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Dark sector Physics at Belle II

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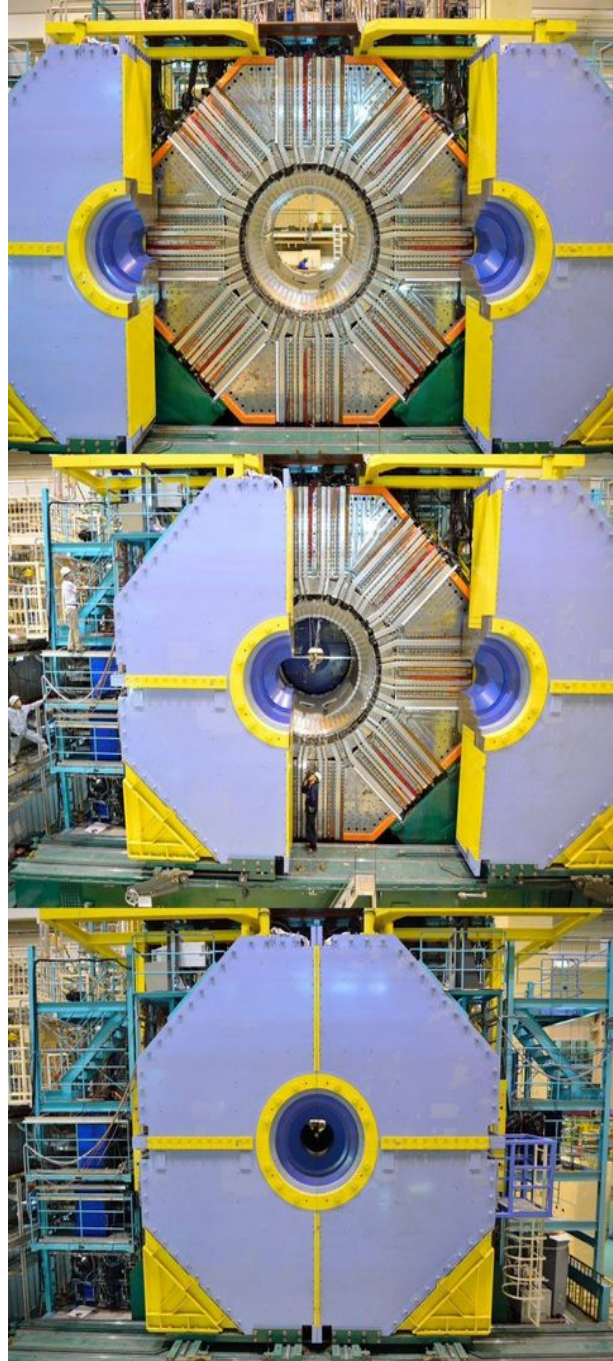
ROMA TRE UNIVERSITÀ DEGLI STUDI

INFN Istituto Nazionale di Fisica Nucleare SEZIONE DI ROMA TRE

Belle II

Outline

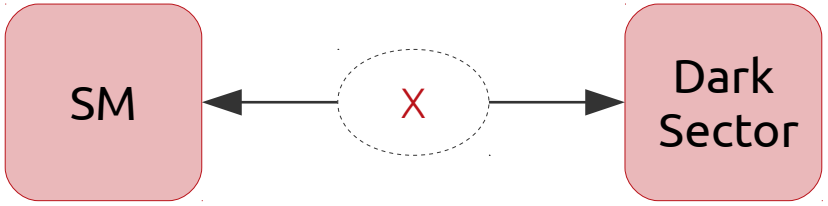
- Dark sector;
- SuperKEKB and the Belle II experiment;
- Recent and ongoing dark sector searches at Belle II:
  - Z’ to invisible;
  - Z’ to visible;
  - Axion-Like Particles;
  - Dark Higgsstrahlung;
  - Invisible dark photon.
- Conclusions.



Dark sector

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.

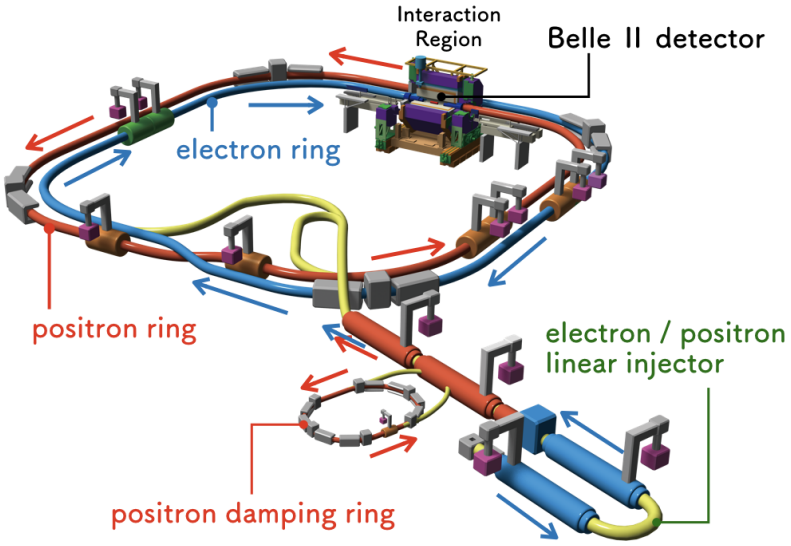


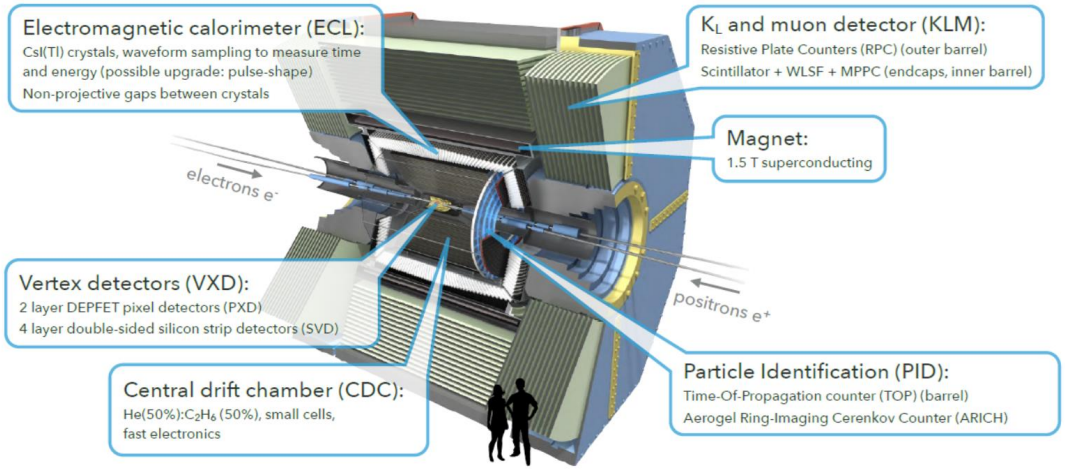
- Light DM weakly interacting to SM through a new light mediator;
- There is a small number of possible portals between dark sector and standard model:

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).

SuperKEKB and Belle II

A 2nd generation B-factory



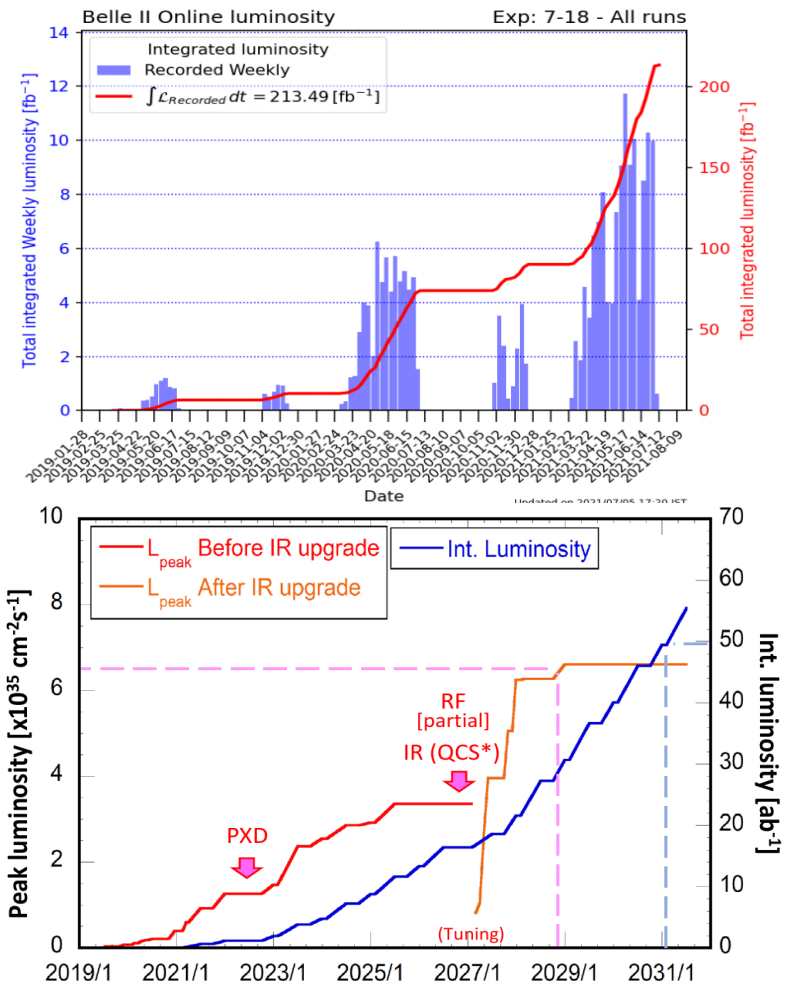


Altough Belle II/SuperKEKB has been designed as a **B-factory** it is the **perfect environment where to search for light dark matter or mediators**:

Hermetic detector and Well known initial condition	Low background	Excellent PID	Dedicated triggers for Low Multiplicity events

SuperKEKB and Belle II

A 2nd generation B-factory



Pilot run(2018):

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

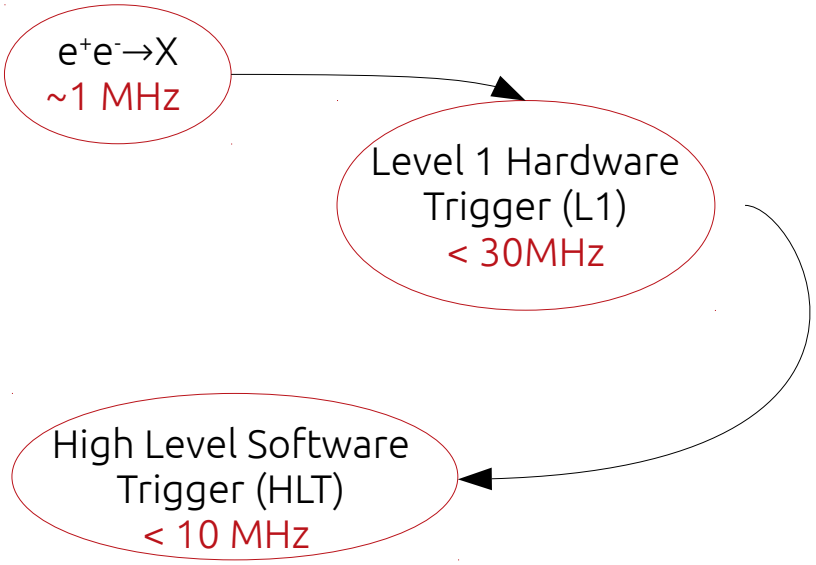
Physics run:

- Started on March 2019, with complete detector;
- up to now ~213.5 fb^{-1}

Goal: 50 ab $^{-1}$ by 2031 (50XBelle)

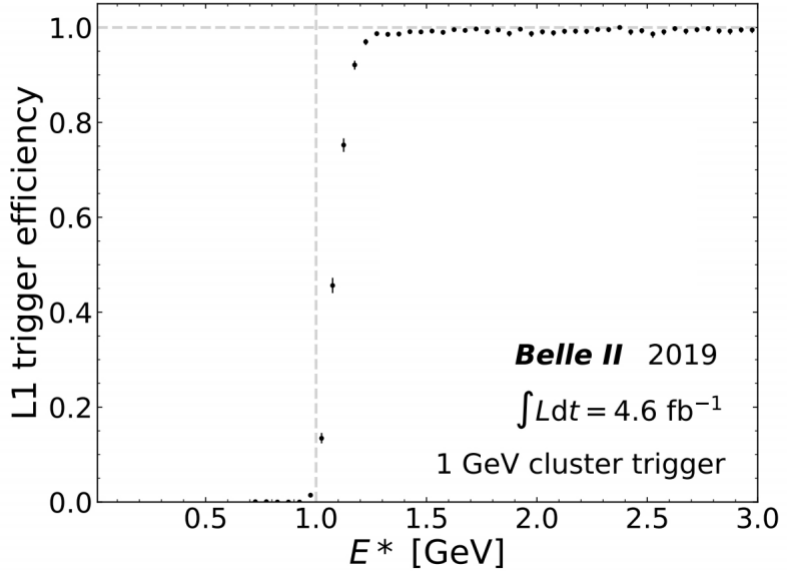
Dark sector

@Belle II
DARK SECTOR TRIGGERS



- The trigger system of Belle II has a non trivial role to identify events of interest during data taking.
- Well-designed trigger system unlocks a broad variety of topics not probed in the previous generation B-factories;
- Excellent examples of triggers for new phenomena include the single photon trigger for dark sector searches.
  - Single photon trigger;
  - 3D track reconstruction at L1.

Single photon trigger, 1 GeV efficiency

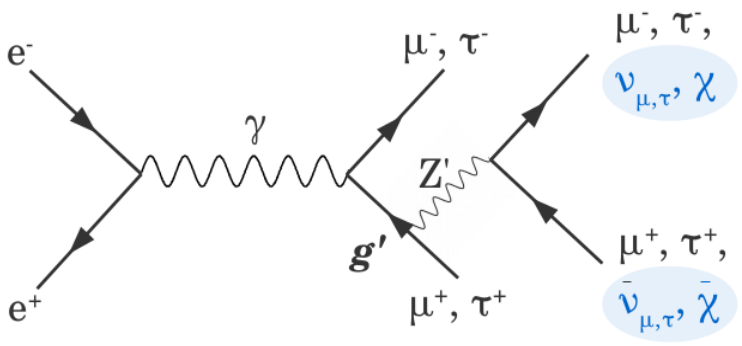


Recent and ongoing dark sector searches at Belle II

Z’ to invisible

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

*Shuve et al. (2014), Phys. Rev. D 89, 113004 (2014)
Altmannshofer et al. (2016), Journal of High Energy Physics 2016(12)



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

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

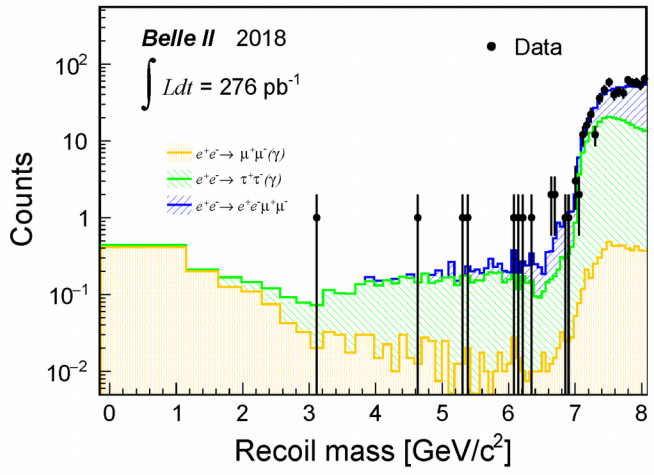
Looking for invisibly decaying Z’ radiated off a muon
(it can decay into DM or neutrinos)

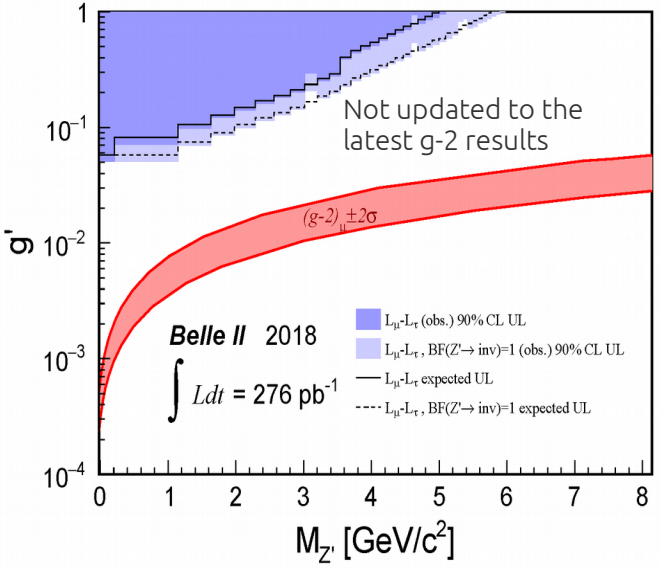
~ 100% BR if Z’ mass is less than $2m_\mu$

Z' to invisible

Experimental signature and g' upper limits

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





Looking for invisibly decaying Z' coming from a muon:

- **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.

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

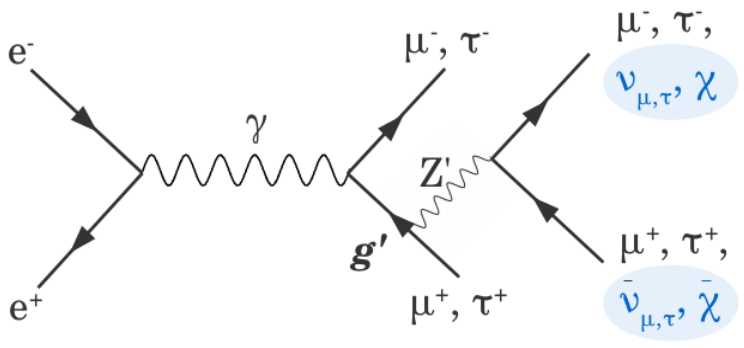
<u>List of systematic uncertainties*</u>

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

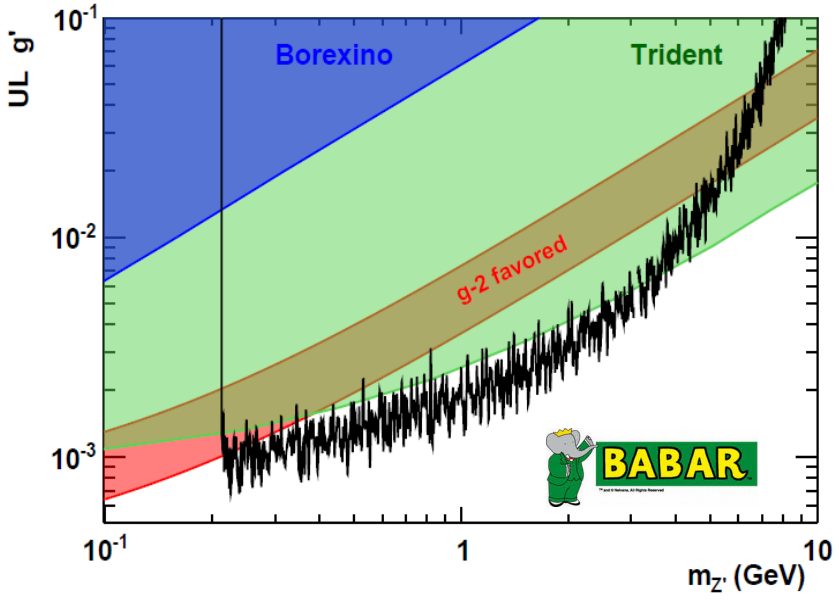
*An improvement of the systematics is expected with more data

Z' to visible

Muonic dark force



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



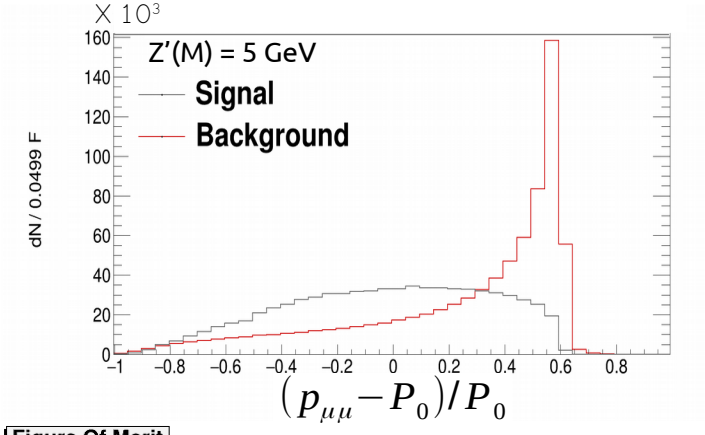
*Phys. Rev. D 94, 011102 (2016)

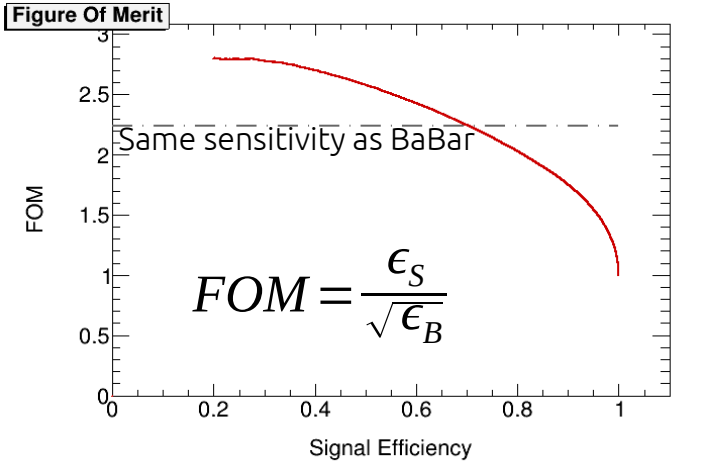
- Already performed by BaBar* with 514 fb^{-1}
  → limits on the coupling parameter g'.
- Same analysis is in progress in Belle;
- We want to obtain the same (or better) performances than BaBar with less luminosity (**100 fb^{-1}**) through an **aggressive background suppression**.

Z’ to visible

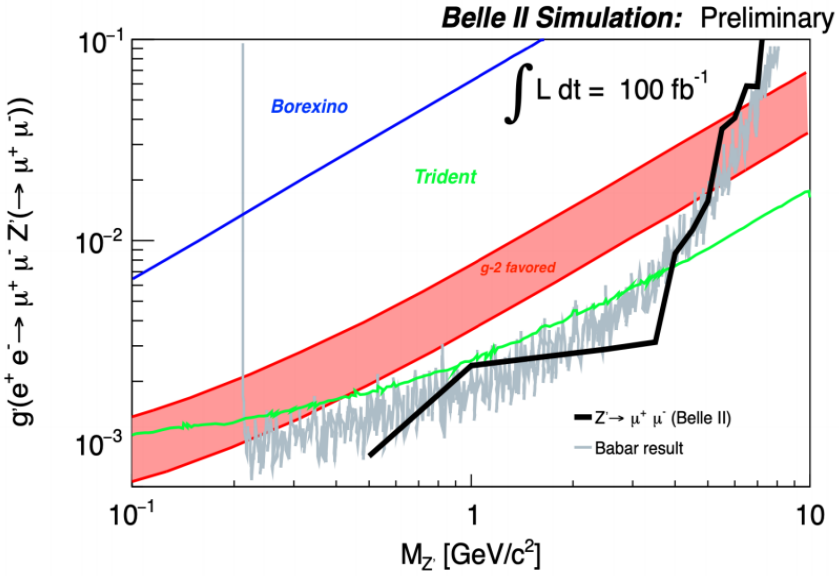
Muonic dark force

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





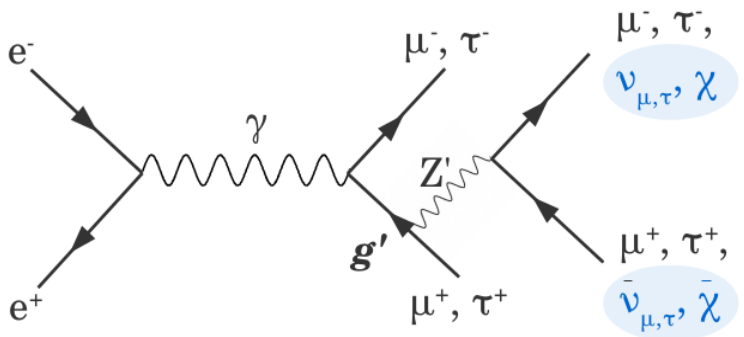
→Sensitivity estimation ongoing



- preliminary results from fitting technique (90% CL upper limits);
- no systematic effects included.

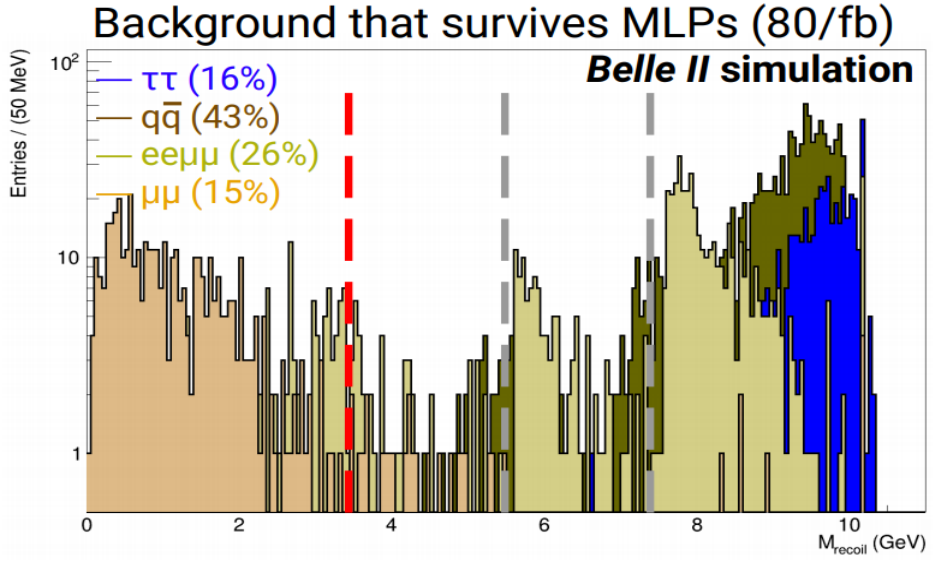
Z’ to visible

Z’ into taus



$e^+e^- \rightarrow \mu^+\mu^- Z'$; $Z' \rightarrow \tau^+\tau^-$

(+ 1 prong decay: τ→e, π, μ)

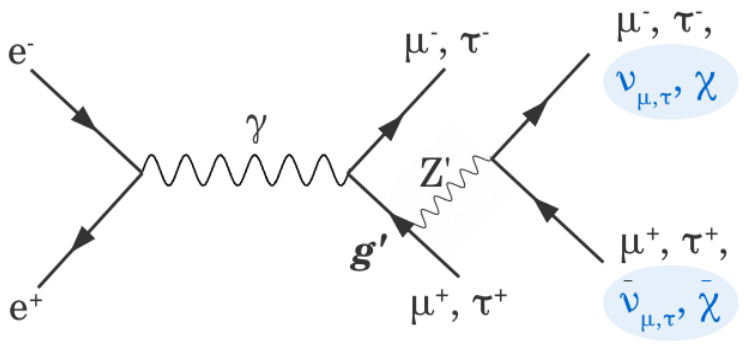


- Same theoretical motivations as for Z' → inv and Z'→ μμ;
- ττ resonance in μμττ have never been searched before;
- challenging because of neutrinos and background.

Same background suppression strategy as Z'→ μμ, based on MLP.

Z’ to visible

Z’ into taus

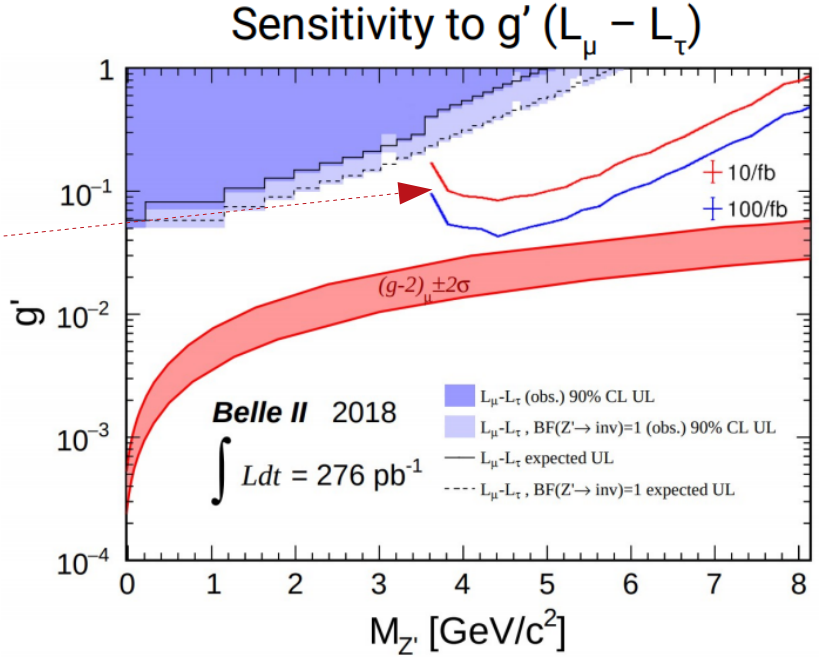


$e^+e^- \rightarrow \mu^+\mu^- Z'$; $Z' \rightarrow \tau^+\tau^-$

- Same theoretical motivations as for Z' → inv and Z'→ μ μ;
- Z' resonance in the final state ττ have never been searched before;
- challenging because of neutrinos and background suppression.

90% CL upper limits calculated as a Poisson counting experiment.

Trigger efficiency and systematic uncertainties are not included.

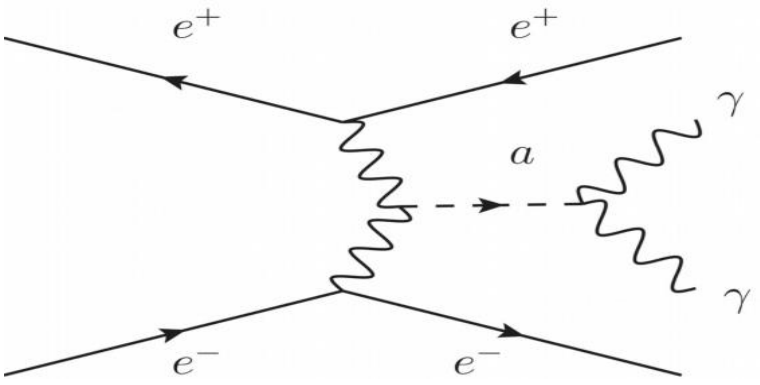


*JHEP12(2017)094

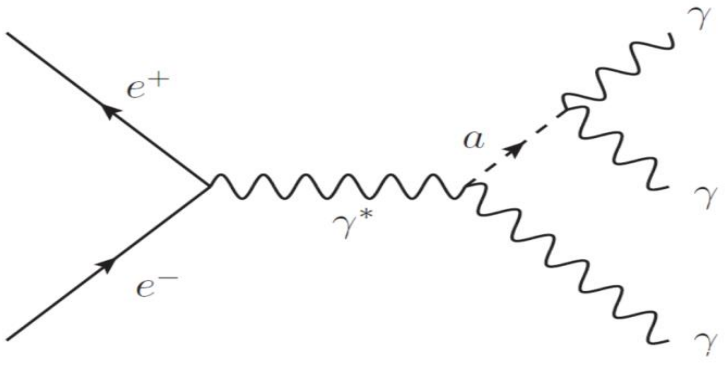
Axion-Like Particles

*Theory

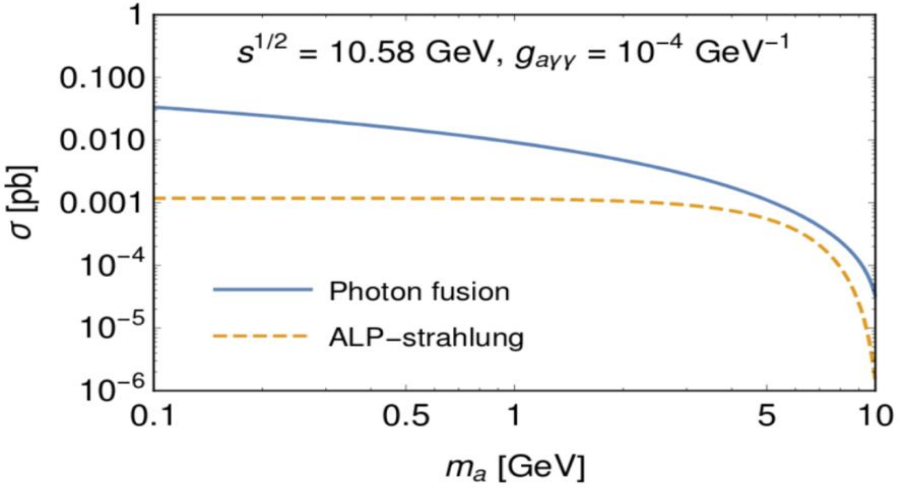
photo-fusion



ALP-strahlung



cross section



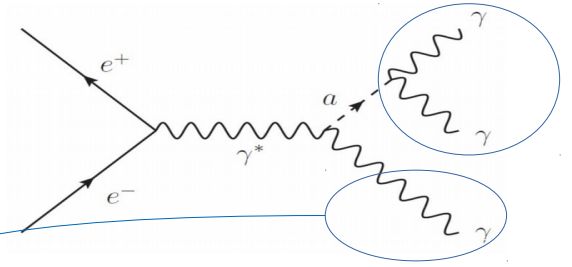
ALPs are pseudo-scalars particles coupling with photons.

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

- Photon-fusion;
- **ALP-strahlung**.

Axion-Like Particles

Experimental signature

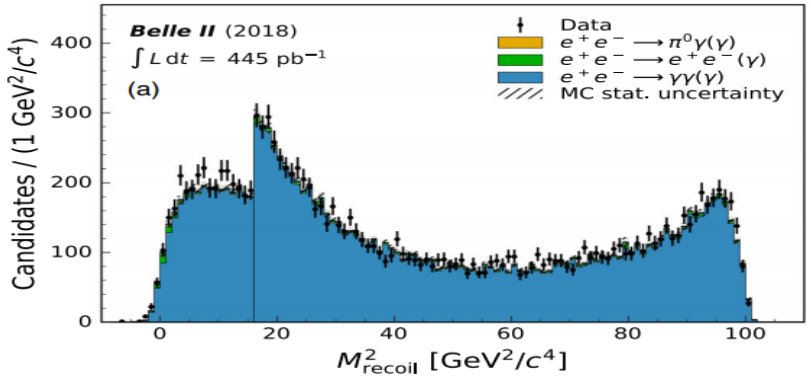


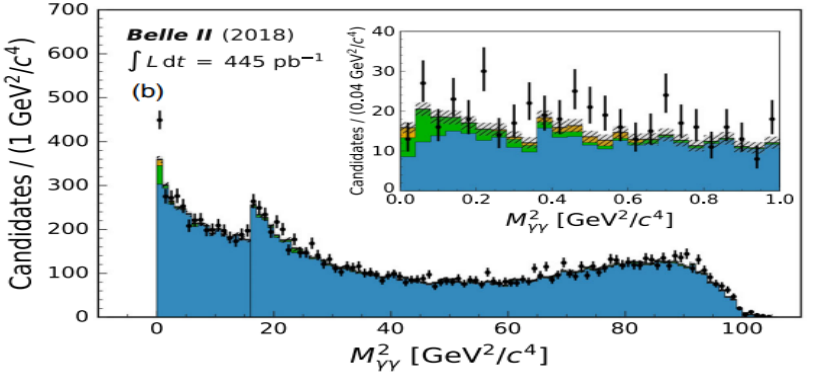
Looking for:

- three photons 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. $e^+e^- \to P\gamma\gamma$, $P = \pi^0, \eta, \eta'$.

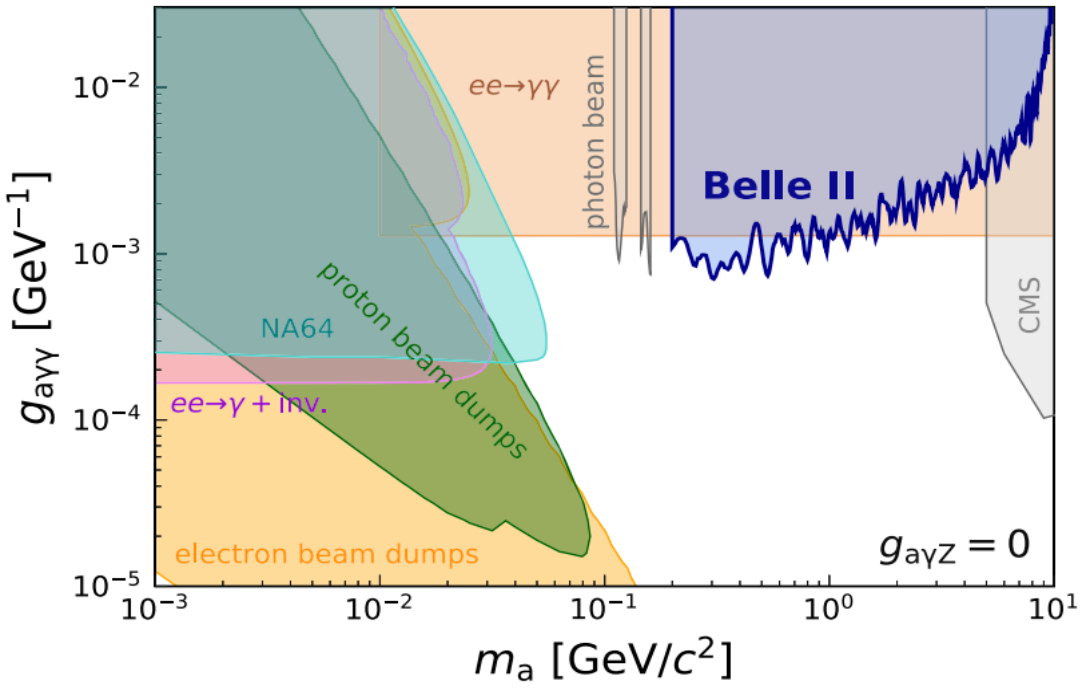


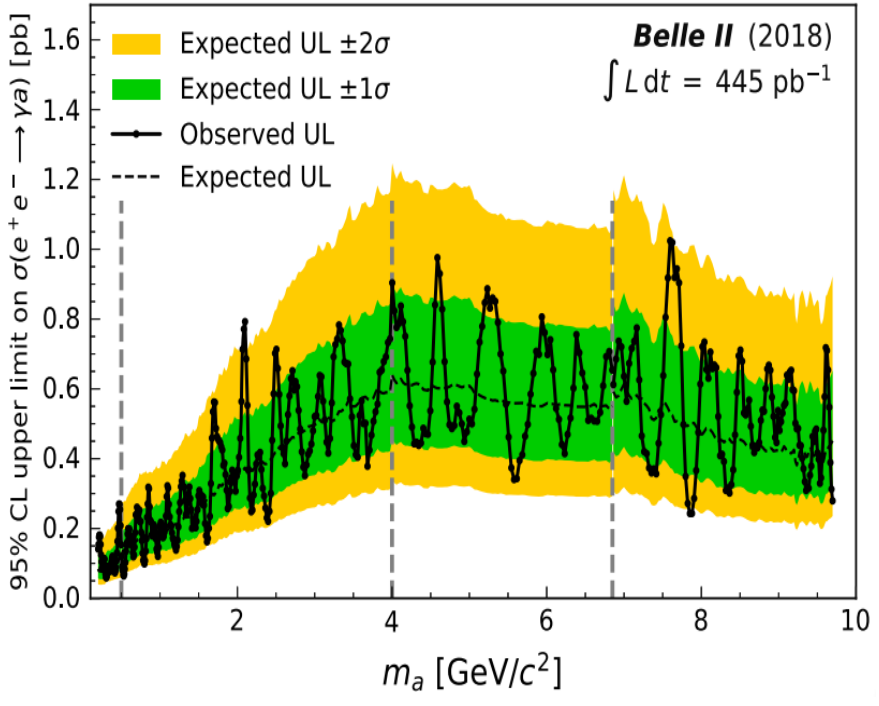


Axion-Like Particles

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

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





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

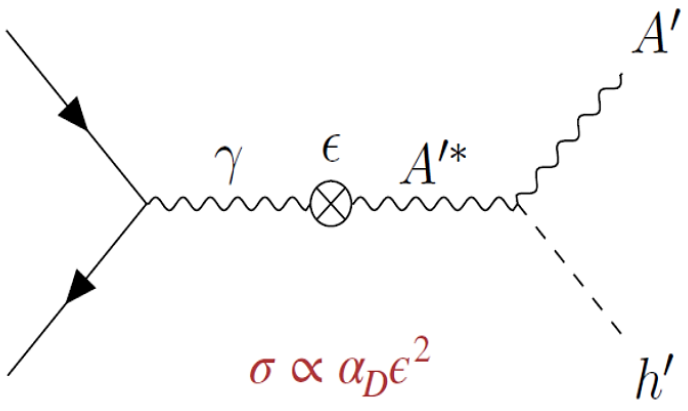
Measurement performed with 445 pb^{-1}

- 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.

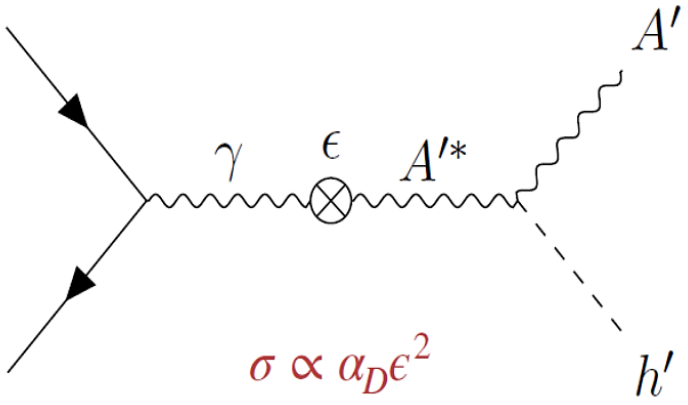
Different scenarios depending on the mass hypothesis.

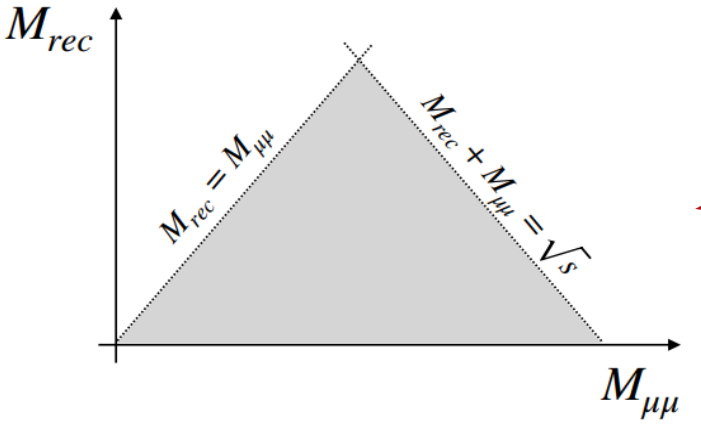
We focus on the case: $m_{h'} < m_{A'}$ with invisible h', up to now only investigated by KLOE.

(Phys.Lett.B 747 (2015) 365-372)

Dark Higgsstrahlung

Experimental signature





Looking for:

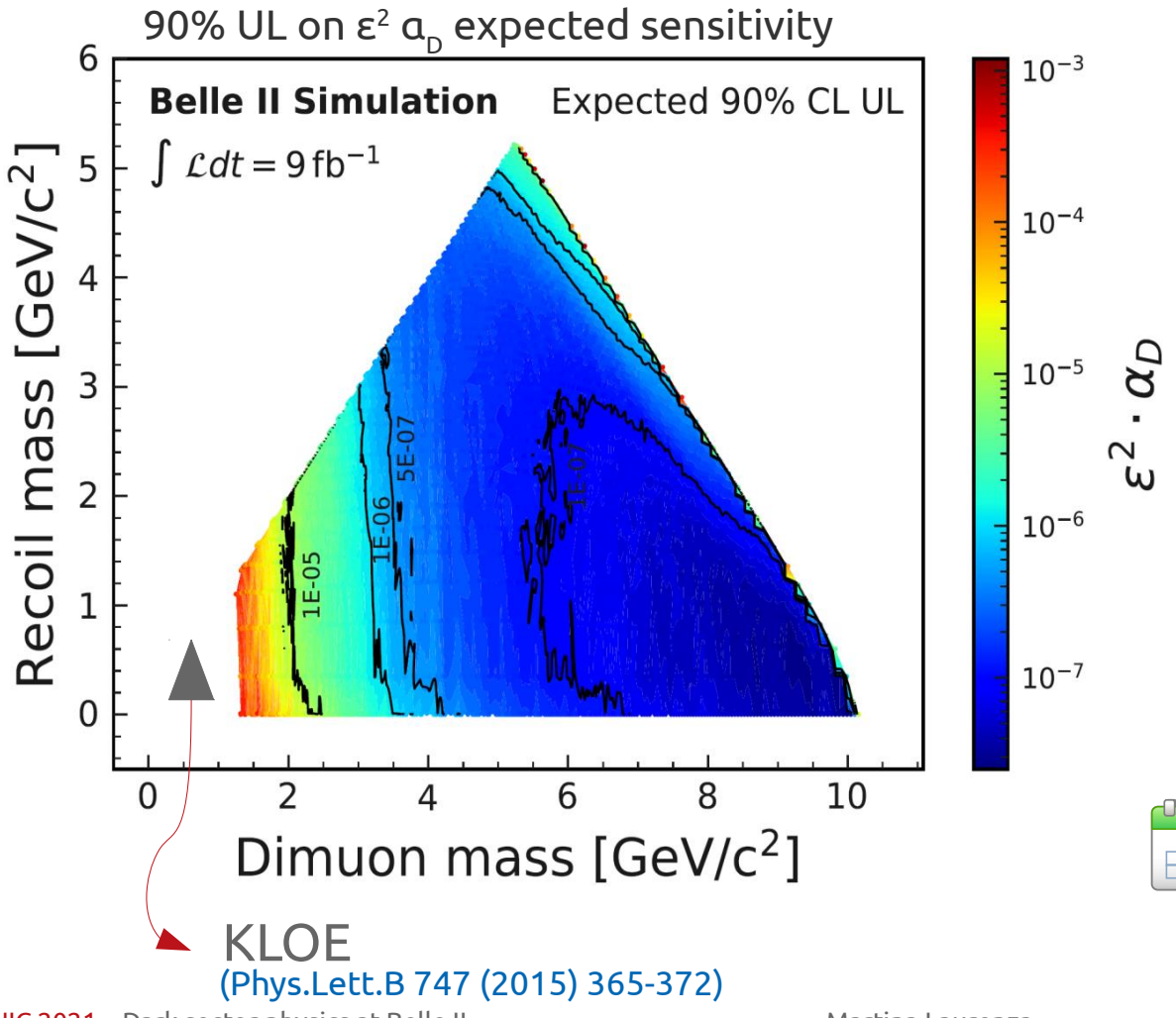
- two oppositely charged muons plus missing energy ;
- a peak in two dimensional distribution of recoiling mass vs dimuon mass.

Main Backgrounds:

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

Dark Higgsstrahlung

Expected sensitivity



Very promising results even with 9 fb^{-1}.

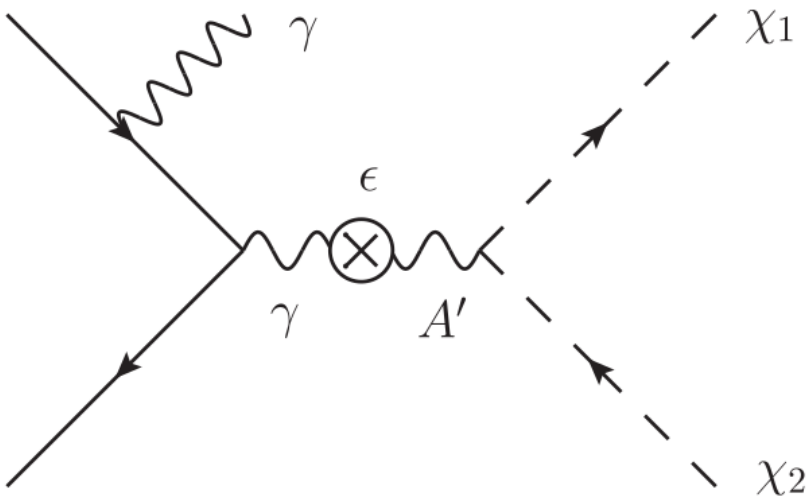
- Accessing unconstrained regions, well beyond KLOE coverage;
- Probing non-trivial $\varepsilon^2 \alpha_D$ couplings.

Analysis to be finalized shortly (by end 2021).

Invisible dark photon

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



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

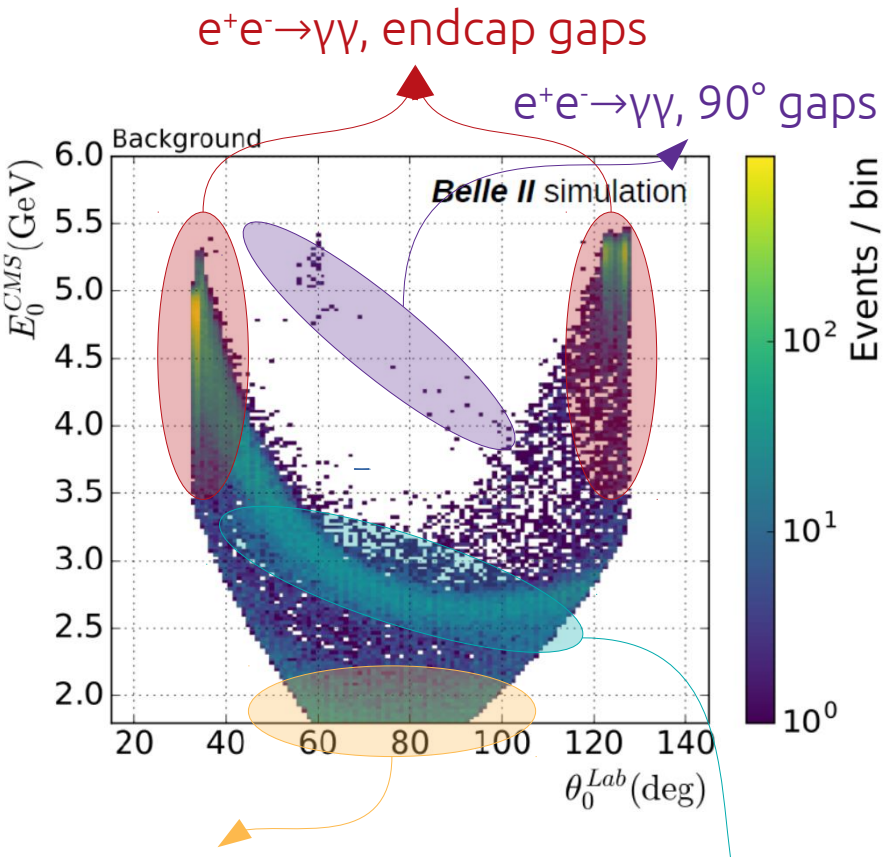
A possible standard model extension with a new massive gauge boson A' of spin = 1 called **dark photon**, that couples to SM.

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

$m_x > 1/2 m_{A'} \rightarrow$ A' visible decays to SM;
$m_x < 1/2 m_{A'} \rightarrow$ A' invisible decays to light DM.

Invisible dark photon

Experimental signature



Looking for:

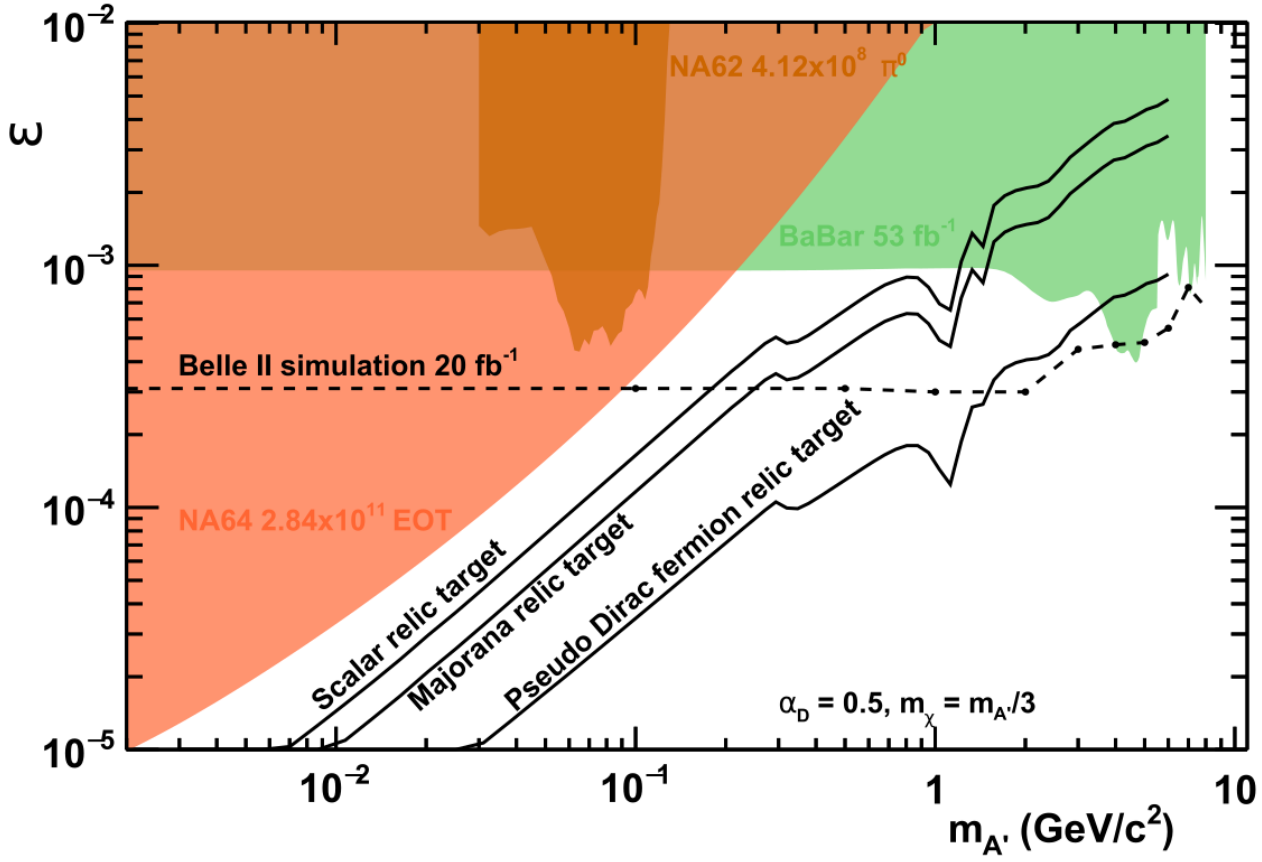
- One photon inside calorimeter acceptance and nothing else in the event;
- Bump hunt in single photon recoil mass (or energy) vs. θ_{LAB};
- Use single-photon trigger.

Backgrounds:

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

Invisible dark photon

Expected sensitivity



Very promising results even with very low luminosity (1/3 BaBar).

We expect a better performance than BaBar:

- no ECL gaps pointing to the interaction region.

Conclusions

- Belle II/Super KEKB is a perfect environment where to search for light dark matter or mediators;
- It has successfully collected 500 pb^{-1} during pilot run and 213.5 fb^{-1} collected up to now;
- A lot of dark sector searches are in progress, and very good results have been obtained also with pilot run data only.

In the next years Belle II is expected to lead the light dark matter field!

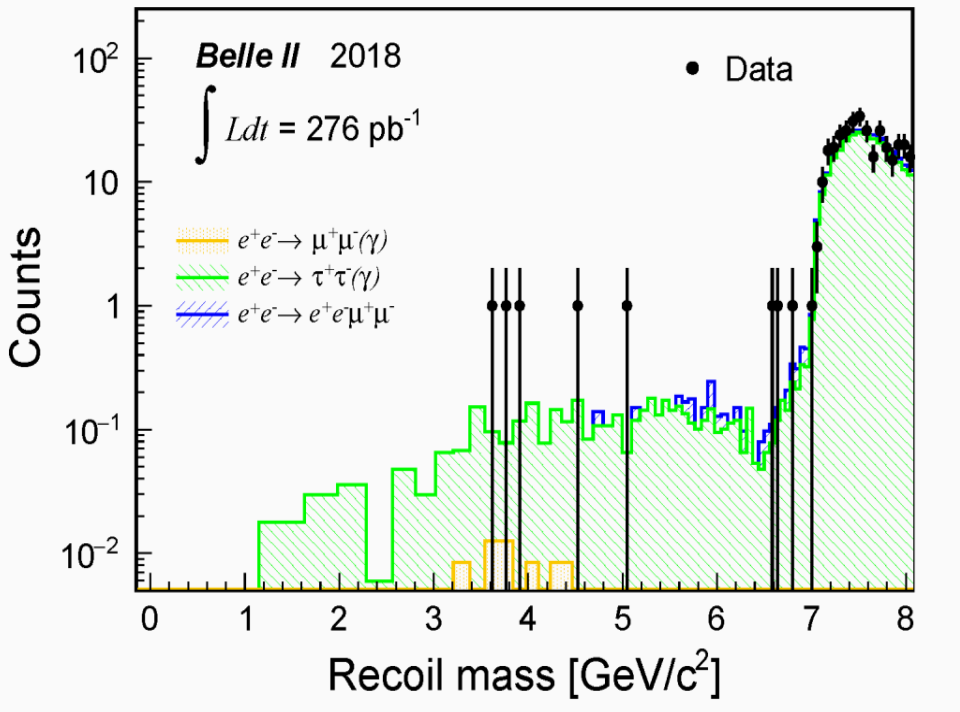
Thank you!

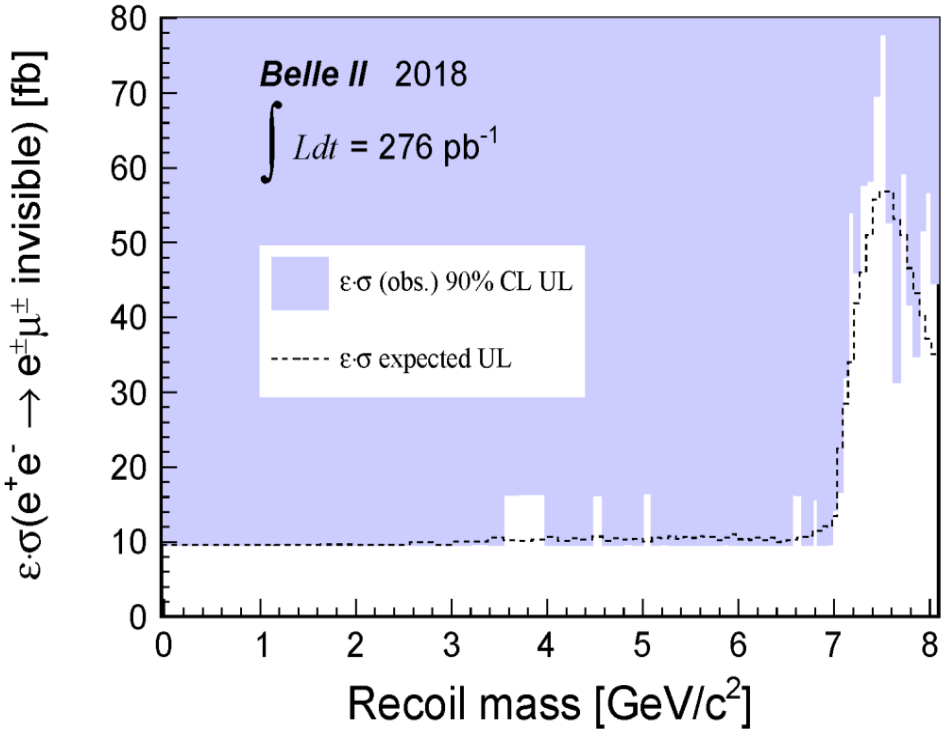
BACKUP

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

LFV Z' to invisible

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



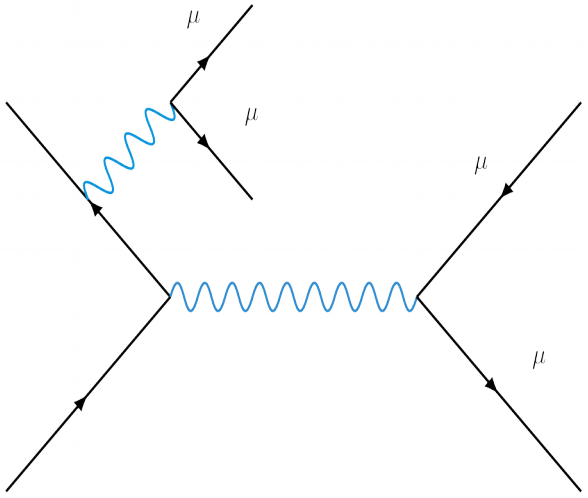


Model independent search with same analysis selection criteria of the Z' to invisible search, with an electron replacing a muon.

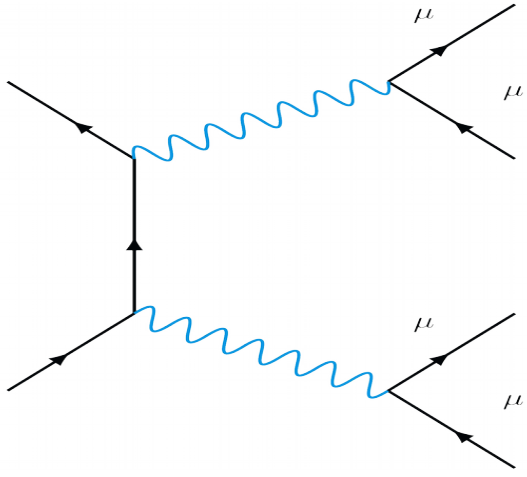
Z' to visible

Muonic dark force

ISR



Double photon conversion



"fixed" to the candidate mass

QED: emission to the lowest mass and low p_t

The **double photon conversion** is dominant, ISR regime is suppressed by the drift chamber acceptance tracks.

dimuon recoiling against a "zero" mass object:

- quasi two body process with peculiar p_t;
- characteristic P_0;
- best discriminant:

$$(p_{\mu\mu} - P_0)/P_0$$

Axion-Like Particles

Experimental signature

Looking for:

- three photons 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. $e^+e^- \to P\gamma\gamma$, $P = \pi^0, \eta, \eta'$.