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First results and prospects for Dark Sector searches at Belle II

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on the behalf of the Belle II collaboration

DM searches

Motivations & Models

What is Dark Matter?

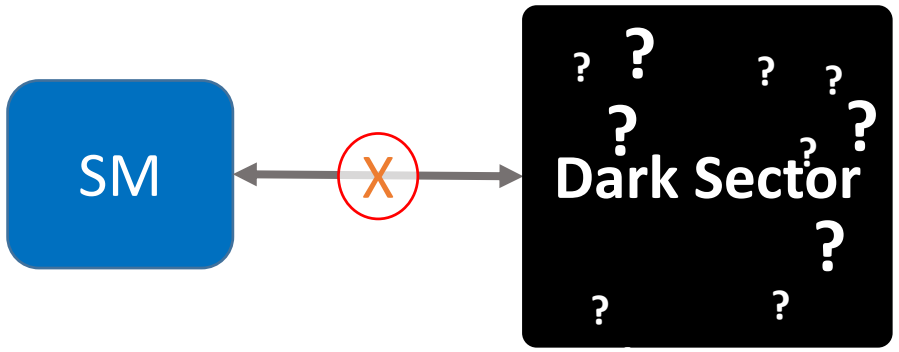
- It's 'dark'
- There is a lot of it

Mainstream searches looking for WIMPs;

A possible MeV - GeV theoretical scenarios:

- Light-DM associated with new dark forces, weakly coupled to SM through new light mediators.
- Different possible portals between Dark Sector and SM:
  - **Vector Portal** → Dark Photon A', Dark Z'
  - **Pseudo-scalar Portal** → Axion Like Particles
  - **Scalar Portal** → Dark Scalars, extended Higgs models
  - **Neutrino Portal** → Sterile Neutrinos

In this talk



Low energy e^+e^- colliders are the perfect places to explore Dark Sector Physics in the MeV - GeV range.

Here, looking for Light DM production, but probability of LDM interaction with the detectors is negligible. So…

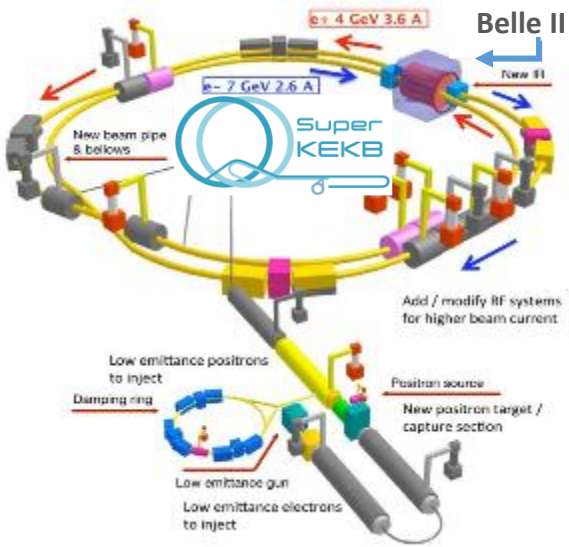
- **Searching for mediators;**
- **Searching for missing energy signature;**

The Belle II Experiment

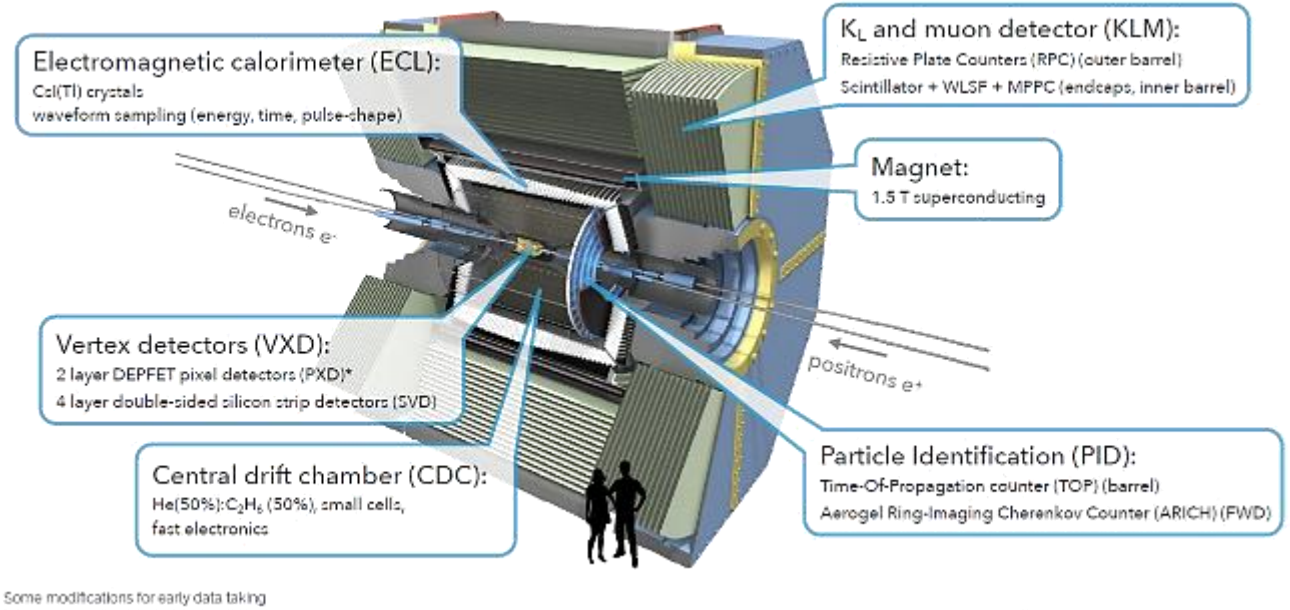
For further details see G. De Pietro's talk on
"Stato dell'esperimento Belle II e primi risultati di fisica"
(16 September 2020)

A look at the detector

- Located at IP of e^+e^- collider SuperKEKB in Tsukuba, Japan.
- Operated at $\sqrt{s} = 10.58\ GeV\ (= M_{\Upsilon(4s)})$
- Design luminosity: $L\ =\ 6.5 \cdot 10^{35}\ cm^{-2}\ s^{-1}$
- Rich physics program: B, D and tau physics, quarkonium and low mass dark sector



Belle II detector



* Some modifications for early data taking

Data taking time schedule

2018

Phase 2 (pilot run)

- First physics data (500 pb^{-1}).
- Incomplete detector (1/8 VXD)
- Commissioning data.

2019

Phase 3

- Belle II routinely integrates more than 1 fb^{-1}/day.
- Up to now ~ 75 fb^{-1} collected

~2030

Goal

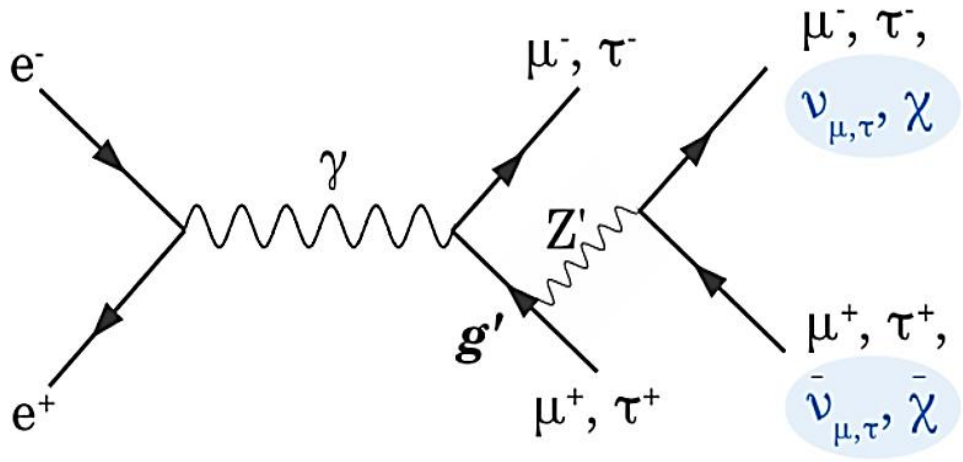
- Integrate up to 50 ab^{-1}
- X50 dataset of its predecessor (Belle)

Z’ to invisible

References:
Shuve et al. (2014), arXiv:1403.2727
Altmannshofer et al. (2016) arXiv:1609.04026

A bit of Theory

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



This model may explain:

- DM puzzle;
- $(g\text{-}2)_\mu$ anomaly;
- $B \to K(*)\mu\mu$, R_K, R_{K*} anomalies;

Several experimental signature:

- Visible decay into a muon/tau pair.
  (constrained by BaBar)
- Invisible decay into SM neutrinos or DM if kinematically accessible, e.g., sterile neutrinos, light Dirac fermions.
  (Never explored before)

@ Belle II: looking for an invisibly decaying Z’ produced with a pair of muons.

$$e^+e^- \to \mu^+\mu^- Z' \quad \hookrightarrow \textit{invisible}$$

Looking for:

- A peak in the mass distribution of the recoiling system against $\mu\mu$ pair;
- Nothing else in the rest of event

Z’ to invisible

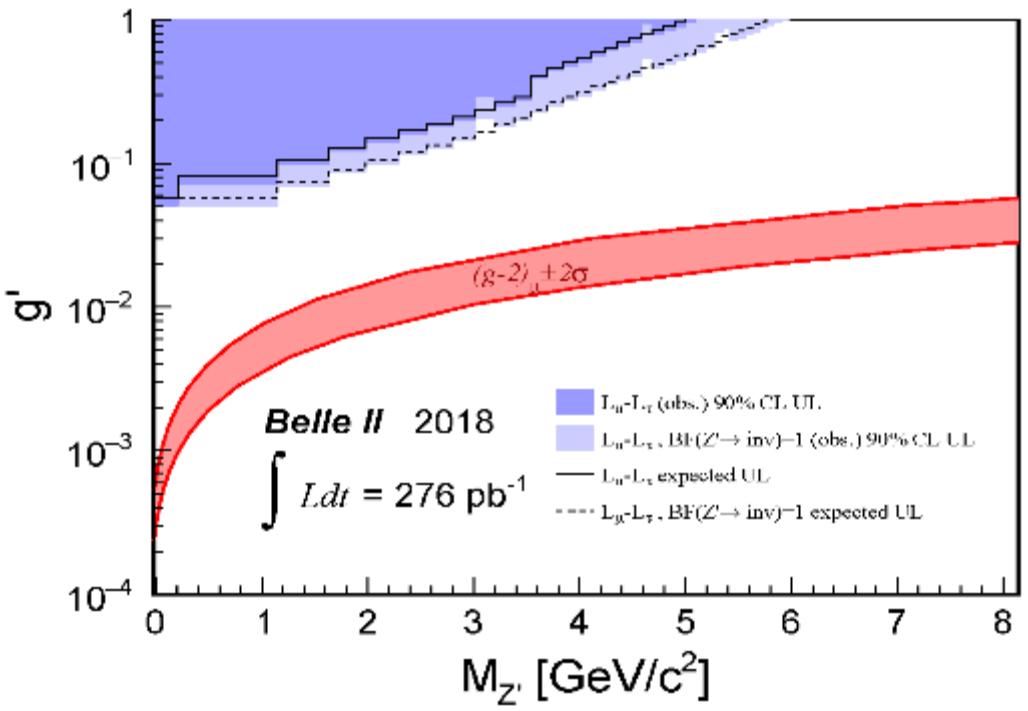
Results

First physics paper by Belle II
PRL 124 (2020) 141801

Measurement performed with 2018 pilot run data.

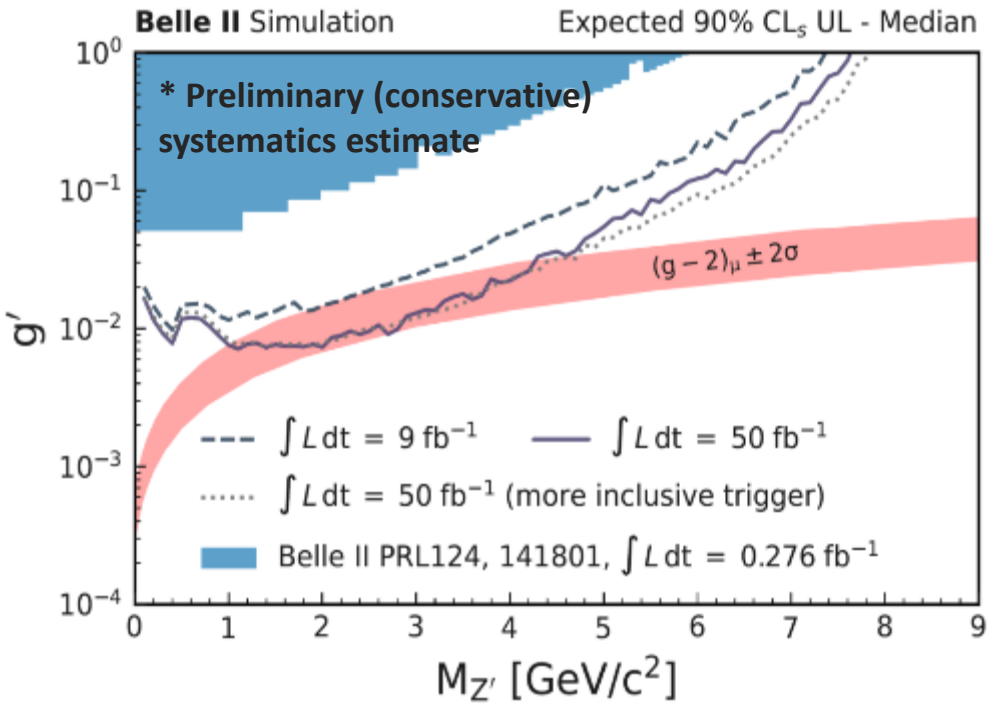
- First results ever for the Z’ to invisible decay.
- Searched also for a LFV Z’ in $e\mu + missing$ final state.

90% CL upper limit on the *g’* coupling constant.



Short term luminosity projection with new data (2019/20)

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



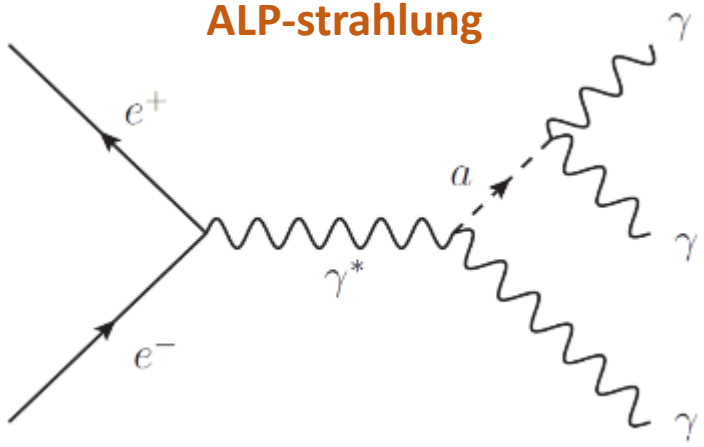
Axion Like Particles

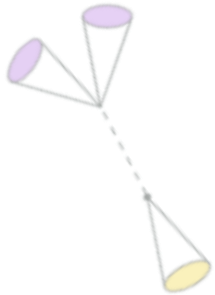
A bit of theory

Axion Like Particles (ALPs) are pseudo-scalars particles (*a*) that couple to bosons.

- They can be DM candidates or mediators and appear in many BSM scenarios.

ALP-strahlung

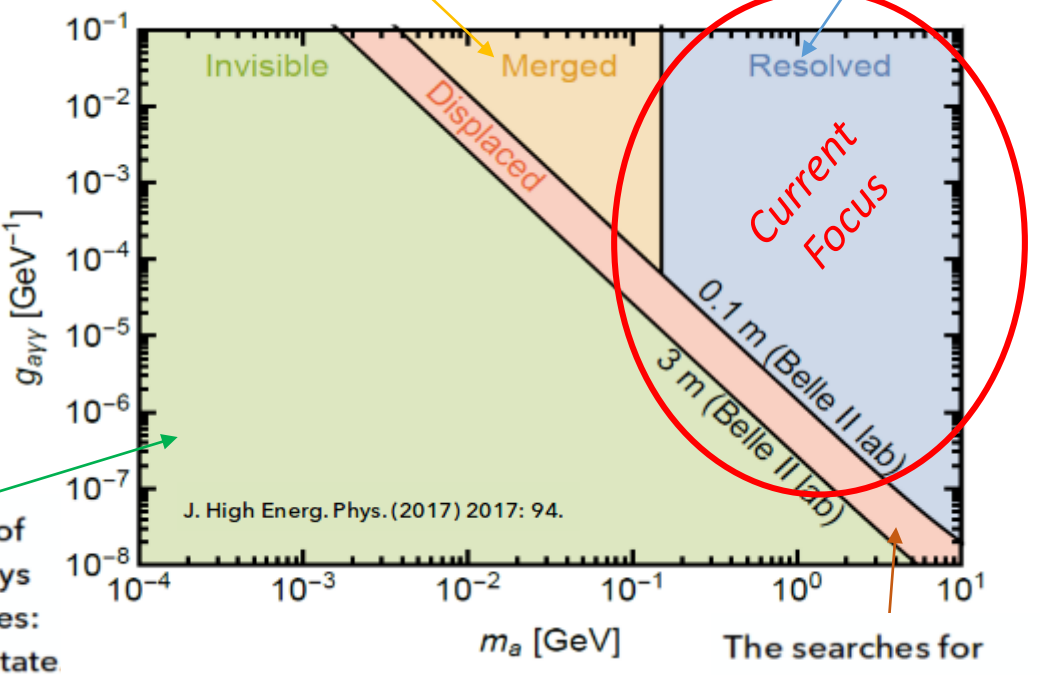




ALP decays outside of the detector or decays into **invisible** particles: Single photon final state

Two of the photons overlap or **merge**.

Three **resolved**, high energetic photons.



The searches for invisible and visible ALP decays veto this region.

@ Belle II exploring photon coupling $g_{a\gamma\gamma}$ in ALP-strahlung

First search at B-factories.

Exploring the 3γ resolved final state:

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

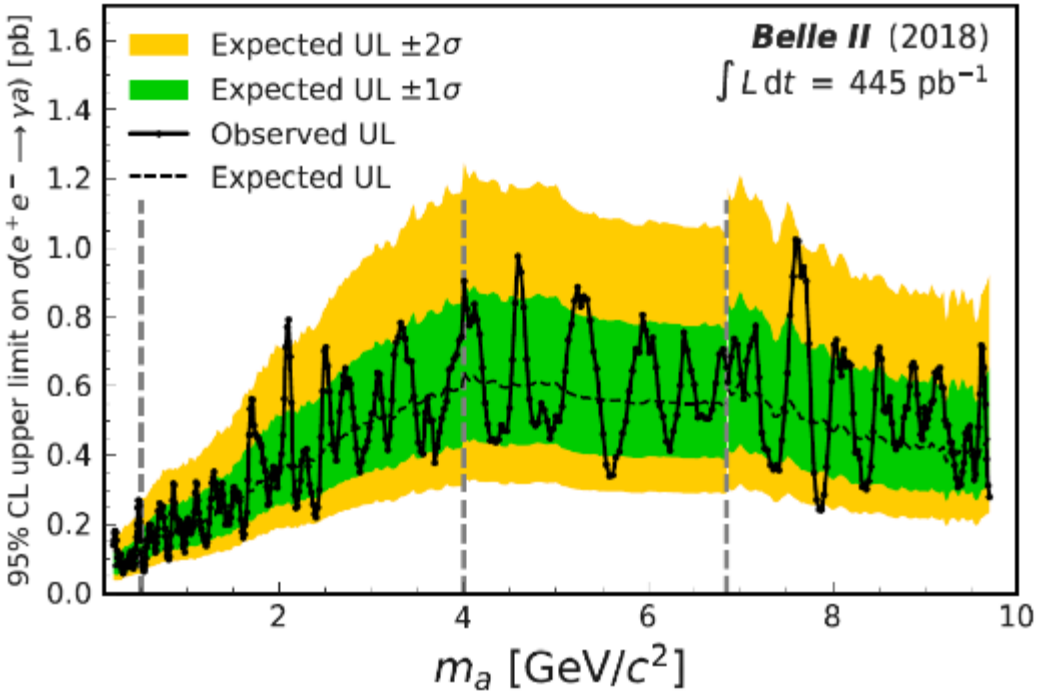
Axion Like Particles

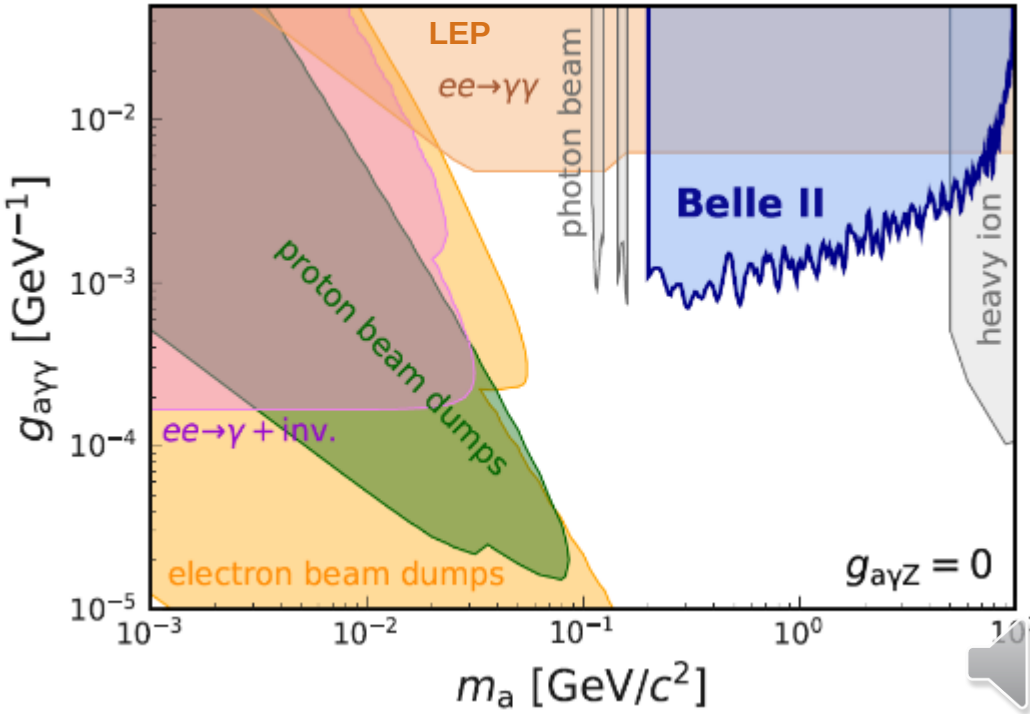
Results

Second physics paper by Belle II
Submitted to PRL arXiv:2007.13071

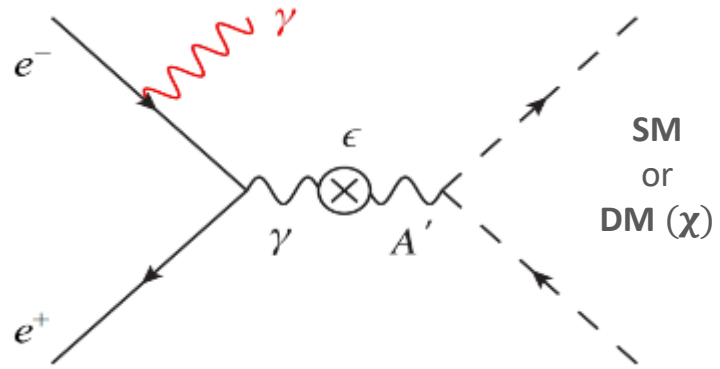
Measurement performed with 2018 pilot run data.

- Explored mass range $0.2 < m_a < 9.7\ \mathrm{GeV}/c^2$
- 95% CL upper limit on the cross section and then translated in terms of the $g_{a\gamma\gamma}$ coupling constant.





Dark Photon to Invisible

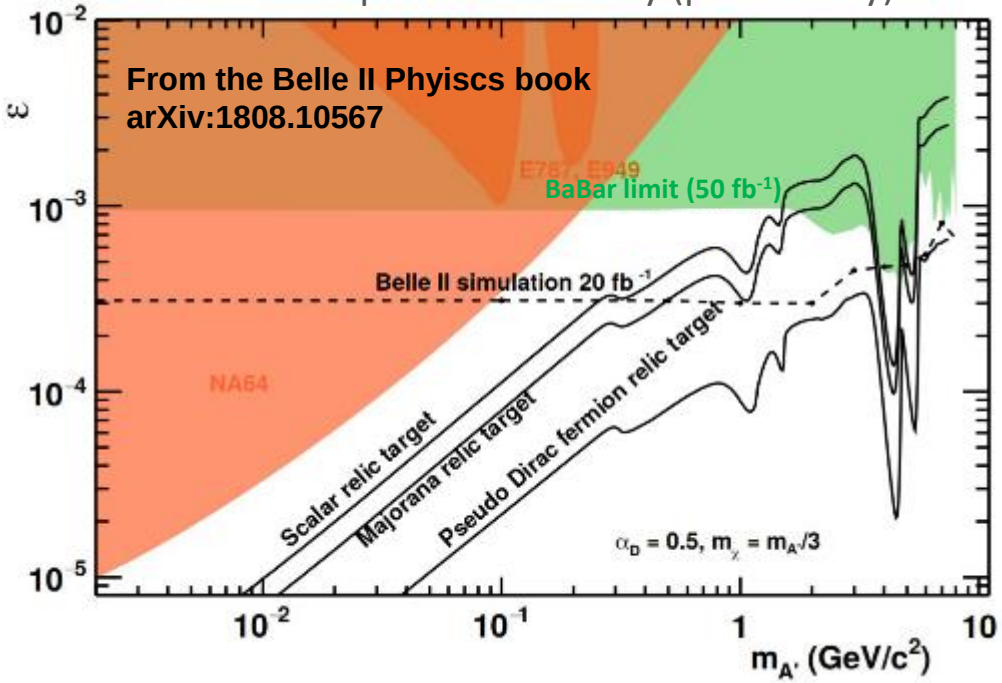


Expected Sensitivity

Dark photon A': a massive gauge boson of spin = 1 coupling to the SM photons through the kinetic mixing with strength ε.

- At e^+e^- colliders looking for $e^+e^- \rightarrow \gamma_{ISR}\, A'$

Belle II expected sensitivity (preliminary)



Different experimental signature:

- $m_x > \frac{1}{2} m_{A'} \rightarrow$ **A' visible decays to SM particles** (strongly constrained by BaBar);
- $m_x < \frac{1}{2} m_{A'} \rightarrow$ **A' invisible decays to LDM** (much looser constrains);

@ Belle II we are first exploring the invisible decay:

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

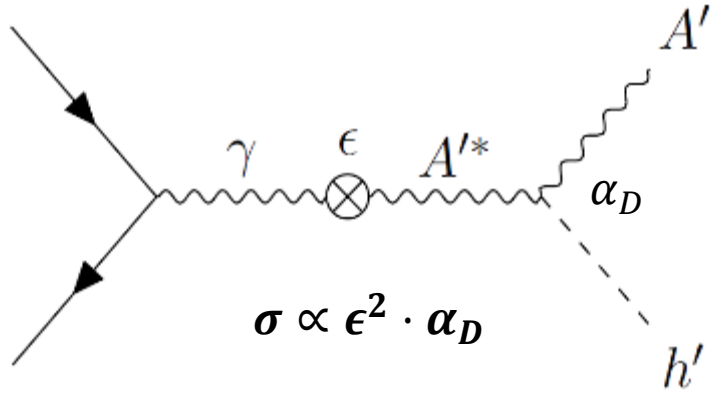
Very promising results even with the early dataset.

Why Belle II is expected to perform better than BaBar?

- no ECL cracks pointing to the interaction regions;
- larger acceptance;
- KLM veto.

Dark Higgsstrahlung

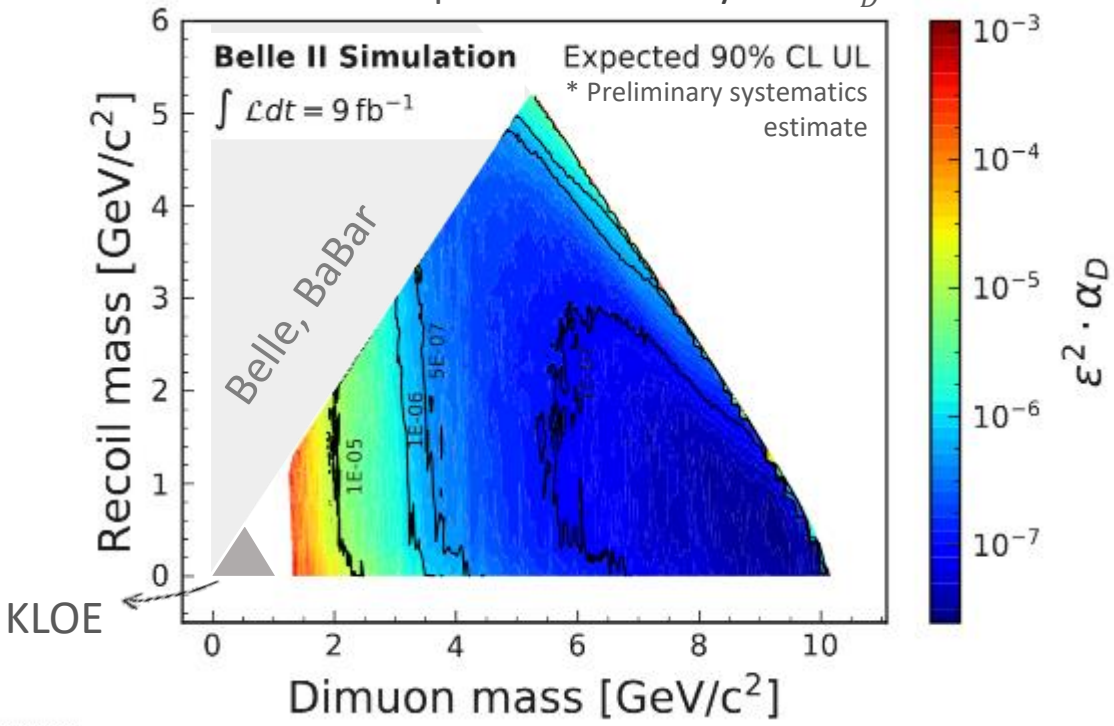
Expected Sensitivity



The dark photon mass could be generated via a spontaneous symmetry breaking mechanism, adding a dark Higgs boson *h*' to the theory.

- *h'* and *A'* produced in the **Dark Higgsstrahlung process**: $e^+e^- \rightarrow A'^* \rightarrow h' A'$

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



Different topologies depending on the mass hypothesis.

- $m_{h'} > m_{A'}$: $h' \rightarrow A'A' \rightarrow 4l, 4had, 2l + 2had$, constrained by Belle and BaBar;
- $m_{h'} < m_{A'}$: h' *is invisible*, constrained only by KLOE;

@ Belle II: exploring the *invisible h'* case.

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

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

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

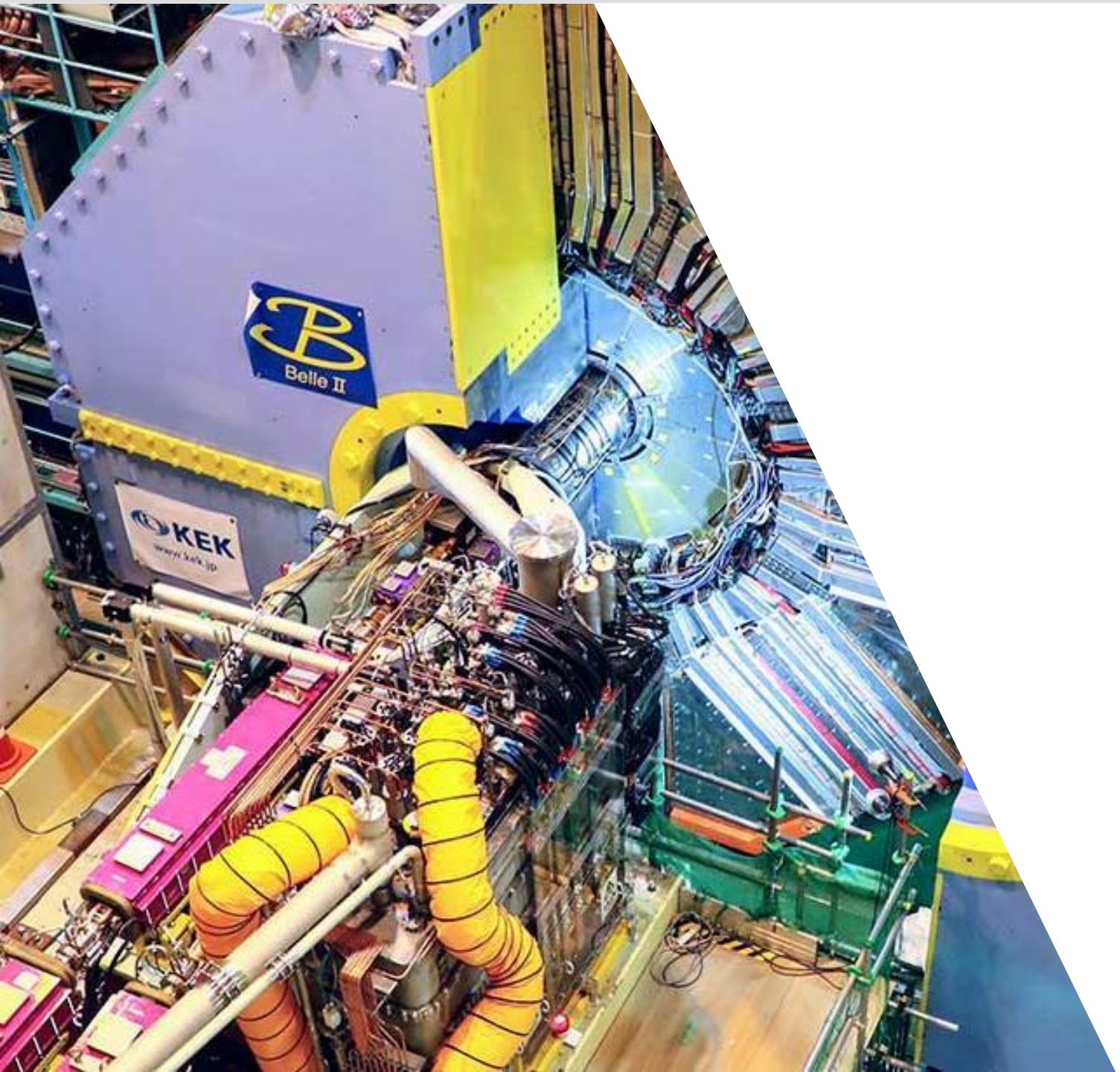
Conclusions

Although designed mainly for B-physics, Belle II has a broad and active program to explore the *Dark Sector Physics*;

- We successfully started operations in 2018. Up to now we collected ~ 75 fb^{-1} of data.
- First results with early data (2018 pilot run) are out:
  - ***Z' to invisible search***.
  - ***ALPs search*** (submitted to PRL);
- Coming soon:
  - ***invisible A'***
  - ***Dark Higgsstrahlung***

  } Good prospects even with 2019/2020 data
- Possibility to explore many more dark sector models.

For further details see:
The Belle II Physics Book, *Progress of Theoretical and Experimental Physics*, Volume 2019, Issue 12, December 2019, arXiv:1808.10567



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