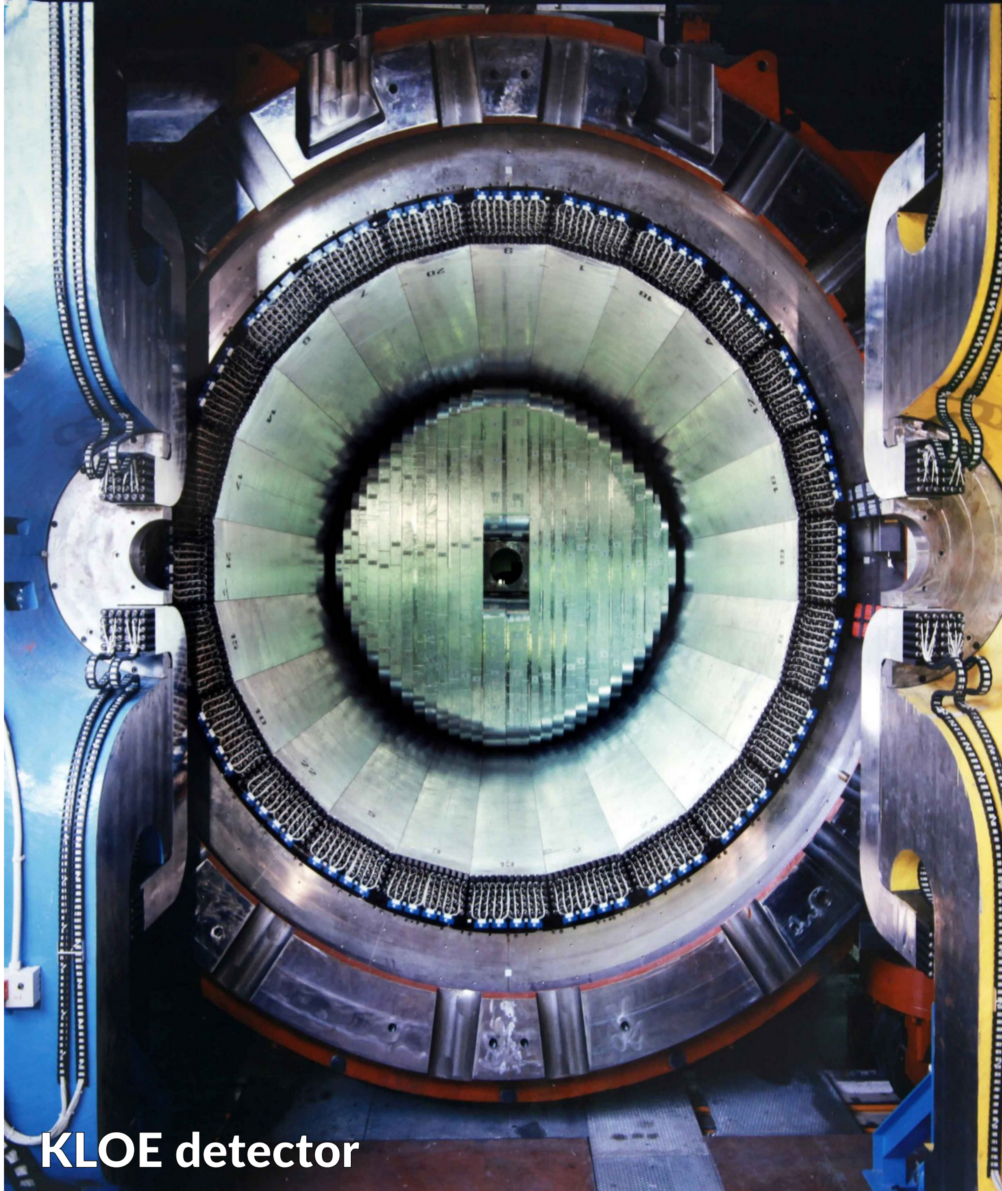
- Belle with 711 fb^{-1}
- Four kaon modes: K^+, K_S^0 and K^{*+}, K^{*0}
- Set **90% CL world-leading upper limits to the $g_{a'W}$ coupling**

TO BE SUBMITTED TO **JHEP**



Invisible decays
Decays to SM particles
ALPs $\rightarrow \gamma\gamma$
Dark Higgs

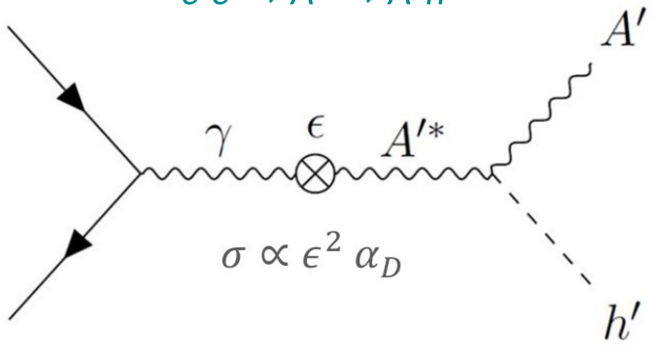
Exploring the dark sectors at experiments at e^+e^- colliders



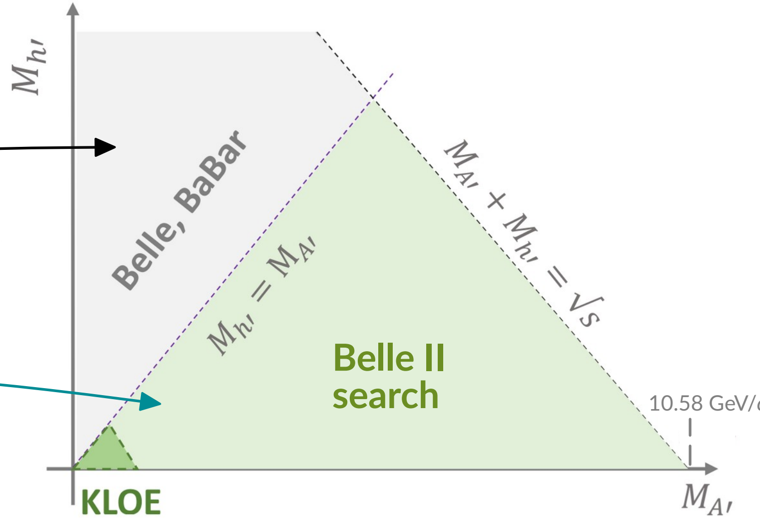
Search for a dark Higgs (and a dark photon)

- **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 $\boldsymbol{\alpha_D}$
- Dark higgstrahlung $e^+e^- \to A'^* \to A'\,h'$
- 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) and Belle II (2023)

$e^+e^- \to A'^* \to A'\,h'$



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

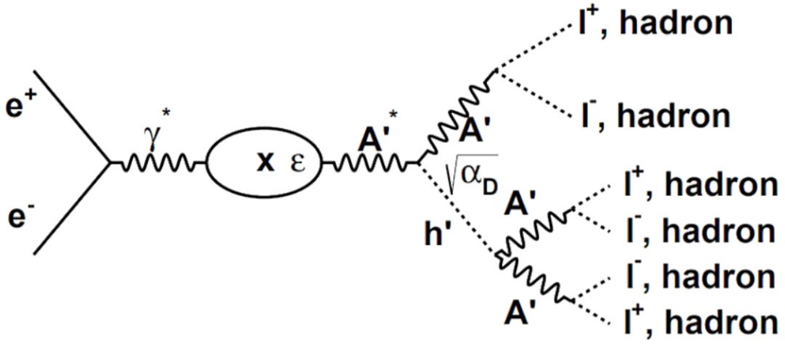


$h' \to A'A'$, $A' \to ll$, hh at BaBar and Belle

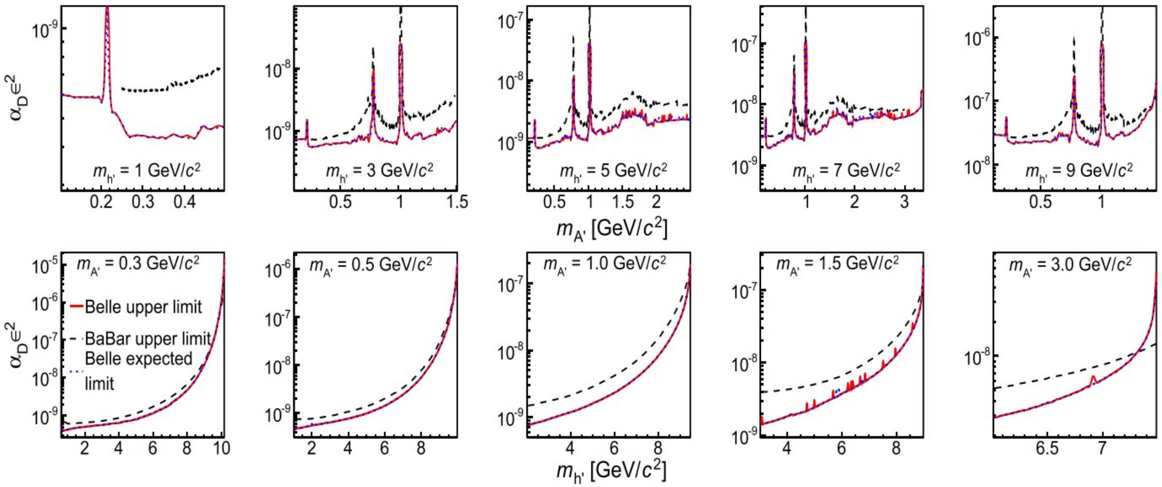
$M_{h'} > M_A$

[1] J. P. Lees et al., Phys. Rev. Lett. 108, 211801 (2012)
[2] I. Jaegle et al., Phys. Rev. Lett. 114, 211801 (2015)

- BABAR[1] and Belle[2] searched for the **visible *h'***
  - Signal: three pairs of tracks (*ee*, *μμ*, *ππ*) at the same mass and no missing energy
  - Background: almost background free
- Full data-sets from both experiments (BABAR: 516 fb^{-1}, Belle: 977 fb^{-1})
- **90% CL upper limits on $\varepsilon^2 \cdot \alpha_D$ at the level of O(10^{-10} - 10^{-8}):**
  - Belle limits improve upon and explore slightly wider mass ranges than BaBar



I. Jaegle et al., Phys. Rev. Lett. 114, 211801 (2015)

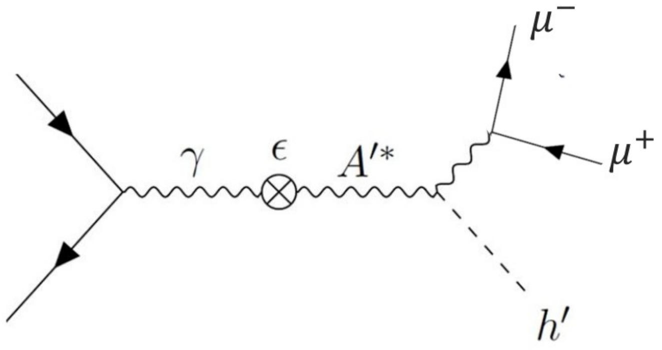


$h' \rightarrow$ invisible at KLOE/KLOE-2

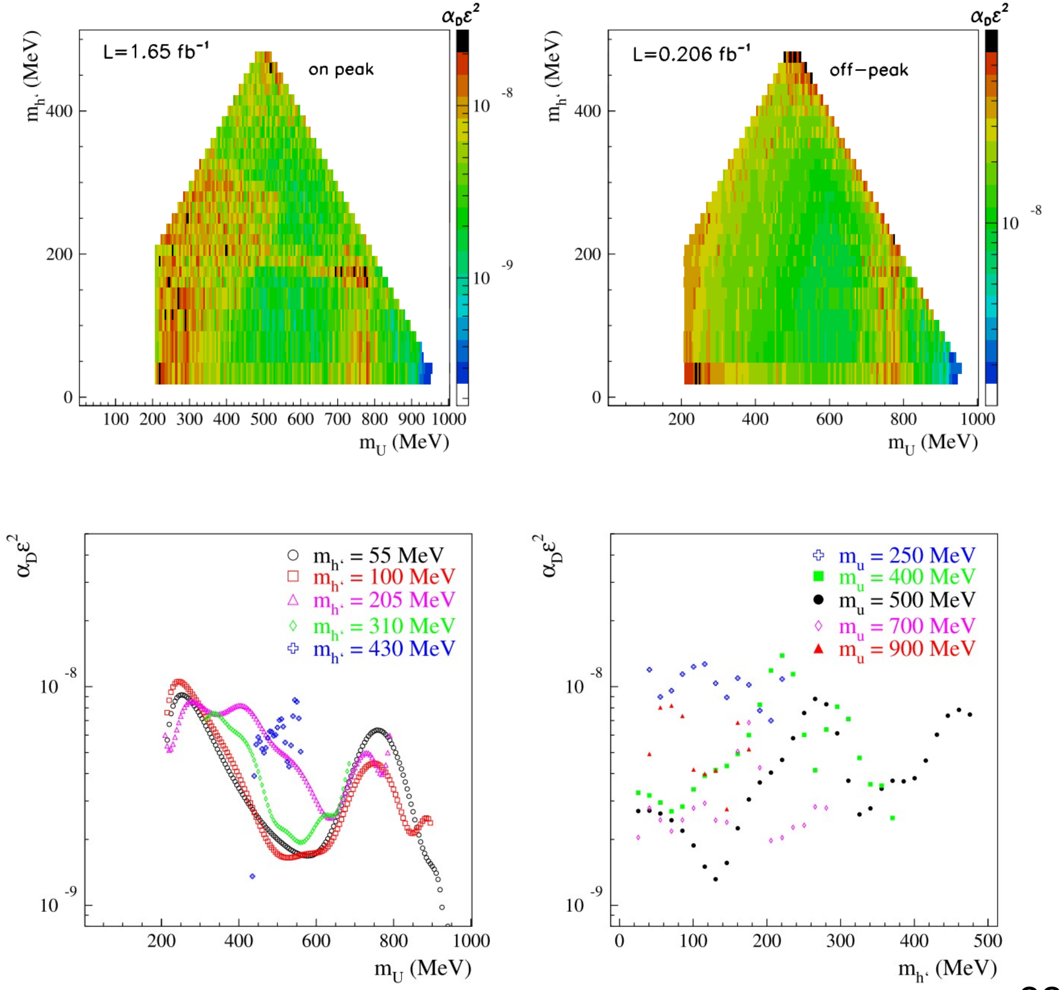
First limits for $M_{h'} < M_{A'}$

A. Anastasi et al., Phys. Lett. B 747 365-372 (2015)

- ***$e^+e^- \rightarrow A'h', A' \rightarrow \mu\mu, h' \rightarrow$ invisible***



- h' rconstructed as recoil to the $\mu\mu$ system
- Signature: 2D peak in recoil vs dimuon mass
- 1.65 fb^{-1} at the ϕ resonance, 0.21 fb^{-1} off-peak
- **Limits on $\varepsilon^2 \cdot \alpha_D$ range from 10^{-9} – 10^{-8}**
- **Assuming $\alpha_D = \alpha_{em} \rightarrow \varepsilon \sim O(10^{-4} – 10^{-3})$**

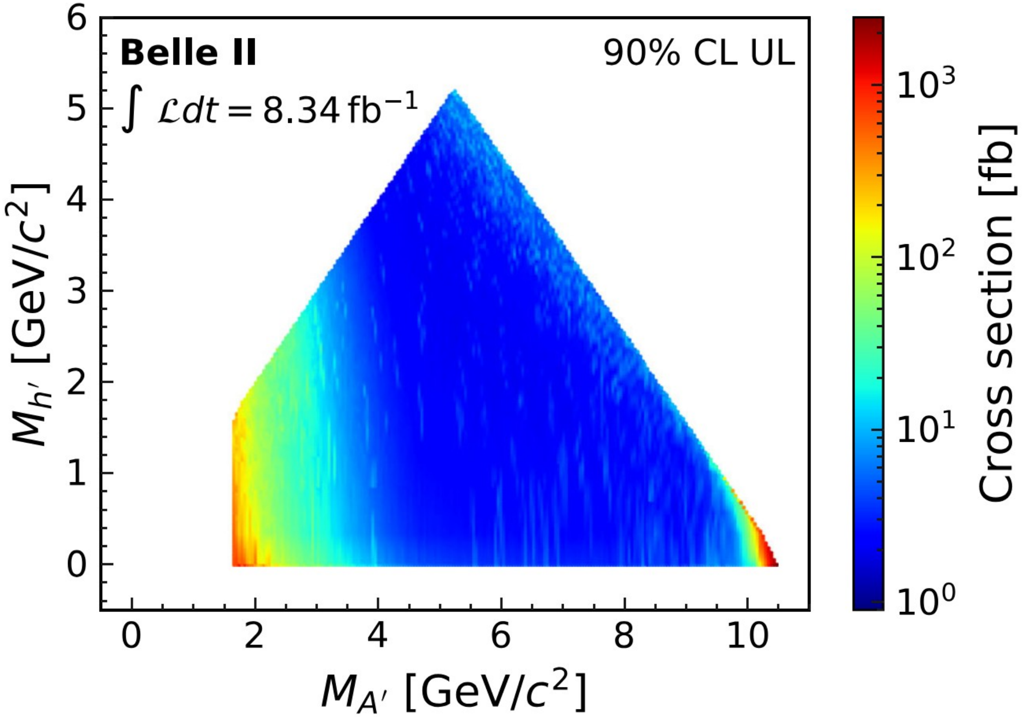


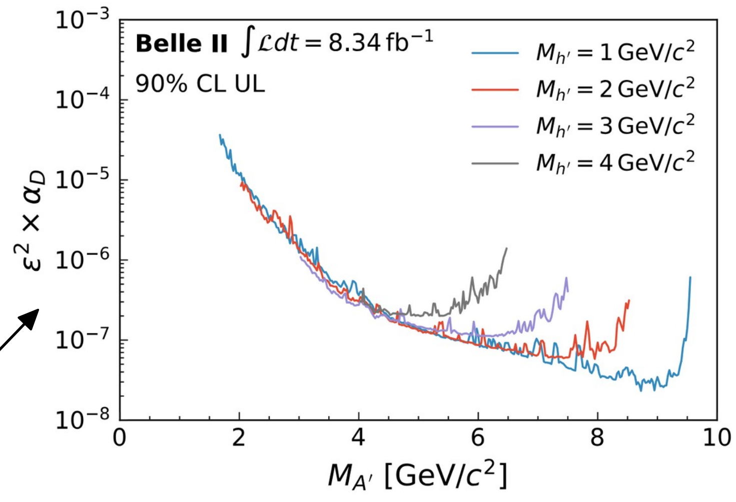
$h' \to$ invisible at Belle II

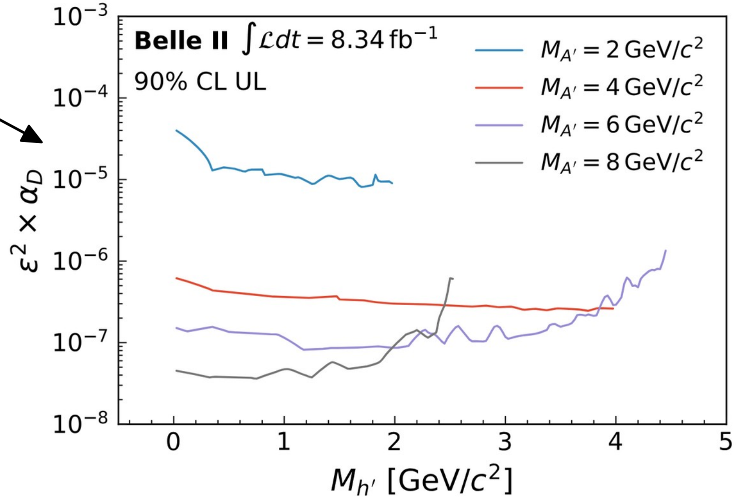
F. Abudinén et al., Phys. Rev. Lett. 130, 071804 (2023)

$M_{h'} < M_A$

- **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**

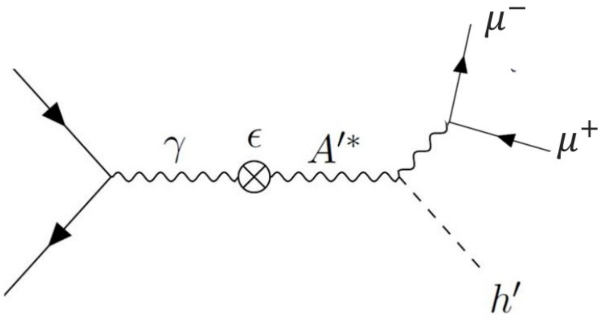




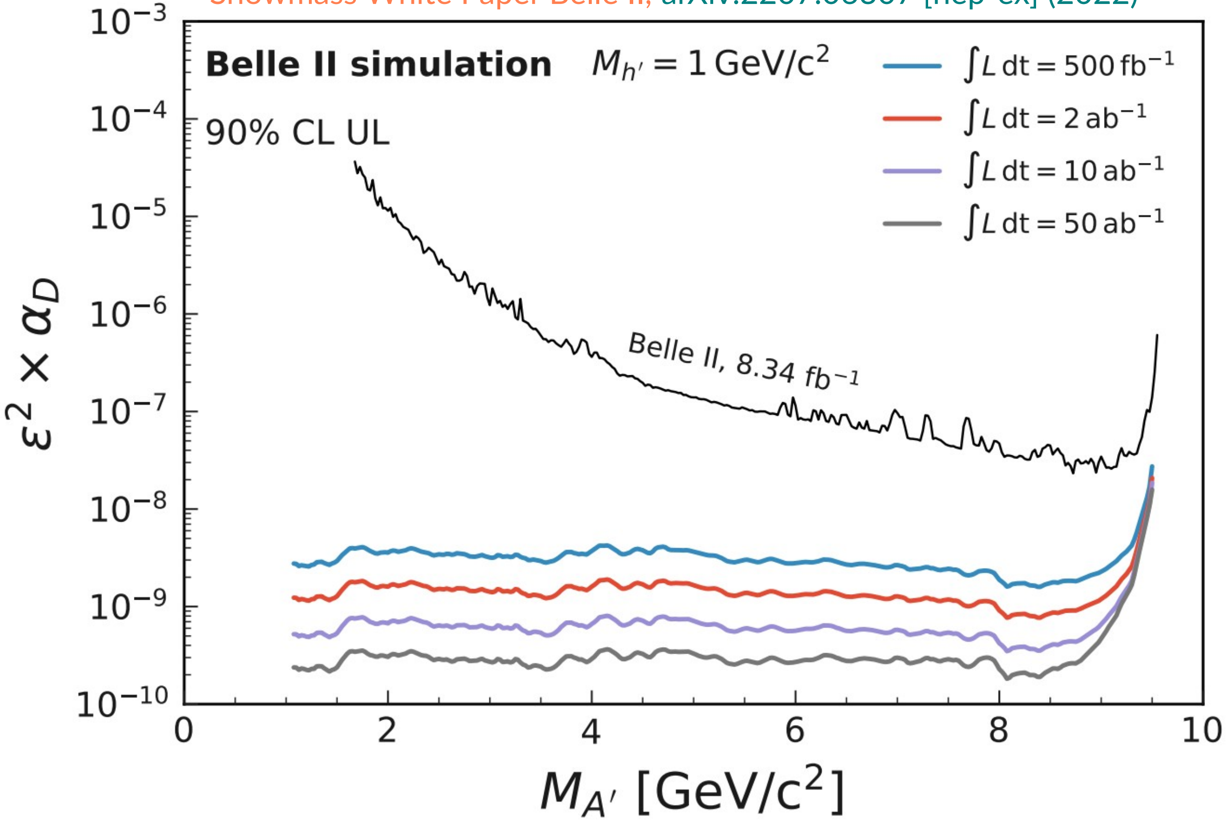


$h' \to$ invisible prospects at Belle II

$e^+e^- \to A'h', A' \to \mu\mu, h' \to$ invisible



Snowmass White Paper Belle II, arXiv:2207.06307 [hep-ex] (2022)



- Next update based on Belle II Run 1 luminosity in progress

Inelastic dark matter with a dark Higgs at Belle II

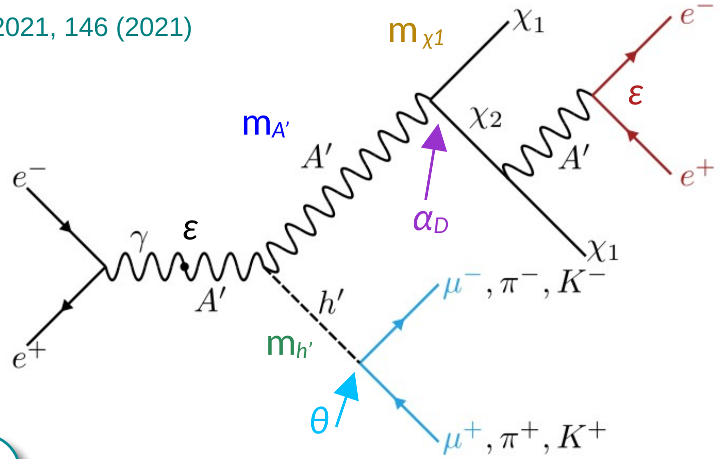
Duerr, M., et al., J. High Energ. Phys. 2021, 146 (2021)

Inelastic dark matter

- Eludes constraints from direct searches
- ***A', χ_1* is stable** (relic candidate), **χ_2 is long-lived**
- Focus on $m_{A'} > m_{\chi 1} + m_{\chi 2}$: the decay $A' \rightarrow \chi_1 \chi_2$ is favored

Dark higgs *h'*

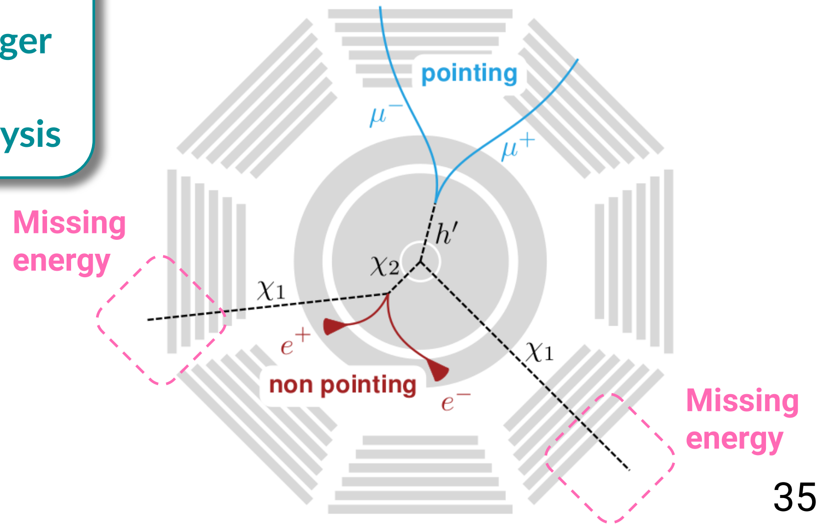
- ***h'* mixes with Standard Model Higgs** with θ
- ***h'* is natural long-lived** (*LLP*) for small θ



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

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

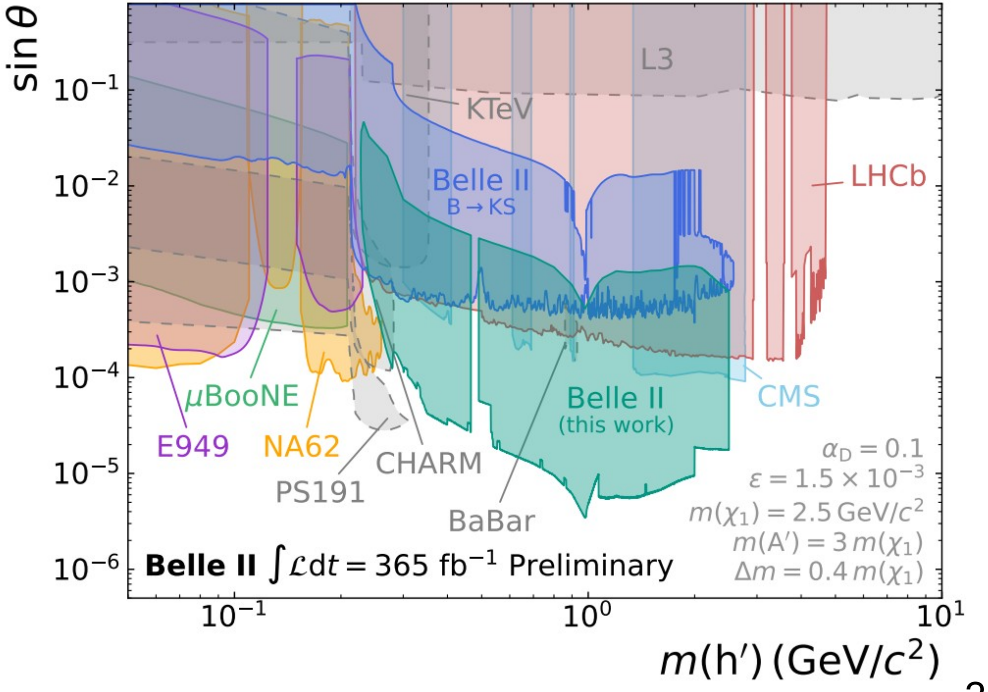
- **Challenging for tracking and trigger**
- **Almost zero background analysis**



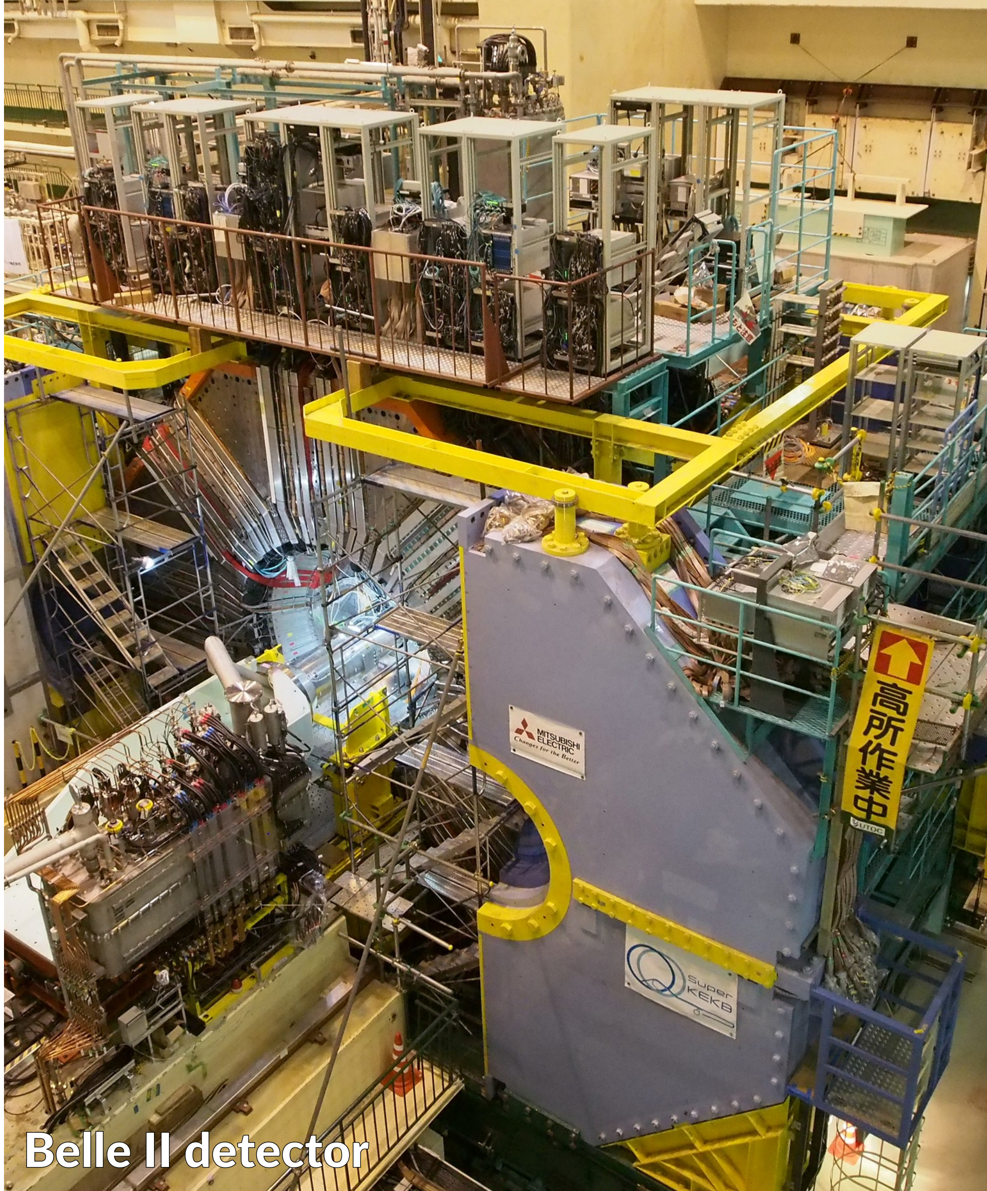
Inelastic dark matter with a dark Higgs at Belle II

- **Cut-and-count strategy** for extracting signal yields
- **Expected background estimated in data** from sidebands
- **No significant excess found** in 365 fb^{-1} in the individual final states or the combination
  - **set 95% CL upper limits**
- **Scan of ($m_{h'}$, sinθ) for different values of the other parameters**
  - Process cross section does not depend on θ, efficiency does
  - Many more plots (~30) for different configurations

TO BE SUBMITTED TO **PRL**



Summary and conclusions



Belle II detector

Summary and conclusions

Experiments at e^+e^- colliders offer excellent opportunities to probe dark sector models

- **Some searches** are motivated by the **$(g\text{-}2)_\mu$ anomaly** → Their **future depends from external inputs**
- Growing interests in LLP searches → low SM background; open the possibility to explore small couplings

Belle II

- **Larger data sets** (427 fb^{-1} (Run1) + 148 fb^{-1} (Run 2) collected)
  - Reasonable luminosity projections
- **Improved analysis techniques**

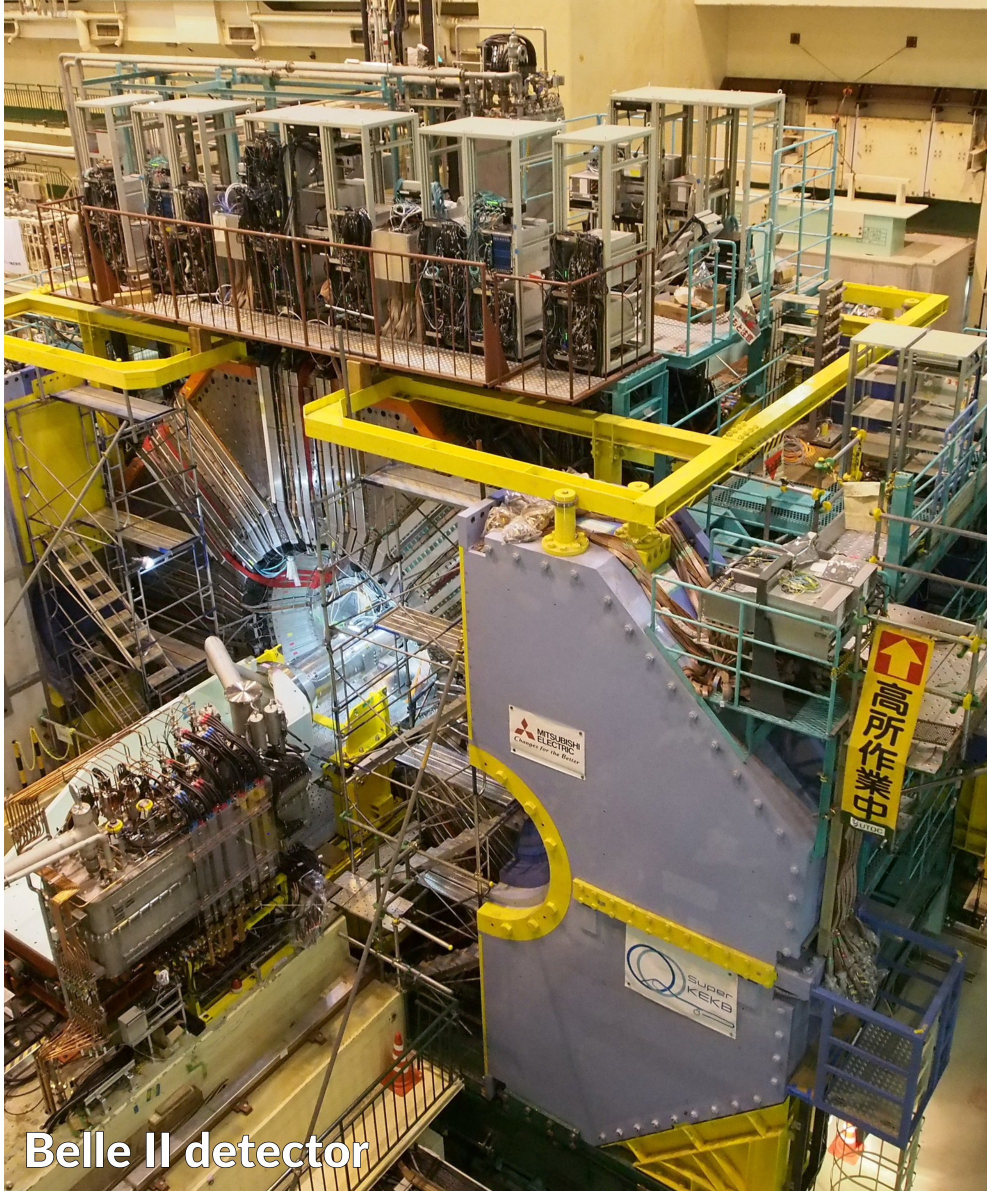
SHORT TERM IMPROVEMENTS

- Increase in luminosity leads to **increase in background levels**
- Keep **low-multiplicity trigger lines** (single-photon, -track, -muon, ...) **in working conditons**
- **Displaced-vertex trigger and tracking** (in preparation)

CHALLENGES

- **Belle II is expected to lead the world sensitivity in most of the dark sector searches**

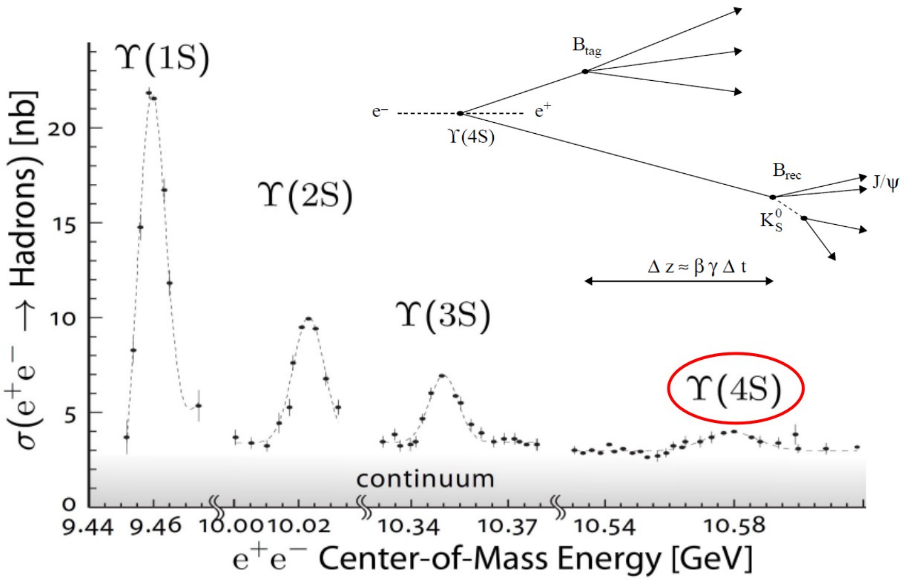
Backup slides



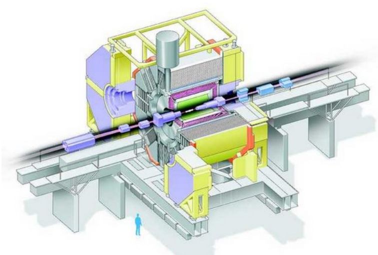
Belle II detector

B-factories

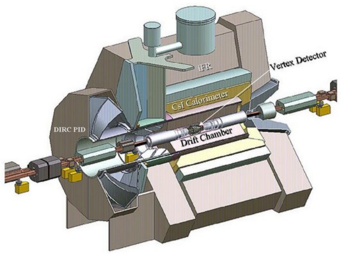
- **Asymmetric e^+e^- colliders** optimized for the production of *B* meson pairs, but also *D* mesons, τ leptons, …
- **Collisions occur at Υ(nS) resonances**
  - Mainly at Υ(4S): $\sqrt{s}$ = 10.58 GeV
    just above the production threshold of $B\bar{B}$
    $BR(\Upsilon(4S) \to B\bar{B}) > 96\%$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



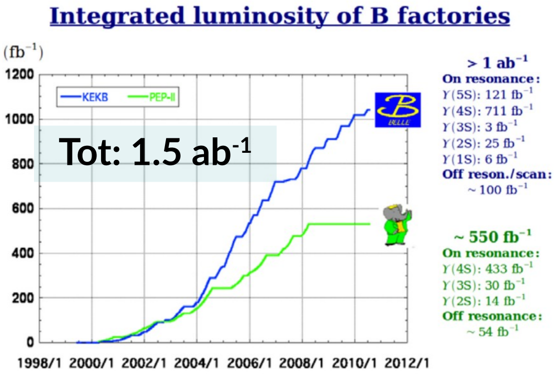
First generation of *B*-factories



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}



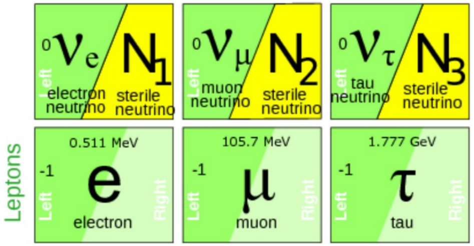
Heavy neutral lepton in τ decays at Belle

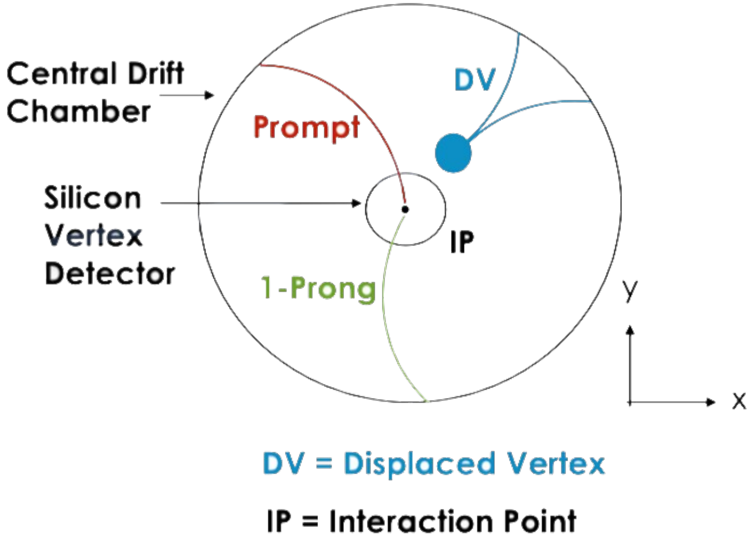
M. Nayak, Phys. Rev. D 109, L111102 (2024)

[1] T. Asaka et al., Phys. Lett. B 631, 151-156 (2005)
[2] F F Deppisch et al., New Journal of Physics (2015)

- **Heavy sterile neutrinos *N*** appears in many extensions of the SM[1]
  - ***N*** mixes with $\boldsymbol{\nu_{SM}}$
  - ***N* long-lived** for small values of N-ν_{SM} mixing
- **Limits on $|V_{\tau N}|^2$ are much weaker** than limits on $|V_{eN}|^2$, $|V_{\mu N}|^2$ [2]
- Process: $e^+e^- \to \tau^+\tau^-$
  - **Signal side:** $\tau^- \to \pi^- N (\to \mu^+\mu^-\nu_\tau)$
    $N \to \mu^+\mu^-$ form a displaced vertex (DV) > 15 cm from the beam axis
  - **Tag side:** $\tau^+ \to \pi^+\bar{\nu}_\tau$, $\tau^+ \to \pi^+\pi^0\bar{\nu}_\tau$, $\tau^+ \to l^+\nu_l\bar{\nu}_\tau$
- Main background from $\boldsymbol{K^0 \to \pi^+\pi^-}$ **vetoed**
- Signal region divided in
  - **Low mass, SRL:** $m^{DV} < 0.42$ GeV/c^2
  - **High mass SRH:** $m^{DV} > 0.52$ GeV/c^2

Around the K^0 mass



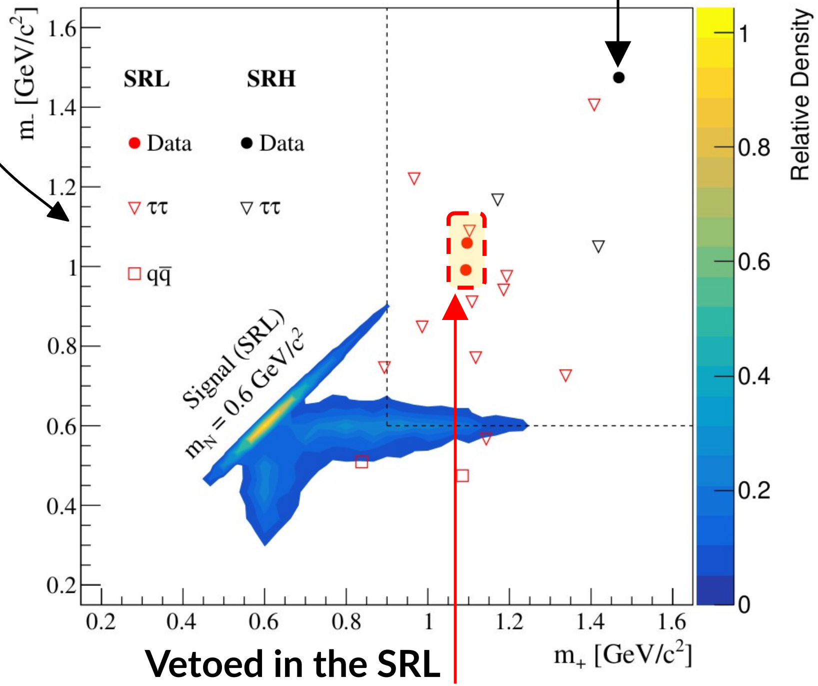


Heavy neutral lepton in τ decays at Belle

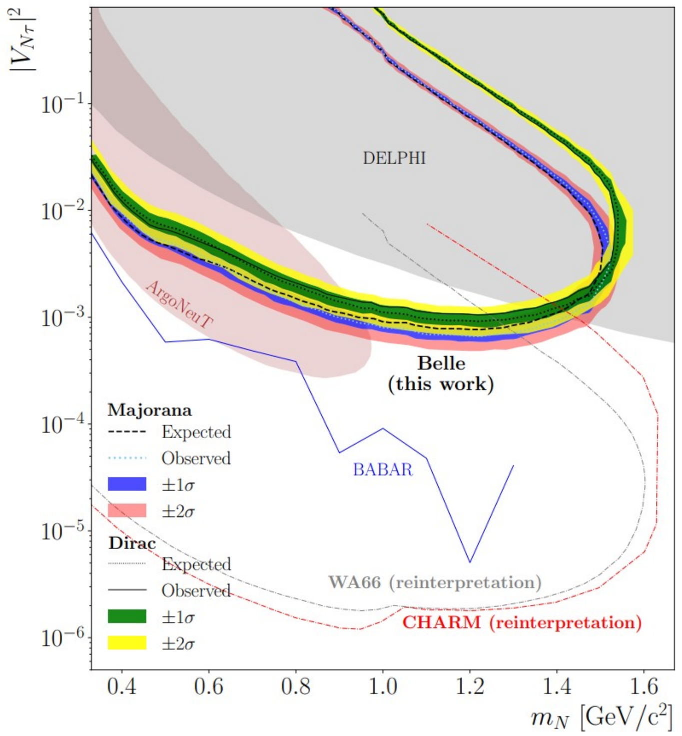
M. Nayak, Phys. Rev. D 109, L111102 (2024)

- **Full kinematics of the signal-decay chain** reconstructed with a **two-fold ambiguity** (m_+ and m_-)
  - In **SRL** and **SRH** observed respectively **0 and 1 events in 915 fb^{-1}**

One event observed



Vetoed in the SRL

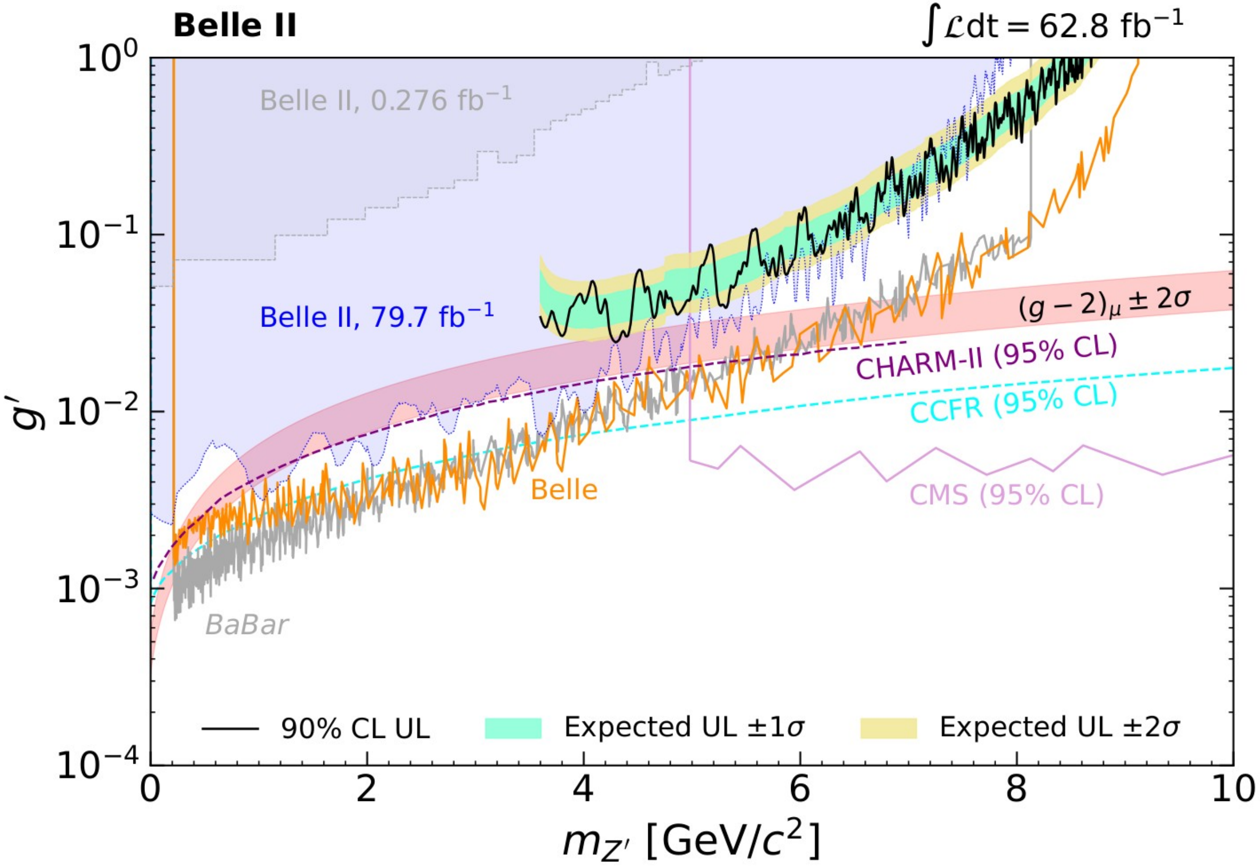


- **No significant excess observed**
  - 95% CL limits on $|V_{\tau N}|^2$ in the mass range 300 - 1600 MeV/c^2

$\tau\tau$-resonance in $e^+e^- \to \mu^+\mu^-\tau^+\tau^-$ at Belle II: Z'

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

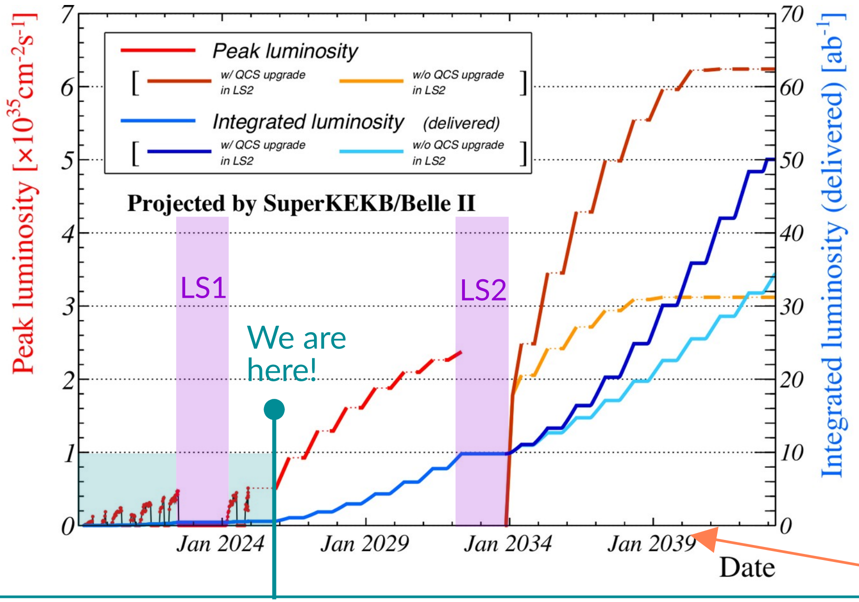
- **No significant excess found in 62.8 fb^{-1}**
  - 90% CL upper limits on the g' coupling of the $L_\mu - L_\tau$ model (Z')



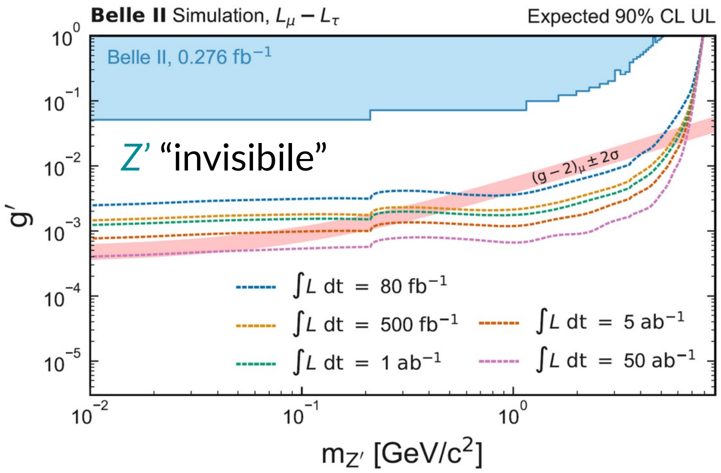
Belle II perspectives

- Target integrated luninosity: 50 ab^{-1}
- Target peak luminosity: 6×10^{35} cm^{-2} s^{-1}

Luminosity projection (plan for next years)



Snowmass paper arxiv:2207.06307

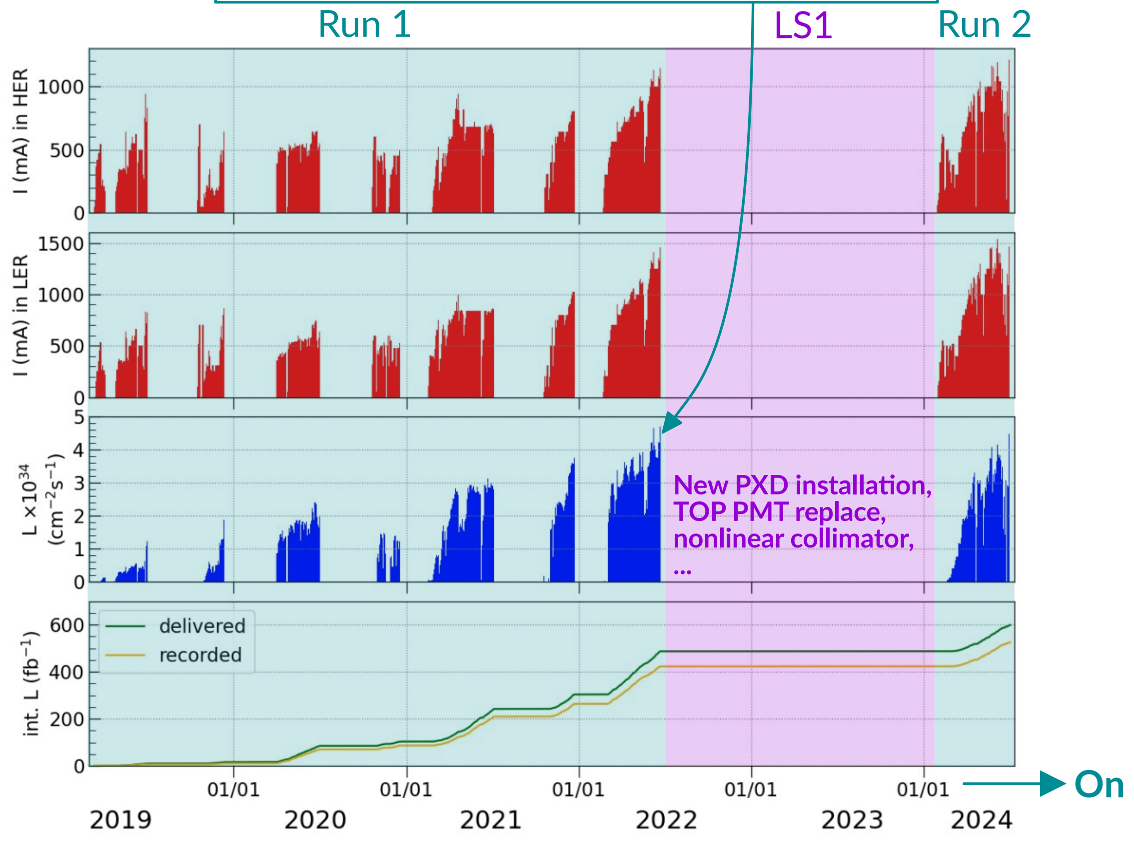


- 575 fb^{-1} collected (Run 1 (427 fb^{-1}) + Run 2 (148 fb^{-1}))
- **Obtained results are strongly limited by statistics** World-leading results already published with early datasets (less than collected dataset of 427 fb^{-1})

- 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

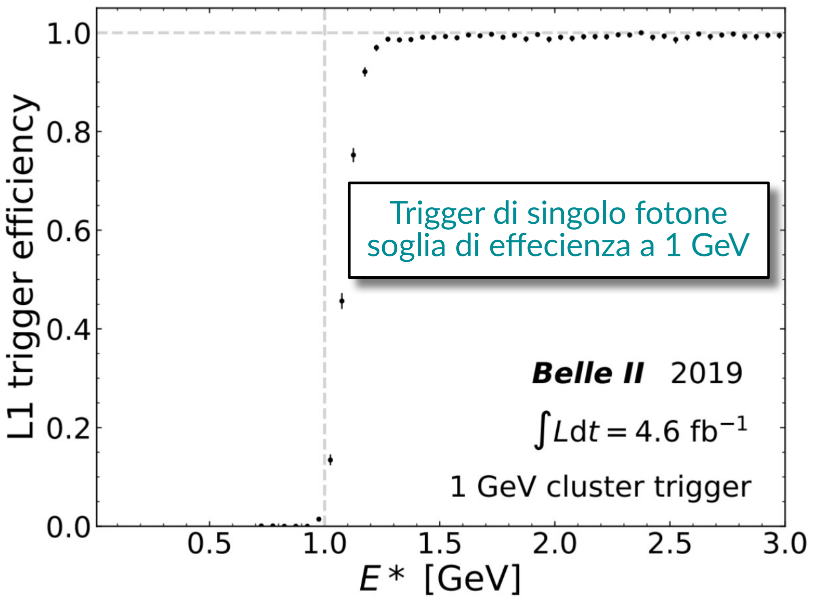
Low-multiplicity triggers

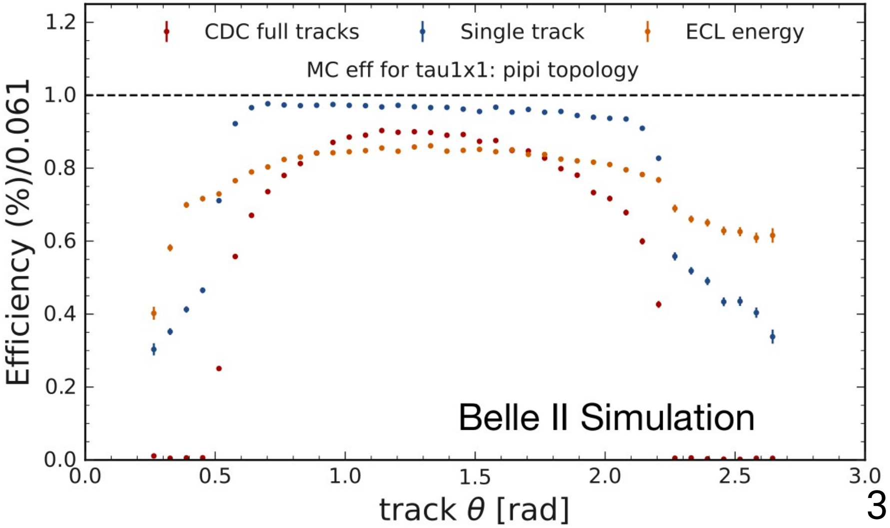
Two-level trigger

- Hardware-based **Level 1 Trigger** (L1): < 30 kHz
  - It combines info from CDC, ECL, KLM (tracks, clusters, muons)
- 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 (ECL)
  - Single-muon trigger (CDC + KLM)
  - Single-track trigger (Neural network based)

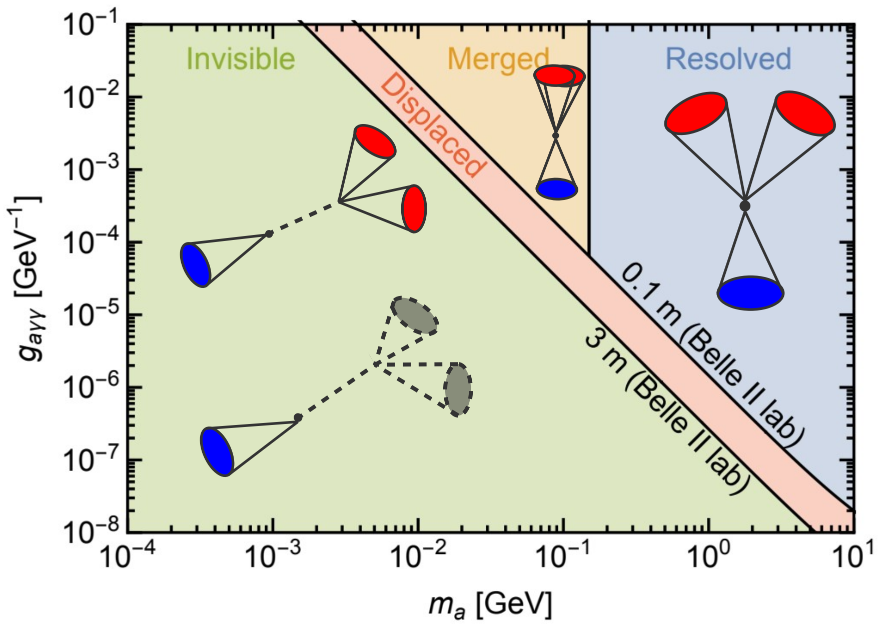


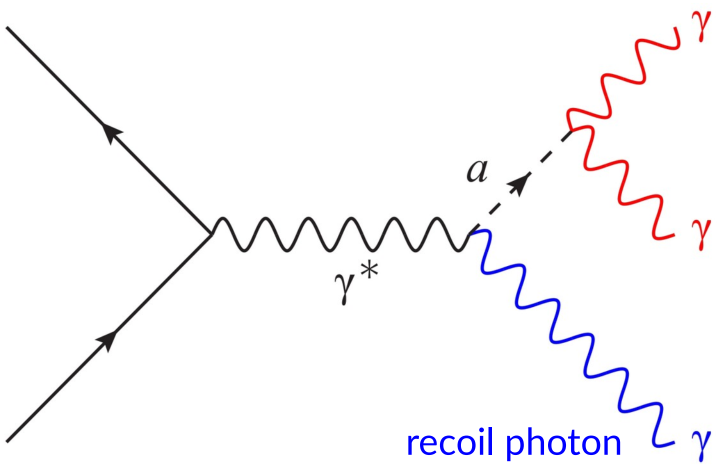


Axion-like particles (*ALPs*) at Belle II

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 $BR(a \to \gamma\gamma) \sim 100\%$
- Focus on mass region where ALP decay is prompt and photons can be well resolved by Belle II

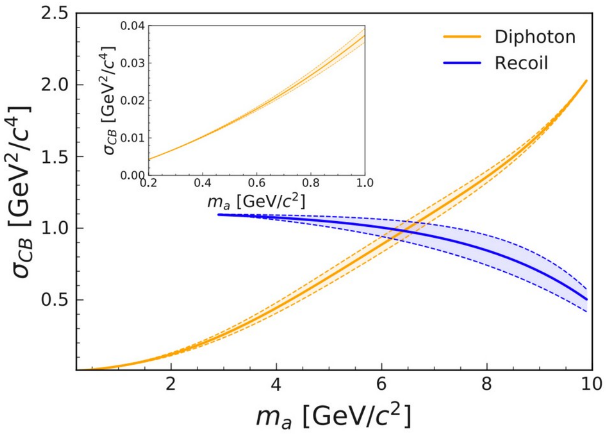




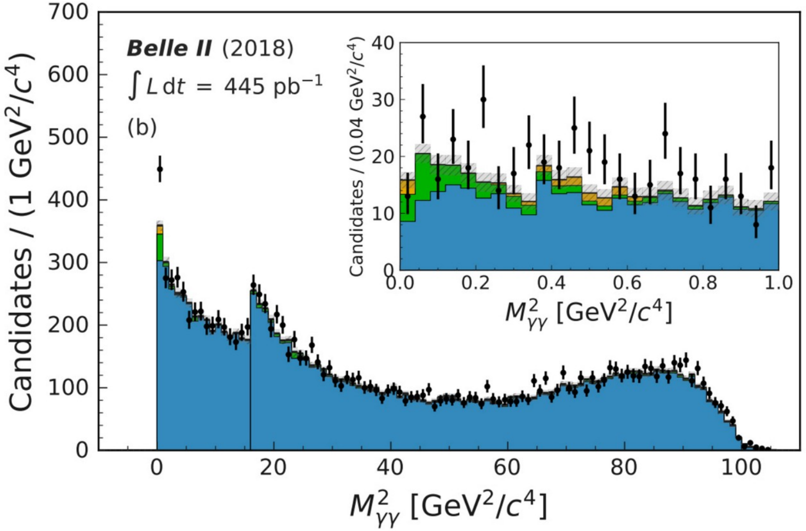
Search for an ALP at Belle II

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

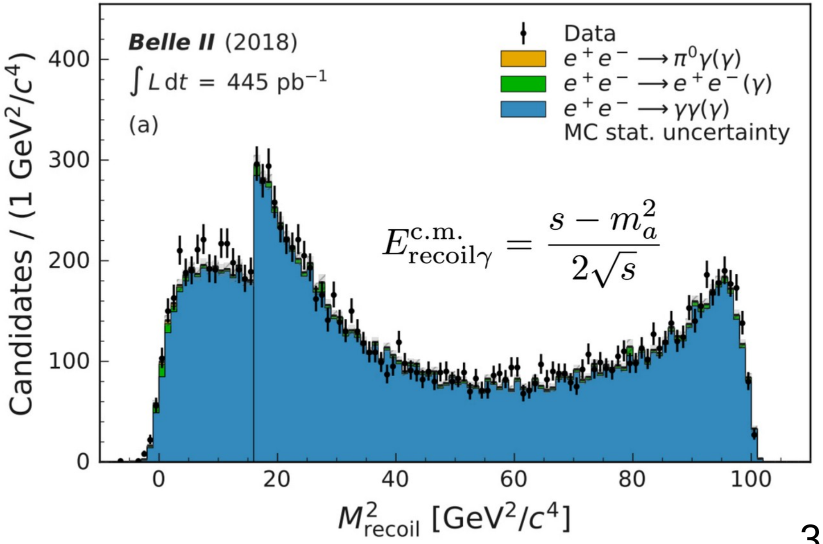
- Select events with three photon invariant mass compatible with collision $\sqrt{s}$
- Search for a narrow peak in $M^2_{\gamma\gamma}$ or M^2_{recoil}, depending on best resolution of signal peak
- Largest background from $e^+e^- \to \gamma\gamma(\gamma)$



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



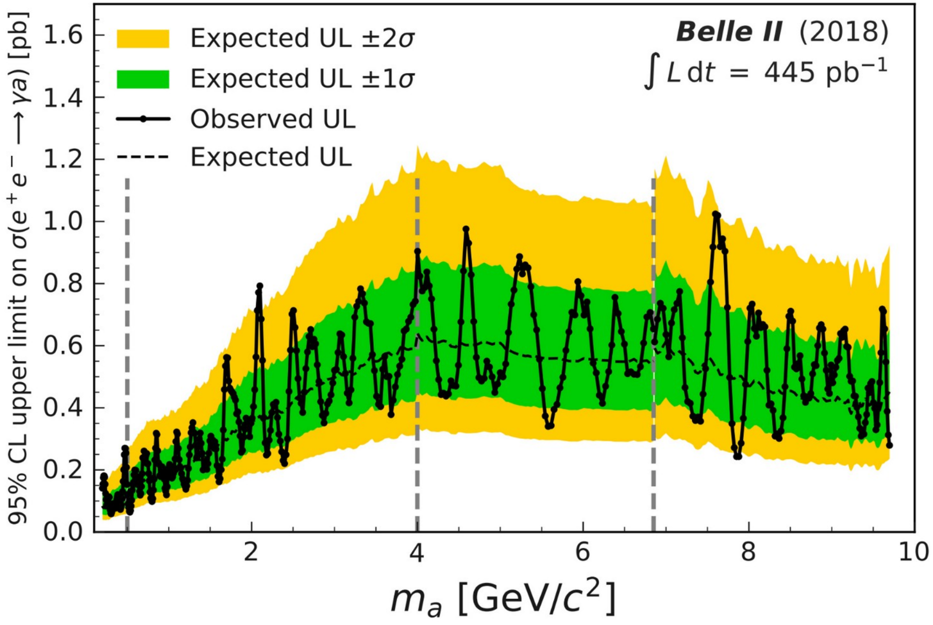
M^2_{recoil}: m_a > 6.85 GeV/c^2

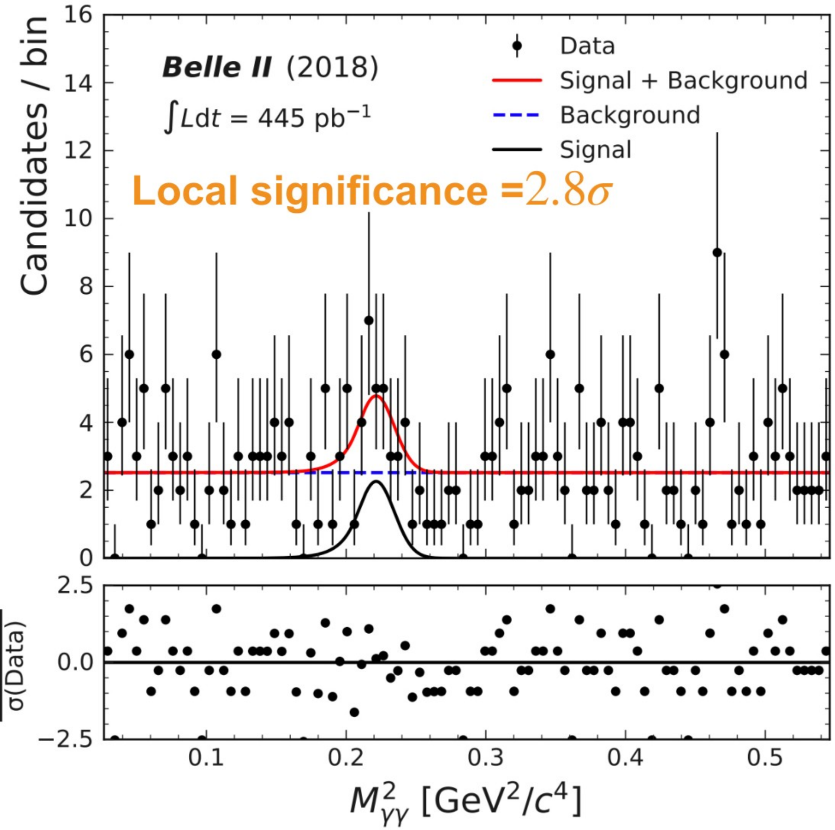


Search for an ALP at Belle II: result

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

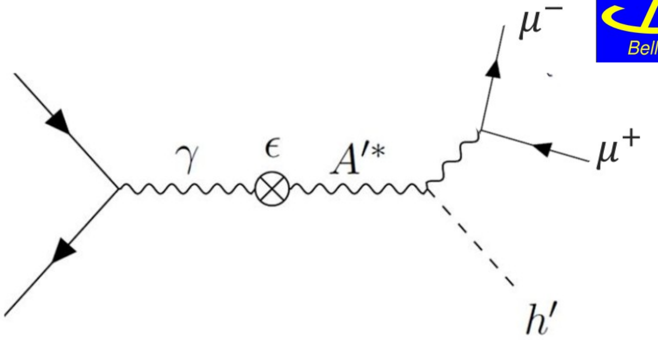
- Search ranges from $0.2 < m_a < 9.7$ GeV/c^2, with the 0.445/fb collected in 2018 with *Belle II*
  - 500 fits with steps of half mass resolution
- No excess in data observed
  - Highest local significance 2.8σ, observed at $m_a = 0.477$ GeV/c^2



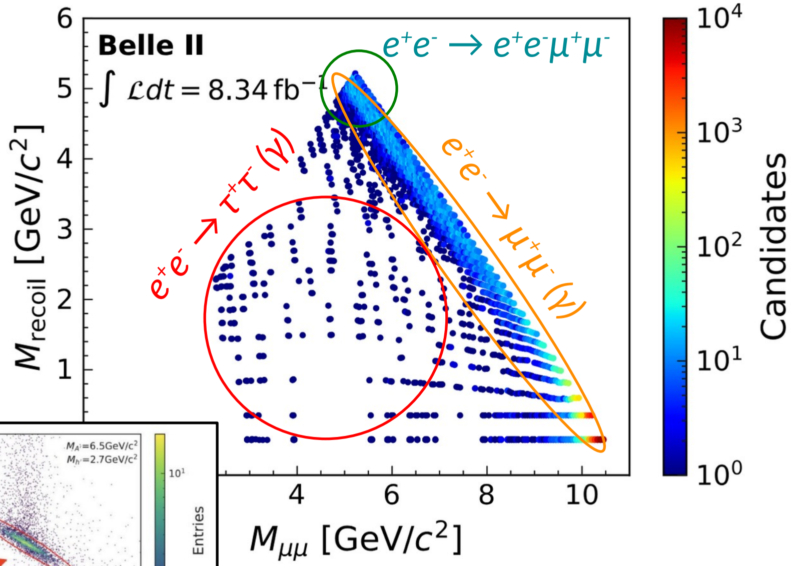


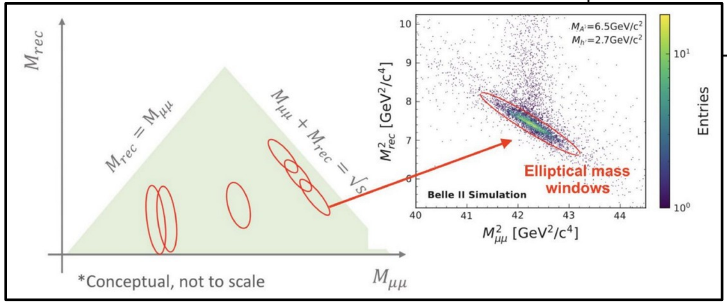
Dark higgsstrahlung at Belle II

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

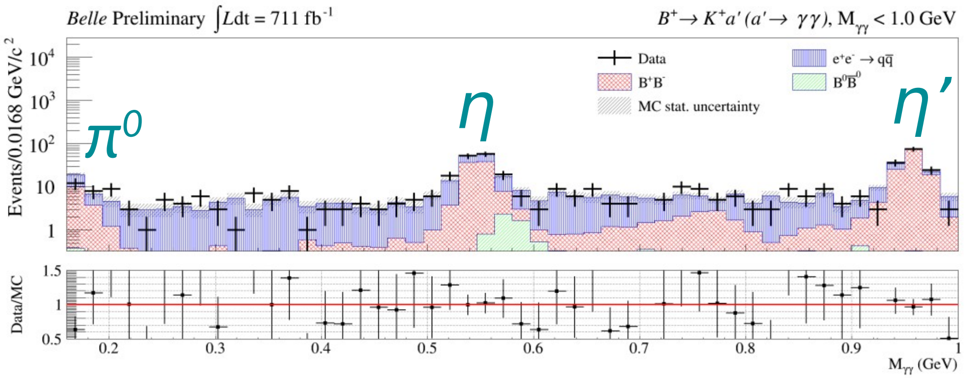


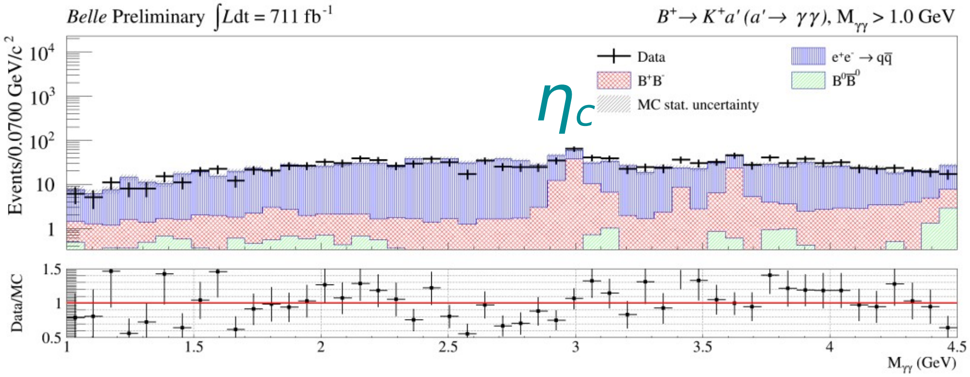


$B \to K^{(*)}\, a\, (\to \gamma\gamma)$ at Belle, highlights

- Signal appears as a **narrow peak in the $\gamma\gamma$ invariant mass, $M_{\gamma\gamma}$**
- Main **background** contribution from **coontinum $e^+e^- \to q\bar{q}$, $e^+e^- \to B\bar{B}$, photons from π^0 decays, SM peaking backgrounds**
- SM **background suppression** performed using **BDTs** applied to two different mass regions
  - Low mass region: $M_{\gamma\gamma} < 1$ GeV/c^2
  - High mass region: $M_{\gamma\gamma} > 1$ GeV/c^2
- **π, η and η' regions are vetoed** from the search
- **Signal extracted through fit scan over $M_{\gamma\gamma}$**

$M_{\gamma\gamma}$ for the K^+ mode

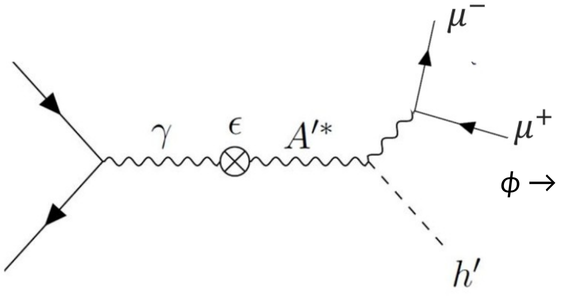


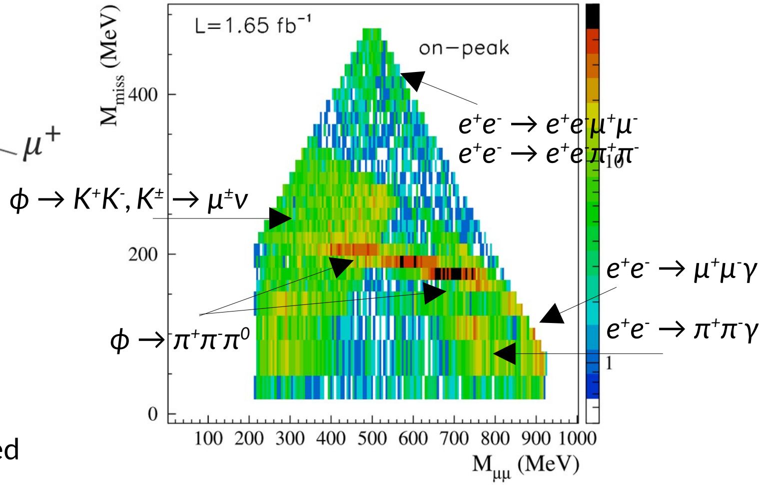


Search for a dark Higgs at KLOE/KLOE-2

A. Anastasi et al., Phys. Lett. B 747 365-372 (2015)

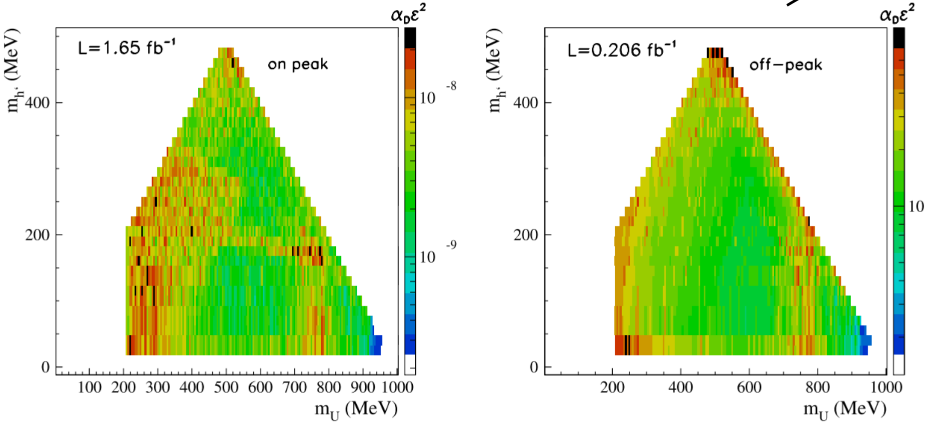
- ***$e^+e^- \to A'h', A' \to \mu\mu, h' \to$ invisible***
- Signature: 2D peak in recoil vs dimuon mass
- Data:
  - 1.65 fb^{-1} at the ϕ resonance
  - 0.21 fb^{-1} off-peak
- Limits on $\varepsilon^2 \cdot \alpha_D$ range from 10^{-9} – 10^{-8}
- Assuming $\alpha_D = \alpha_{em} \to \varepsilon \sim O(10^{-4} - 10^{-3})$
- First limits for $M_{h'} < M_{A'}$

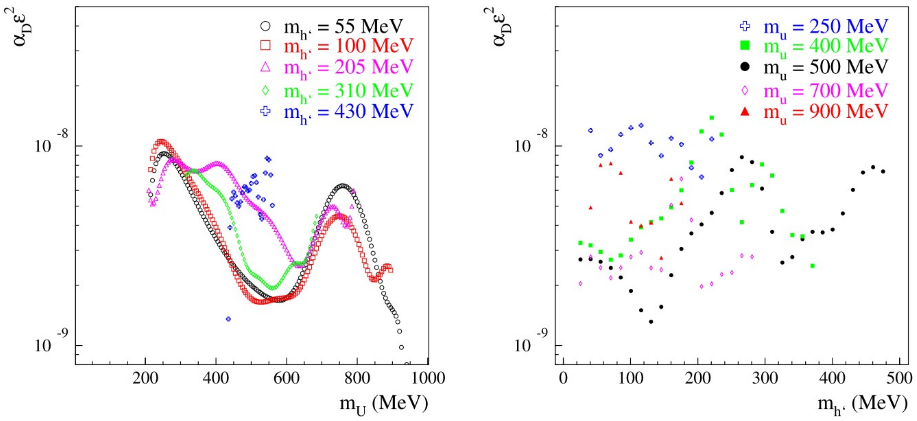




on-peak and off-peak combined

90% CL upper limits in $\varepsilon^2 \cdot \alpha_D$

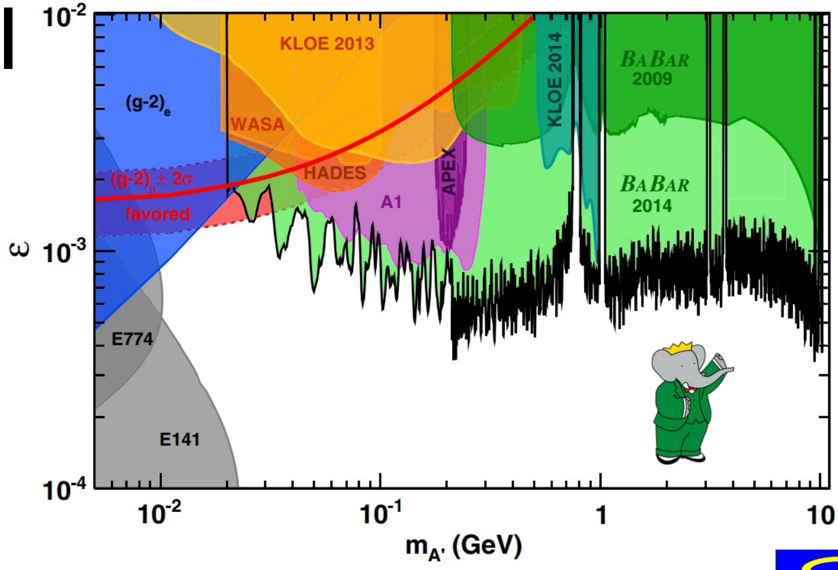




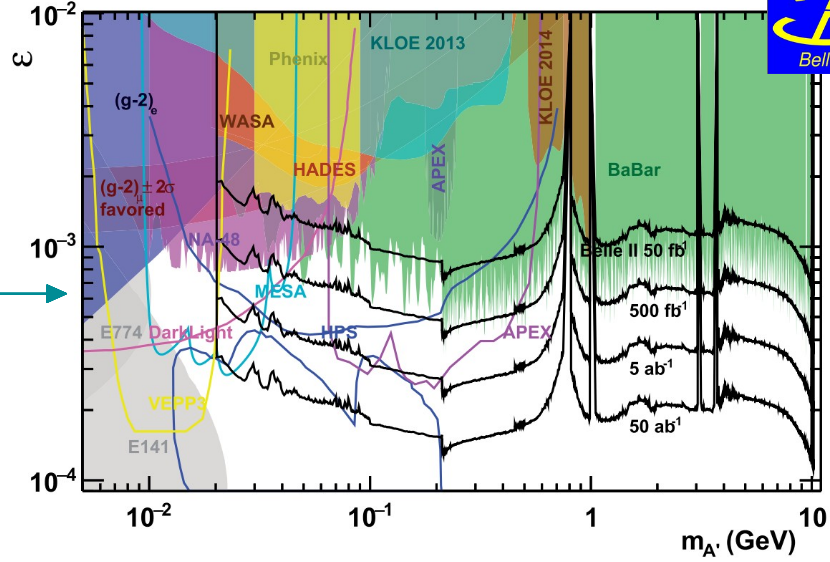
Visible dark photon at Belle II

BABAR[1]

- Full data-set of 514 fb^{-1}
- dark photon visible decay in e^+e^- and $\mu^+\mu^-$ final states
- Signature: bump in the di-lepton invariant mass
- Background: QED processes $e^+e^- \to e^+e^-(\gamma)$, $e^+e^- \to \mu^+\mu^-(\gamma)$ and resonant backgrounds from J/ψ, $\psi(2S)$ etc. (vetoed)
- Set 90% CL upper limit on the mixing strength ε at level of $O(10^{-3})$



Belle II is expected to achieve the leading sensitivity[3] (search in progress)

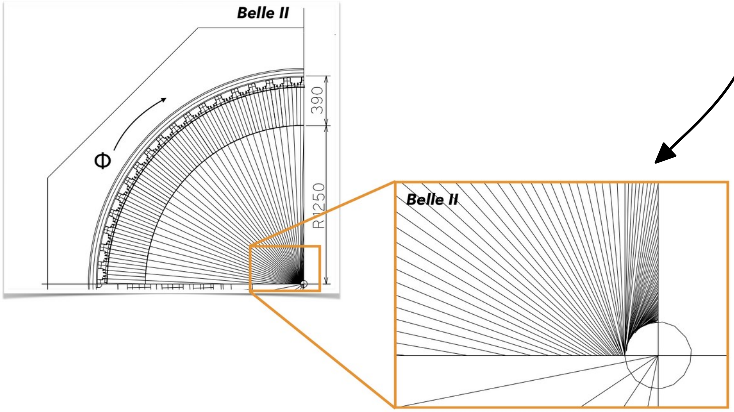


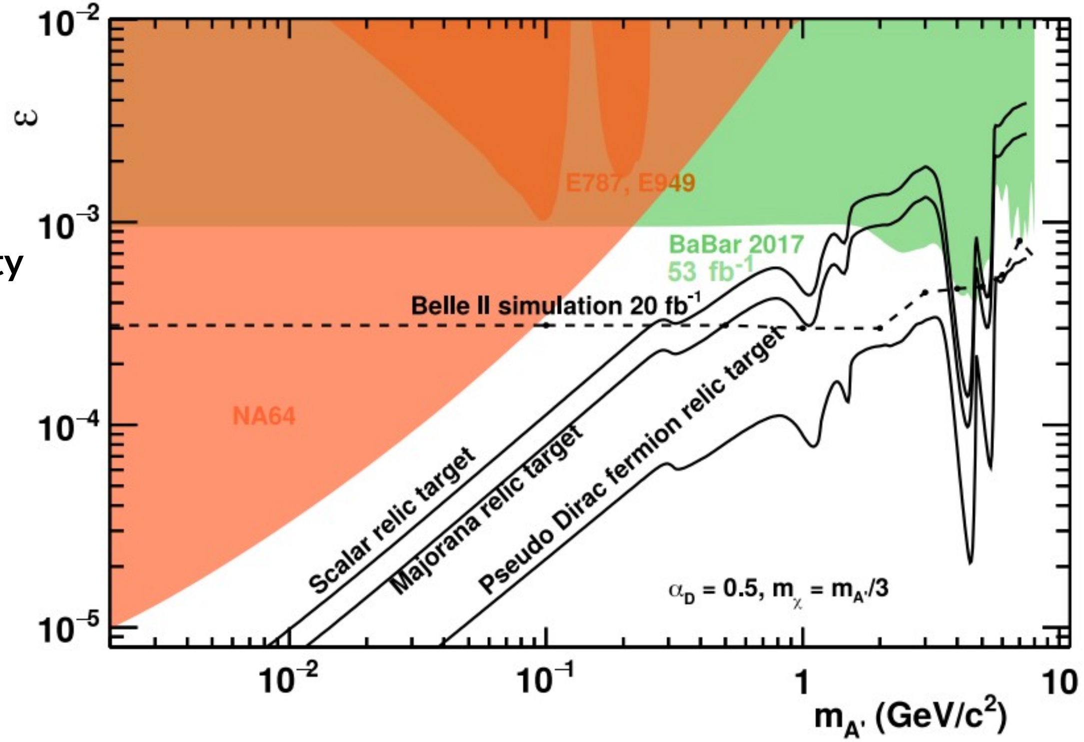
[1] J.P. Lees et al, Phys. Rev. Lett. 113, 201801 (2014)
[2] E. Kou et al, Prog Theor Exp Phys (2019)

Expected 90% CL exclusion on ε

[1] Belle II Physics Book, PTEP 2019 12 (2019)
[2] Lees et al, Phys. Rev. Lett. 119, 131804 (2017)

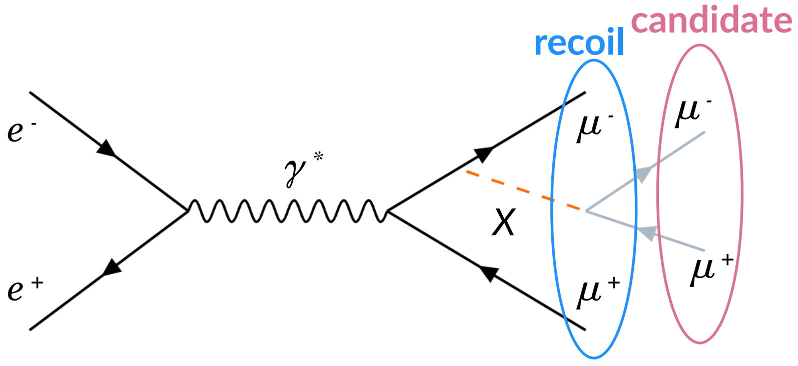
- $e^+e^- \to \gamma_{ISR}A'$ $(A' \to inv.)$: very promising at Belle II, even with low statistics[1]
- Expected to perform better than BaBar[2]
  - Smaller boost: **larger acceptance**
  - **Muon detector veto**: reject events with a photon undetected in the calorimeter
  - No e.m calorimeter cracks in pointing to the interaction region: **better calorimeter hermeticity**





$\mu\mu$-resonance in $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$ at Belle II

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 $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$**
  - 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 $M(\mu\mu)$**