9th International Conference on

New Frontiers in Physics

ICNFP2020 *Kolymbari, Crete, Greece - 4-12 September 2020*

Dark Sector first results at Belle II

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> on the behalf of the Belle II collaboration

SuperKEKB and Belle II

A second generation B-factory

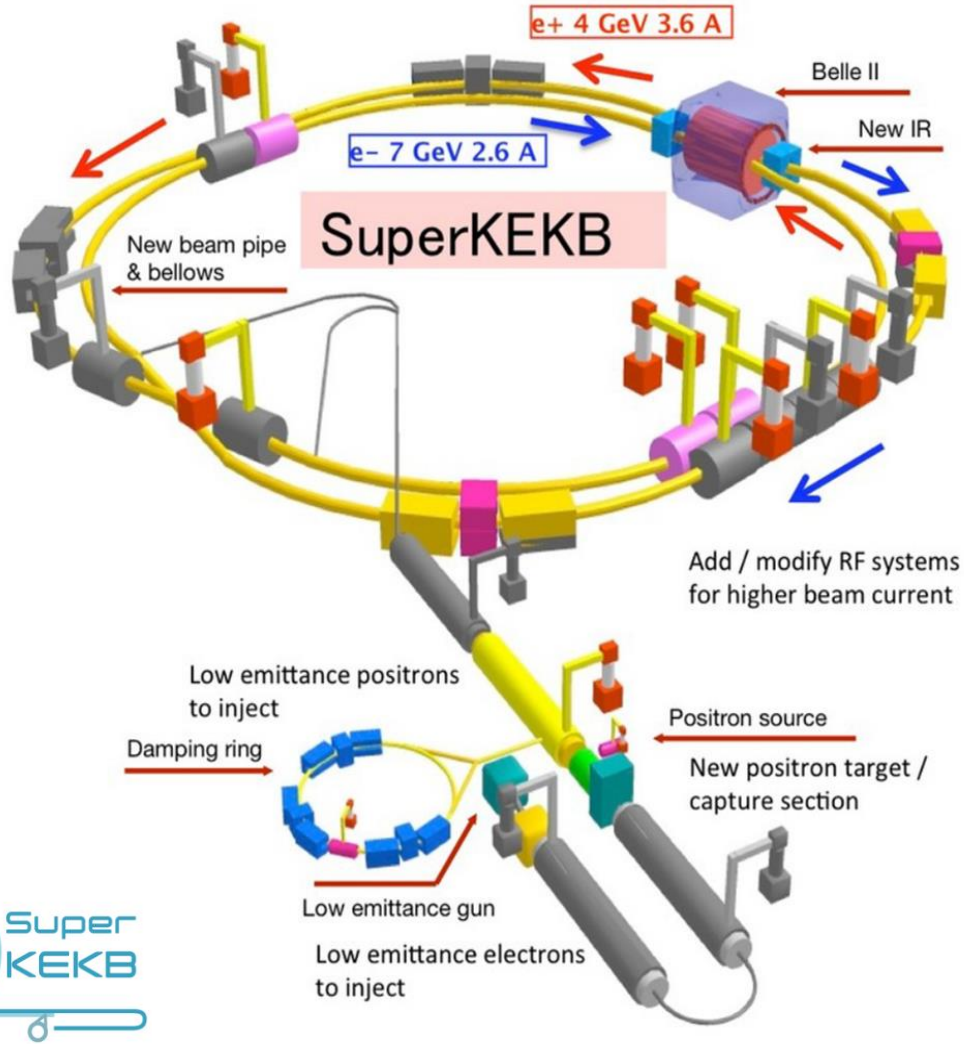
Located at KEK Laboratory in Tsukuba, Japan.

SuperKEKB is an asymmetric *e+e-* collider, operated mainly at the center of mass energy of 10.58 GeV ($= m_{Y(4s)}$).

A second generation B-factory:

- 30 times increase in instantaneous luminosity with respect to predecessor KEKB
  - **1.5x** from higher beam current
  - **20x** from final focus magnets

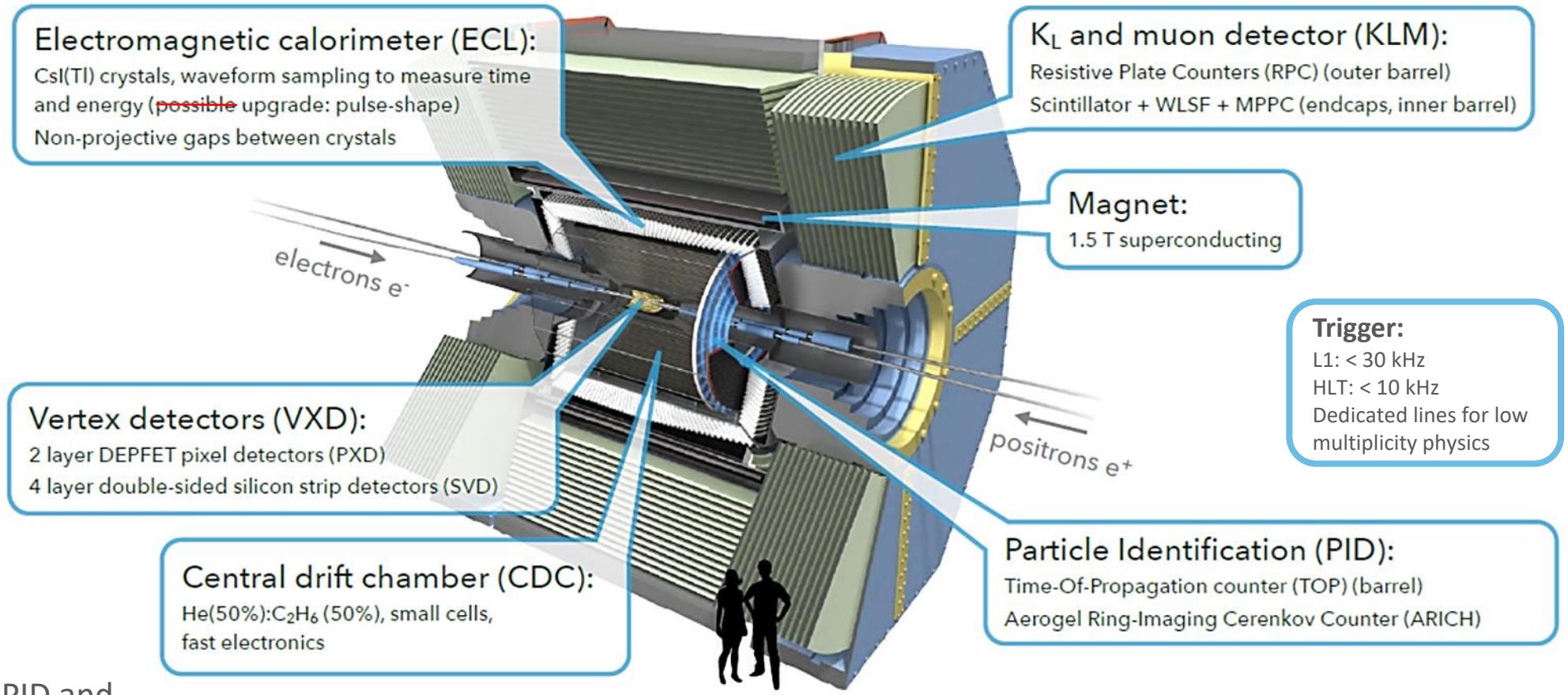
It will be **the world highest luminosity** (L = 6.5x10^{35} $cm^{-2}s^{-1}$).



The Belle II Experiment

Inside the detector

TDR: arXiv:1011.0352



Belle vs Belle II

Better resolution, PID and capability to cope with higher background

The Belle II Experiment

See the tomorrow talk by J. Baudot on
"The Belle II Experiment: status and prospects"

Time schedule

2018

Phase 2 (pilot run)

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

2019

Phase 3

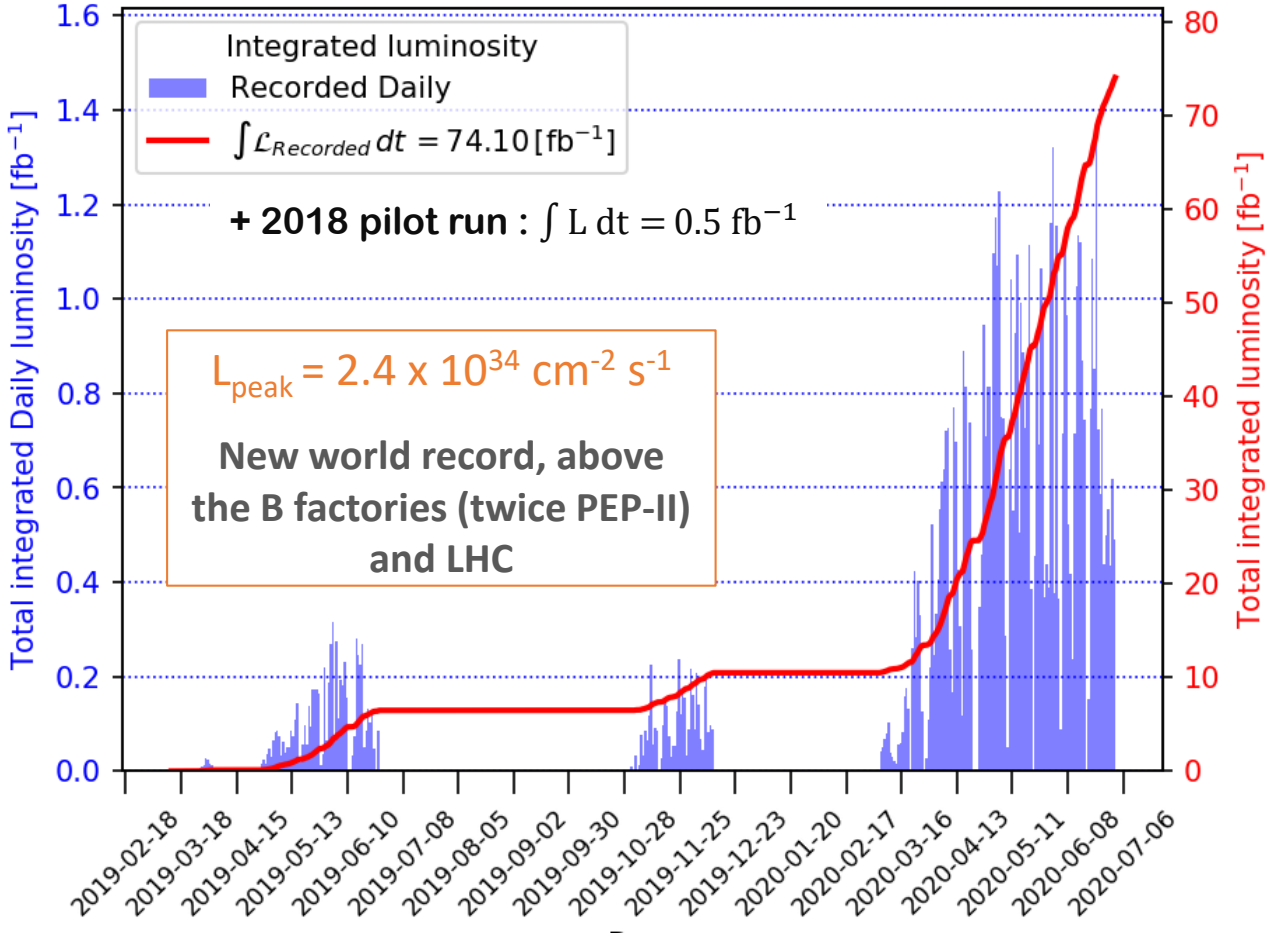
Belle II routinely integrates more than 1 fb^{-1}/day.

Up to now ~ 74 fb^{-1} collected

~2030

Goal

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



DM searches

Motivations & Models

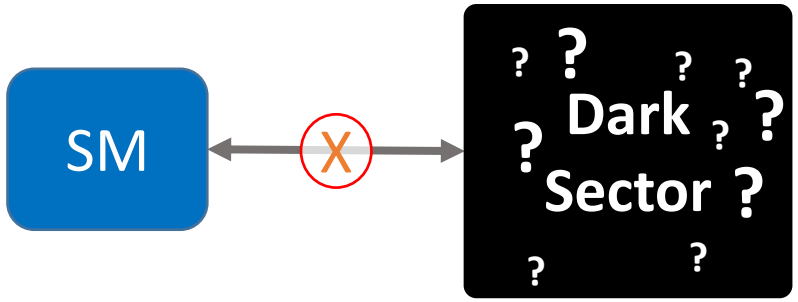
The absence of DM discoveries by the LHC or direct detection experiments motivate the interest for models with low-mass dark matter candidates.

A possible GeV and sub-GeV theoretical scenarios:

↘ **Light-DM associated with new dark forces, weakly coupled to SM through a new light mediator X.**

Additional benefits. The explanation of:

- some astrophysics anomalies (PAMELA, AMS, FERMI, …);
- the $(g\text{-}2)_\mu$ effect;
- some flavour anomalies (LHCB, Belle, …)



Different possible portals between Dark Sector and Standard Model depending on the mediator X:

In this talk

- **Vector Portal** → Dark Photon A', Dark Z'
- **Pseudo-scalar Portal** → Axion Like Particles
- **Scalar Portal** → Dark Scalars, extended Higgs models
- **Neutrino Portal** → Sterile Neutrinos

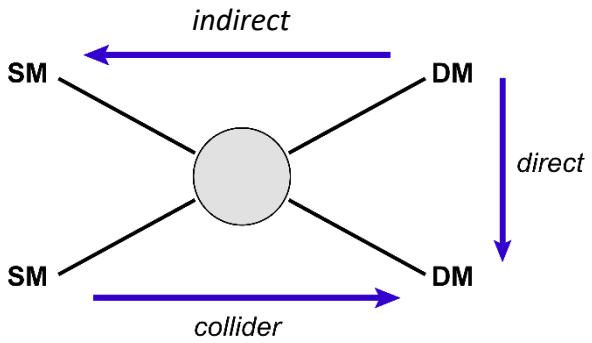
The Belle II Experiment

Not just a B-factory

Collider experiments strategy

Looking for Light DM production.. but probability of LDM interaction with the detectors is negligible.

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



@ Belle II:

- Clean environment with well defined initial state and low background level;
- Hermetic detector (>90% solid angle);
- Excellent PID capability;
- Dedicated triggers for low-multiplicity events;
- Closeness to the LDM mass region;

- **very efficient in the reconstruction of recoiling system and missing energy final states.**
- **it's a perfect place to explore Dark Sector Physics in the MeV - 10 GeV range**

Z’ to invisible

Z’ to invisible

A bit of Theory

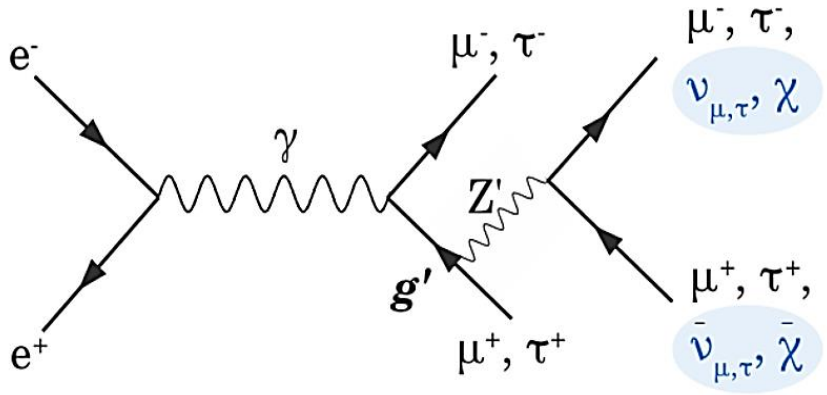
Shuve et al. (2014), arXiv:1403.2727
Altmannshofer et al. (2016) arXiv:1609.04026

New light gauge 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:

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



Looking for an invisibly decaying Z’ produced with a pair of muons.

- Z’ could decay to SM neutrinos or **DM** if kinematically accessible (e.g., sterile neutrinos, light Dirac fermions)

Invisible channel explored for the first time.

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

Z’ to invisible

Experimental signature

Looking for:

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

Background:

- Everything with 2 particles identified as muons and missing momentum.
- Mainly from QED processes:

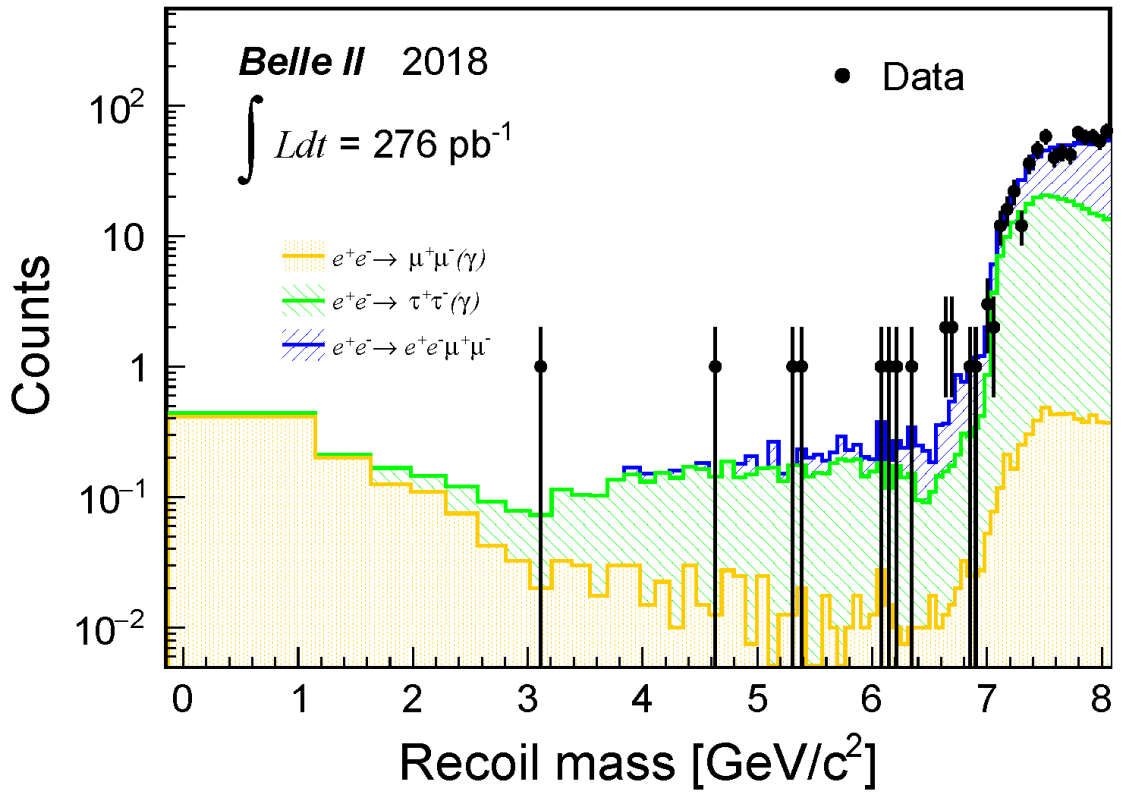
  $e^+e^- \rightarrow \mu^+\mu^-(\gamma)$;

  $e^+e^- \rightarrow \tau^+\tau^-(\gamma), (\tau \rightarrow \mu\nu\nu)$;

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

Measurement performed with 2018 pilot run data.

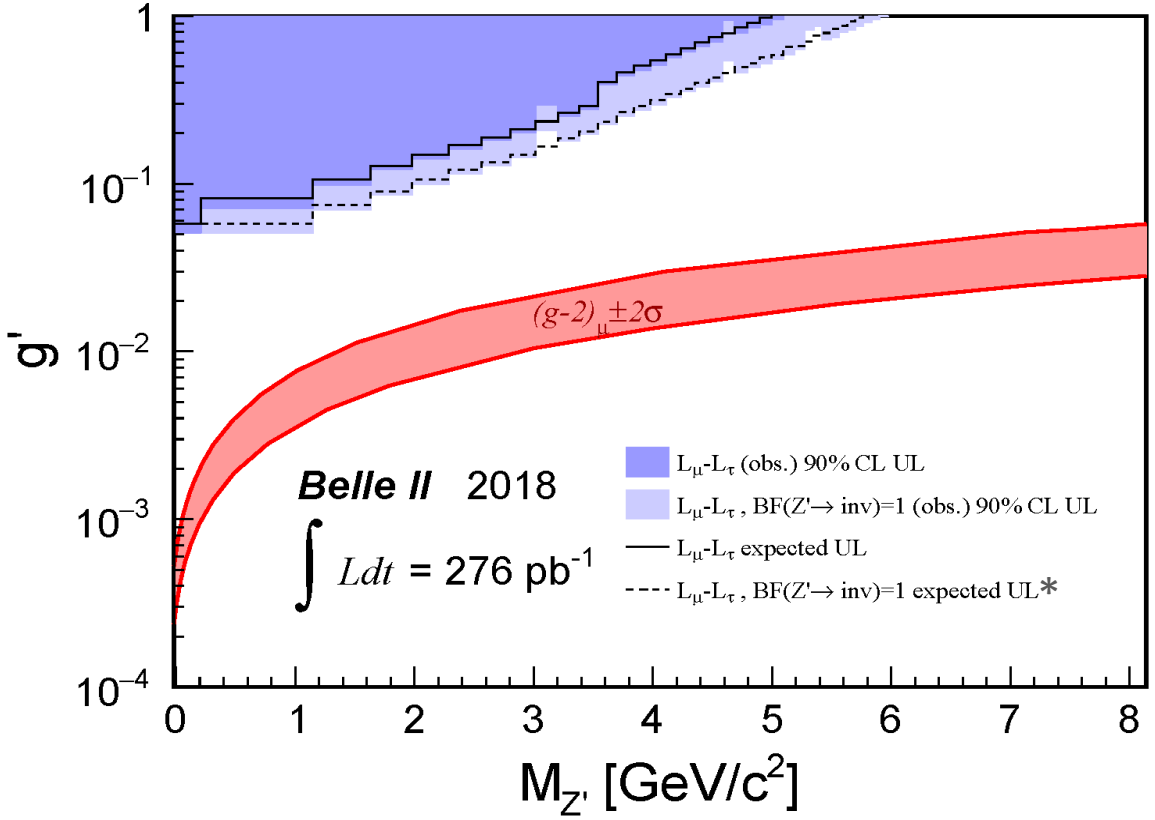
Only 276 pb^{-1} usable due to trigger conditions for 2 track events.



Z’ to invisible

g’ Upper Limit

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



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

First results ever for the *Z’ to invisible* decay.

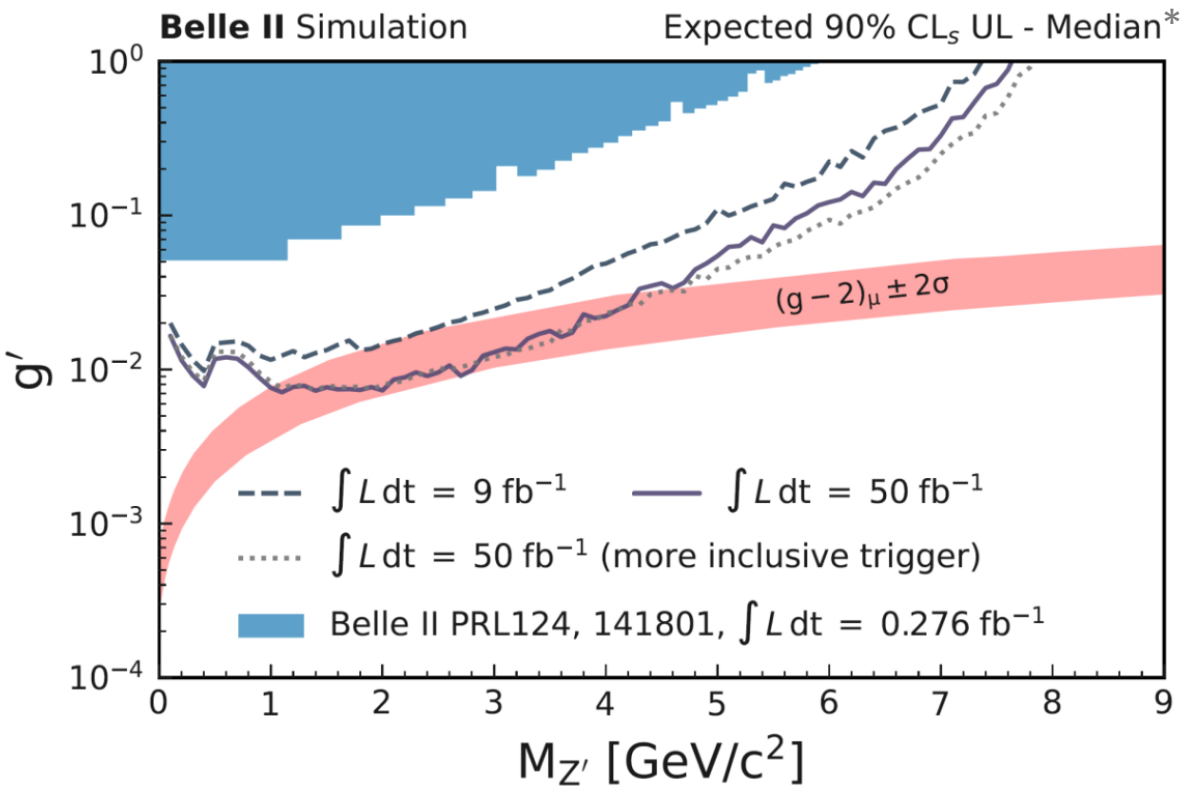
List of systematic uncertainties

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

*If DM is kinematically accessible, *BR(Z’→ inv)~1 can* be assumed.

Z’ to invisible

Short term projections



* Preliminary (conservative) systematics estimate

Short term projections with several improvements:

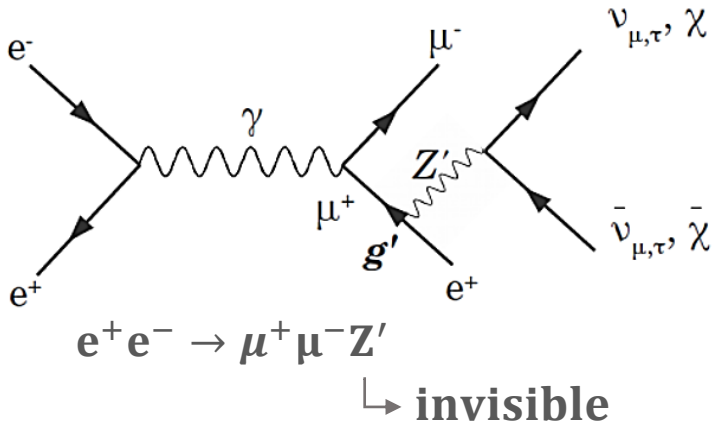
- Much higher integrated luminosity (already on tape).
- Analysis improvements.
  - KLM µID
  - MVA selection
- New triggers.

Starting to probe the $(g\text{-}2)_\mu$ band with 50 fb^{-1} !!

Z’ to invisible

Results for a LFV Z’

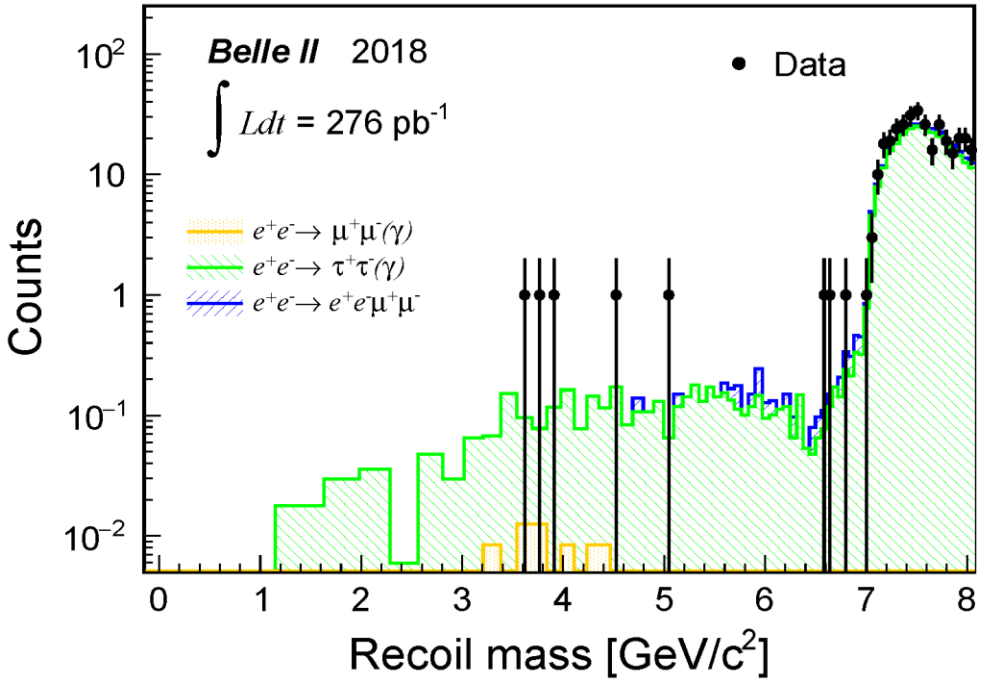
For example
I. Galon et al. (2016) arXiv:1610.08060



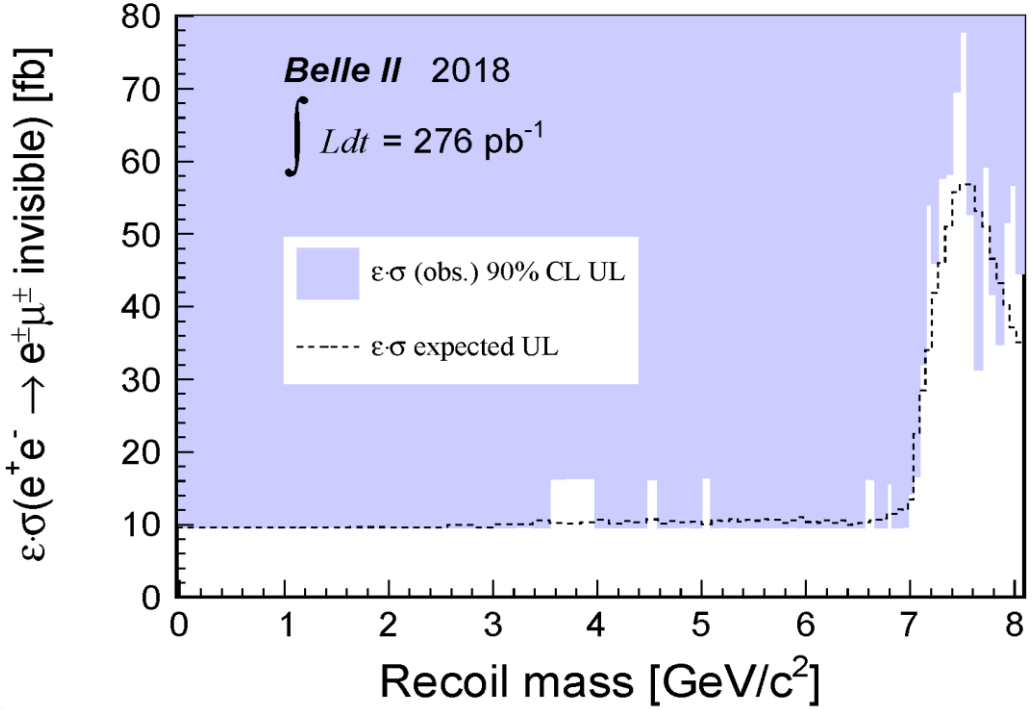
Searching for a Lepton Flavour Violating Z’ that couples to eμ;

Model independent search. Same analysis selection criteria of the invisible Z’ search.

Same publication of the ‘Standard’ Z’.



90% CL UL to $\epsilon \cdot \sigma$



Axion Like Particles

Axion Like Particles

A bit of theory

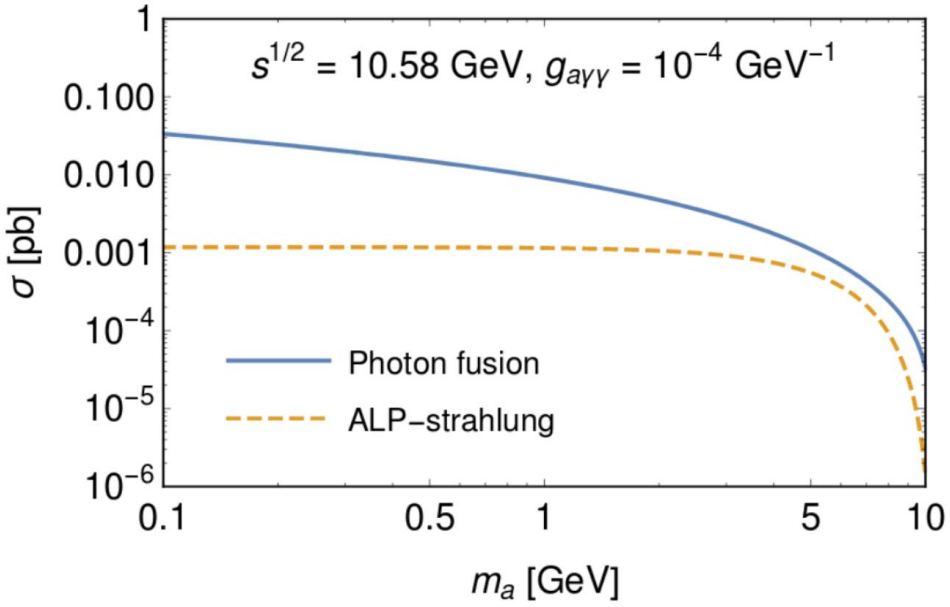
Axion Like Particles (ALPs) are pseudo-scalars particles (a) that couple to bosons.

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

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

@ Belle II focus on coupling to photons. Two possible processes:

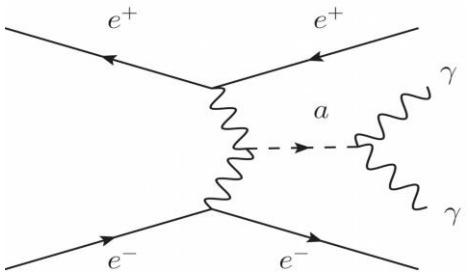
Production cross section



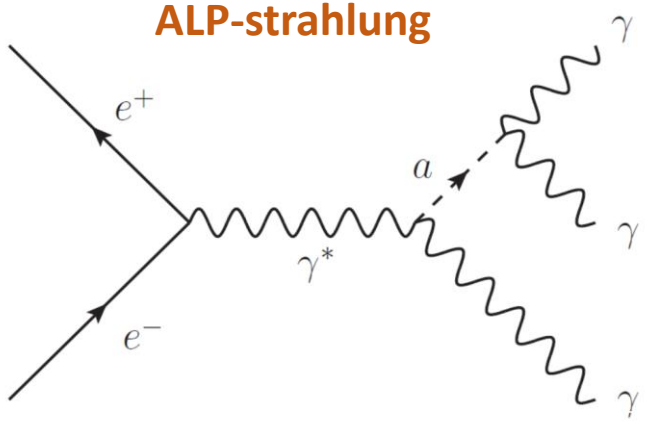
JHEP 1712 (2017) 094

Photon fusion

Under study



ALP-strahlung



Exploring photon coupling $g_{a\gamma\gamma}$ in ALP-strahlung

First search at B-factories

Axion Like Particles

Experimental signature

Several topologies depending on ($\mathbf{m_a}$, $\mathbf{g_{a\gamma\gamma}}$) parameters;

ALPs can also decay to DM;

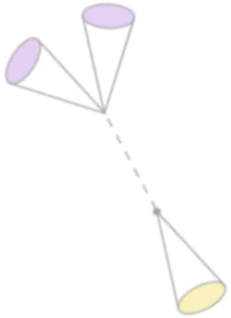
$$\tau \sim 1/g_{a\gamma\gamma}^2 M_a^2$$

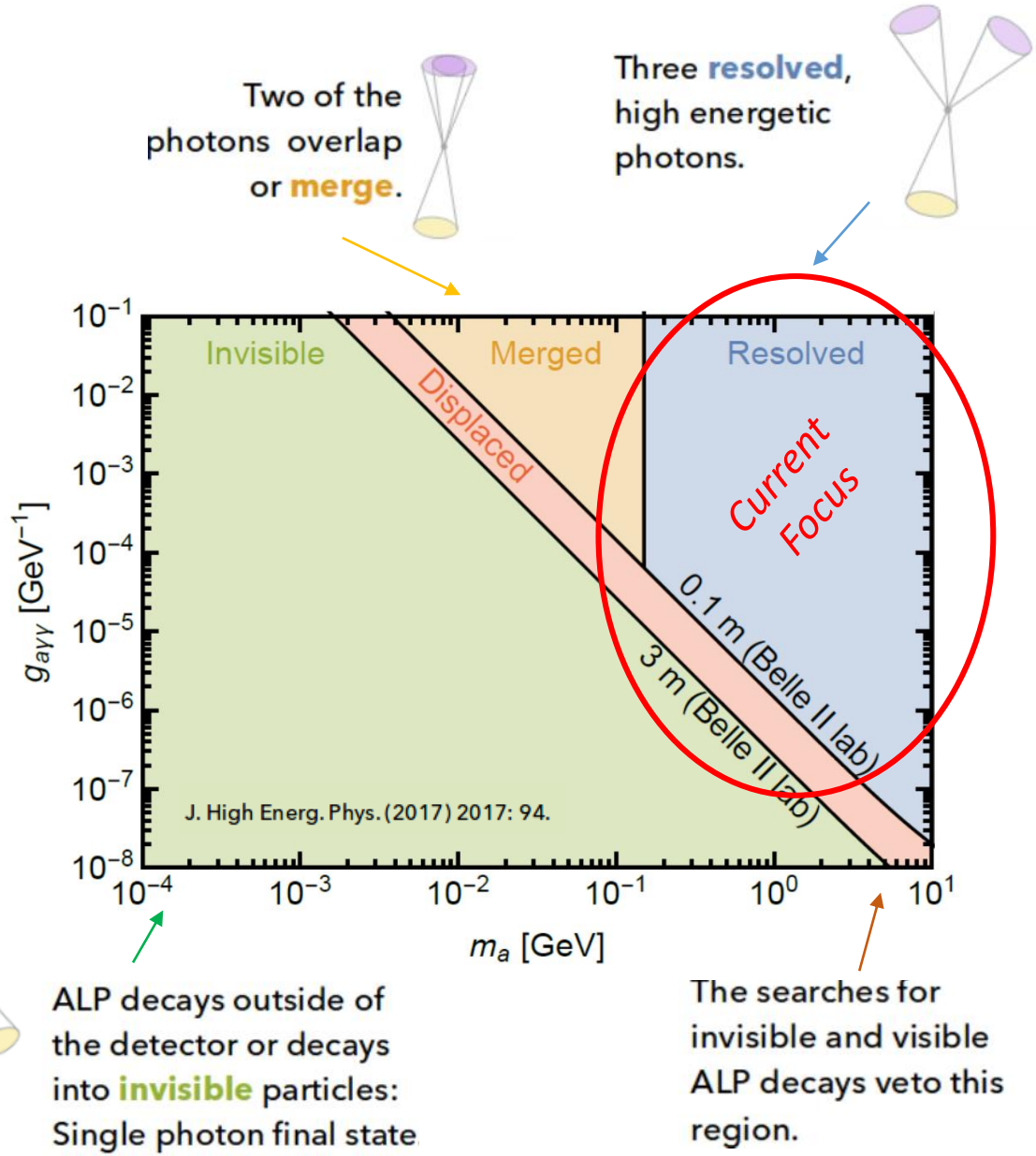
First exploring the 3γ resolved final state:

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

Background:

- $\boldsymbol{e^+e^- \rightarrow \gamma\gamma(\gamma)}$;
- $e^+e^- \rightarrow e^+e^-(\gamma)$;
- $e^+e^- \rightarrow P\,\gamma(\gamma),\ P = \pi^0, \eta, \eta'$;



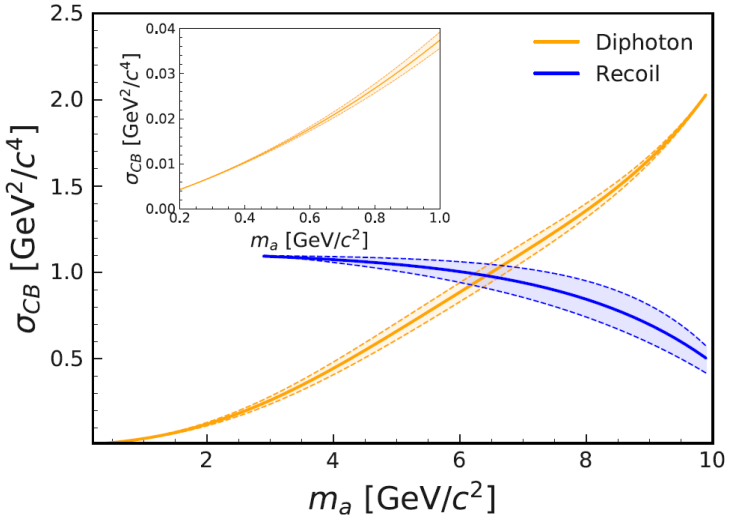


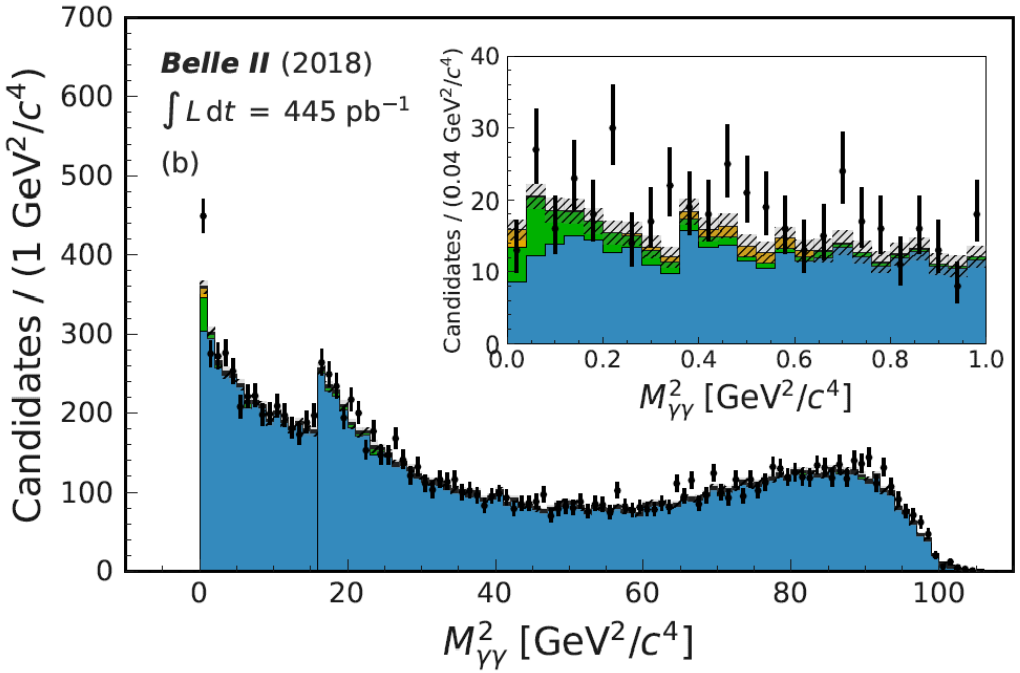
Axion Like Particles

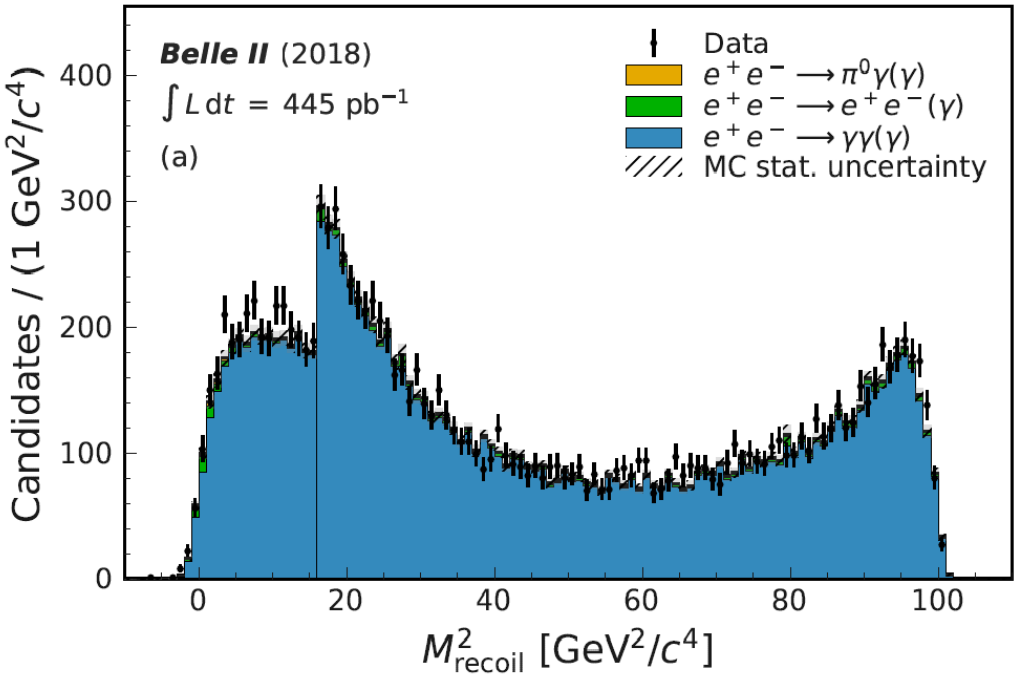
Results

Measurement performed with 2018 pilot run data.

- Explored mass range $0.2 < m_a < 9.7\ \mathrm{GeV/c^2}$
- Search for peaks either in the recoil mass (high m_a) or in di-photon invariant mass (low m_a)





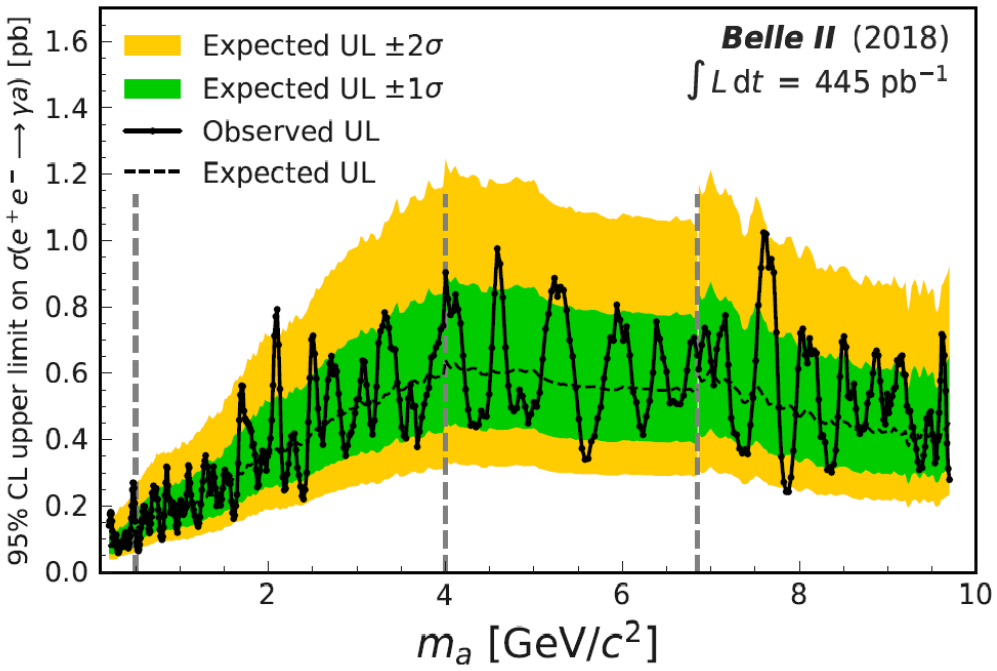


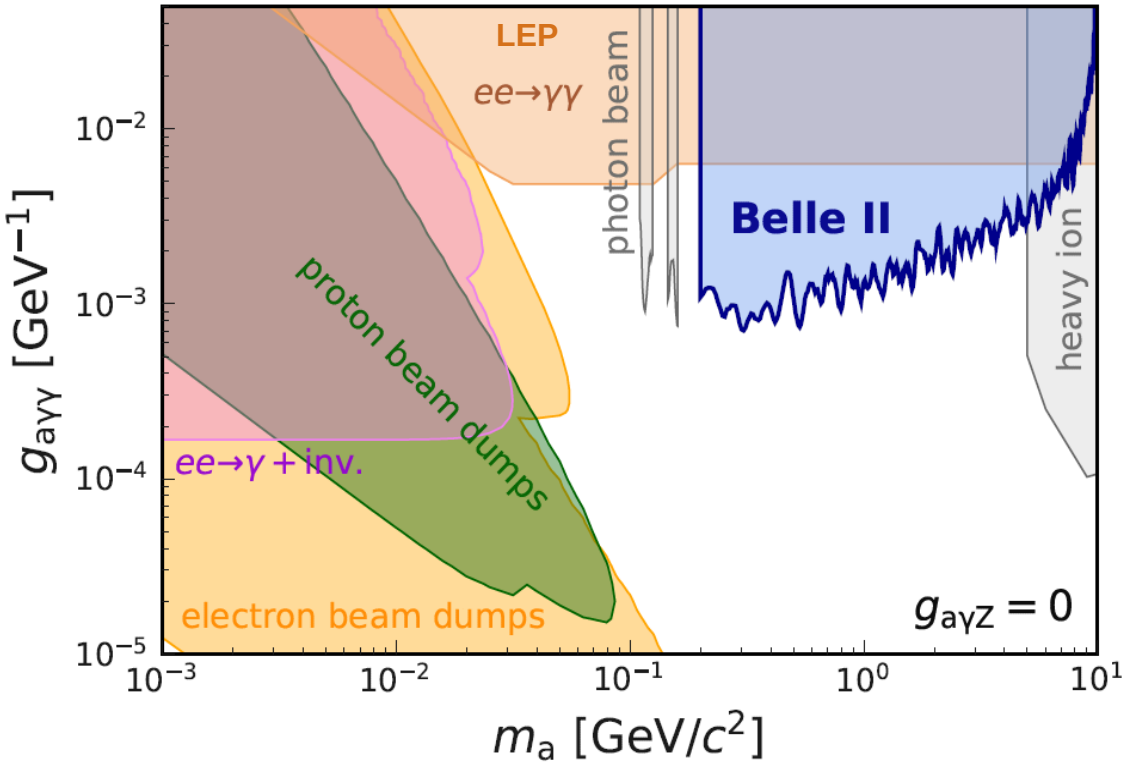
Axion Like Particles

Results

95% CL upper limit on the cross section and then translated in terms of the $g_{a\gamma\gamma}$ coupling constant.

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





Dark Photon

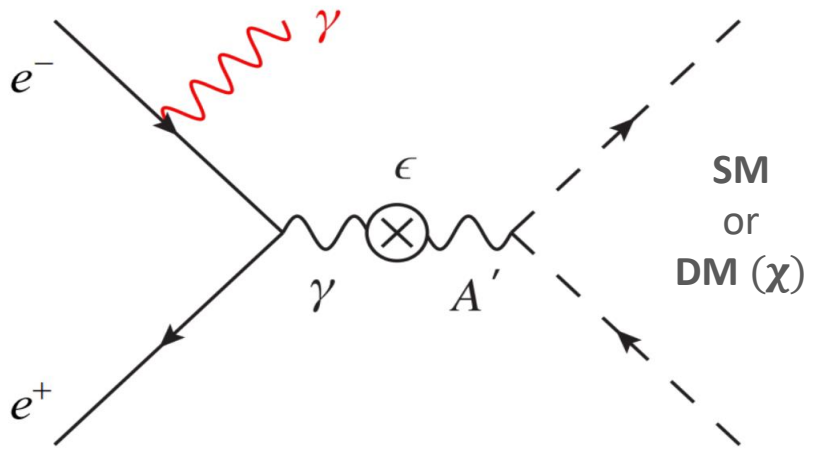
Dark Photon to invisible

A bit of 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 (2009)

A possible extension of the SM includes a new massive gauge boson *A'* of spin = 1 coupling to the SM photons through the kinetic mixing with strength ε, called ***dark photon***.

$$\mathcal{L} \supset \epsilon g_D A'_\mu J^\mu_{\mathrm{EM}}$$



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

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

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

First exploring the invisible decay:

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

Dark Photon to invisible

Analysis strategy

Signal Signature:

- **Only one mono-chromatic, high-E photon γ_{ISR}** in the detector.
- No tracks, no other good photons.
- Bump in the photon energy:

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

Needs a special **single photon trigger**

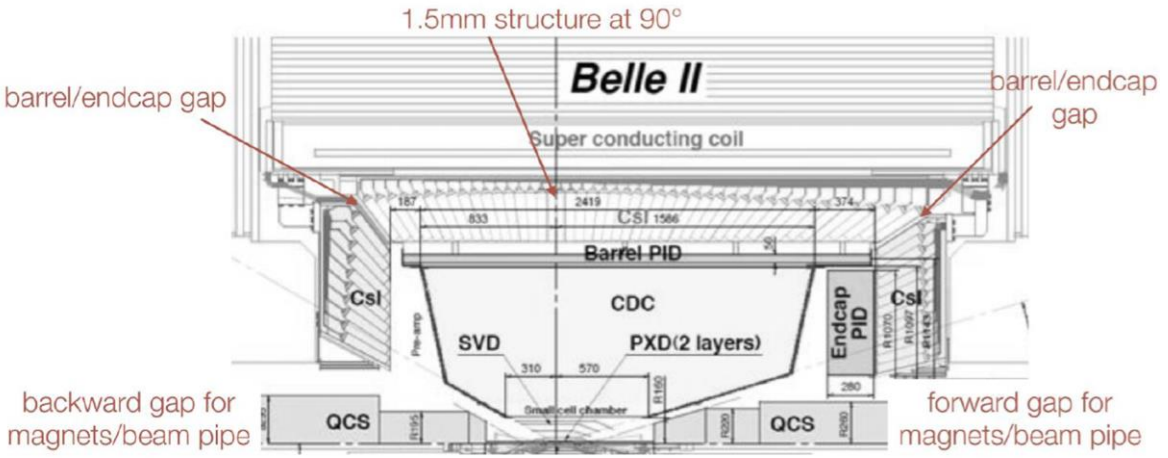
- (not available in Belle, ≈ 10% of data in BaBar)

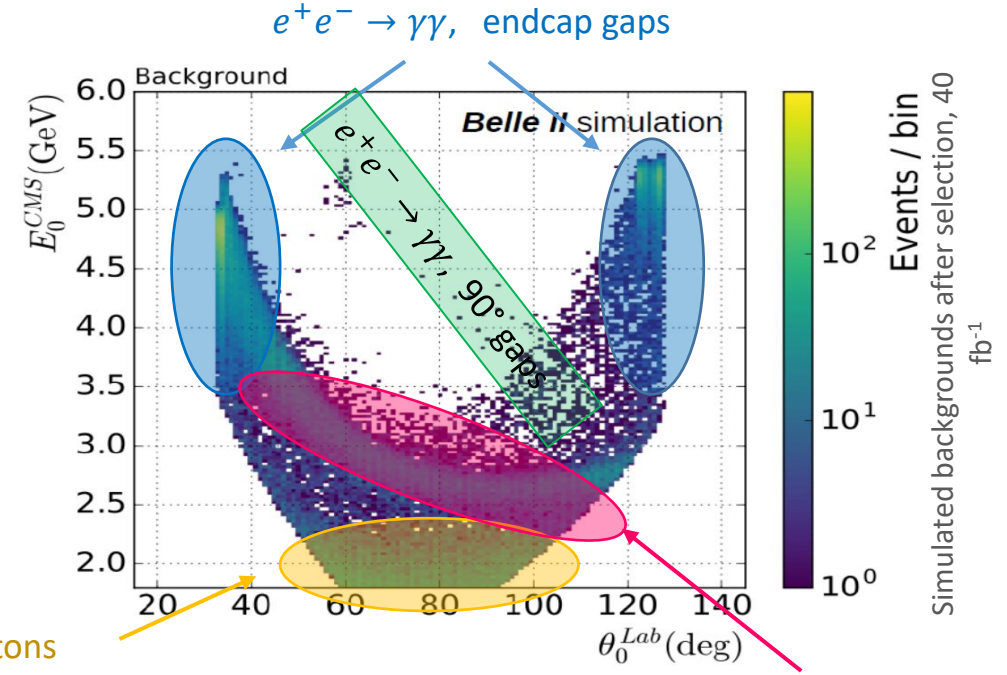
SM backgrounds:

- $ee \rightarrow \gamma\gamma(\gamma)$
- $ee \rightarrow ee(\gamma)$
- Cosmics

Discriminant variables:

- E_{CMS} vs. polar angle of "single photon"

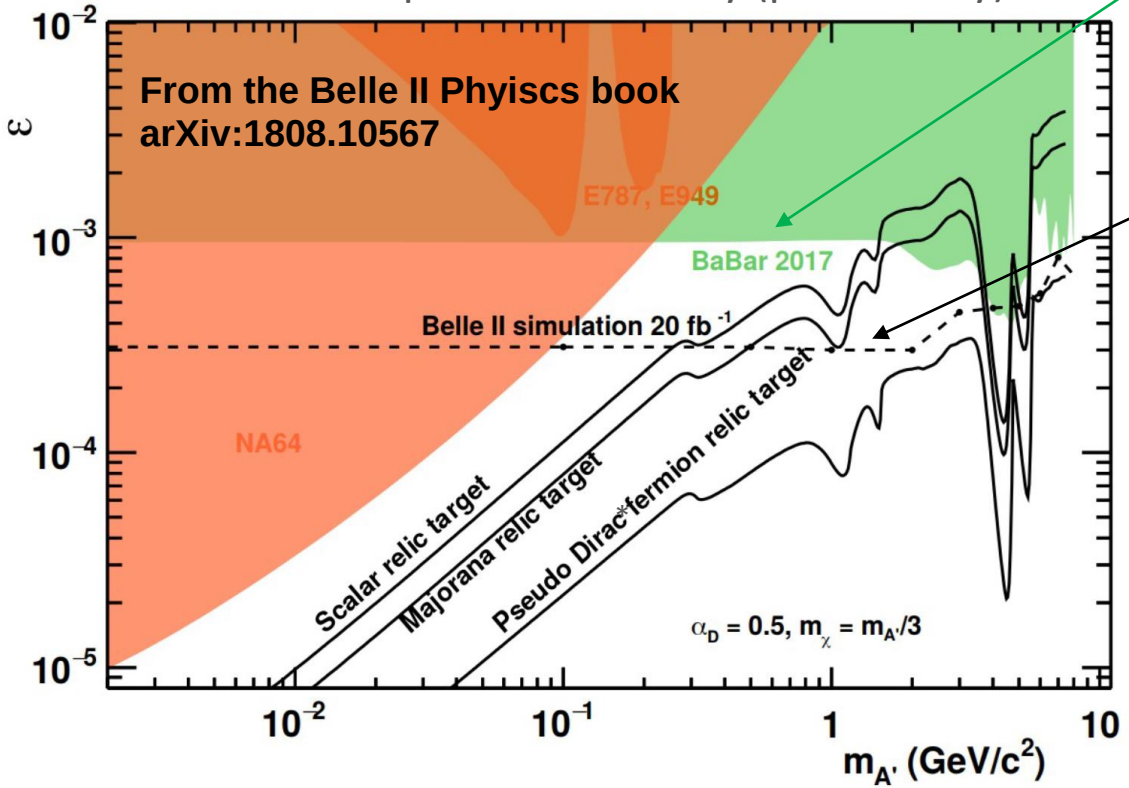




Dark Photon to Invisible

Expected Sensitivity

Belle II expected sensitivity (preliminary)



BaBar limit, 50 fb^{-1}
Phys. Rev. Lett. 119, 131804 (2017)

Belle II projection, 20 fb^{-1}
KEK-2018-27, arXiv: 1808.10567

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;
- smaller boost and larger calorimeter
  ⇒ larger acceptance
- KLM veto;

*If astronomical dark matter is due to the dark sector, parameters will lie along one of these lines.
Derived from E. Izaguirre, G. Krnjaic, P. Schuster, N. Toro, Phys. Rev. Lett. 115, 251301 (2015)

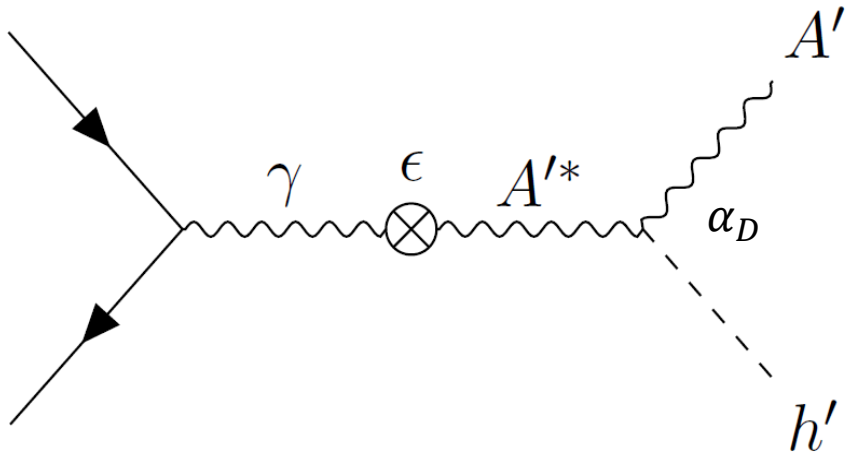
Dark Higgsstrahlung

B. Batell, et al. Phys. Rev. D 79, 115008 (2009)

General remarks

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'.



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.

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

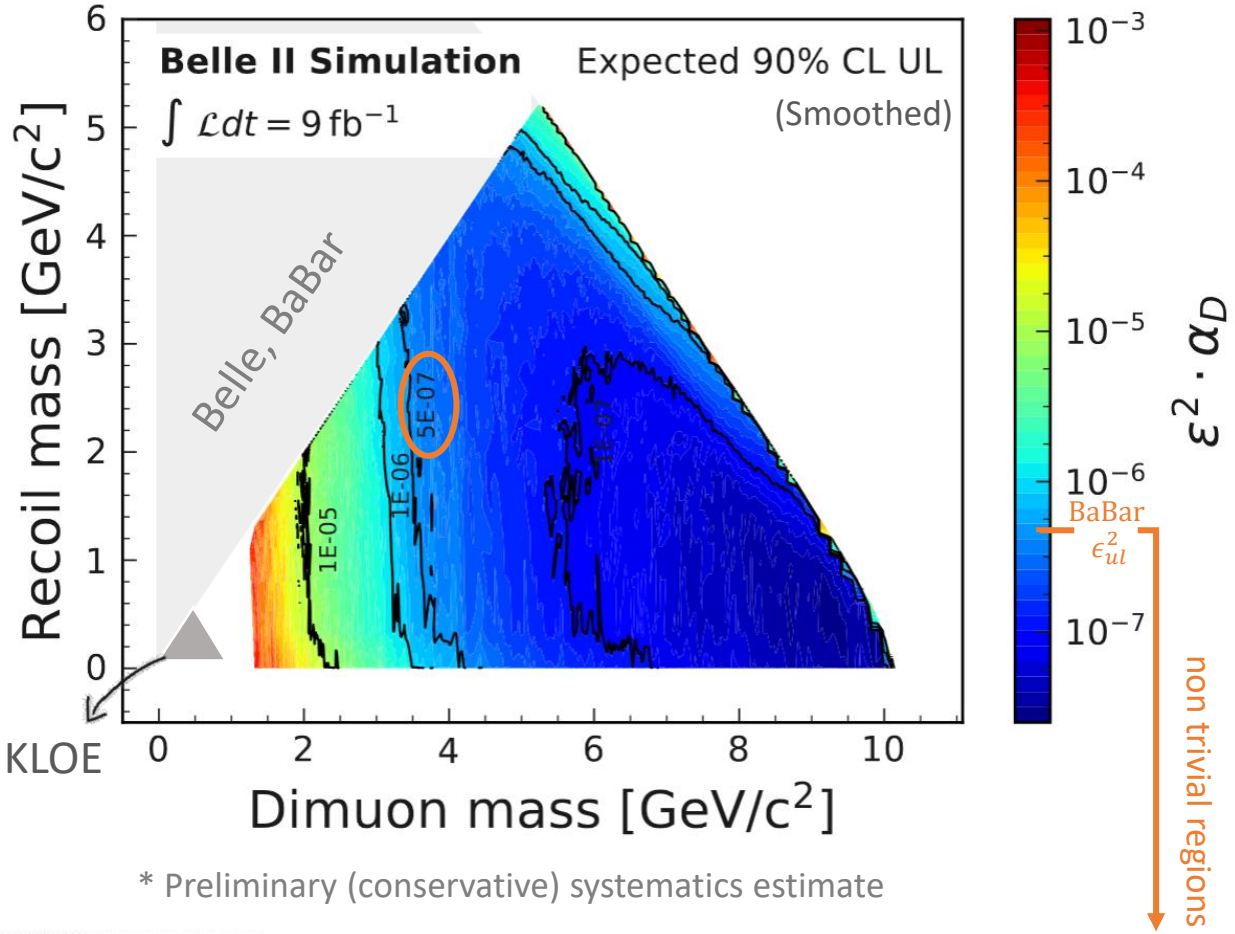
@ Belle II: exploring the *invisible h'* case.

$$e^+e^- \to A'^* \to h'\,A' \quad (h' \to \mu^+\mu^-)$$

Dark Higgsstrahlung

Expected sensitivity

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



* Preliminary (conservative) systematics estimate

Looking for a 2d peak in *recoil vs dimuon* mass

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

- Accessing unconstrained region beyond the KLOE coverage.
- Probing non-trivial $\epsilon^2\ \alpha_D$ couplings.
  - 90% C.L. UL on ϵ^2 in Dark Photon searches lies in $\sim 5 \cdot 10^{-7}$ regime.
- Large trigger inefficiency for $M_{A'} < 4\ GeV/c^2$, recoverable in 2020 with new CDC and KLM single-muon trigger;

Conclusions

- Belle II started operations in 2018. Up to now ~ 74 fb^{-1} collected.
- Although designed mainly for B-physics, the **Belle II experiment** has a broad and active program to explore the ***Dark Sector Physics***;

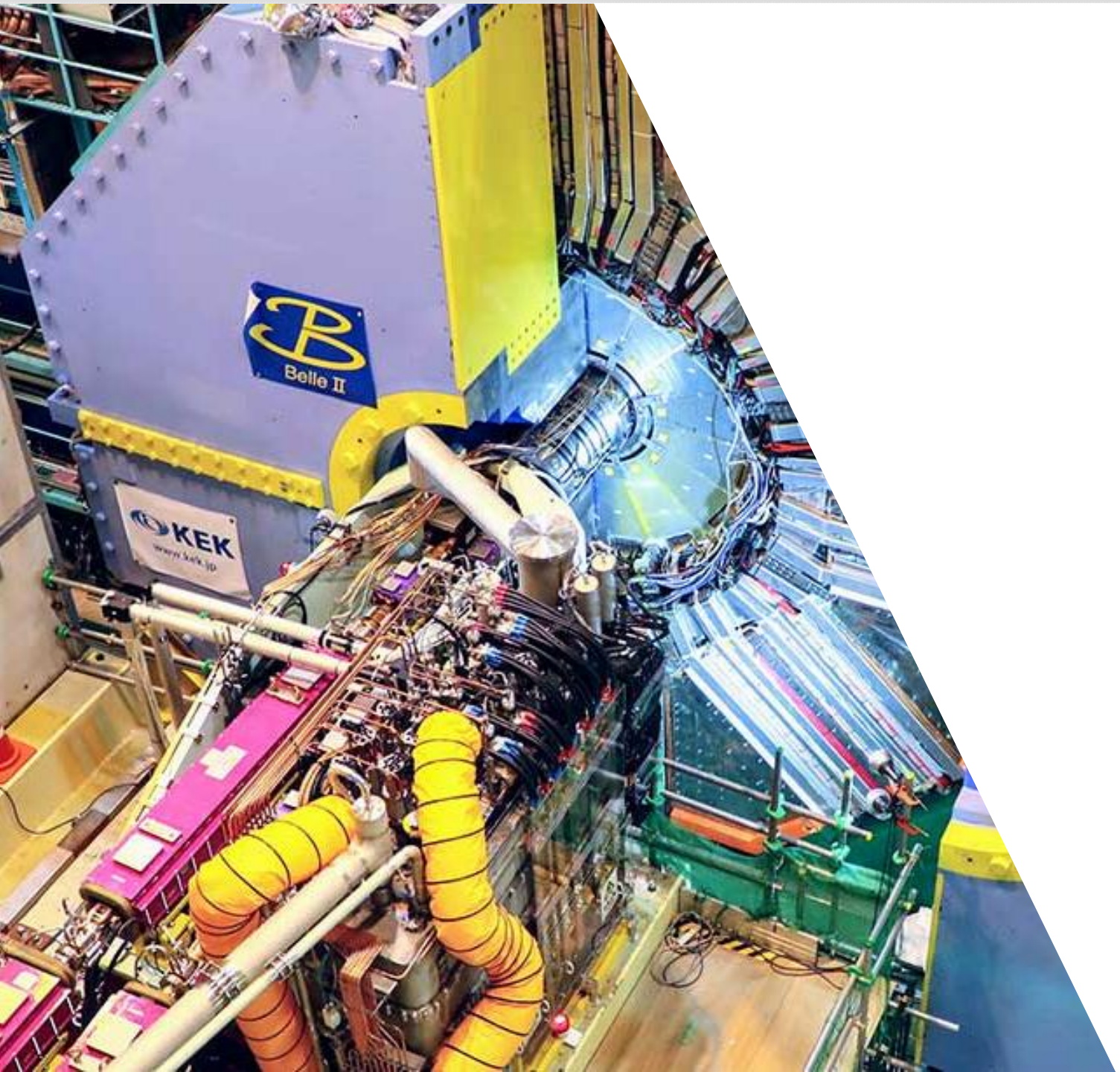
- First results with early data are out:
  - ***Z' to invisible search***.
  - ***ALPs search*** (submitted to PRL);

- 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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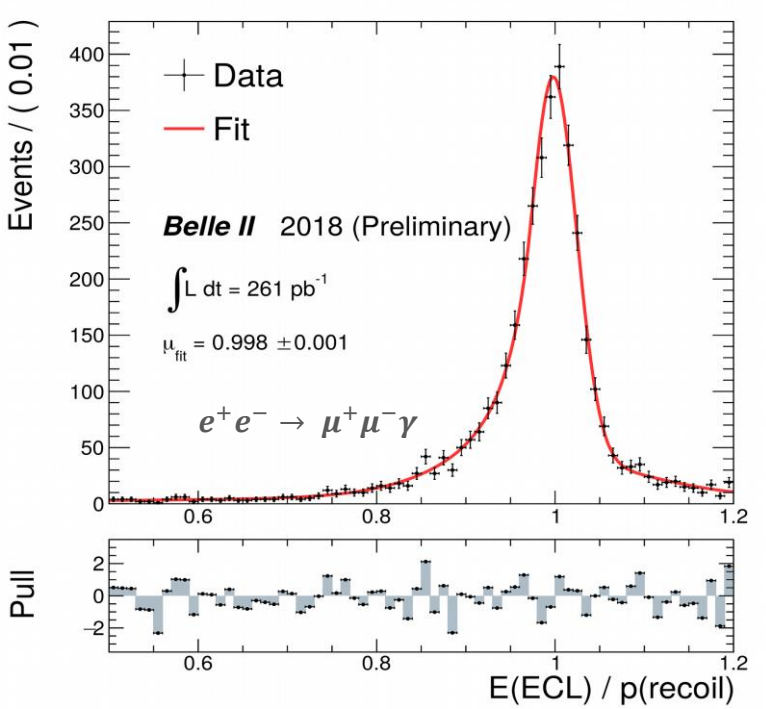
Spare

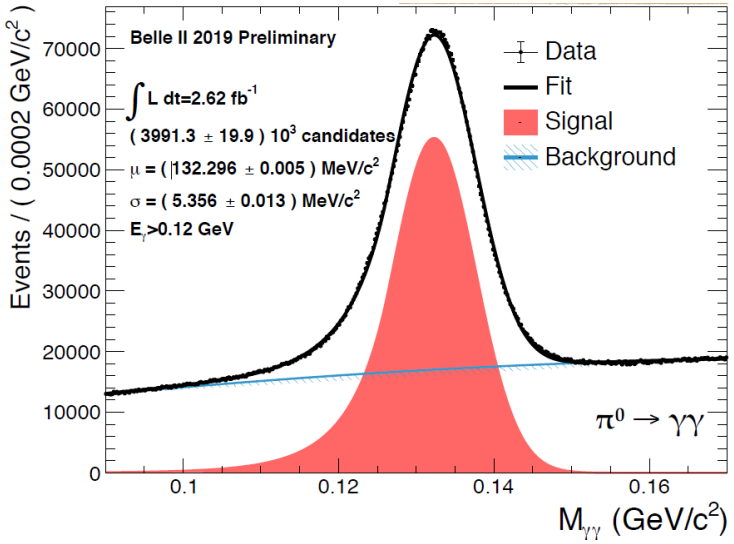
Others Dark Sector searches

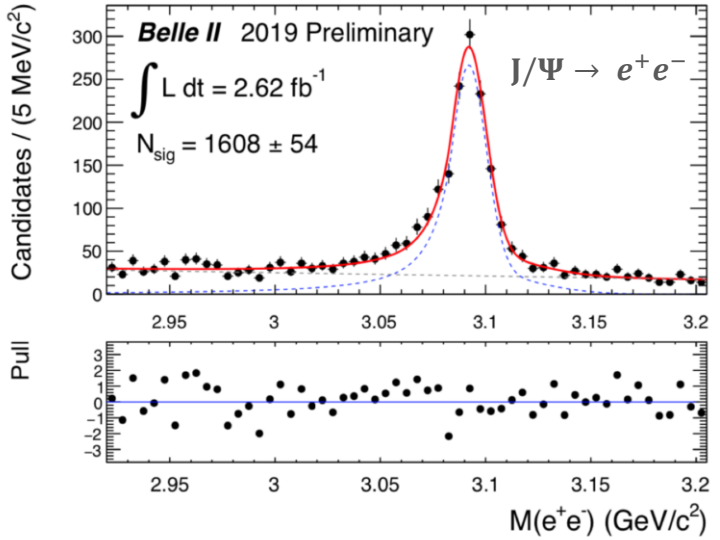
- Visible dark photon decays
- Off-shell dark photon decays
- Muonic dark force: $e^+e^- \rightarrow \mu^+\mu^- Z',\ Z' \rightarrow \mu^+\mu^-$
- Magnetic monopoles with small magnetic charges
- Long-lived particles (LLPs)

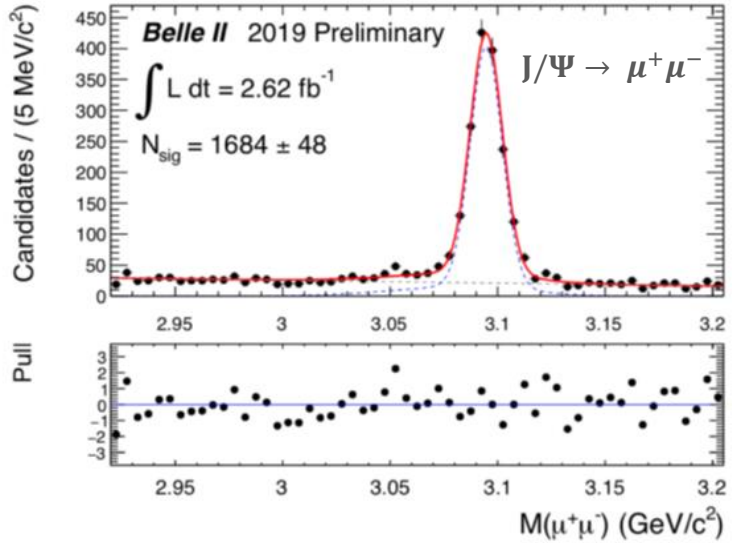
Spare

Belle II performances snapshots



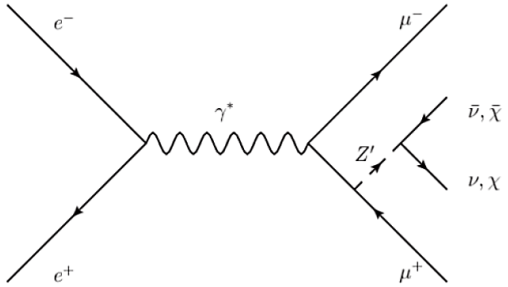






Spare

Z’ to invisible



Analysis cuts:

- Require p_{rec} to point into calorimeter barrel region (only for $M_{rec} < 3$ GeV/c^2)
- Calorimeter-based particle identification (E/p)
- Reject events with additional energy E >0.4 GeV or any π^0 candidates
- Reduce $\tau^+\tau^-$ background with kinematic cuts on transverse momenta of Z’(missing momentum) wrt max and min momentum muons;