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Dark Sector at Belle II

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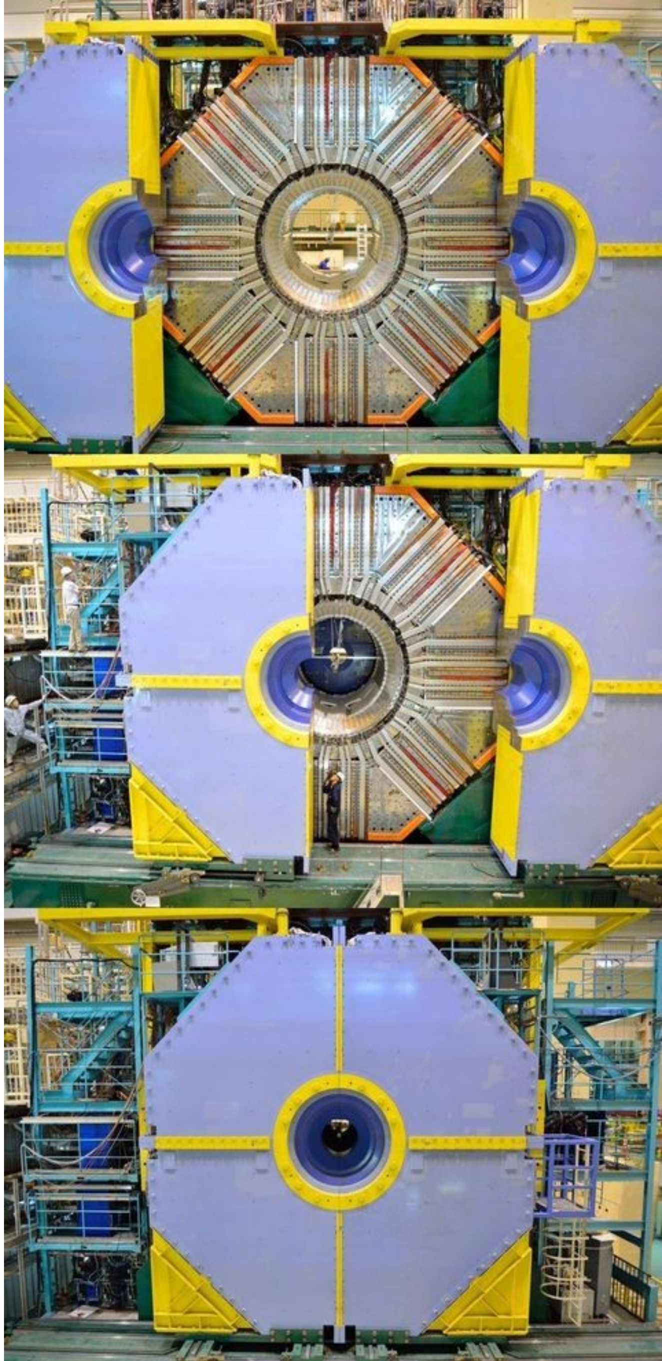
ROMA TRE UNIVERSITÀ DEGLI STUDI

INFN Istituto Nazionale di Fisica Nucleare SEZIONE DI ROMA TRE

Belle II

Outline

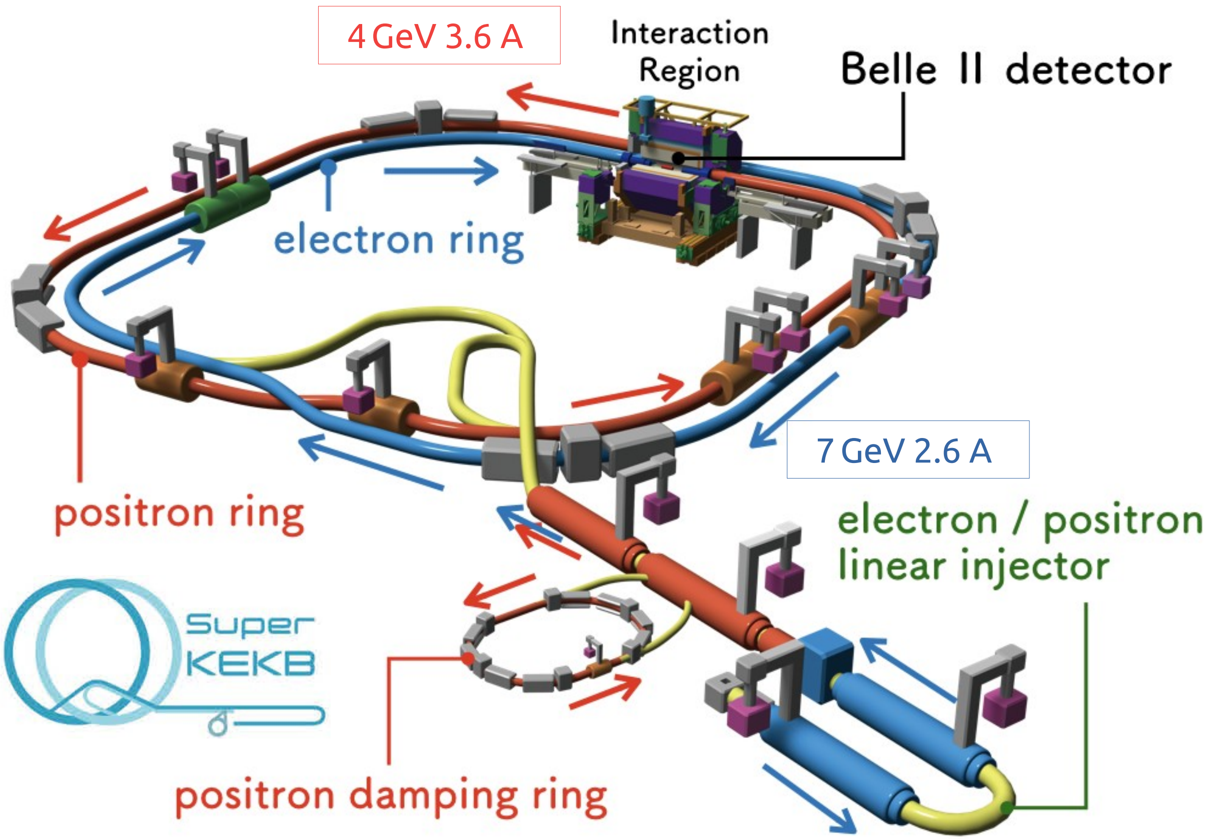
- SuperKEKB and the Belle II experiment;
- Dark sector;
- Ongoing dark sector searches at Belle II:
  - Z' to invisible;
  - Z' to visible;
  - Axion-Like Particles;
  - Dark Higgsstrahlung;
  - Invisible dark photon.
- Conclusions.



1. SuperKEKB and the Belle II experiment

SuperKEKB

A KEKB upgrade



$$L = \frac{\gamma_{\pm}}{2 e r_e} \left(\frac{I_{\pm} \xi_{y\pm}}{\beta^*_{y\pm}} \right) \left(\frac{R_L}{R_{\xi y}} \right)$$

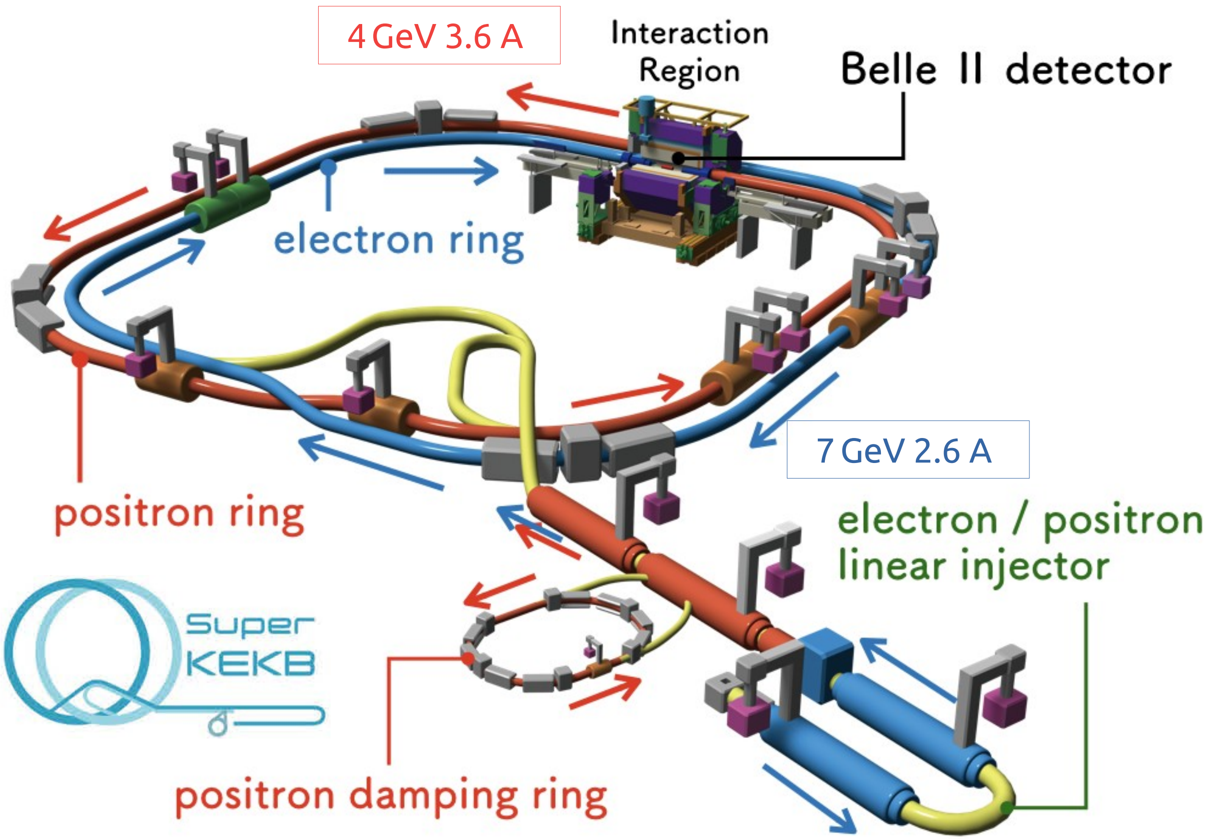
Lorentz factor

Electric charge

Electric radius

SuperKEKB

A KEKB upgrade

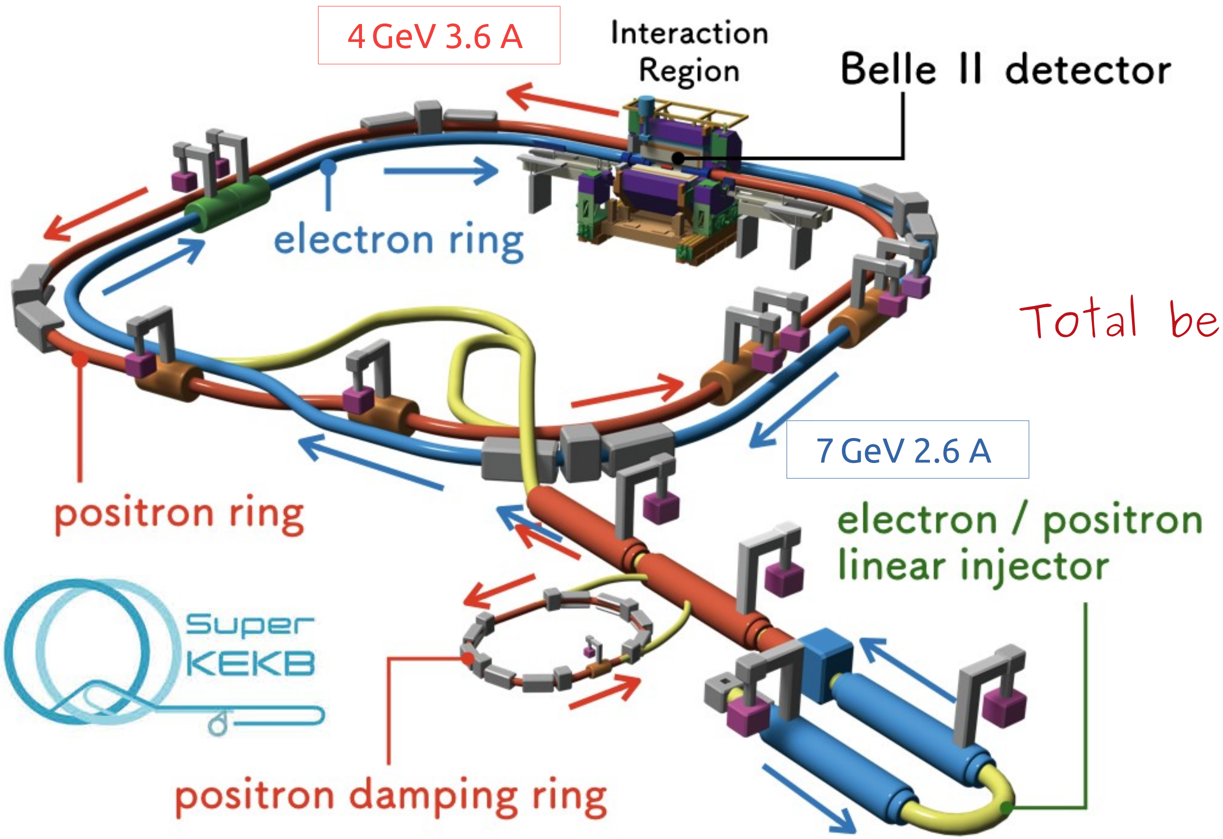


Reduction factors

$$L = \frac{\gamma_{\pm}}{2 e r_e} \left(\frac{I_{\pm} \xi_{y\pm}}{\beta^*_{y\pm}} \right) \left(\frac{R_L}{R_{\xi y}} \right)$$

SuperKEKB

A KEKB upgrade



Vertical beam-beam parameter

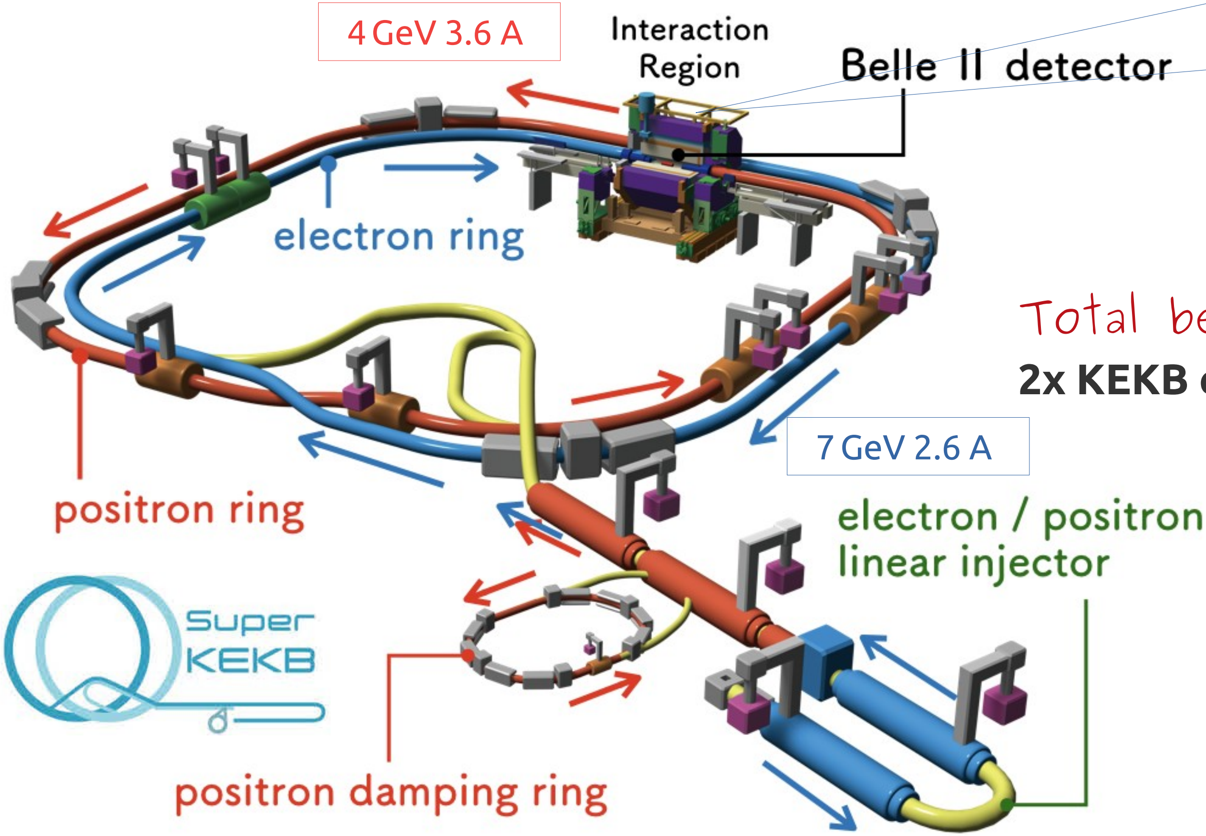
Total beam current

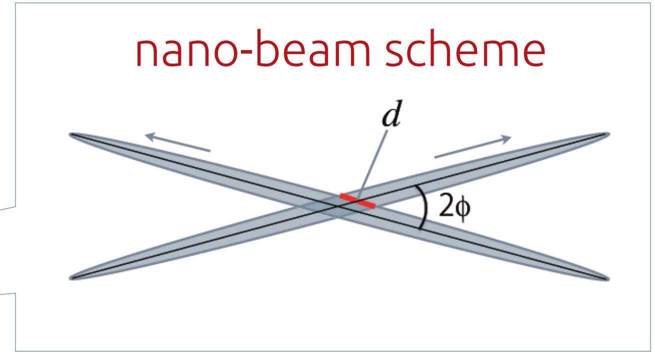
$$L = \frac{\gamma_{\pm}}{2 e r_e} \left(\frac{I_{\pm} \xi_{y\pm}}{\beta^*_{y\pm}} \right) \left(\frac{R_L}{R_{\xi y}} \right)$$

Beta function at the IP

SuperKEKB

A KEKB upgrade





Vertical beam-beam parameter

Total beam current

2x KEKB current

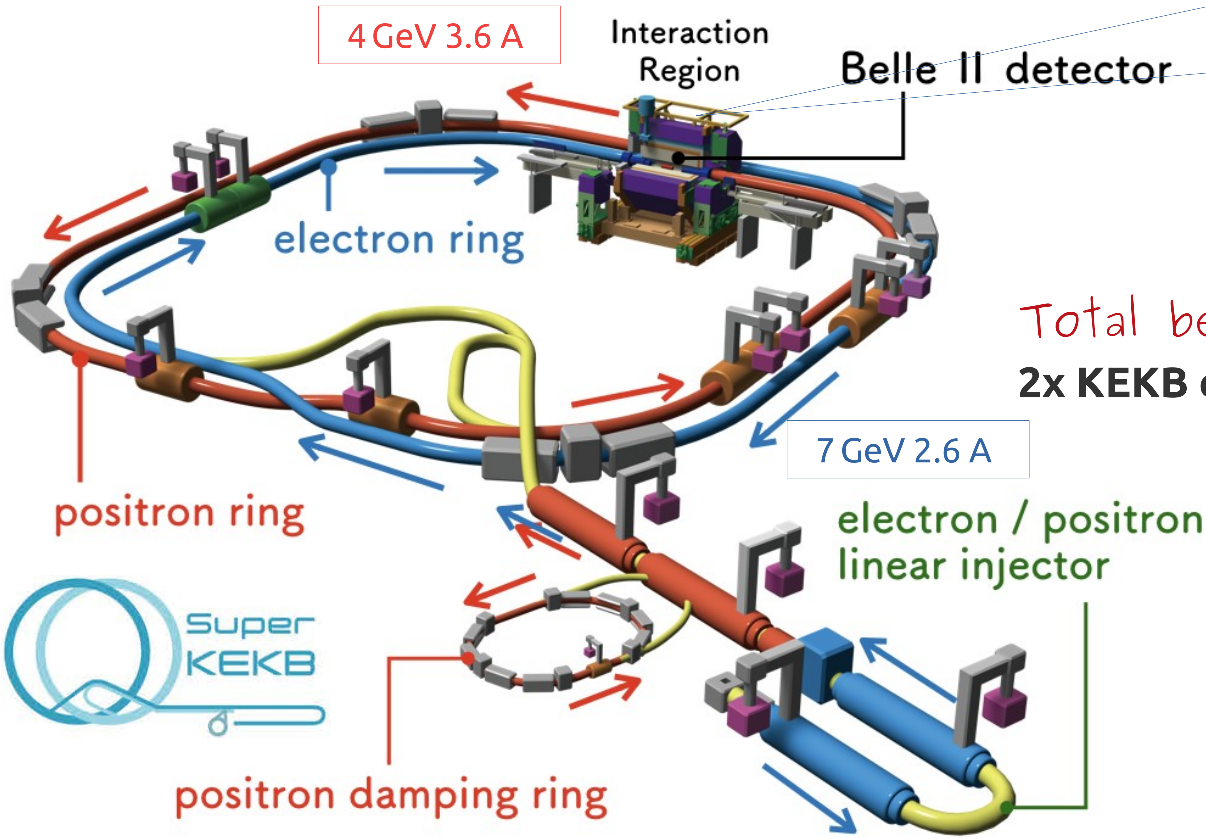
$$L = \frac{\gamma_{\pm}}{2 e r_e} \left(\frac{I_{\pm} \xi_{y\pm}}{\beta^{*}_{y\pm}} \right) \left(\frac{R_L}{R_{\xi y}} \right)$$

Beta function at the IP

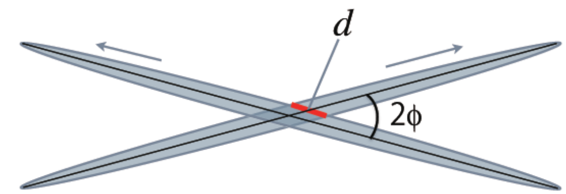
20 times smaller than KEKB

SuperKEKB

A KEKB upgrade



nano-beam scheme



Total beam current
2x KEKB current

Vertical beam-beam parameter

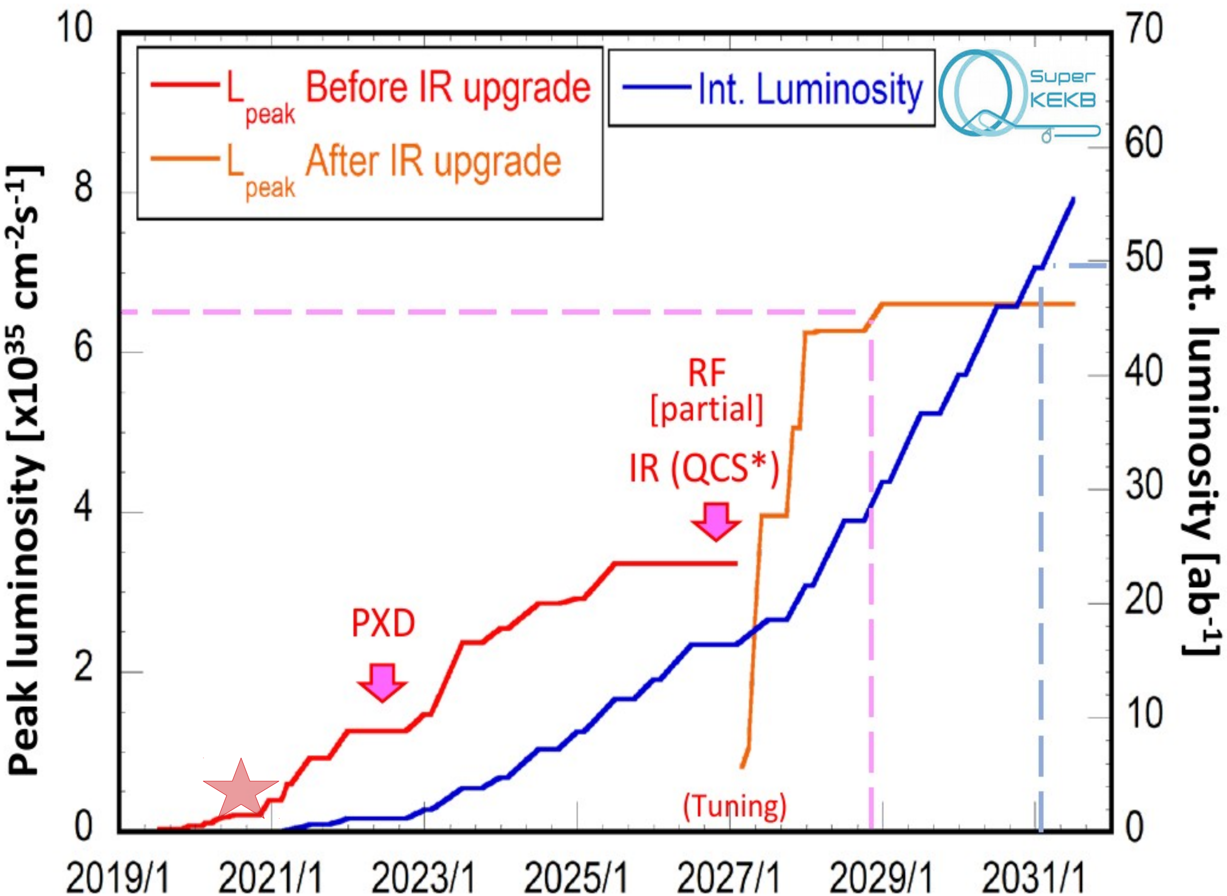
$$L = \frac{\gamma_{\pm}}{2 e r_e} \left(\frac{I_{\pm} \xi_{y\pm}}{\beta^*_{y\pm}} \right) \left(\frac{R_L}{R_{\xi y}} \right)$$

Beta function at the IP
20 times smaller than KEKB

Luminosity target: 6 x 10^{35} $cm^{-2}s^{-1}$

SuperKEKB

A KEKB upgrade



Pilot run:

- 500 pb $^{-1}$ collected;
- Belle II incomplete (**1/8 vertex detector**)

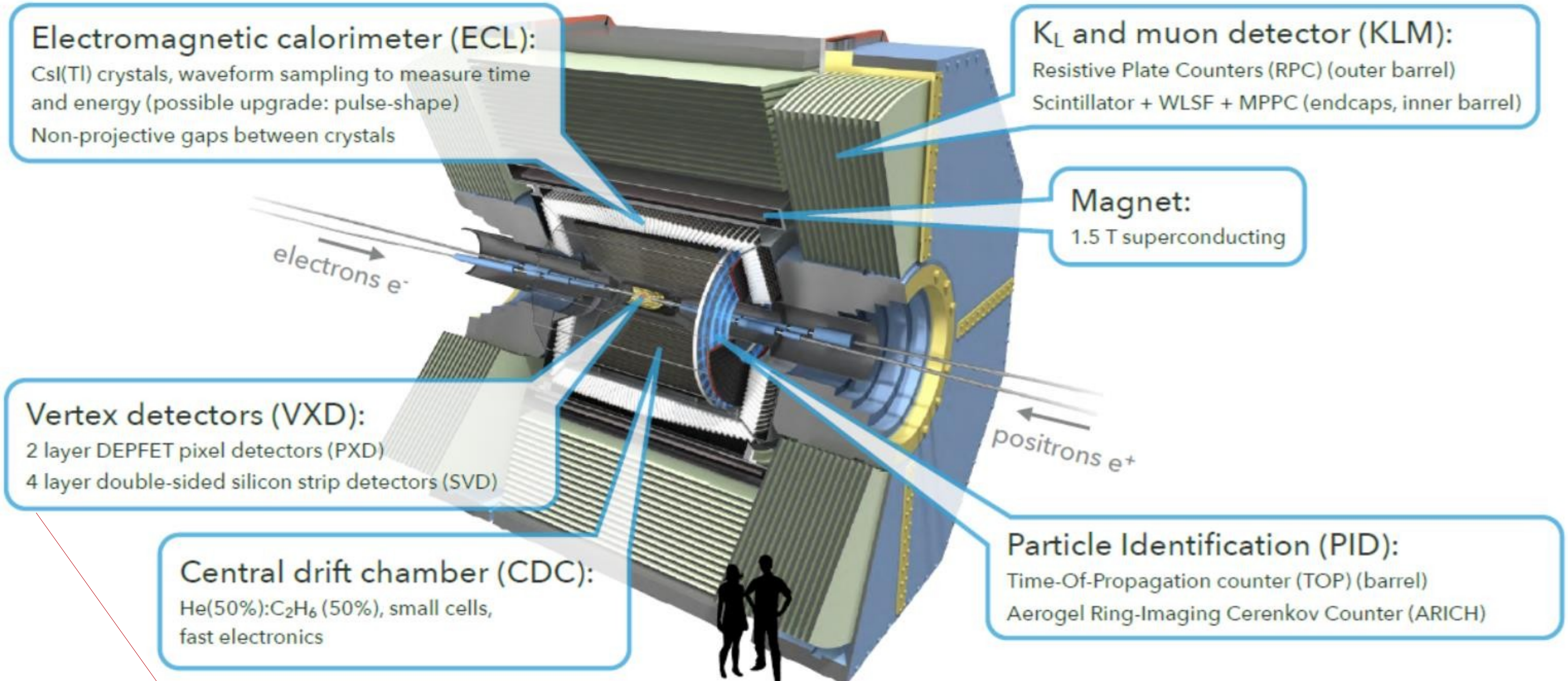
Phase III:

- Started on March 2019, with complete detector
- up to last summer 74 fb^{-1} has been collected but fall run 2020c is in progress

Goal: 50 ab $^{-1}$

Belle II detector

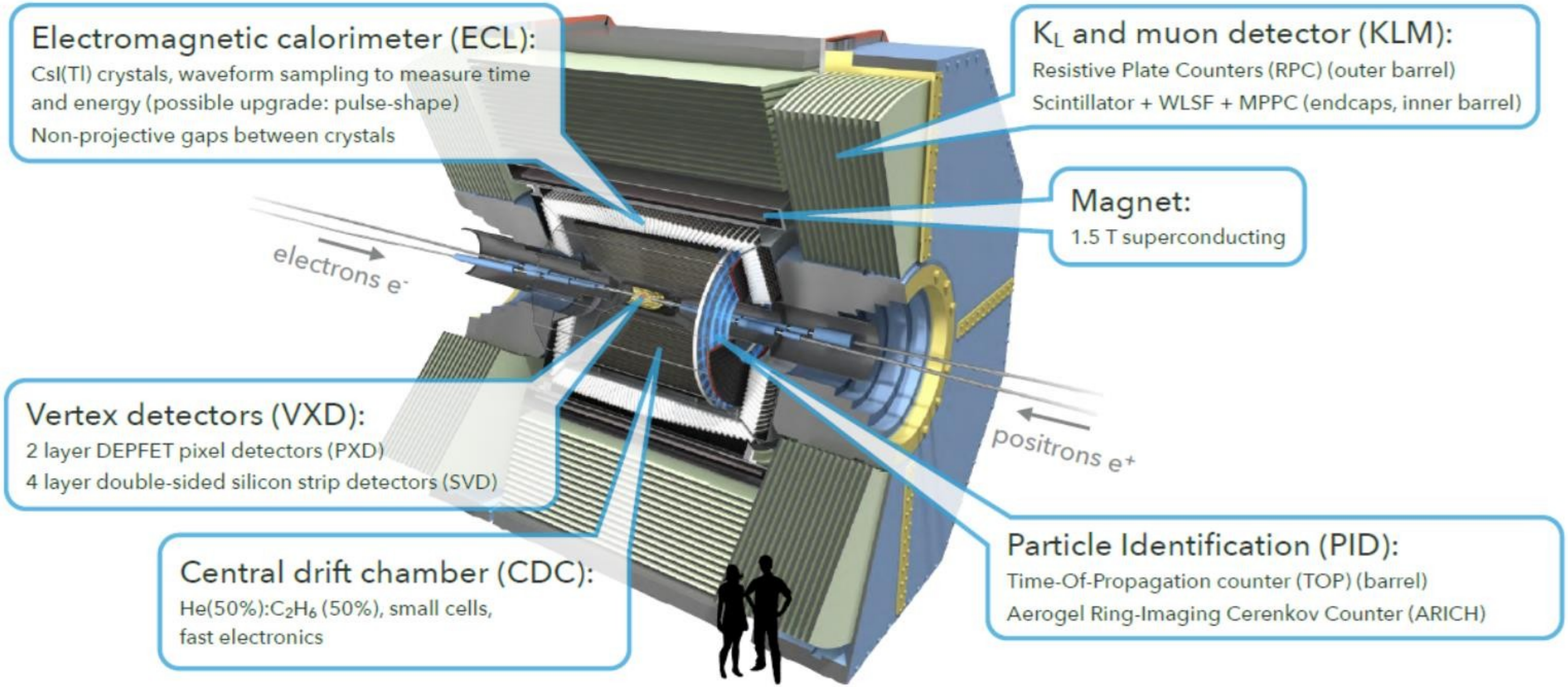
An overview



PXD incomplete, to be replaced in 2022

Belle II detector

Compared to Belle



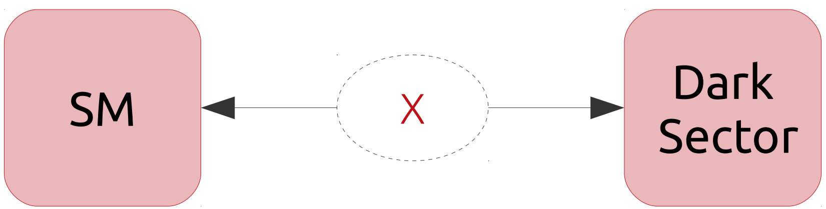
1. Better vertex resolution
2. Larger volume of the silicon strip detector
3. Better PID
4. New electronics for ECAL

2.Dark sector

Dark sector search

Introduction

In recent years the possibility that both DM and the particles mediating its interactions to the Standard Model (SM) have a mass at or below the GeV–scale has gained much attraction.



- Light DM weakly interacting to SM through a new light mediator;
- There is a small number of possible portals between dark sector and standard model:

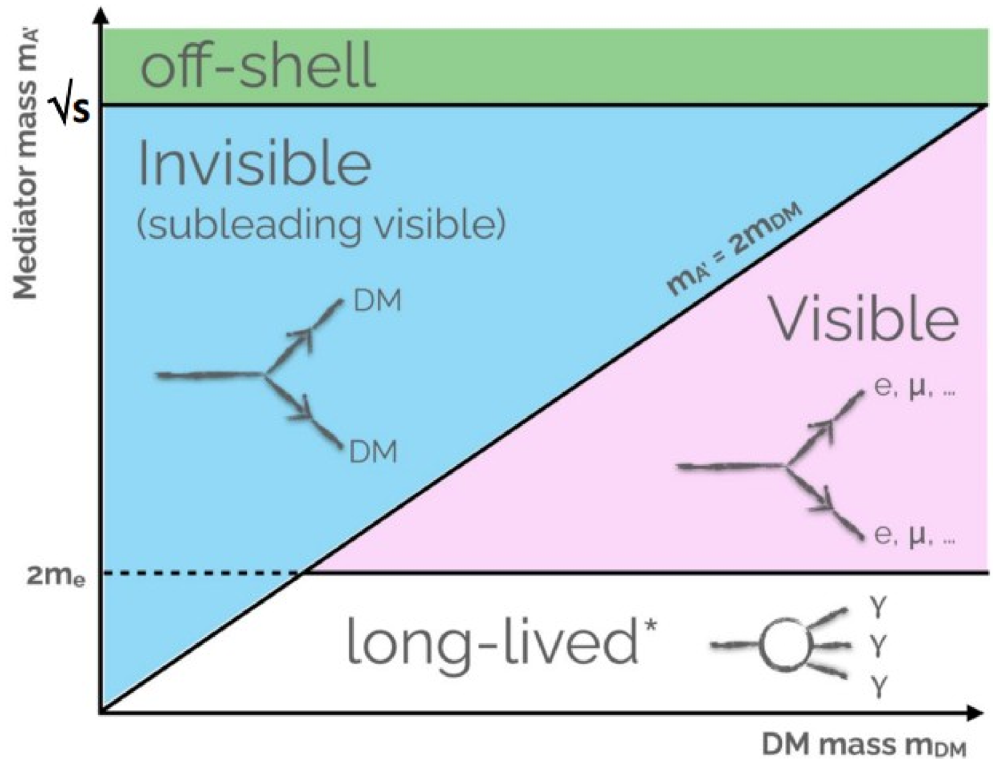
1. VECTOR PORTAL (dark photon A′, Dark Z′);
2. PSEUDO-SCALAR PORTAL (Axion-Like particle);
3. SCALAR PORTAL (dark scalars, extended higgs model);
4. NEUTRINO PORTAL (sterile neutrino).

Dark sector search

@Belle II

Altough Belle II/SuperKEKB has been designed as a **B-factory** it is the **perfect environment where to search for dark matter or mediators**:

- **Hermetic detector** and well-known initial conditions;
- Minimal background from collision pile-up;
- **Excellent PID**;
- **Dedicated triggers** for low multiplicity events.

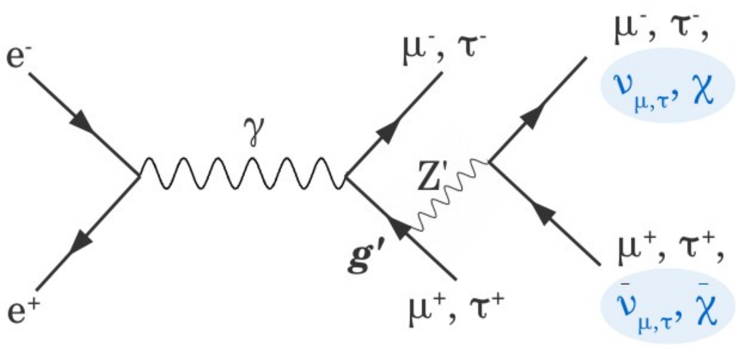


2.Dark sector search at Belle II

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

Z' to invisible

Theory: $L_\mu - L_\tau$ model*



$e^+e^- \to \mu^+\mu^- Z'$; $Z' \to$ invisible

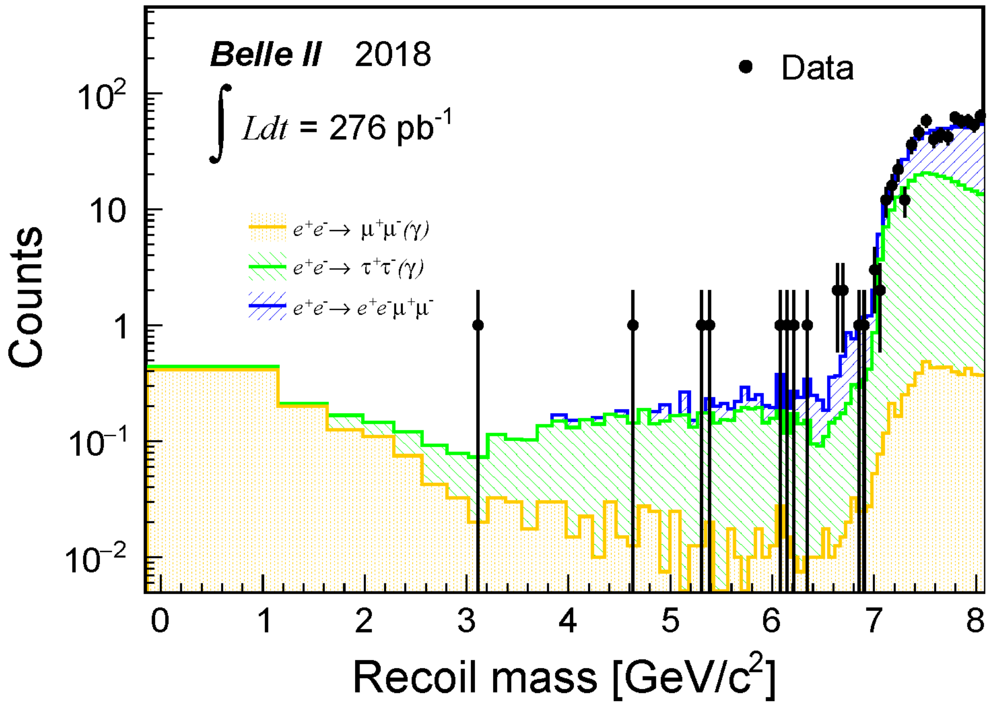
- New light gauge boson Z' only interacting with the second and the third generation of leptons;
- This model would explain:
  - DM puzzle;
  - $(g\text{-}2)_\mu$ anomaly;
  - $B \to K^{(*)}\mu\mu$, R K , R K* anomalies.

Looking for: invisibly decaying Z' coming from a muon
(it can decay into DM or neutrinos if lighter than 2 muons)

First Belle II physics paper:
Adachi et al. (Belle II Collaboration)
Phys. Rev. Lett. 124, 141801

Z' to invisible

Experimental signature



Measurement performed with data collected during Phase 2:

→Only 276 pb^{-1} usable due to trigger conditions.

- Looking for a **peak in the distribution of the invariant mass of the system recoiling** against the lepton pair;
- **Nothing else** in the rest of the event;
- The analysis uses events with exactly **two tracks** identified as μμ.
- **Backgrounds:**
  1. $e^+e^- \to \mu^+\mu^-(\gamma)$
  2. $e^+e^- \to \tau^+\tau^-(\gamma)$
  3. $e^+e^- \to e^+e^-\mu^+\mu^-$

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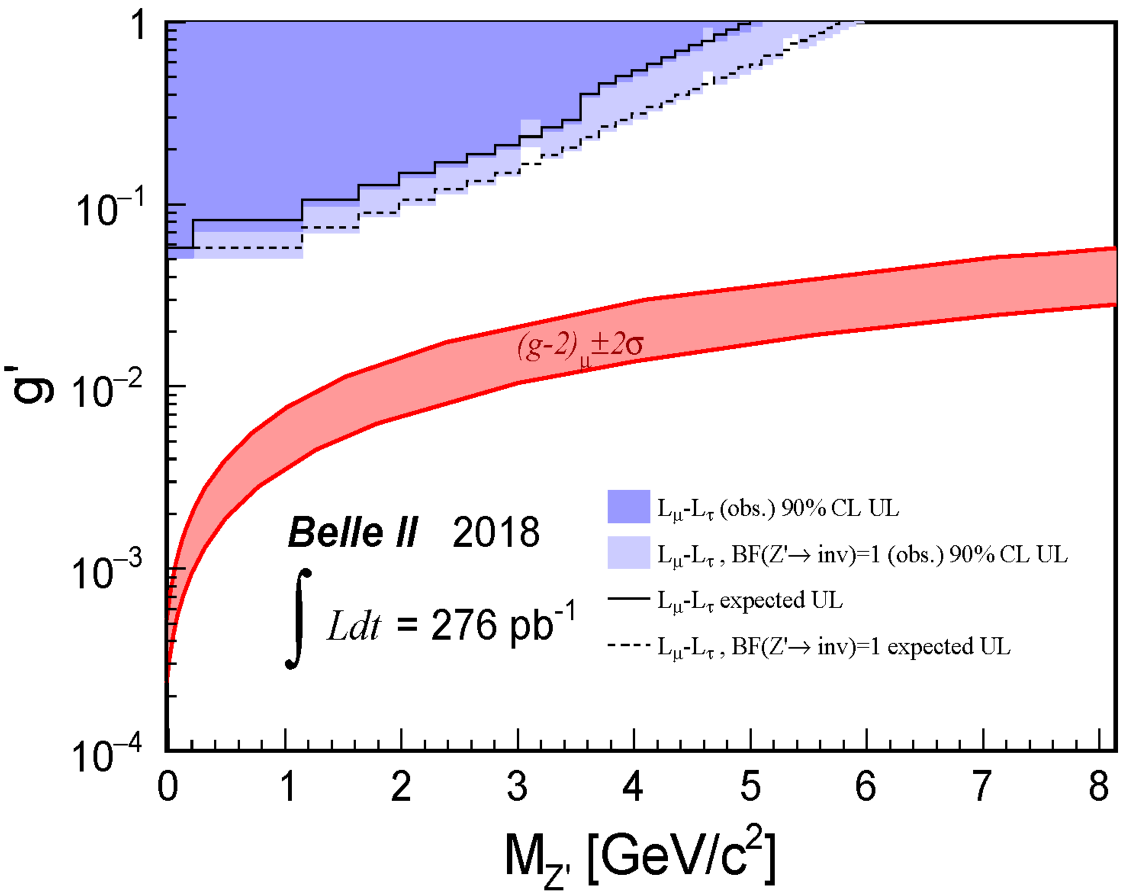
Z' to invisible

g' upper limits



90% CL upper limits on coupling constant g ': first results ever.

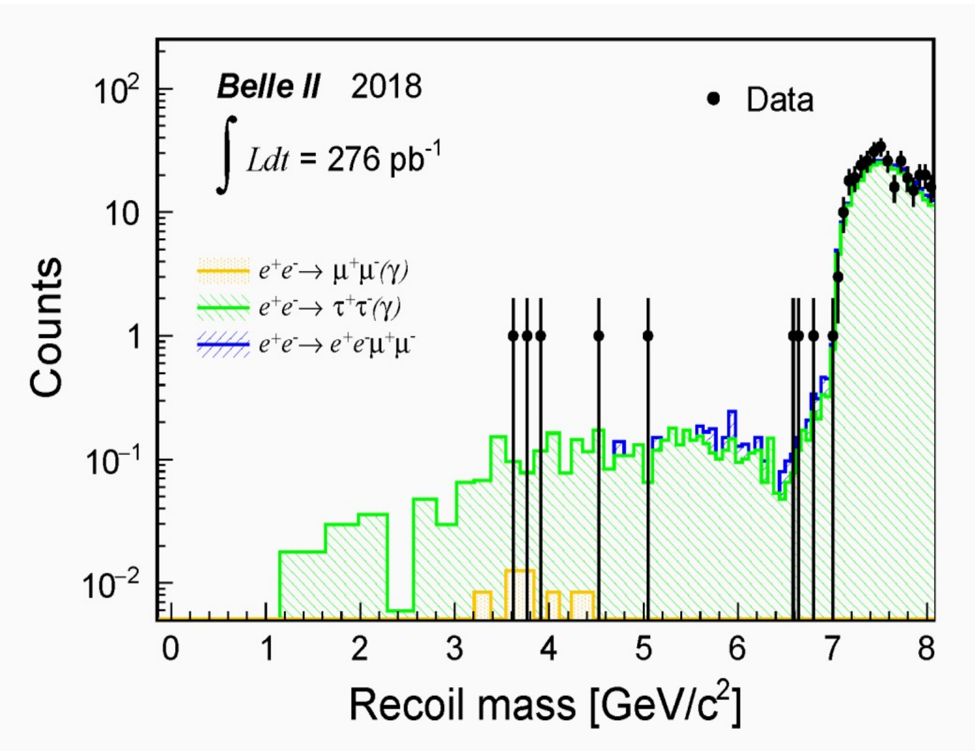
List of systematic uncertainties
Tracking 4%
Trigger 6%
LeptonID 4%
Luminosity 0.7%
Background suppression 22%
Muon yields (signal) 12.5%
Background level 2%

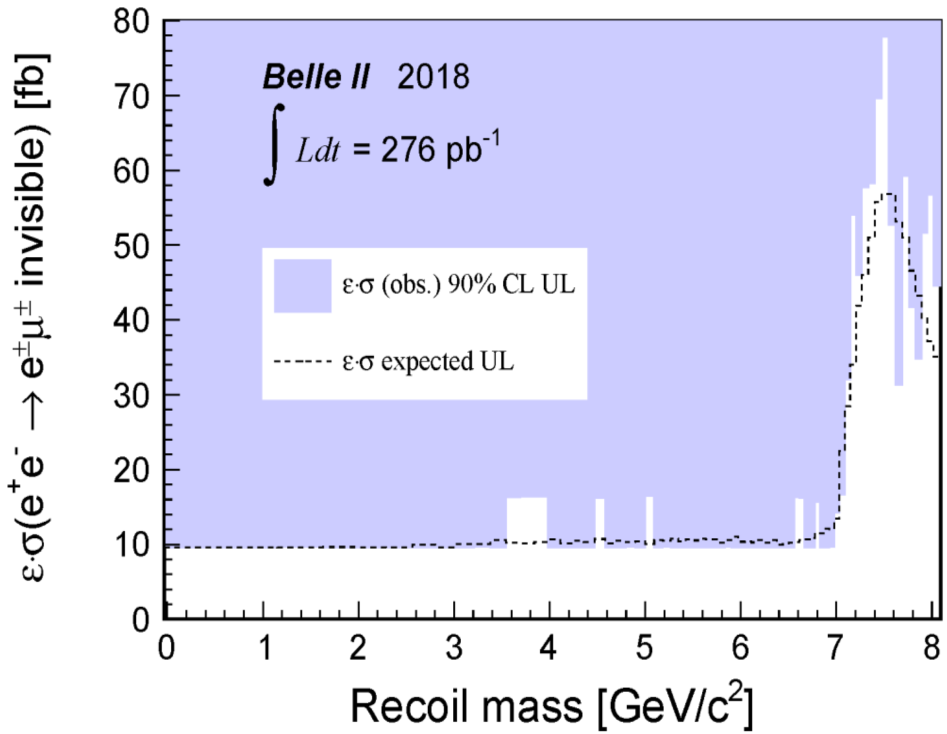
Z' to invisible

First Belle II physics paper:
Adachi et al. (Belle II Collaboration)
Phys. Rev. Lett. 124, 141801

Results for a LFV Z'

I. Galon et al. (2016), arXiv:1610.08060



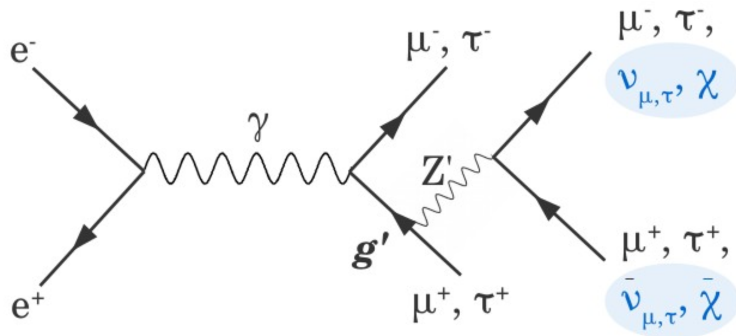


Model independent search with same analysis selection criteria of the Z' to invisible search, with an electron replacing a muon.

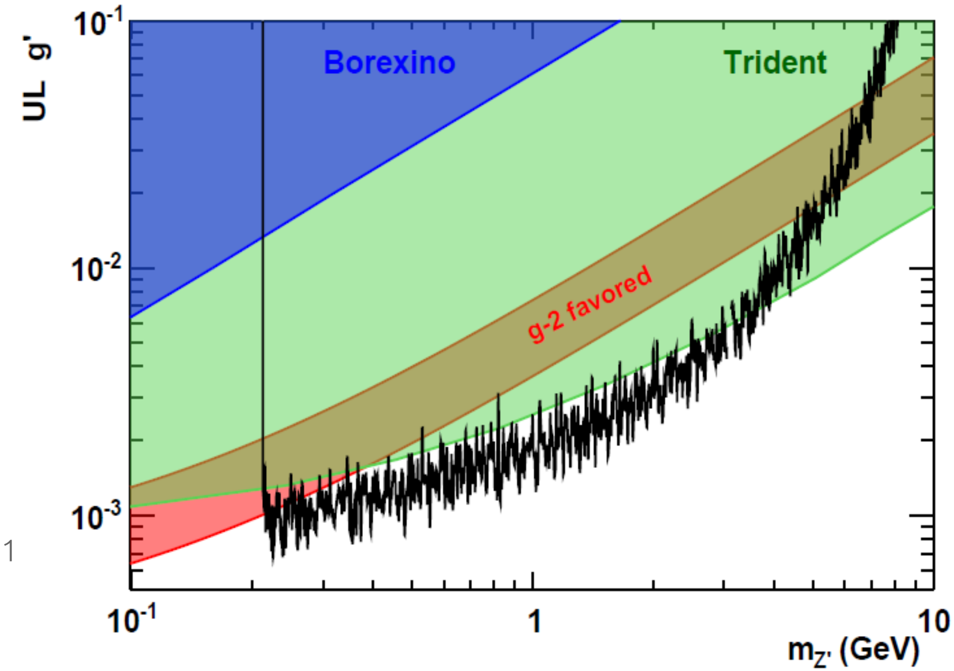
Z’ to visible

Muonic dark force

*Phys. Rev. D 94, 011102 (2016)



$e^+e^- \to \mu^+\mu^- Z'$; $Z' \to \mu^+\mu^-$

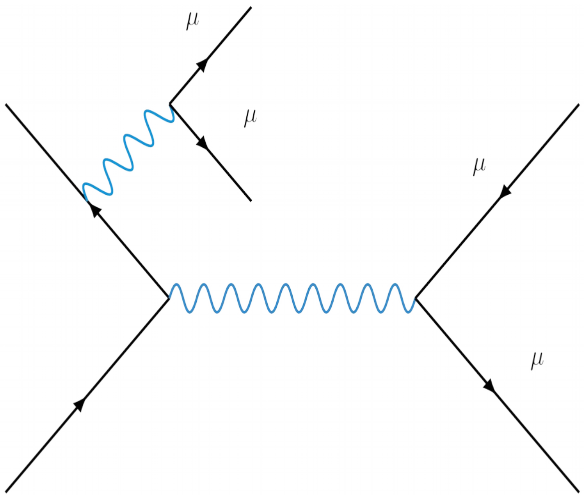


- Already performed by BaBar* with 514 fb^{-1} → limits on the coupling parameter g’.
- Same analysis is in progress in Belle;
- We want to reproduce the BaBar analysis and obtain the same (or better) performances with less luminosity (**100 fb^{-1}**) through an **aggressive background suppression**.

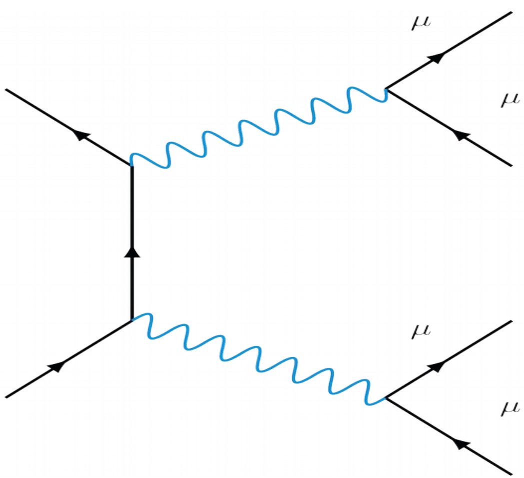
Z' to visible

Background suppression

ISR



Double photon conversion



"fixed" to the candidate mass

QED: emission to the lowest mass and low p_t

- Same diagram (the second is just 90^0 rotated). Nevertheless, they define two different regimes;
- The **double photon conversion** is dominant, ISR regime is suppressed by CDC acceptance tracks.

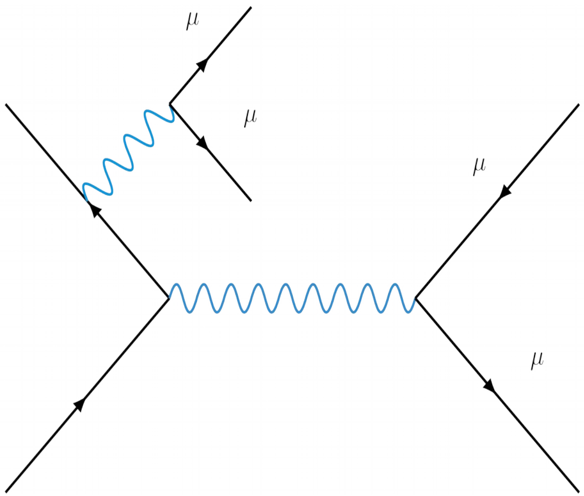
dimuon recoiling against a "zero" mass object:

- quasi two body process with peculiar p_t;
- $p_{\mu\mu}$ best discriminant.

Z’ to visible

Background suppression

ISR



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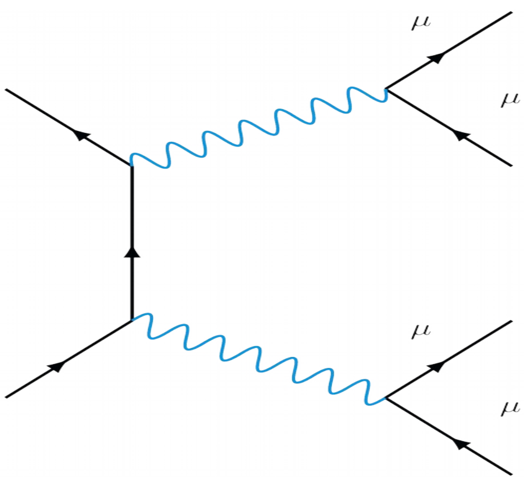

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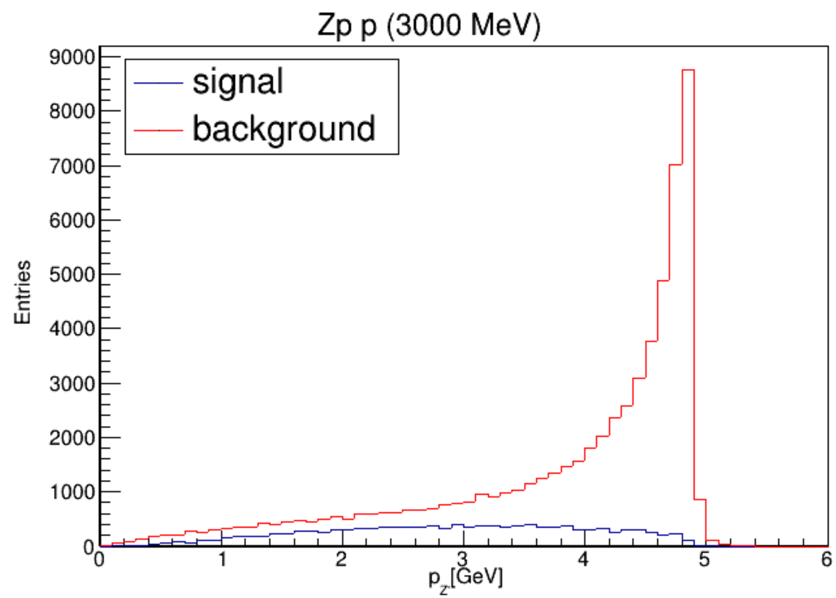
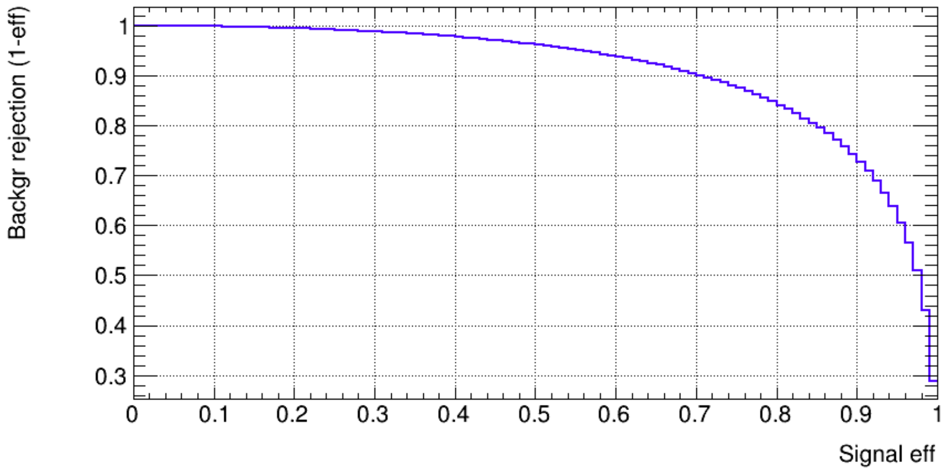


Z' to visible

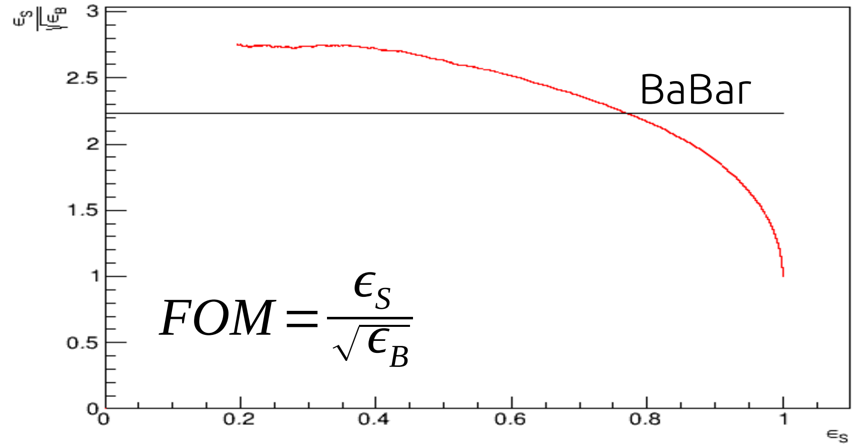
Background suppression

$P_{\mu\mu}$ and other discriminant variables have been used to perform a Multivariate Analysis through a Multi Layer Perceptron.

ROC curve



Net performance



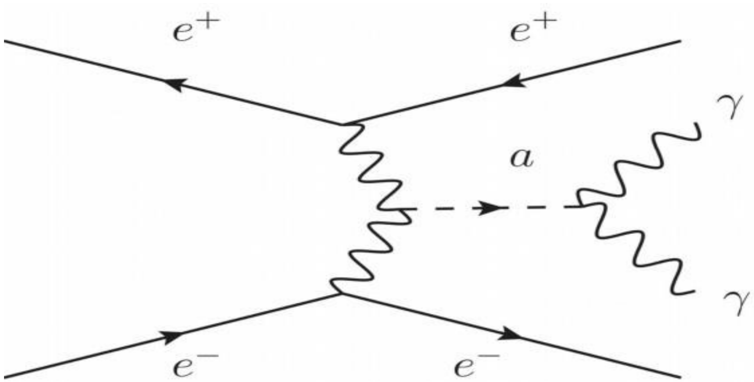
→Sensitivity computation in progress.

Second Belle II physics paper:
Abudinén et al. (Belle II Collaboration)
Phys. Rev. Lett. 125, 161806

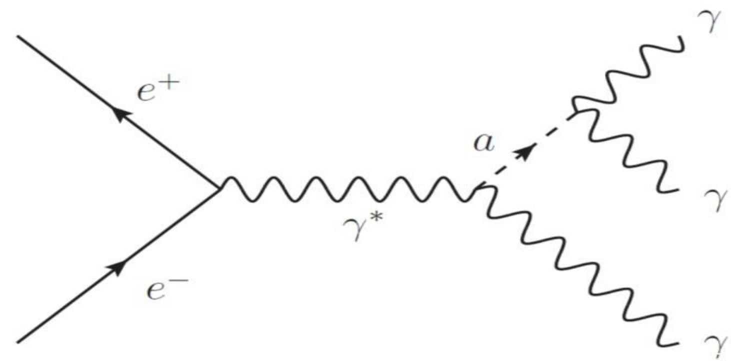
Axion-Like Particles

Theory

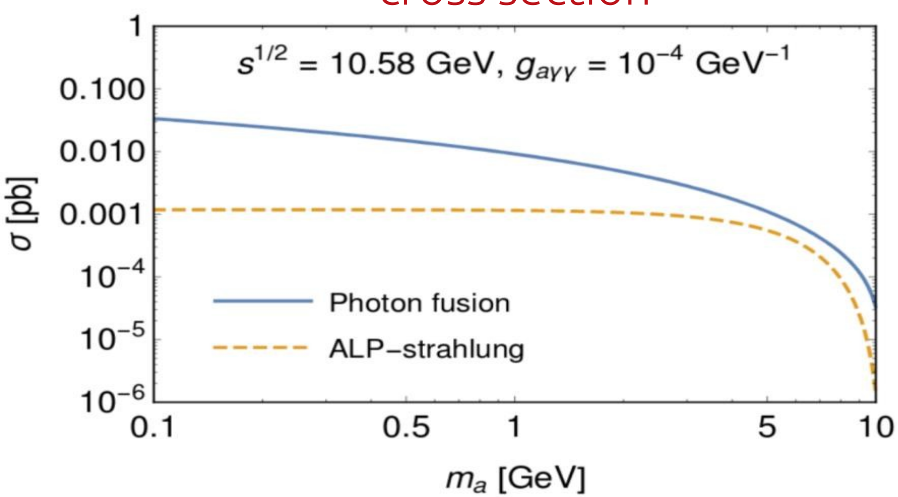
photo-fusion



ALP-strahlung



cross section



ALPs are pseudo-scalars particles coupling with photons.

Two possible scenarios are possible at e^+e^- colliders:

- Photo-fusion;
- **ALP-strahlung**.

Second Belle II physics paper:
Abudinén et al. (Belle II Collaboration)
Phys. Rev. Lett. 125, 161806

Axion-Like Particles

Experimental signature

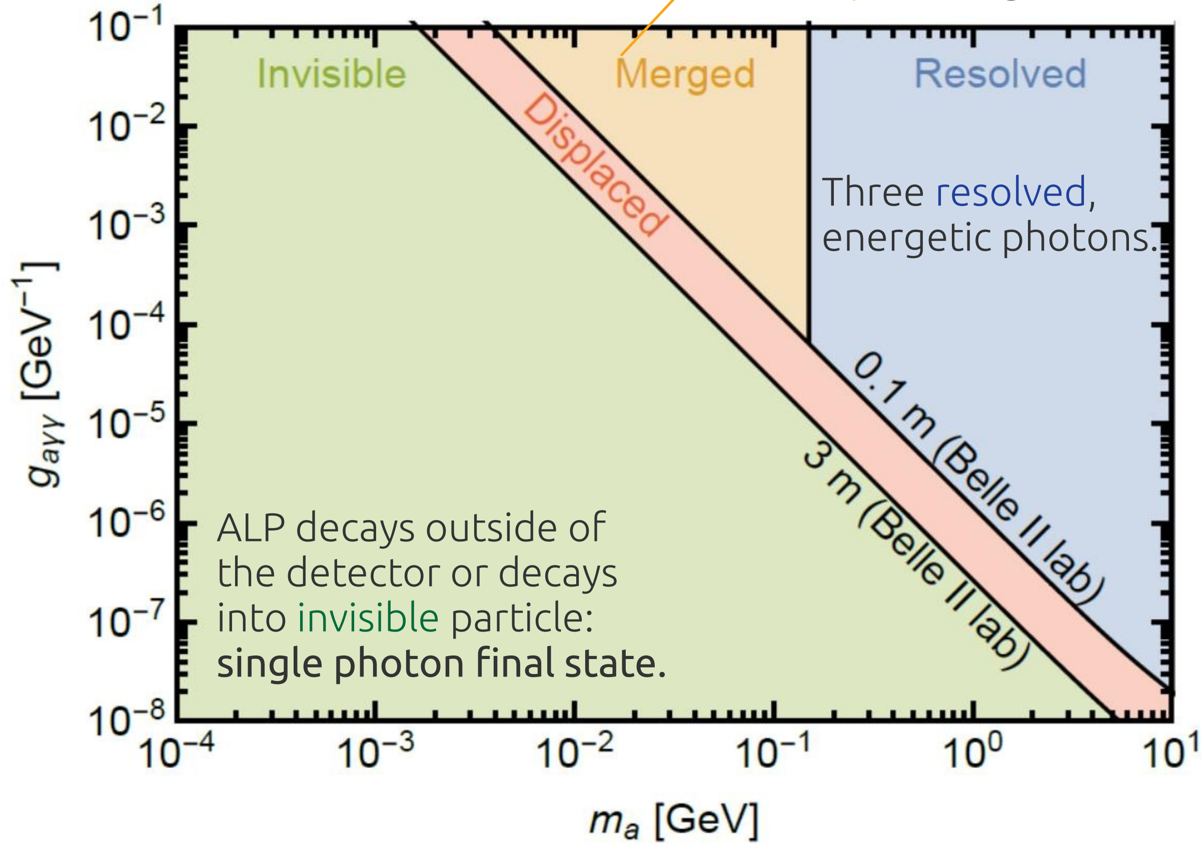
Looking for:

- **three photon** summing up to beam energy and no other particles;
- **No tracks**;
- **Search for a bump** into di-photon and recoil mass.

Backgrounds:

1. $e^+e^- \to \gamma\gamma(\gamma)$;
2. $e^+e^- \to e^+e^-(\gamma)$;
3. $e^+e^- \to P\gamma\gamma$, $P = \pi^0, \eta, \eta'$.

Two of the photons overlap or merge.



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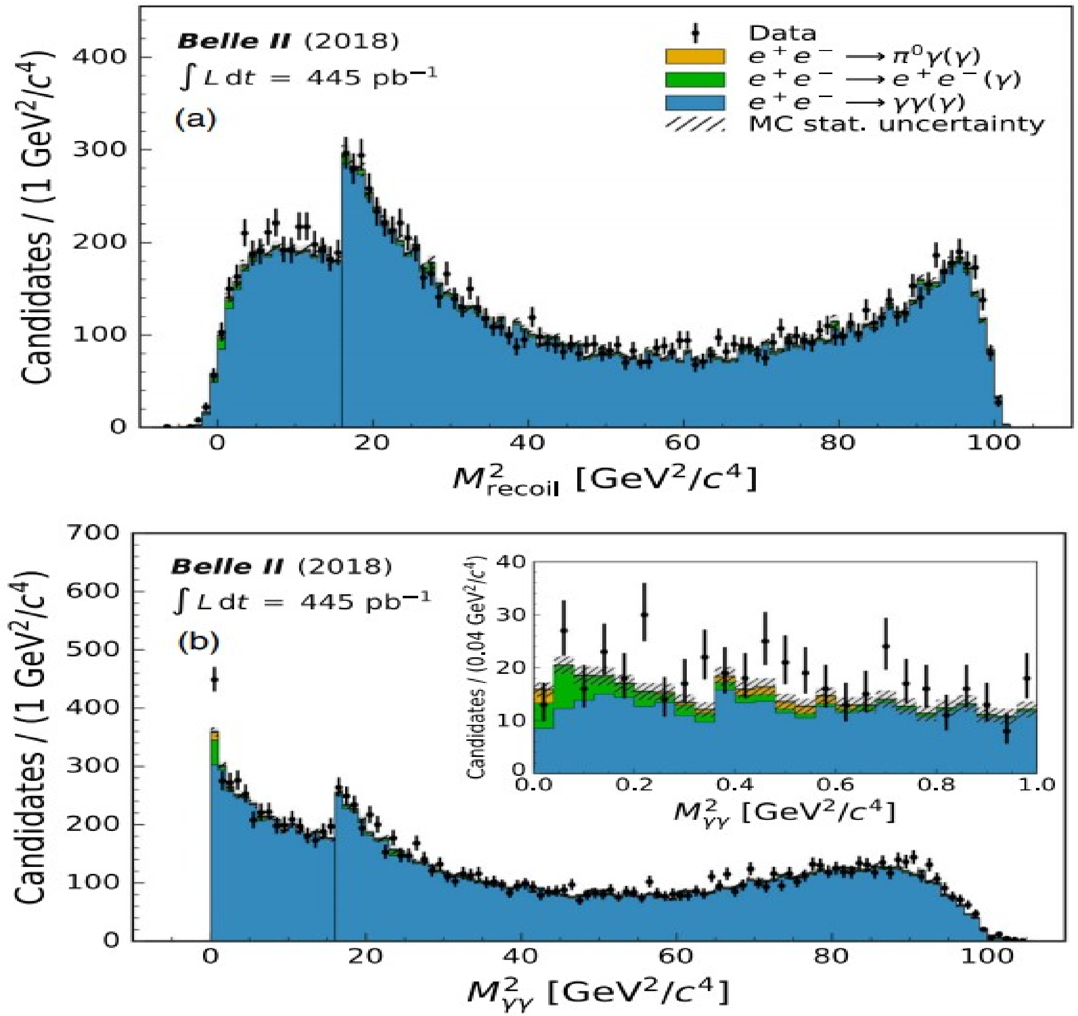
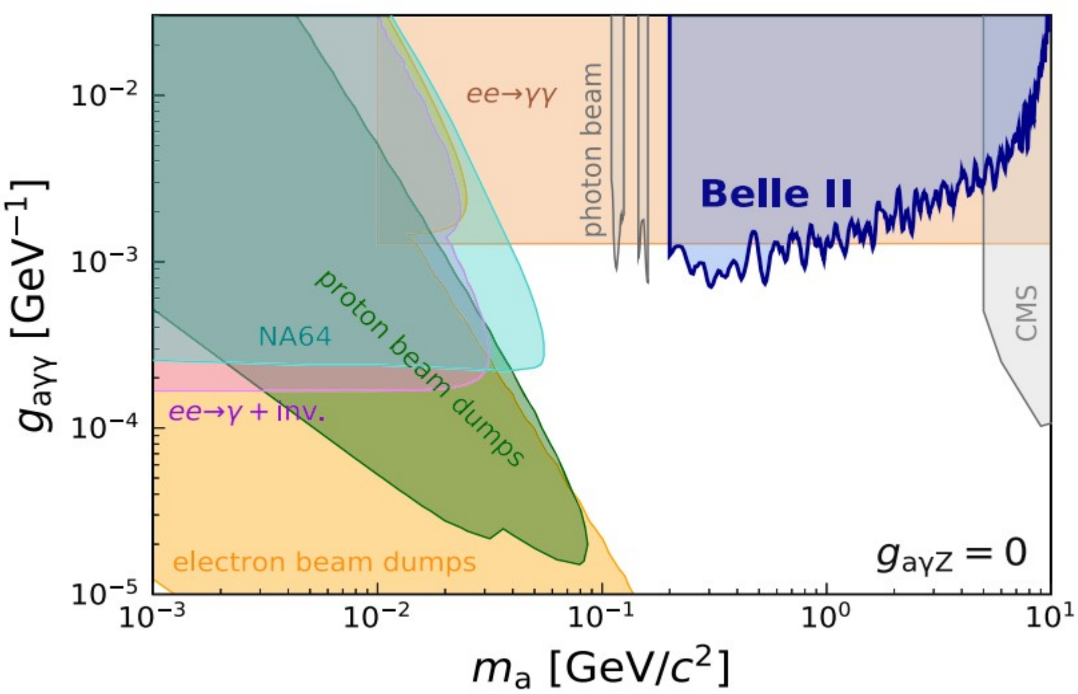
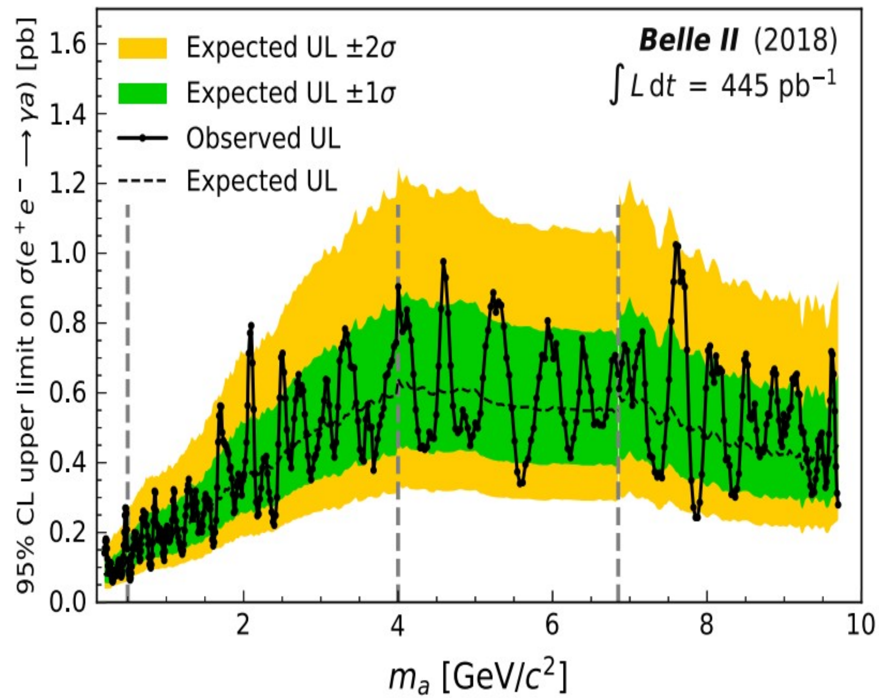


Second Belle II physics paper:
Abudinén et al. (Belle II Collaboration)
Phys. Rev. Lett. 125, 161806

Axion-Like Particles

$g_{a\gamma\gamma}$ and cross-section upper limit





$$\sigma_a = \frac{g_{a\gamma\gamma}^2 \alpha_{QED}}{24}\left(1 - \frac{m_a^2}{s}\right)^3$$

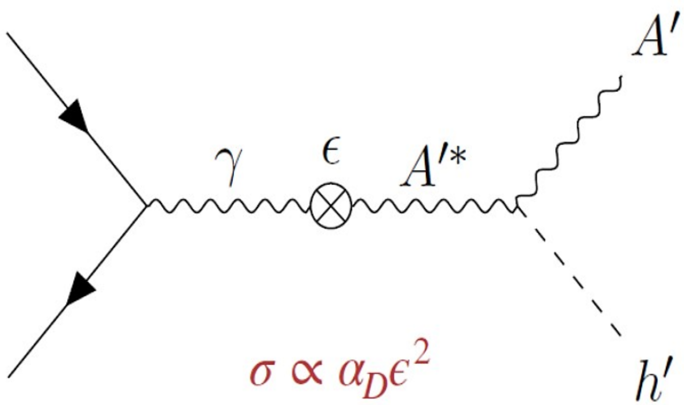
Measurement performed with 445 pb^{-1}

- These limits are the **first** obtained for the fully reconstructed three-photon final state;
- They are **more restrictive than previous limits**.

Dark Higgsstrahlung

Theory*

*Batell, Pospelov, Ritz, Phys. Rev. D 79, 115008 (2009)



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

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

In a minimal scenario: a single dark photon A' and a single dark Higgs boson h'.

The h' could be produced in the Higgsstrahlung process, which is also sensitive to the dark sector coupling constant α_D.

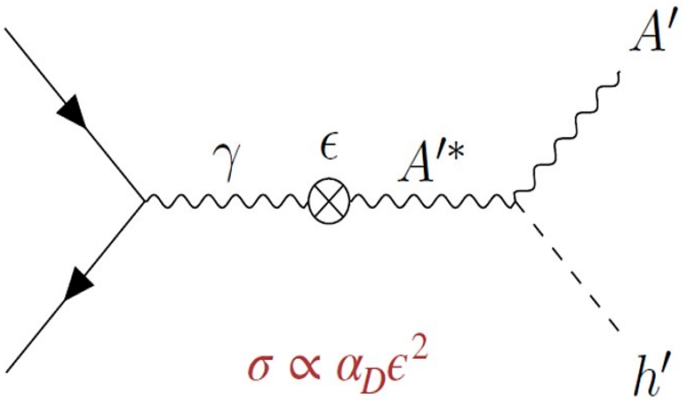
Different scenarios depending on the mass hypothesis.

We focus on the case: $m_{h'} < m_{A'}$ up to now only investigated by KLOE.

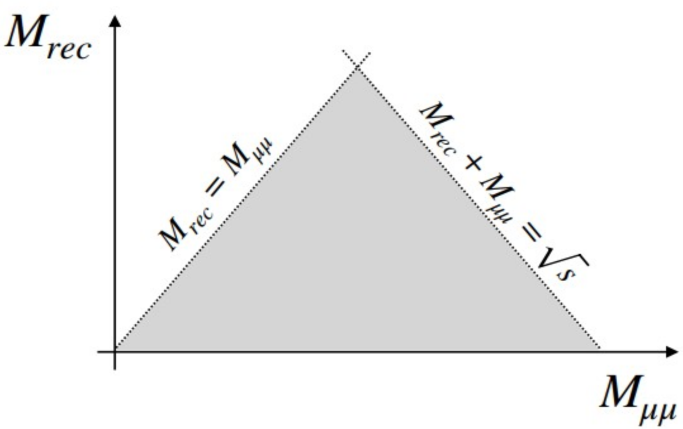
Dark Higgsstrahlung

Experimental signature

Batell, Pospelov, Ritz, Phys. Rev. D 79, 115008 (2009)



$\sigma \propto \alpha_D \epsilon^2$



Looking for:

- two oppositely charged muons plus missing energy ;
- a peak in two dimensional distribution of recoiling mass vs dimuon mass.

Backgrounds:

1. $e^+e^- \to \mu^+\mu^-\gamma$;
2. $e^+e^- \to \tau^+\tau^-\gamma$;
3. $e^+e^- \to e^+e^-\mu^+\mu^-$;
4. $e^+e^- \to \pi^+\pi^-\gamma$.

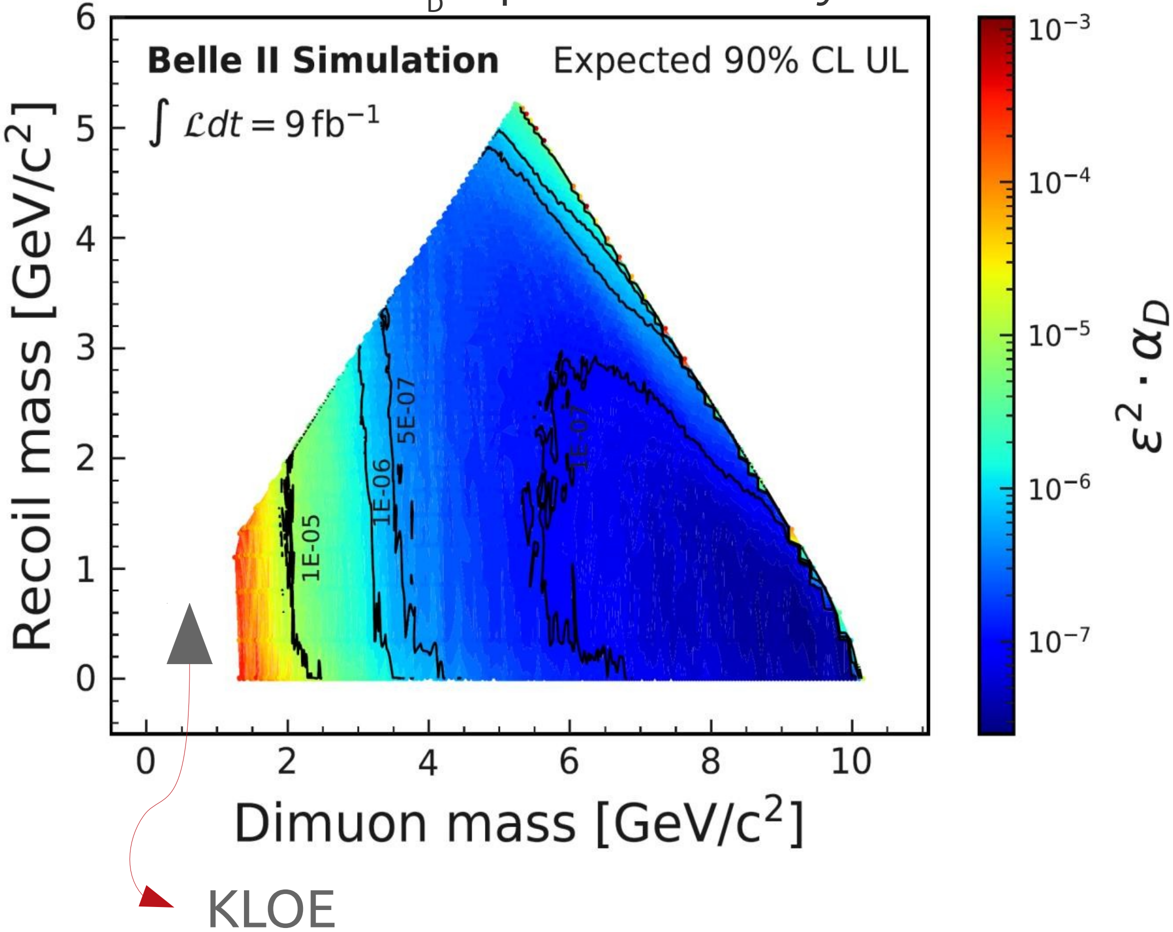
...but additional background sources are studied.

Batell, Pospelov, Ritz, Phys. Rev. D 79, 115008 (2009)

Dark Higgsstrahlung

Expected sensitivity

90% UL on $\varepsilon^2 \alpha_D$ expected sensitivity



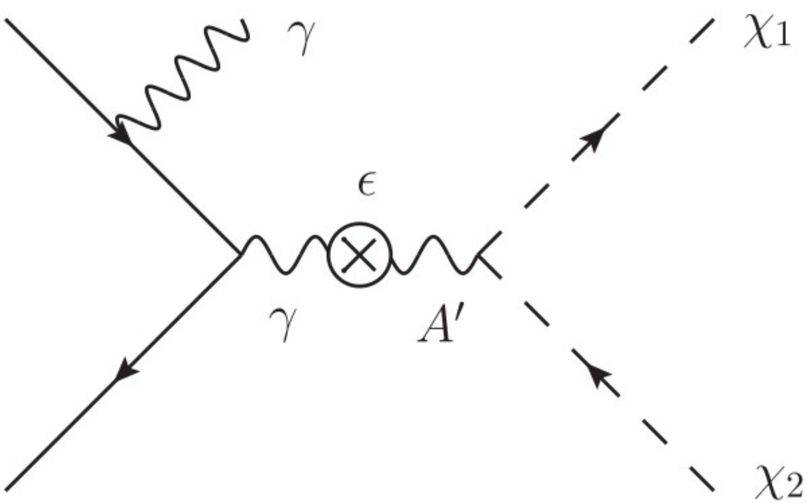
Very promising results even with the 2019 only dataset (9 fb^{-1})

- Accessing unconstrained regions, well beyond KLOE coverage;
- Probing non-trivial $\varepsilon^2 \alpha_D$ couplings.

Dark photon to invisible

Theory*

*P. Fayet, Phys. Lett. B 95, 285 (1980)
P. Fayet, Nucl. Phys. B 187, 184 (1981)
B. Batell, et al. Phys. Rev. D 79, 115008



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

A possible standard model extention with a new massive gauge boson A' of spin = 1 called **dark photon**, that couples to SM.

Two basic scenarios depending on A' vs DM mass relationship:

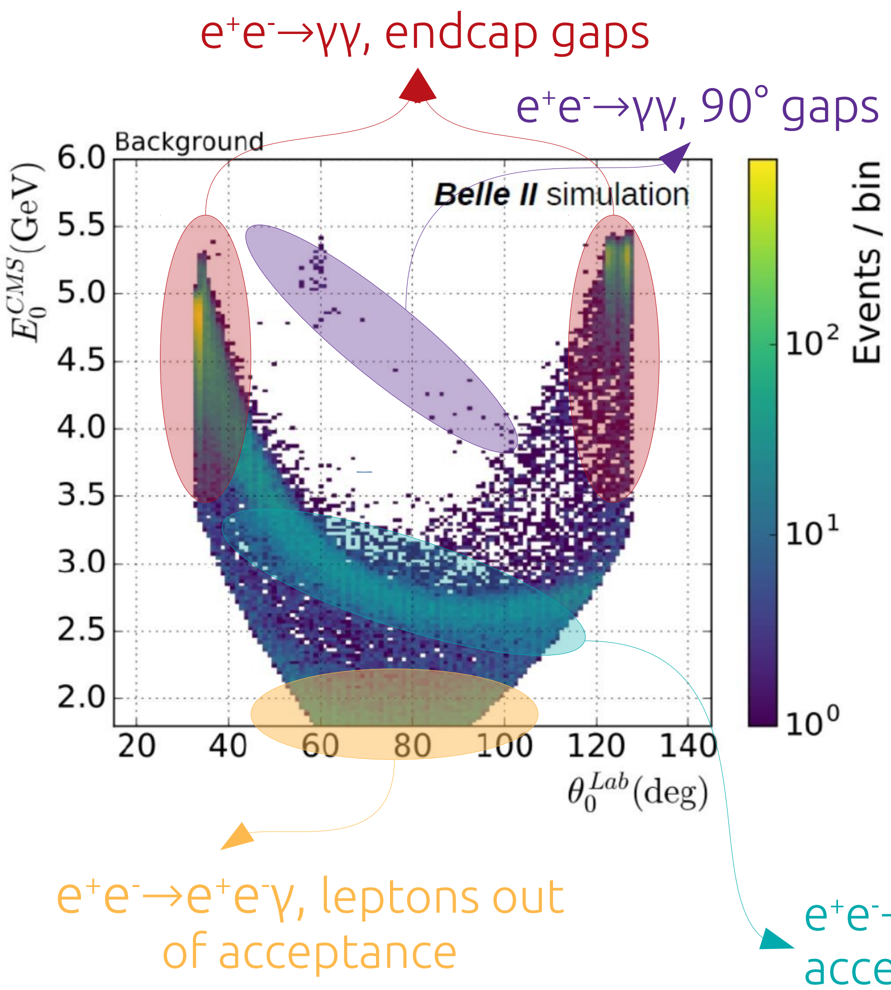
$m_\chi > 1/2 m_{A'}$ → A' visible decays to SM;

$m_\chi < 1/2 m_{A'}$ → A' invisible decays to light DM.

Dark photon to invisible

Experimental signature

P. Fayet, Phys. Lett. B 95, 285 (1980),
P. Fayet, Nucl. Phys. B 187, 184 (1981)
B. Batell, et al. Phys. Rev. D 79, 115008



Looking for:

- One photon inside calorimeter acceptance and nothing else in the event;
- Bump hunt in single photon recoil mass (or energy) vs. θ_{LAB};
- Needs single-photon trigger.

Backgrounds:

1. $e^+e^-\to\gamma\gamma\gamma$;
2. $e^+e^-\to ee\gamma$;
3. cosmics.

Dark photon to invisible

Expected sensitivity

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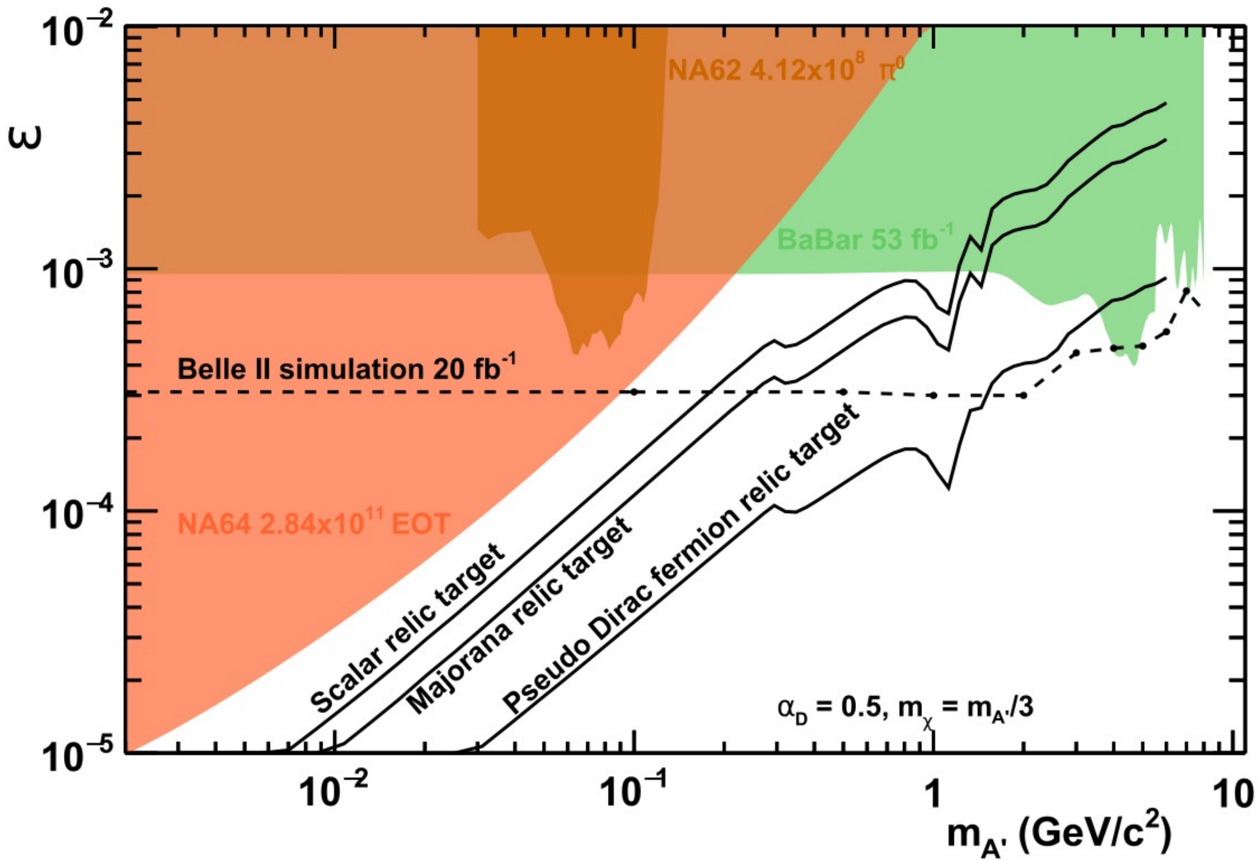

Very promising results even with early Phase 3 dataset (~ 20 fb -1).

We expect a better performance than BaBar:

- no ECL gaps pointing to the interaction region.

Conclusions

- Belle II/Super KEKB is not only a B-factory, but a perfect environment where to search for dark matter or mediators;
- It has successfully collected 500 pb^{-1} during commissioning phase and currently phase 3 is ongoing;
- A lot of dark sector searches are in progress, and very good results have been obtained also with phase 2 data only.