European Physical Society Conference on High Energy Physics.

Online conference, July 26-30, 2021

Dark Matter searches at Belle II, Belle and BaBar

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On behalf of the Belle II collaboration

Dark Sector searches

[1] Batell et al., *Phys. ReV. D* **80** (2009)
[2] Essig et al., arXiv:1311.0029 (2013)

Motivations & Models

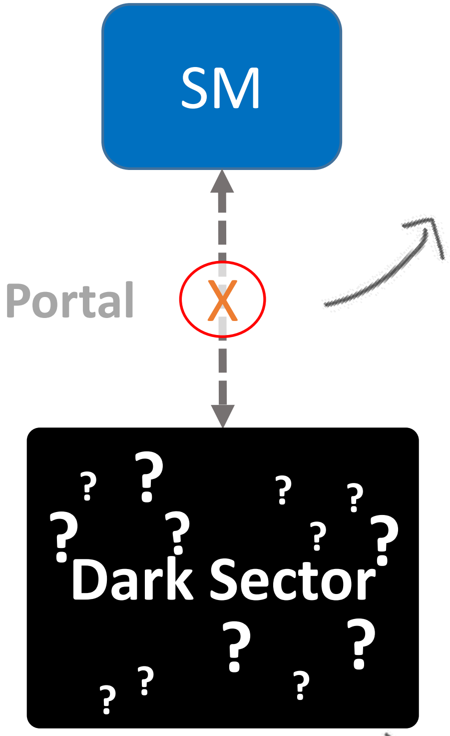
The absence of DM discoveries by the LHC or direct detection experiments motivate the interest for models with **low-mass dark matter** candidates or mediators.

A possible MeV - GeV theoretical scenarios:

- DM not charged directly under the SM;
- DM may interact with SM through several "**portal**" interactions (e.g. [1, 2]).

$$\mathcal{L}_{\text{portals}} = -\frac{\epsilon}{2}B^{\mu\nu}A'_{\mu\nu} - H^\dagger H(AS + \lambda S^2) - Y_N^{ij}\bar{L}_i H N_j + \cdots$$

Vector portal   Higgs portal   Neutrino portal



Non-gravitational interaction with matter

- Dark matter;
- Dark Forces;
- ……

Not just solving the DM puzzle. Could explain:

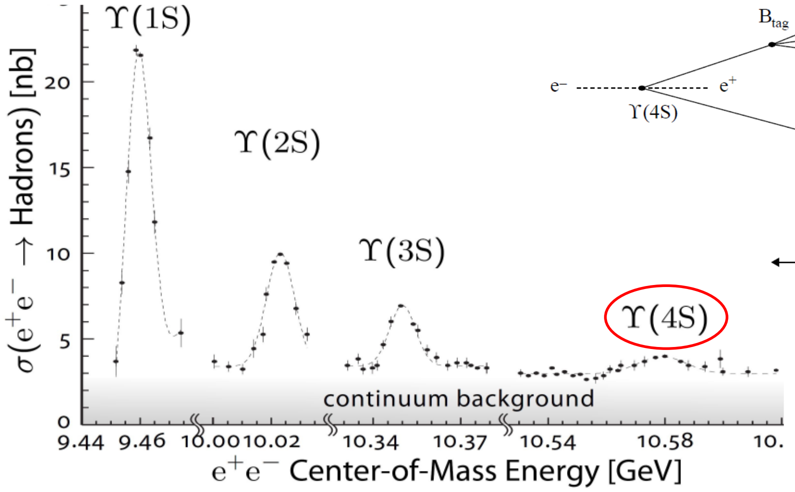
- some astrophysics anomalies (positron excess, 3.5 keV line, …);
- the $(g\text{-}2)_\mu$ anomaly;
- some flavour anomalies: R_K, R_{K^*} …. (LHCb, Belle, ..).

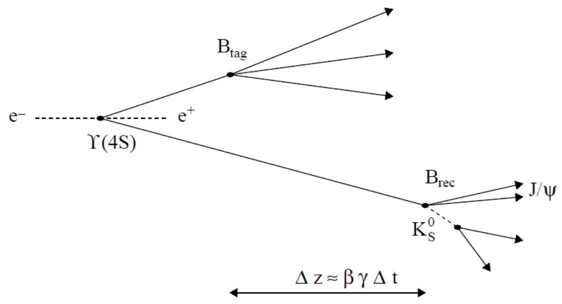
B-factory experiments

At the intensity frontier

Dedicated **experiments at e^+e^- asymmetric-energy colliders** for the production of quantum coherent $B\bar{B}$ pairs.

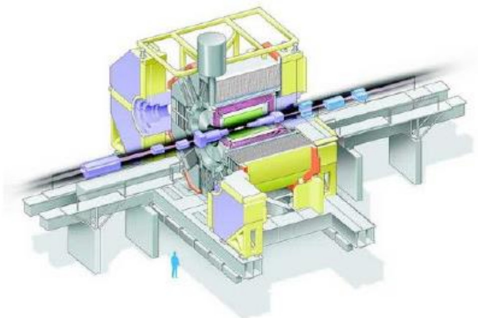
- **Collision energy at Y(nS):**
  - **Mainly at Y(4S): 10.58 GeV;**
    - BR(Y(4S)→ B$\bar{\text{B}}$) > 96%;
- **Asymmetric beam energies**: e.g. 8.0/3.5 GeV (e-/e+) (Belle):
  - Boosted $B\bar{B}$ pairs;
- **Very high luminosity**: > 10^{34} cm^{-2} s^{-1} ;

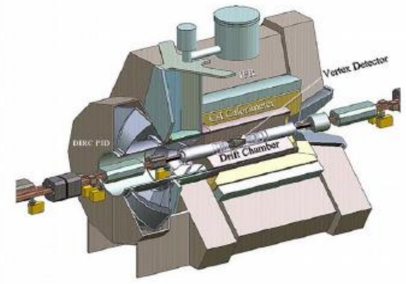




First generation of B-Factories:

- **Belle@KEKB**, KEK, Tsukuba (JP), 1999-2010, $\int L\,dt = 1\ \mathrm{ab}^{-1}$;
- **BaBar@PEP-II**, SLAC (USA), 1999-2008, $\int L\,dt = 0{,}5\ \mathrm{ab}^{-1}$;





Belle II @ SuperKEKB

A next generation B-factory

See talks on:
- *Status and perspectives of the SuperKEKB project*
- *Highlights from the BELLE II Experiment and Flavour Physics in e^+e^-*

Major upgrade to the accelerator with a **x30** increase in the instantaneous luminosity with respect to KEKB (expected luminosity **L = 6.5x10^{35} cm^{-2}s^{-1}**):

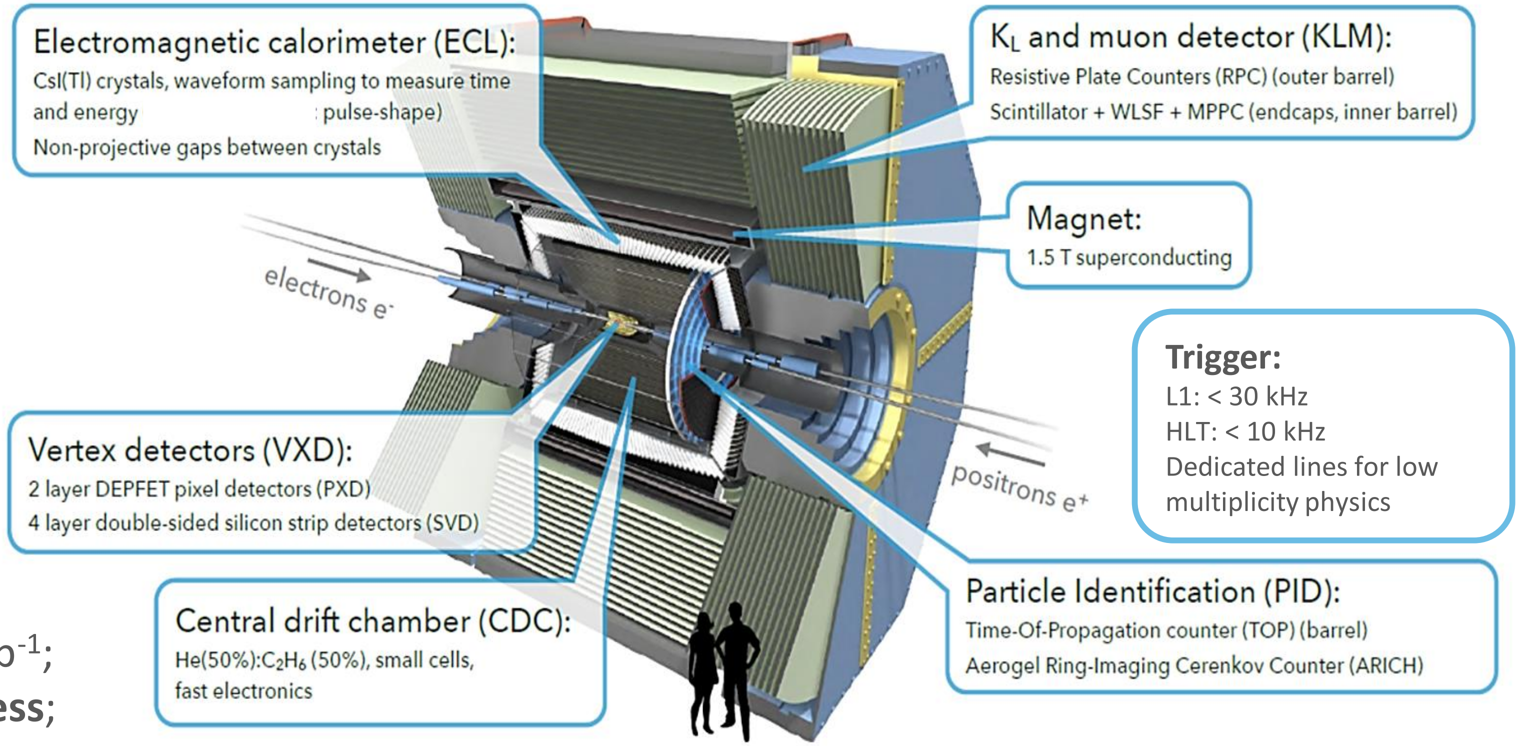
- **1.5x** from higher beam current;
- **20x** from final focus magnets;

Upgraded detector:

- Better performances;
- but higher backgrounds;
- Much better trigger;

Data taking schedule:

- First collisions in 2018 (Commissioning) ~ 0.5 fb^{-1};
- Main operation since 2019. **213.5 fb^{-1} in progress**;
- **Ultimate goal: 50 ab^{-1} (50× Belle).**



Trigger:
L1: < 30 kHz
HLT: < 10 kHz
Dedicated lines for low multiplicity physics

The Belle II Physics Book, *PTEP* **2019** 12 (2019)

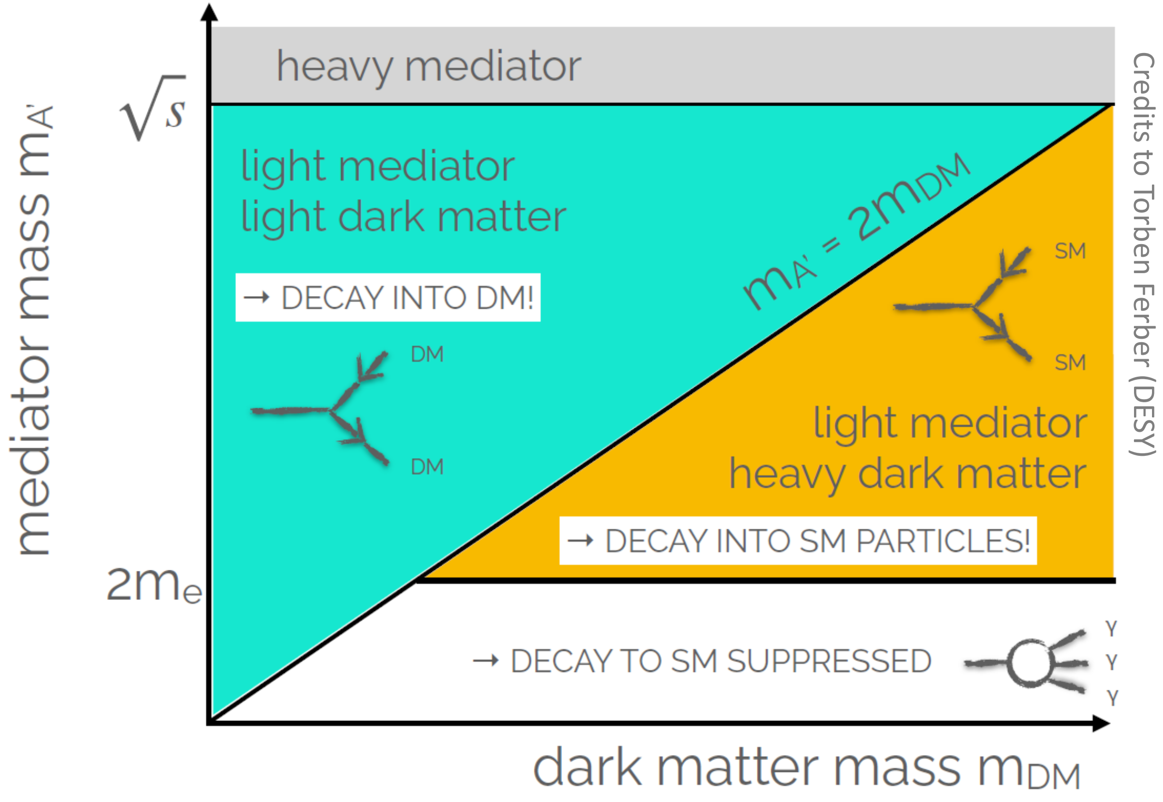
Dark Sector searches

at B-factories

The relationship between masses of the mediator and DM candidates lead to **different topologies**.

Probability of interaction of DM with detectors is negligible:

- Search for mediators;
- Search for missing energy signatures;
- Search for both;



Why dark sector searches at B-factories?

- High luminosity;
- Closeness to the light region;
- Well defined initial state, closed kinematics;
- Clean environment and low background;
- Hermetic detector;
- Excellent PID capability;

↘ **@ B-factories excellent capabilities for low multiplicity and missing energy signatures**

Dark Sector searches

State of art @ B-factories

✓ Discussed today

A lot of DM searches @ B-factories excluded Dark Sector parameters down to:

	Belle	BaBar	Belle II
$ee \to \gamma A'$, $A' \to ll$ ✓	-	$\epsilon < 5 \times 10^{-4}$ ($514\ \text{fb}^{-1}$) [1]	-
$ee \to \gamma A'$, $A' \to$ invisible ✓	-	$\epsilon < 10^{-3}$ ($53\ \text{fb}^{-1}$) [2]	-
$B^0 \to A'A'$	BF $< 10^{-7}$ ($711\ \text{fb}^{-1}$) [3]	-	-
$ee \to \gamma \Upsilon_D$ (DM bound state)	-	$\epsilon < 10^{-3}$ ($514\ \text{fb}^{-1}$) [*]	-
$ee \to A'h'$, $h' \to A'A'$ ✓	$\alpha_D \epsilon < 10^{-9}$ ($977\ \text{fb}^{-1}$) [4]	$\alpha_D \epsilon < 10^{-9}$ ($514\ \text{fb}^{-1}$) [5]	-
$ee \to \mu\mu Z'$, $Z' \to ll$ ✓	$g' < 10^{-3}$ ($643\ \text{fb}^{-1}$) [*]	$g' < 10^{-3}$ ($514\ \text{fb}^{-1}$) [1]	-
$ee \to \mu\mu Z'$, $Z' \to$ invisible ✓	-	-	$g' < 5 \times 10^{-2}$ ($0.27\ \text{fb}^{-1}$) [6]
$\eta \to \gamma A'_q$, $A'_q \to \pi\pi$	$\alpha_q < 5 \times 10^{-3}$ ($976\ \text{fb}^{-1}$) [7]	-	
$ee \to \tau\tau\phi_\tau$, $\phi_\tau \to ll$	-	$\eta < 5 \times 10^{-1}$ ($514\ \text{fb}^{-1}$) [8]	
$ee \to \gamma a$, $a \to \gamma\gamma$ ✓	-	-	$g_{a\gamma\gamma} < 10^{-3}\,\text{GeV}^{-1}$ ($0.45\ \text{fb}^{-1}$) [9]
$B^\pm \to K^\pm a$, $a \to \gamma\gamma$	-	$g_{aWW} < 10^{-5}\,\text{GeV}^{-1}$ ($424\ \text{fb}^{-1}$) [*]	-
$\Upsilon(2S,3S) \to \gamma A^0$, $A^0 \to \mu\mu$	-	($99, 122 \times 10^6\, \Upsilon(2S,3S)$) [10]	-
$\Upsilon(3S) \to \gamma A^0$, $A^0 \to \tau\tau$	-	BF $< 10^{-5}(122 \times 10^6\, \Upsilon(3S))$ [11]	-
$\Upsilon(2S) \to \Upsilon(1S)\pi\pi$, $\Upsilon(1S) \to \gamma A^0$, $A^0 \to$ invisible	BF $< 10^{-6}(157 \times 10^6\, \Upsilon(2S))$ [12]	BF $< 10^{-6}(98 \times 10^6\, \Upsilon(2S))$ [13]	-
$\Upsilon(2S,3S) \to \pi\pi\Upsilon(1S)$, $\Upsilon(1S) \to \gamma A^0$, $A^0 \to \mu\mu$	-	BF $< 10^{-6}(93, 117 \times 10^6\, \Upsilon(2S,3S))$ [14]	-

References in *spare slides*

Disclaimer: a non exhaustive talk (biased overview on some recent results).

Dark Photon searches

[1] P. Fayet, *Phys. Lett. B* **95**, 285 (1980),
[2] P. Fayet, *Nucl. Phys. B* **187**, 184 (1981)

General remarks

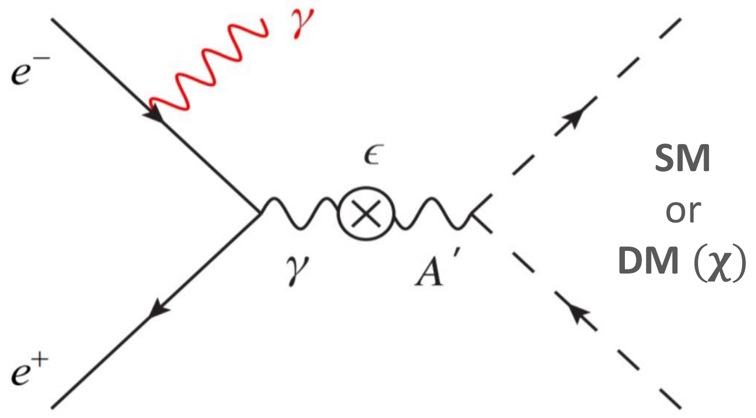
A new massive gauge boson *A'* of spin = 1 coupling to the SM photons through the kinetic mixing with strength ε, called ***dark photon*** [1,2].

$$\mathcal{L}_{int} = \epsilon e A'_\mu J^\mu_{em}$$

At e^+e^- colliders different production mechanisms:

- **Direct production**, meson decay, **Higgsstrahlung**.

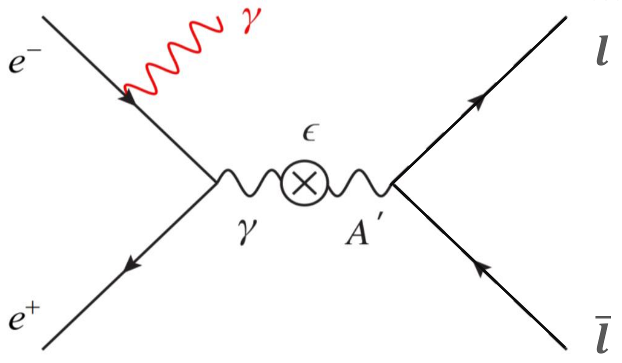
Direct production with ISR particularly interesting: $e^+e^- \to \gamma_{ISR}\, A'$;



- Two basic scenarios depending on A' vs DM masses relationship:
  - $m_x > \frac{1}{2} m_{A'}$ → **A' visible decays to SM particles BaBar(2014);**
  - $m_x < \frac{1}{2} m_{A'}$ → **A' invisible decays to LDM BaBar(2017);**

Dark Photon searches

Visible decay



BaBar searched for a dark photon visible decay in e^+e^- and $\mu^+\mu^-$ final states (τ or hadrons much harder experimentally);

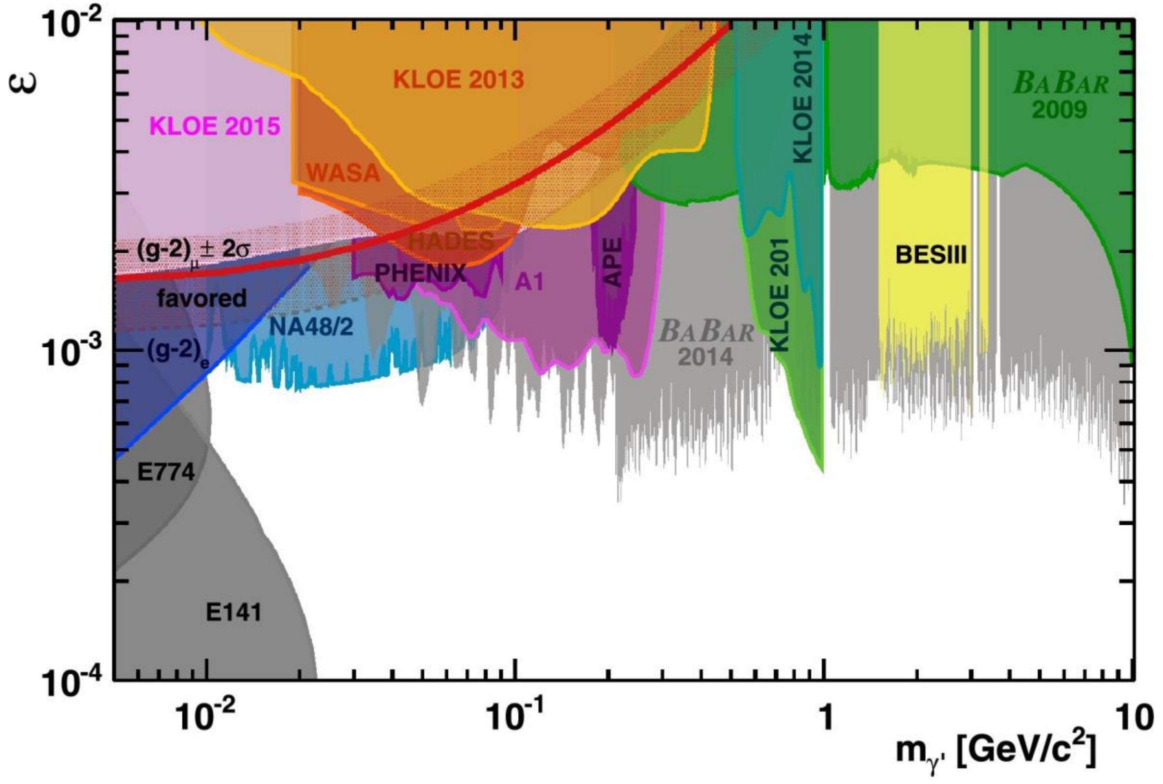
- **Signature**: bump in the di-lepton invariant mass;
- **Background**: resonant backgrounds from J/ψ, ψ(2S) etc. (excluded from the measurement) but otherwise smoothly varying background;

Full data-set (514 fb^{-1}) collected at Υ(2S), Υ(3S) and Υ(4S) used.

90% C.L. upper limit on the mixing strength ε as a function of A' mass at level of *O*(10^{-3}):

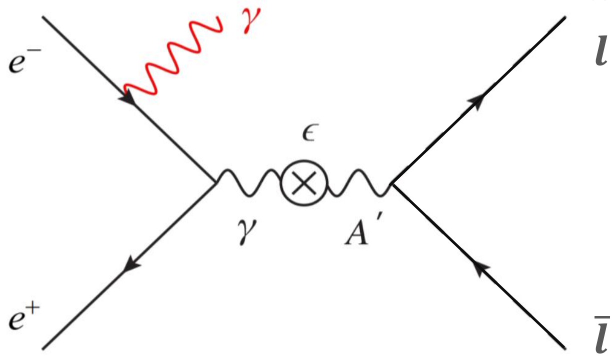
- Best limits almost everywhere in the GeV range;
- In the ~ 200-700 MeV range LHCb better results.

[*Phys. Rev. Lett.* **113**, 201801 (2014)](#)



Dark Photon searches

Visible decay



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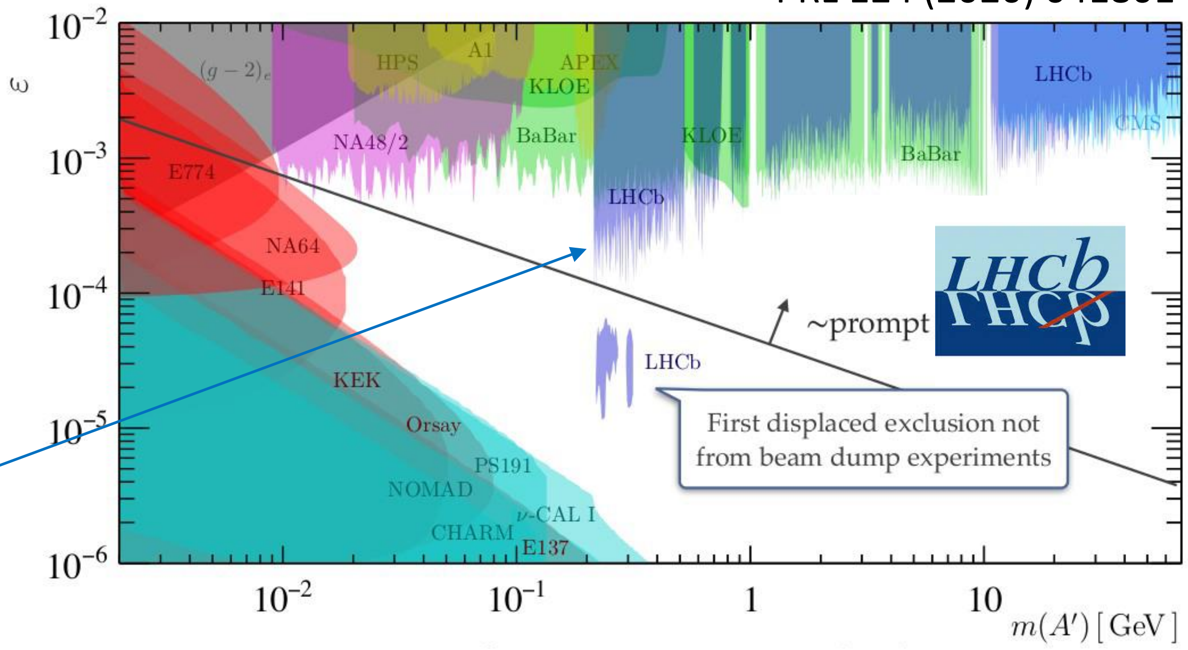
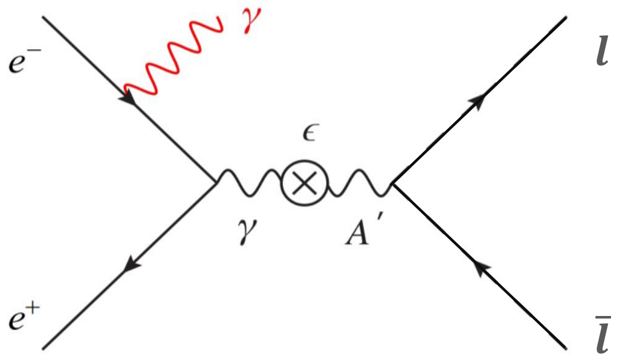
PRL 124 (2020) 041801



Dark Photon searches

Visible decay



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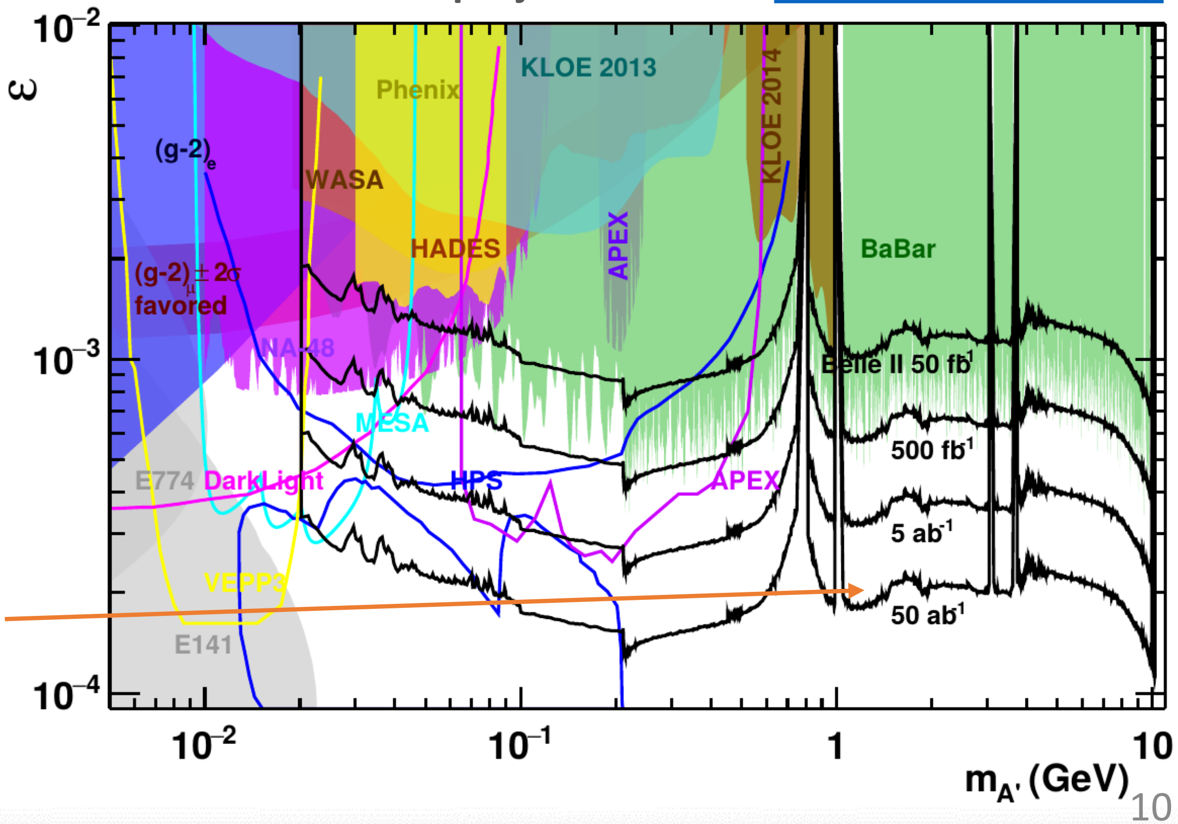
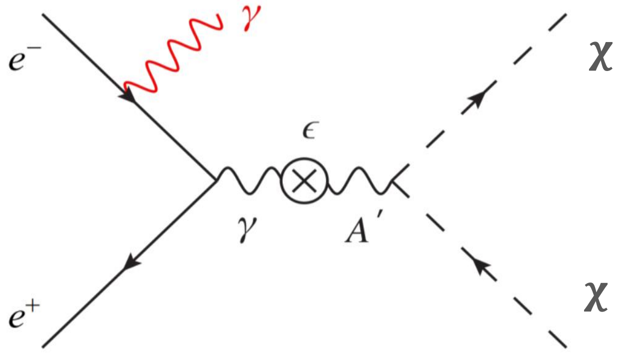
Belle II is expected to achieve the leading sensitivity: search currently in preparation.

Belle II projections from *PTEP* **2019** 12 (2019)



Dark Photon searches

Invisible decay



BaBar searched also for the invisible decay:

- **Signal:**
  - Only one mono-chromatic high-E photon γ_{ISR};
  - Bump in the photon energy:

$$E_\gamma = \frac{s - M^2_{A'}}{2\sqrt{s}} \quad (on\text{-}shell)$$

- **SM backgrounds:** $ee \to \gamma\gamma(\gamma)$, $ee \to ee(\gamma)$, Cosmics;
  (low mass) (high mass)

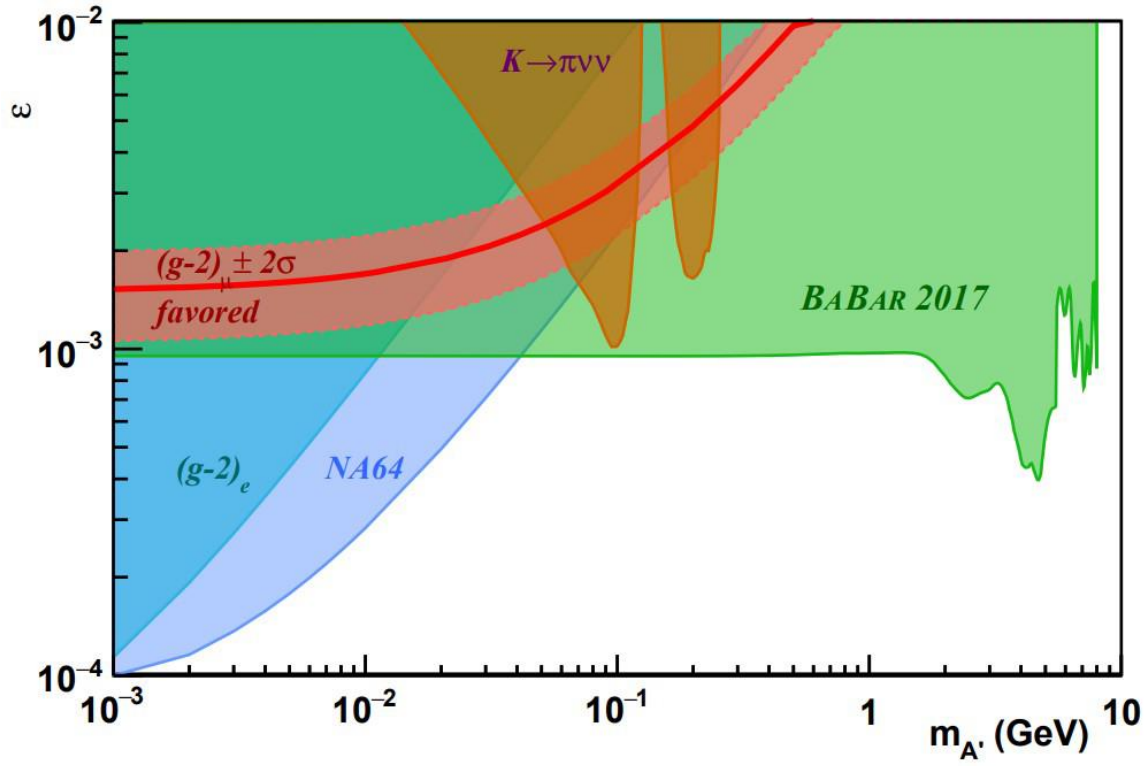
  → Needs an excellent knowledge of the detector.

Requires a single photon trigger:

- Available only on ~ 10% of data (50 fb^{-1});
- trigger threshold: E_γ > 1.5 GeV;

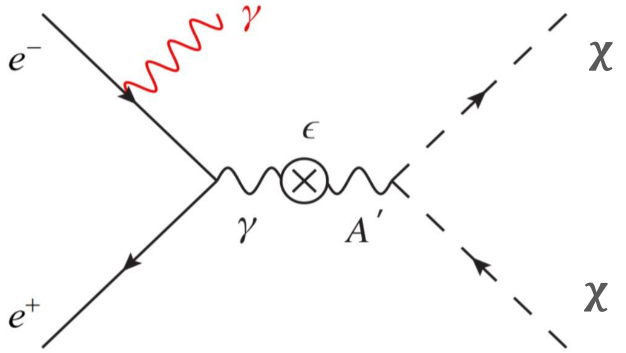
90% C.L. upper limits on mixing strength ε at the level of *O*(10^{-3}).

Phys. Rev. Lett. **119**, 131804 (2017)



Dark Photon searches

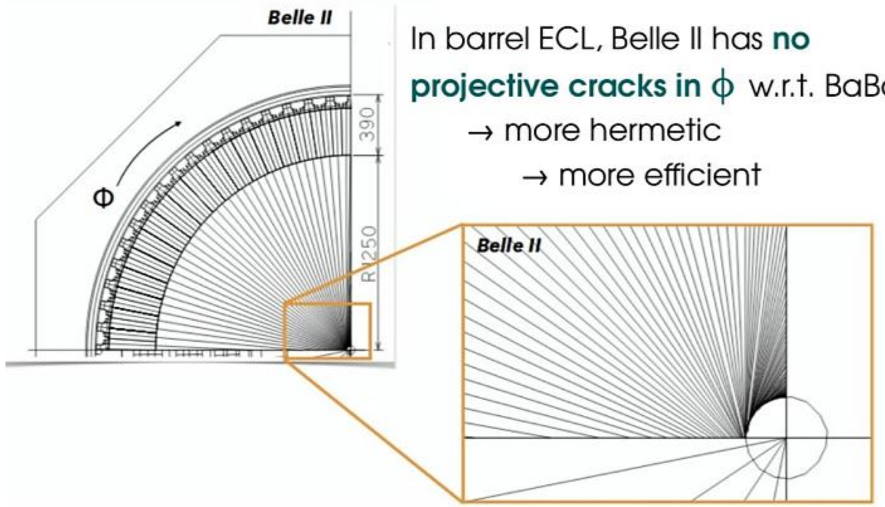
Invisible decay



@ Belle II very promising expectations even with the early dataset.

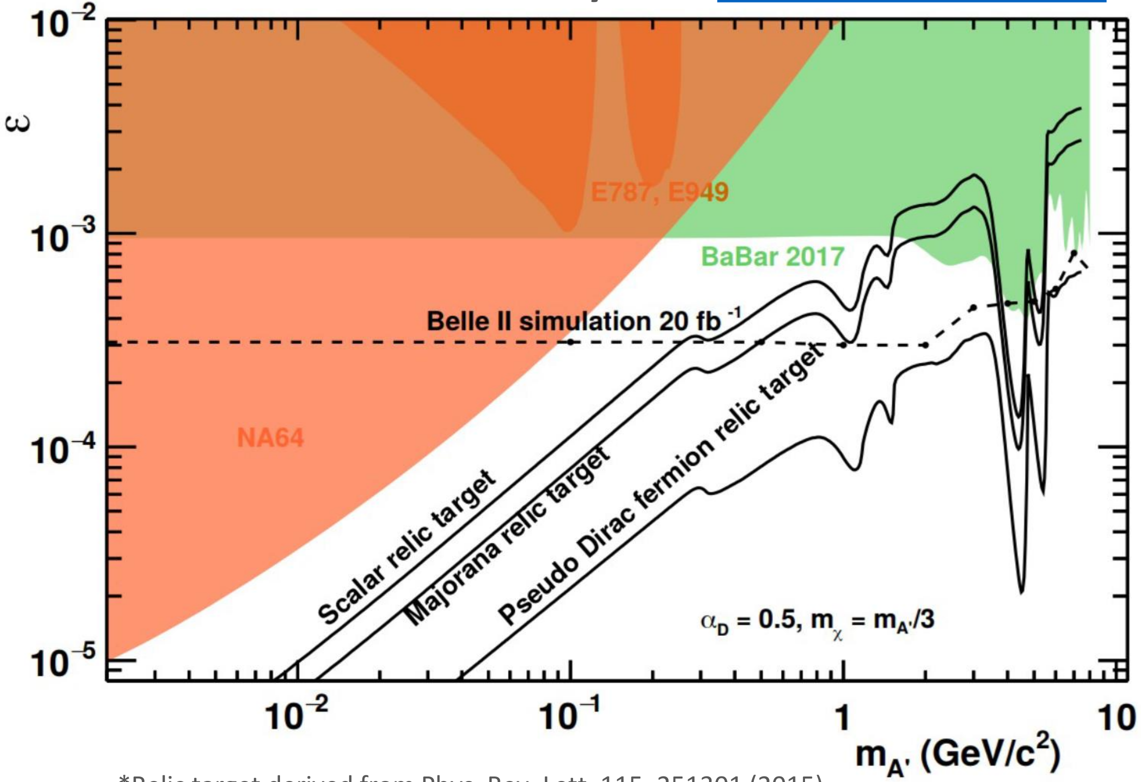
Expected to perform better than BaBar due to:

- smaller boost and larger calorimeter ⇒ larger acceptance;
- Trigger threshold lower than in BaBar;
- KLM veto;
- no ECL cracks pointing to the interaction regions;



In barrel ECL, Belle II has **no projective cracks in ϕ** w.r.t. BaBar:
→ more hermetic
→ more efficient

Belle II sensitivity from [*PTEP* **2019** 12 (2019)]



*Relic target derived from Phys. Rev. Lett. 115, 251301 (2015)

Dark Higgsstrahlung searches

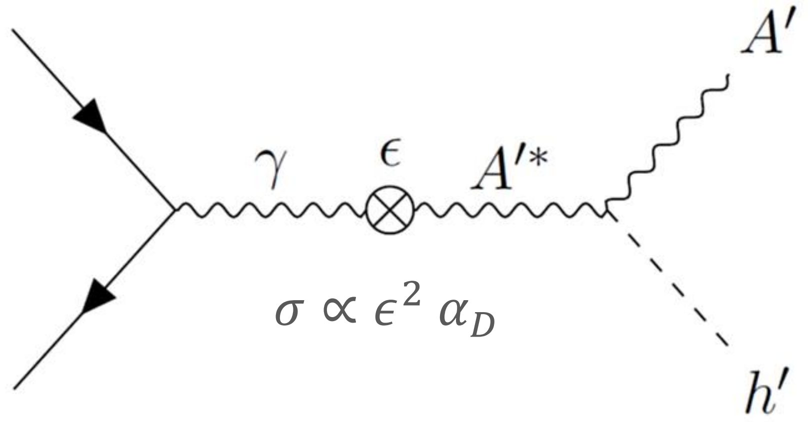
[1] B. Batell, et al., *Phys. Rev. D* **79**, 115008 (2009)

General remarks

Next to minimal dark photon model:

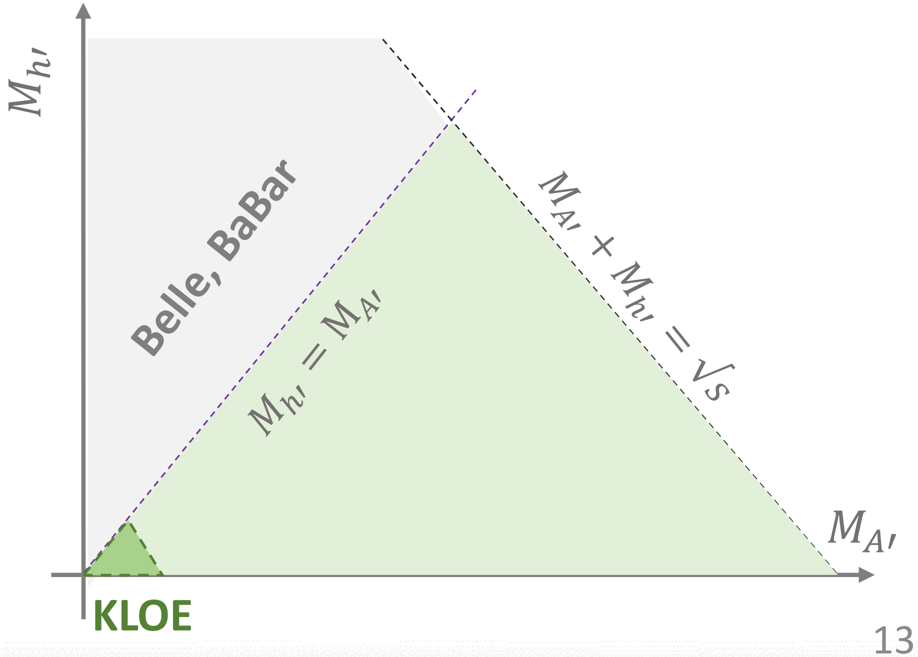
- A’ mass could be generated via a spontaneous symmetry breaking mechanism, adding a dark Higgs boson *h*' to the theory [1].
- Both the dark photon and the dark Higgs can be produced at an e^+e^- collider via the dark Higgsstrahlung process:

$$e^+e^- \rightarrow A'^* \rightarrow h' A'$$



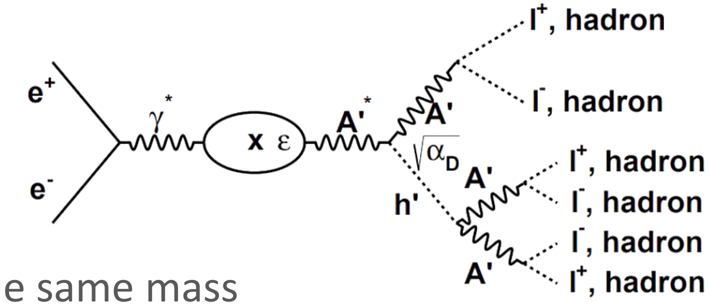
Different scenarios depending on the mass hypothesis.:

- $\boldsymbol{m_{h'} > m_{A'}}$: $h' \rightarrow A'A' \rightarrow 4l, 4had, 2l + 2had.$
  Investigated by **BaBar(2012)** and **Belle(2015)**
- $\boldsymbol{m_{h'} < m_{A'}}$: h' is long-lived, thus invisible.
  Constrained only by **KLOE(2015)**.



Dark Higgsstrahlung searches

Visible dark Higgs



BaBar and Belle searched for the visible DH:

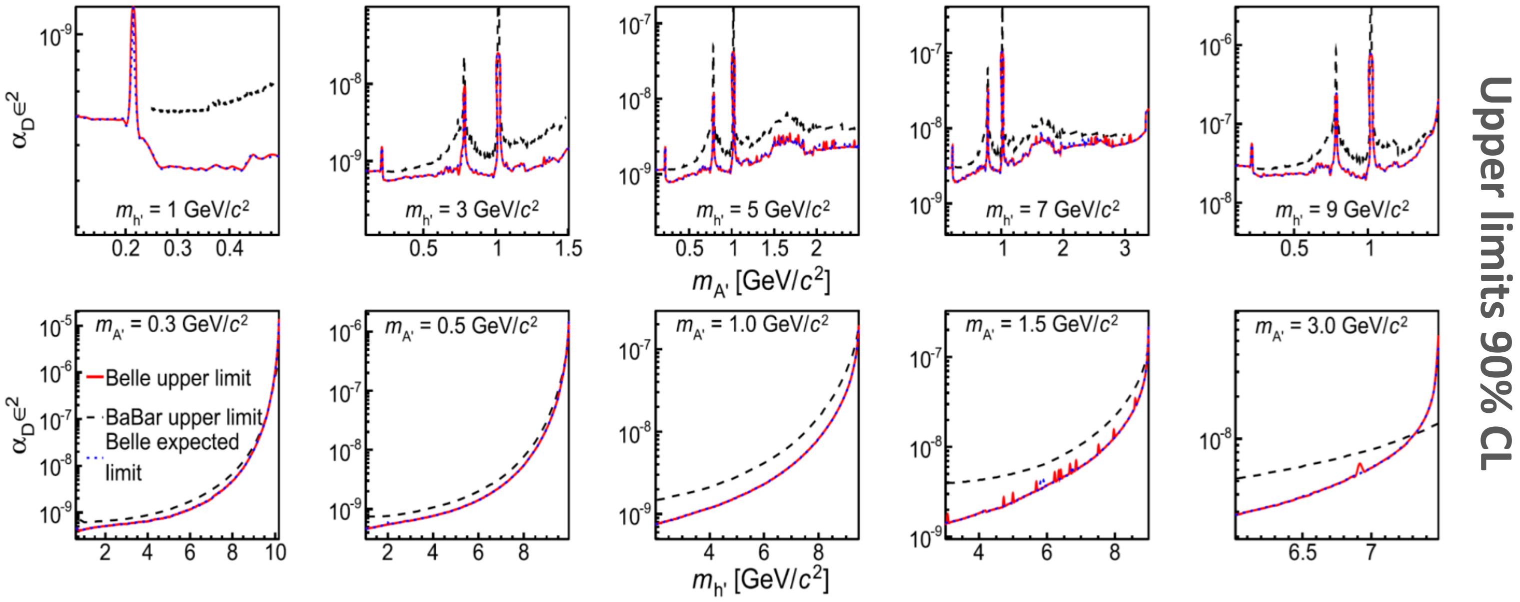
- **Signal**: three pairs of tracks ($ee, \mu\mu, \pi\pi$) at the same mass and no missing energy;
- **Background**: almost background free;

Full data-sets from both experiments.

90% C.L. upper limits on $\epsilon^2 \times \alpha_D$ at the level of $O(10^{-8} - 10^{-10})$:

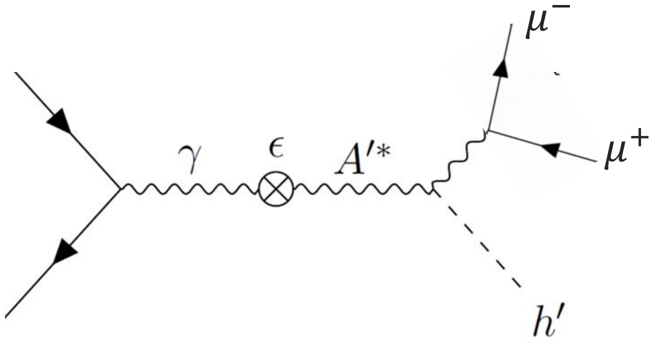
- Belle limits improve upon and explore slightly wider mass ranges than BaBar.

Phys. Rev. Lett. **108**, 211801 (2012) *Phys. Rev. Lett.* **114**, 211801 (2015)

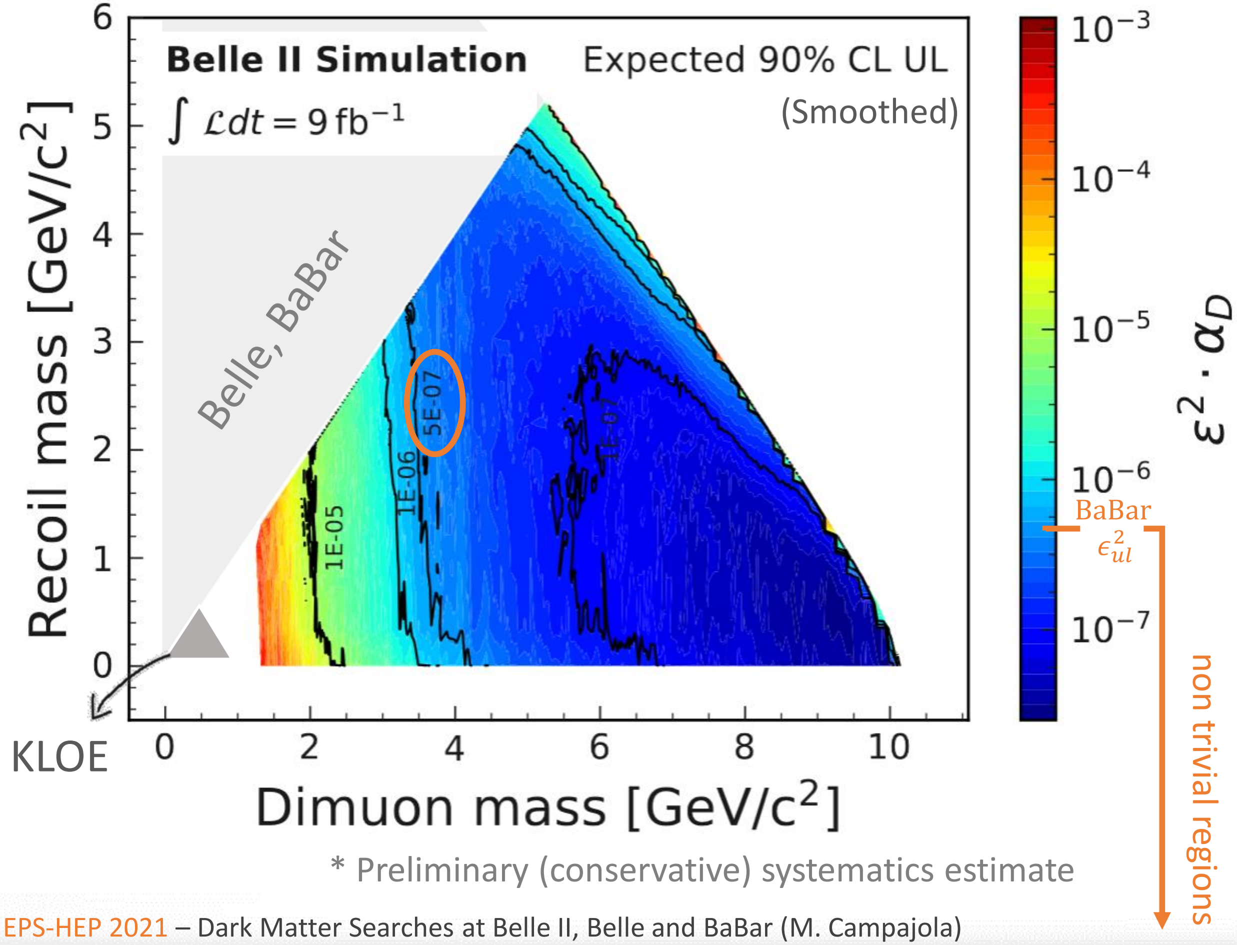


Dark Higgsstrahlung searches

Invisible dark Higgs



Belle II expected sensitivity on $\epsilon^2\alpha_D$ *



* Preliminary (conservative) systematics estimate

Belle II is exploring the *invisible h'* case in two muons and missing energy final state:

- **Signature:** a 2d peak in *recoil vs dimuon* mass;
- **Background** from QED processes: $\mu\mu(\gamma), \tau\tau(\gamma), ee\mu\mu$;

Very promising expectations even with the 2019 only dataset (~ 9 fb^{-1}).

- Accessing unconstrained region beyond the KLOE coverage;
- Probing non-trivial $\epsilon^2\ \alpha_D$ couplings.

Analysis to be finalized shortly (by end 2021).

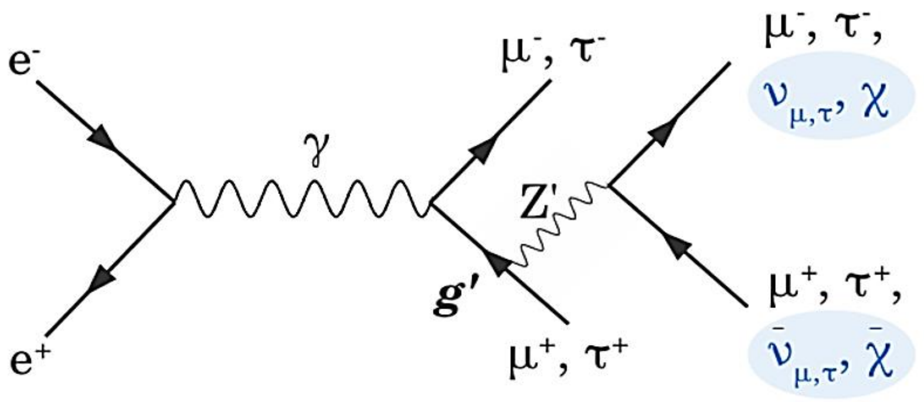
Z' searches

[1] Shuve et al., *Phys. Rev. D* **89** (2014)
[2] Altmannshofer et al., *JHEP* **106** (2016)

General remarks

New massive vector boson *Z'* coupling only to the 2nd and 3rd generation of leptons *($L_\mu - L_\tau$ model)*;

$$\mathcal{L} = \sum_{\ell=\mu,\tau,\nu_{\mu,L},\nu_{\tau,L}} \theta g' \bar{\ell}\gamma^\mu Z'_\mu \ell$$



This model may explain [1, 2]:

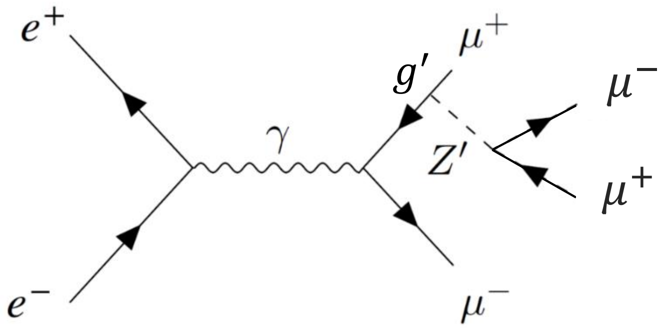
- DM puzzle;
- $(g-2)_\mu$ anomaly;
- B-physics anomalies: e.g., R_K, R_{K*};

Experimental signatures:

- **Visible decay** into a muon (tau) pair. Constrained by **BaBar(2016)** and **CMS(2019)** and neutrino-nucleus scattering processes (neutrino trident production, CCFR experiment at Fermilab);
- **Invisible decay**. First physics result from **Belle II (2020)**;

Z' searches

Visible decay



BaBar searched a Z' visible decay in a four muon final state.

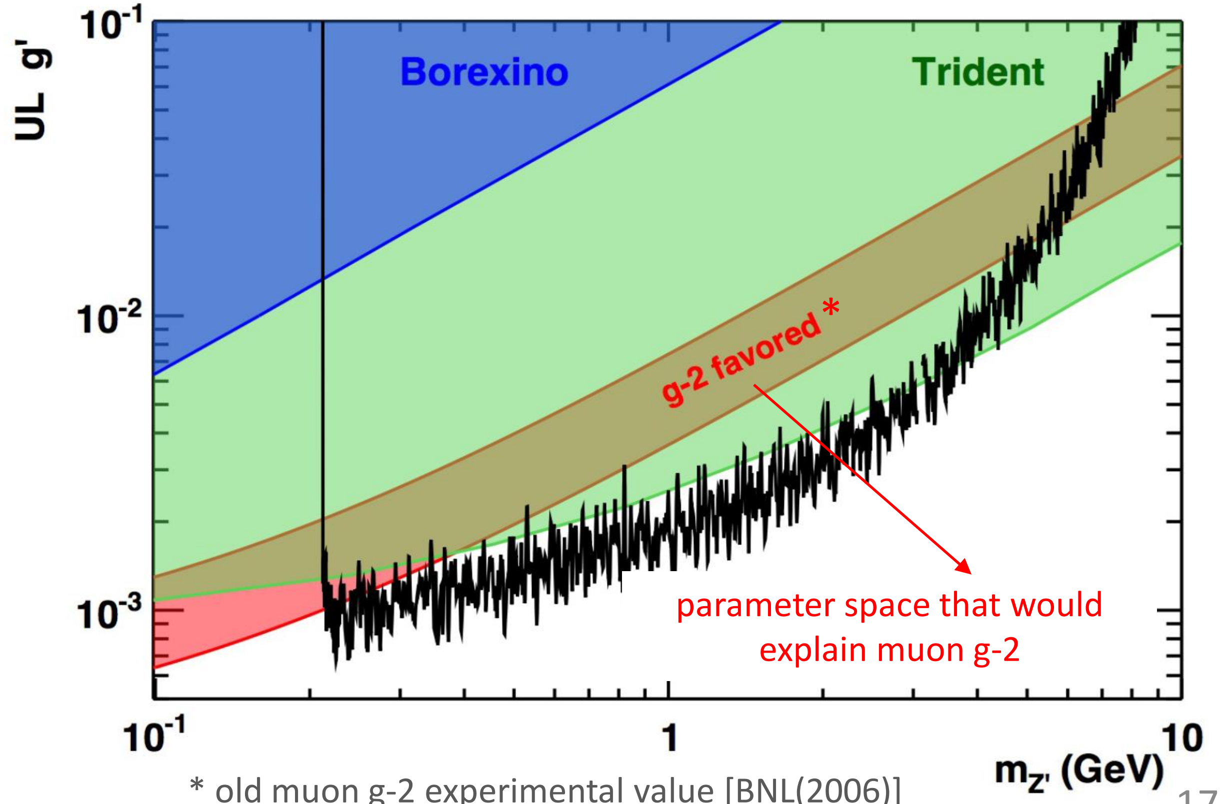
- **Signature**: peak in the invariant mass of two muons;
- **Background**: QED combinatorial backgrounds, as well as peaking backgrounds from $e^+e^- \rightarrow \pi+\pi- J/\psi$ and ρ;

Full BaBar data set: 514 fb^{-1}.

90% C.L. upper limits on g' at the level of *O*(10^{-3}):

- $(g-2)_\mu$ band largely excluded;

[Phys. Rev. D **94** 011102 (2016)]



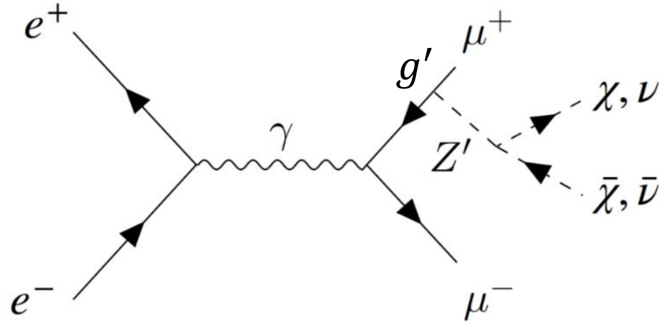
* old muon g-2 experimental value [BNL(2006)]

Post scriptum:

- **@ Belle:** same measurement based on Belle full luminosity, to be submitted to journal very soon. -> see ***Belle talk*** ;
- **@ Belle II**: good prospects with O(100 fb^{-1}) (with aggressive background suppression);

Z’ searches

Invisible decay



Belle II looked at the two muon + missing energy final state.

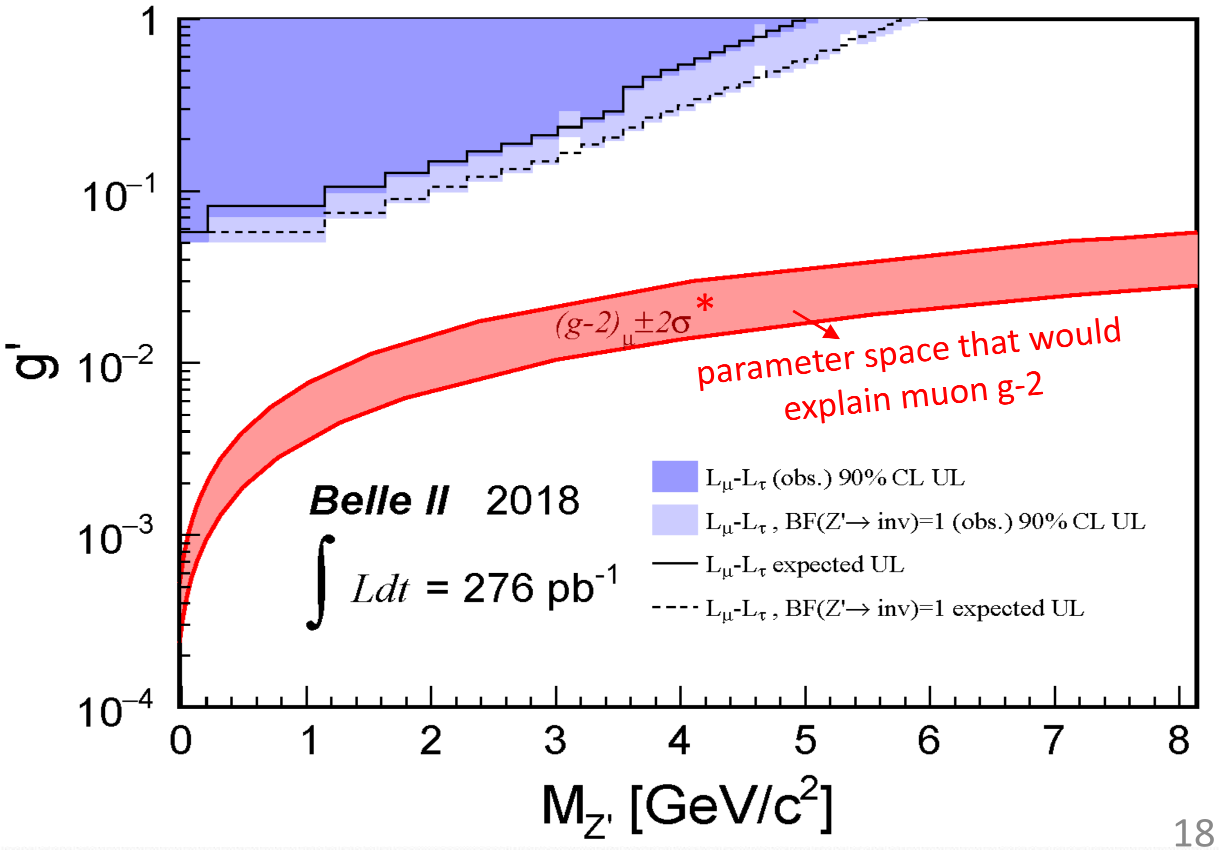
- **Signature: a peak in the mass distribution of the recoiling system against $\mu\mu$ pair;**
- **Background sources: $\mu\mu(\gamma), \tau\tau(\gamma), ee\mu\mu$;**

Used first data from 2018 commissioning run (0.276 fb^{-1}).

90% C.L. upper limits on g’ down to *O*(5 x 10^{-2}).

First physics paper by Belle II
First results ever for the *Z’ to invisible* decay
***Phys. Rev. Lett.* 124 (2020) 141801**

Phys. Rev. Lett. **124** (2020) 141801



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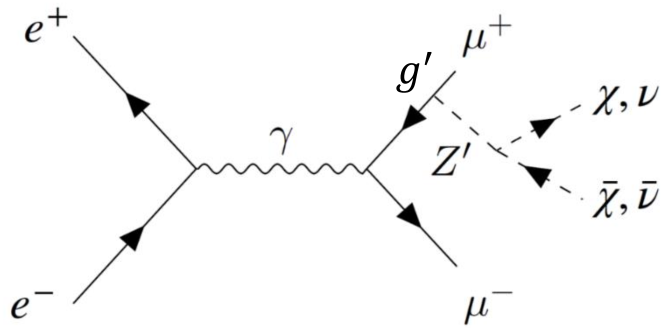
Z' searches

Invisible decay



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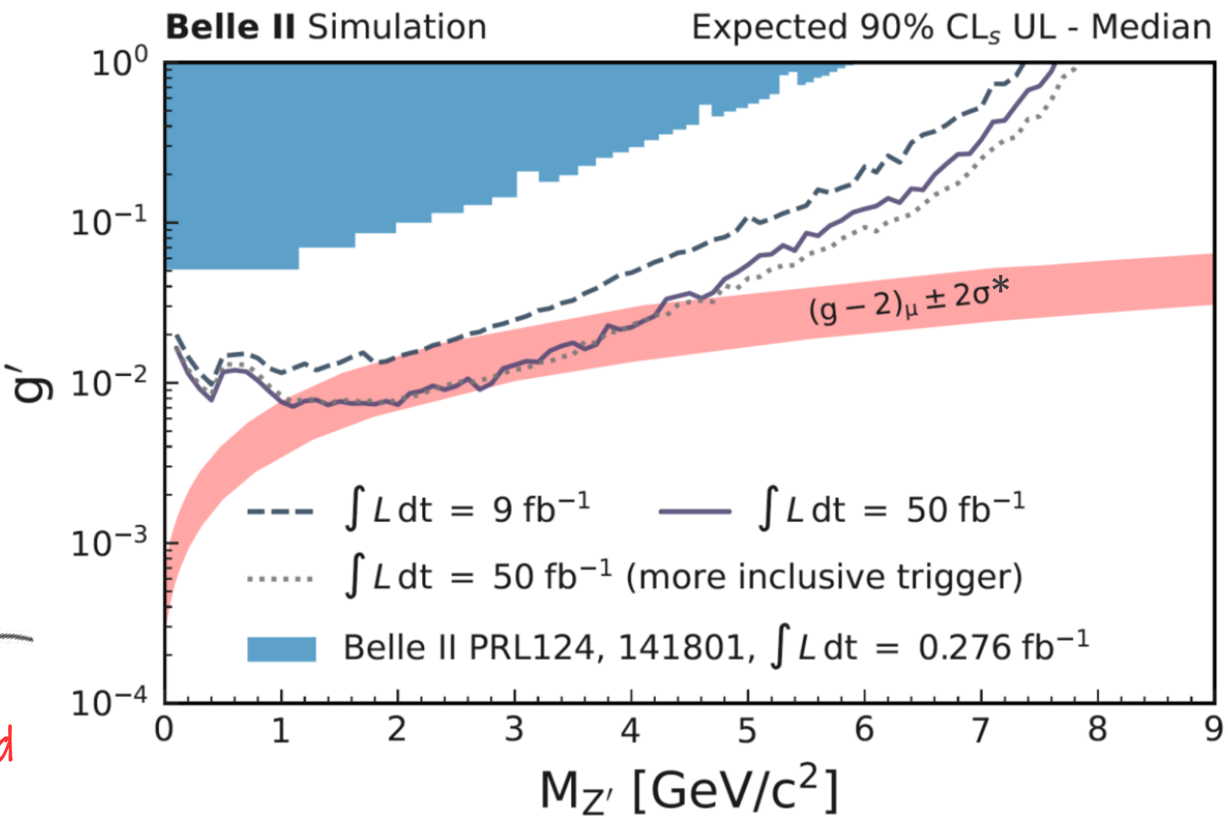
- **Background sources: $\mu\mu(\gamma), \tau\tau(\gamma), ee\mu\mu$;**

Short term projections with several improvements:

- Much higher integrated luminosity (already on tape);
- Analysis improvements;
- New triggers.



* old muon g-2 experimental value [BNL(2006)]

Starting to probe the $(g\text{-}2)_\mu$ band

Axion Like Particles

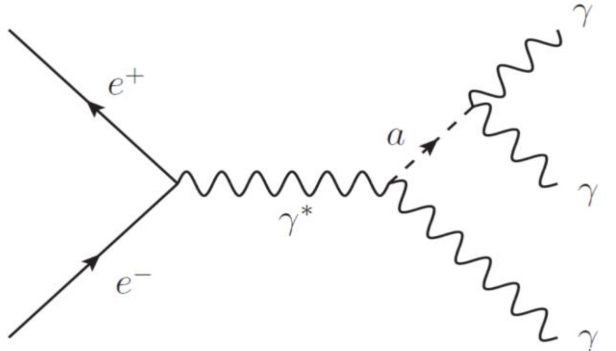
General remarks

Axion Like Particles (ALPs) are pseudo-scalars particles (*a*) that couple to fermions or boson.
Naturally coupling to photons:

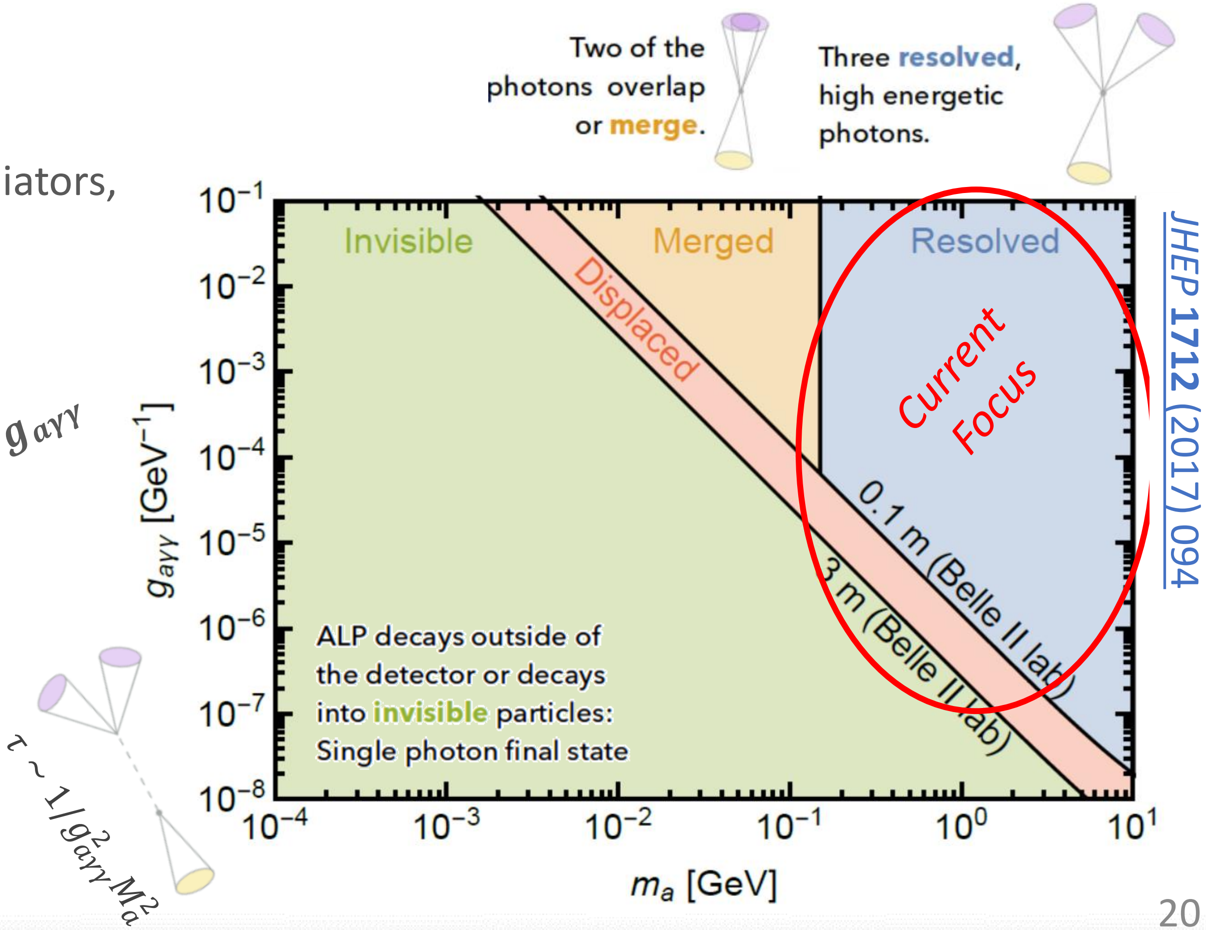
$$\mathcal{L} \supset -\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

- ALPS can be both Dark Matter candidates and Dark Sector mediators, and they appear in many BSM scenarios.

Belle II searched for the ALP-strahlung process.



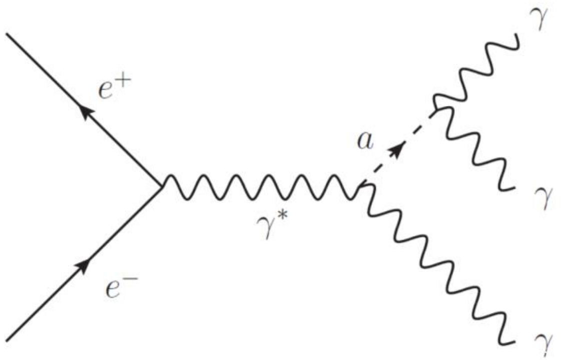
Several topologies depending on M_a and $g_{a\gamma\gamma}$



JHEP **1712** (2017) 094

Axion Like Particles

ALP-strahlung



Belle II searched for ALP-strahlung in the 3γ resolved final state;

Signature:

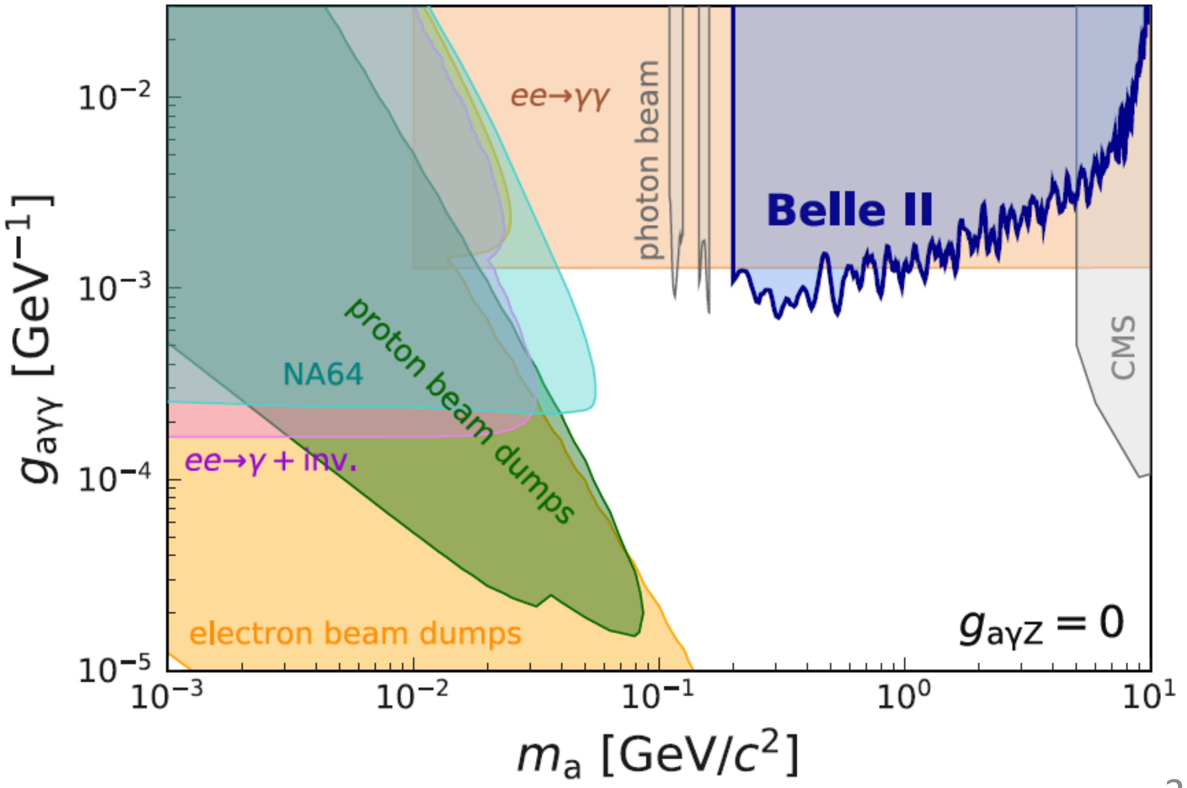
- 3γ that add up to the beam energy;
- bump on di-photon mass;

Background: $\gamma\gamma(\gamma)$; $e^+e^-(\gamma)$; $P\ \gamma(\gamma)\ with\ P = \pi^0, \eta, \eta'$;

Used first data from 2018 commissioning run (0.455 fb^{-1});

90% C.L. upper limits on $g_{a\gamma\gamma}$ down to $O(10^{-3})$.

Phys. Rev. Lett. **125**, 161806 (2020)



Second physics paper by Belle II
First results ever for ALPs @ B-factories
Phys. Rev. Lett. **125**, 161806 (2020)

Conclusions

The persisting null results from heavy new physics LHC searches and direct underground searches (not definitive in both cases) make the light dark sector scenario more and more attractive.

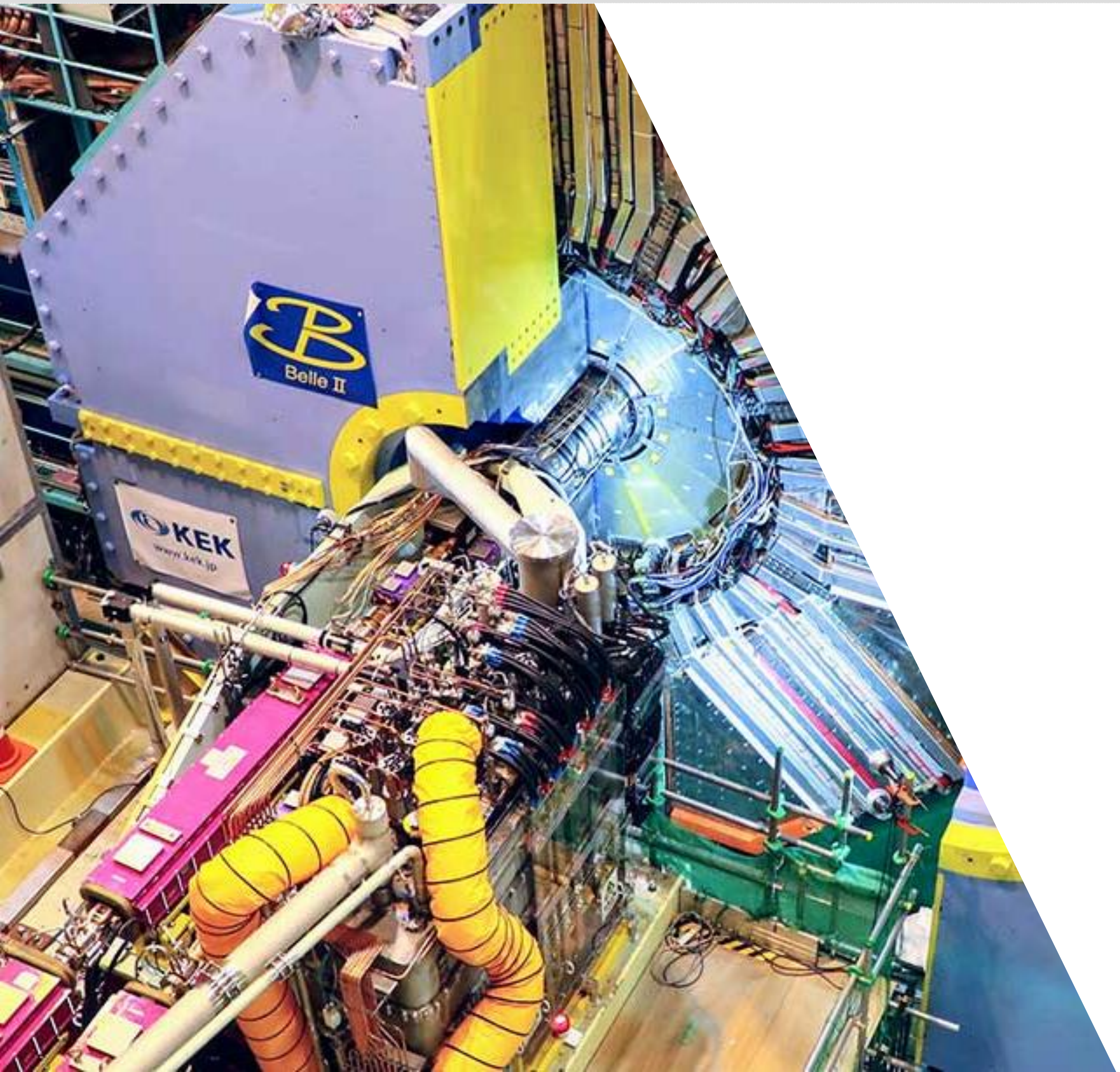
B-factories are an excellent laboratory to probe dark sector models: → sensitive to regions of parameter space that would explain dark matter and/or other SM anomalies

- **Belle** and **BaBar** already excluded many DS models.
  - In this talk: a subset of the results from the past years;

→ parallel talks
Latest dark sector searches at the Belle Experiment
Search for self-interacting dark matter with the BABAR detector

- **Belle II** started operations in 2018. Up to now ~ 213 fb^{-1} collected.
  - **Broad program of dark searches;**
    - First physics results and publications are already out: invisible Z' and ALP→$\gamma\gamma$;
    - Dark Higgsstrahlung and invisible dark photon coming soon;
    - Many more dark sector models (to be) explored.
    - **Leading sensitivity over the next few years.**

→ e.g., see parallel talk on:
Prospects for long-lived particle searches at Belle II



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Belle II

Dark Sector searches

State of art @ B-factories

✓ Discussed today

A lot of DM searches @ B-factories excluded Dark Sector parameters down to:

	Belle	BaBar	Belle II
$ee \to \gamma A'$, $A' \to ll$ ✓	-	$\epsilon < 5 \times 10^{-4}$ (514 fb^{-1}) [1]	-
$ee \to \gamma A'$, $A' \to \text{invisible}$ ✓	-	$\epsilon < 10^{-3}$ (53 fb^{-1}) [2]	-
$B^0 \to A'A'$	BF $< 10^{-7}$ (711 fb^{-1}) [3]	-	-
$ee \to \gamma \Upsilon_D$ (DM bound state)	-	$\epsilon < 10^{-3}$ (514 fb^{-1}) [*]	-
$ee \to A'h'$, $h' \to A'A'$ ✓	$\alpha_D \epsilon < 10^{-9}$ (977 fb^{-1}) [4]	$\alpha_D \epsilon < 10^{-9}$ (514 fb^{-1}) [5]	-
$ee \to \mu\mu Z'$, $Z' \to ll$ ✓	$g' < 10^{-3}$ (643 fb^{-1}) [*]	$g' < 10^{-3}$ (514 fb^{-1}) [1]	-
$ee \to \mu\mu Z'$, $Z' \to \text{invisible}$ ✓	-	-	$g' < 5 \times 10^{-2}$ (0.27 fb^{-1}) [6]
$\eta \to \gamma A'_q$, $A'_q \to \pi\pi$	$\alpha_q < 5 \times 10^{-3}$ (976 fb^{-1}) [7]	-	
$ee \to \tau\tau\phi_\tau$, $\phi_\tau \to ll$	-	$\eta < 5 \times 10^{-1}$ (514 fb^{-1}) [8]	
$ee \to \gamma a$, $a \to \gamma\gamma$ ✓	-	-	$g_{a\gamma\gamma} < 10^{-3}\,\text{GeV}^{-1}$ (0.45 fb^{-1}) [9]
$B^\pm \to K^\pm a$, $a \to \gamma\gamma$	-	$g_{aWW} < 10^{-5}\,\text{GeV}^{-1}$ (424 fb^{-1}) [*]	-
$\Upsilon(2S,3S) \to \gamma A^0$, $A^0 \to \mu\mu$	-	(99, 122 $\times 10^6 \Upsilon(2S,3S)$) [10]	-
$\Upsilon(3S) \to \gamma A^0$, $A^0 \to \tau\tau$	-	BF $< 10^{-5}(122 \times 10^6 \Upsilon(3S))$ [11]	-
$\Upsilon(2S) \to \Upsilon(1S)\pi\pi$, $\Upsilon(1S) \to \gamma A^0$, $A^0 \to \text{invisible}$	BF $< 10^{-6}(157 \times 10^6 \Upsilon(2S))$ [12]	BF $< 10^{-6}(98 \times 10^6 \Upsilon(2S))$ [13]	-
$\Upsilon(2S,3S) \to \pi\pi\Upsilon(1S)$, $\Upsilon(1S) \to \gamma A^0$, $A^0 \to \mu\mu$	-	BF $< 10^{-6}(93, 117 \times 10^6 \Upsilon(2S,3S))$ [14]	-

References in spare slides

Spare

Dark Sector state of art @ B-factories

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