Conference on Neutrino and Nuclear Physics CNNP 2020

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Dark Matter searches at Belle II

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> on the behalf of the Belle II collaboration

SuperKEKB and Belle II

A second generation B-factory

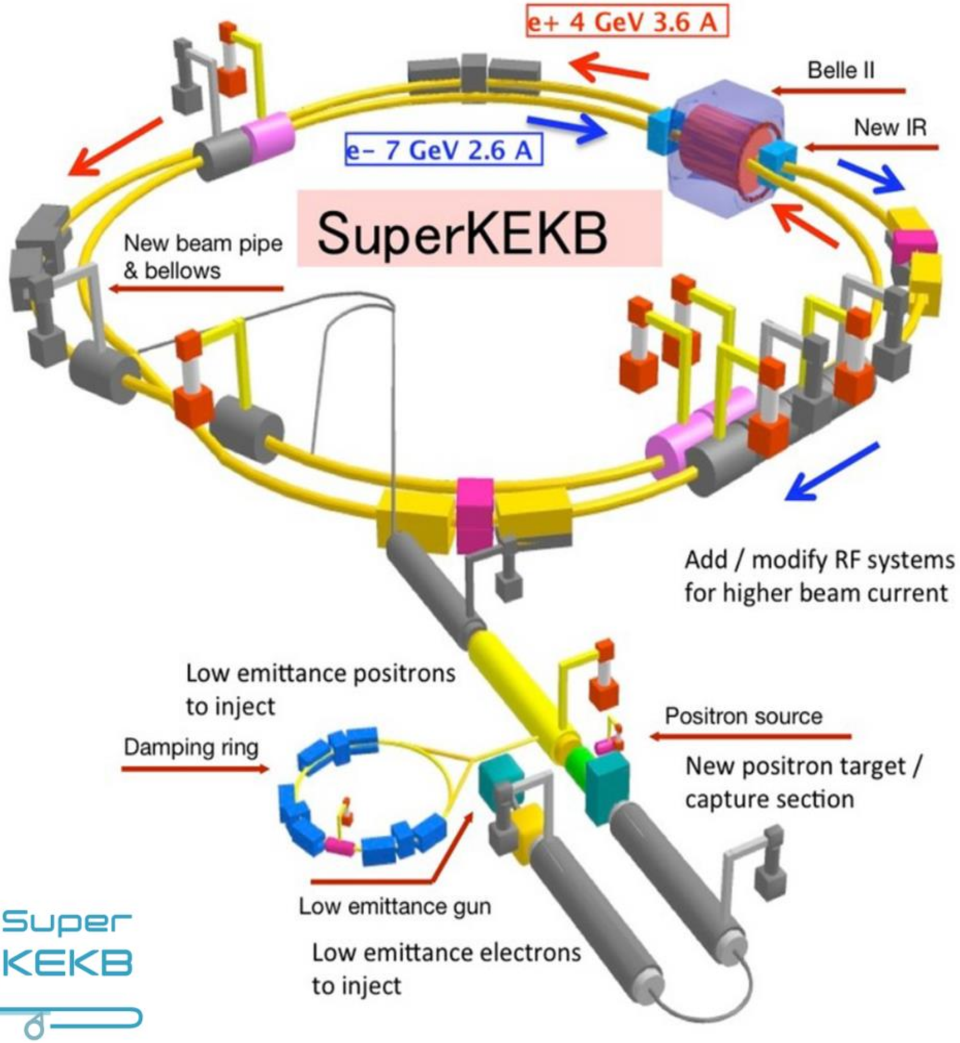
Located at KEK Laboratory in Tsukuba, Japan.

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

A second generation B-factory:

- 40 times increase in instantaneous luminosity with respect to predecessor KEKB
  - **2x** from higher beam current
  - **20x** from final focus magnets

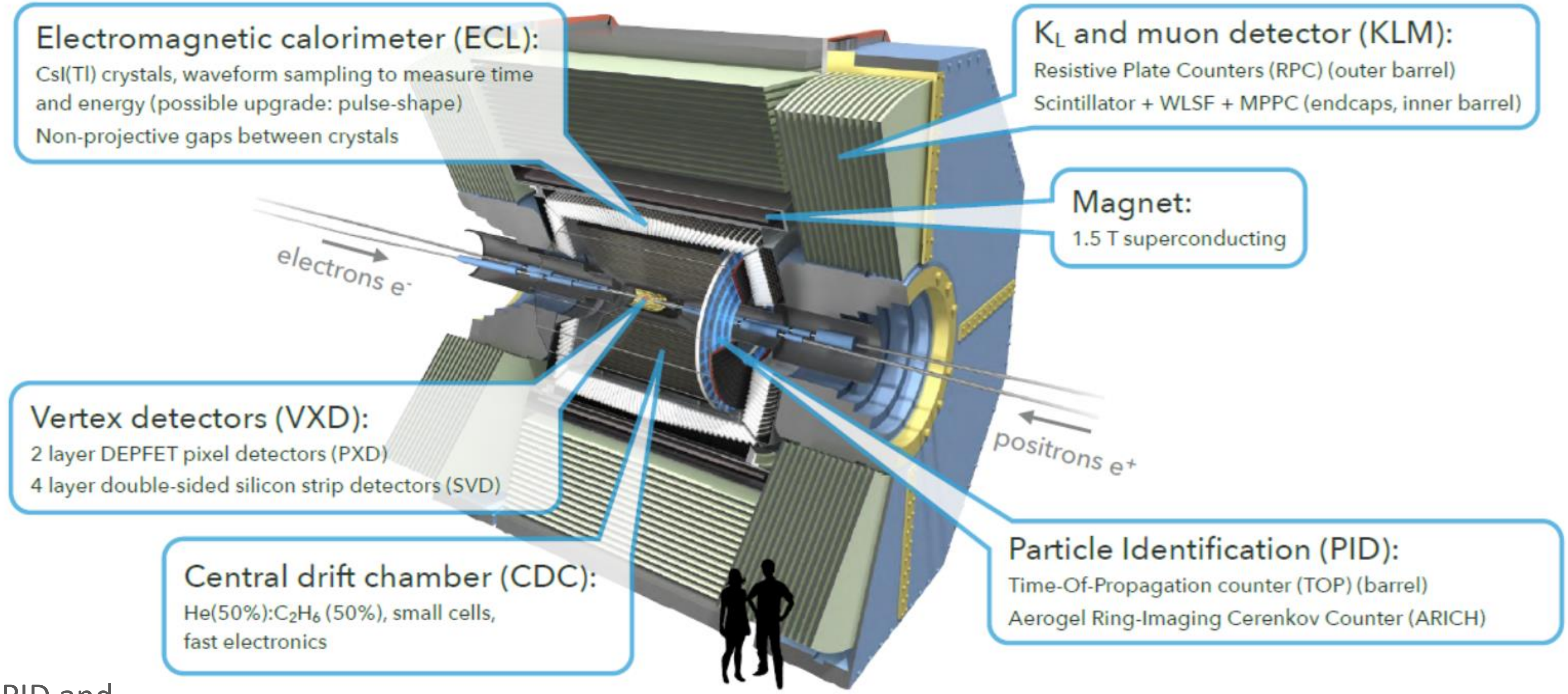
It will be **the world highest luminosity** (L = 8x10^{35} cm^{-2}s^{-1}).



The Belle II Experiment

Inside the detector

TDR: arXiv:1011.0352

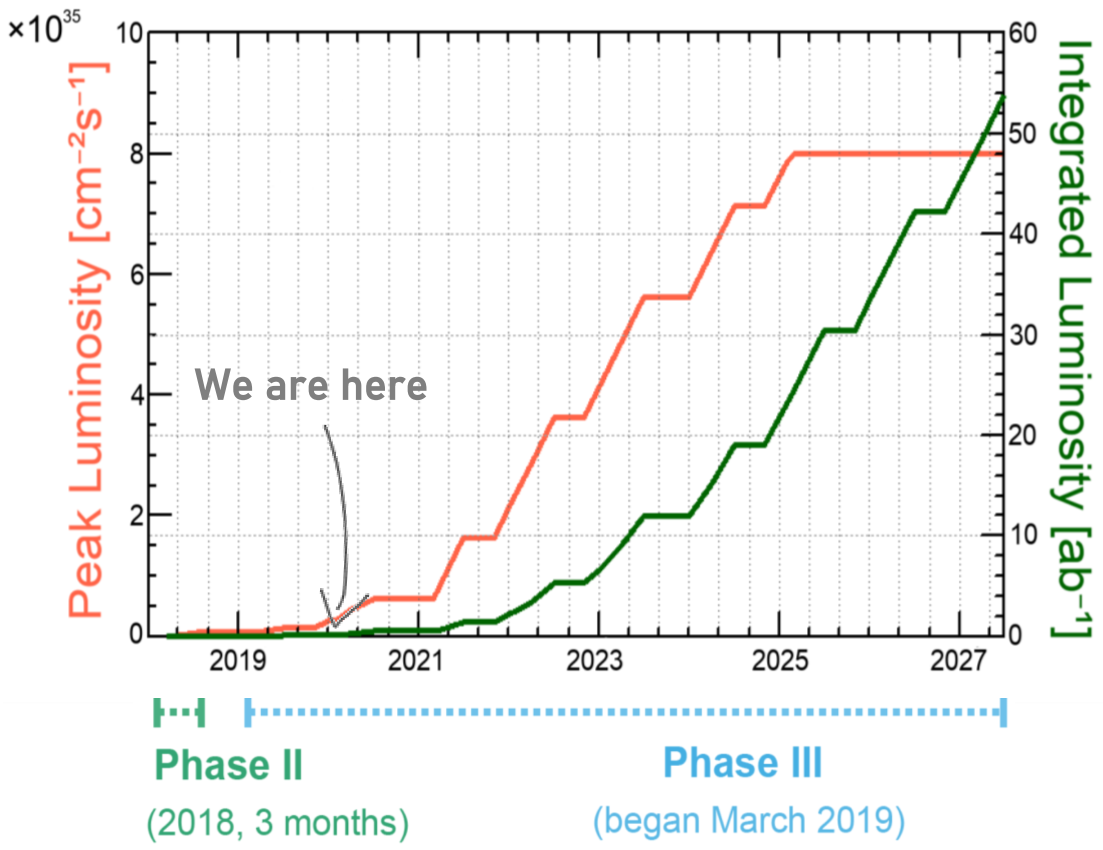


Belle vs Belle II

Better resolution, PID and capability to cope with higher background

The Belle II Experiment

Time schedule



2018

Phase 2

First physics data (500 pb^{-1}).

Incomplete detector (1/8 VXD)

Commissioning data.

2019

Phase 3

Up to now ~10 fb^{-1} collected

Will continue 7-9 month/years

~2027

Goal

Integrate up to 50 ab^{-1}

X50 dataset of its predecessor (Belle)

DM Searches

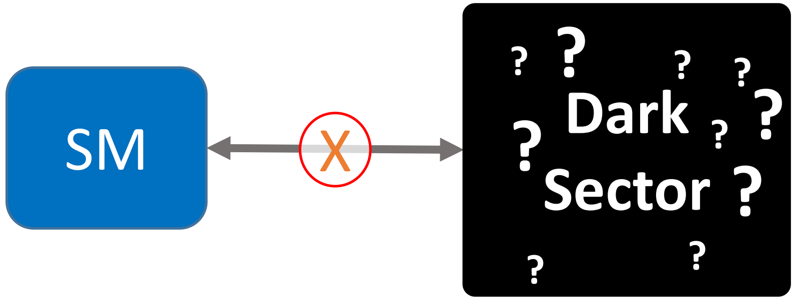
Motivations & Models

The absence of discoveries by the LHC or dark matter direct detection experiments as well as independent theoretical motivations 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.**

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



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

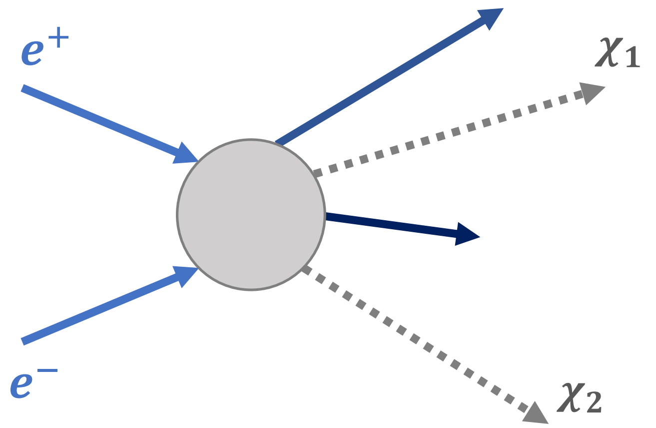
The Belle II Experiment

Not just a B-factory

Although designed mainly for B-physics, Belle II has excellent features to explore the Dark Sector Physics:

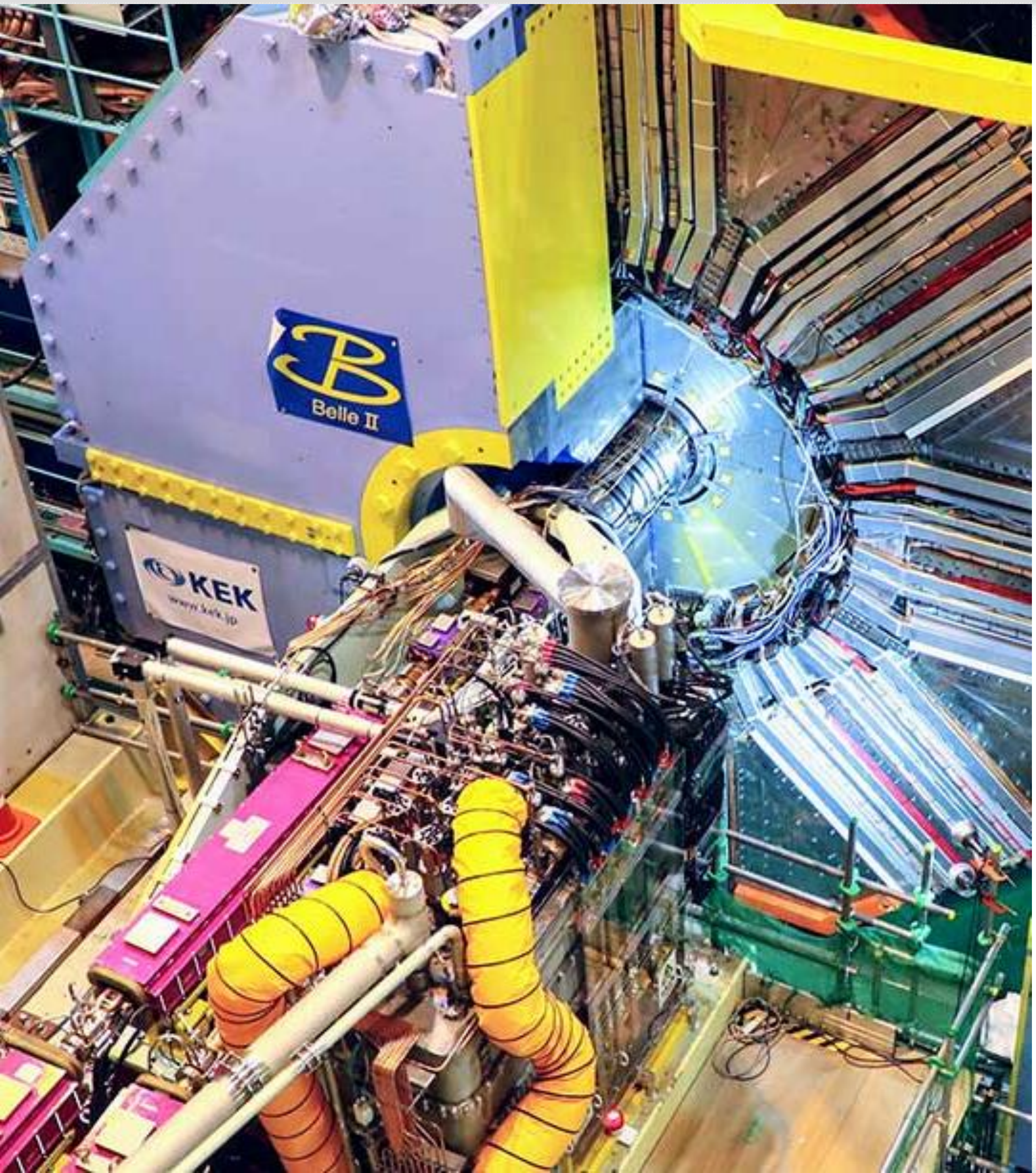
- Clean environment with well defined initial state and low background level;
- Hermetic detector (>90% solid angle);
- Excellent PID capability;
- Dedicated triggers for low-multiplicity events (e.g. single photon trigger)

Probing DM at a collider



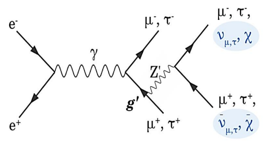
Belle II is very efficient in the reconstruction of recoiling system and missing energy final states

Perfect place to explore Dark Sector Physics in the ~ MeV - 10 GeV range

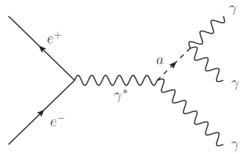


Outline

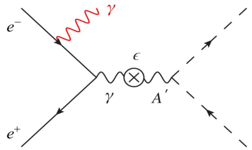
Focus on analyses competitive with available Phase 2 (0.5 fb^{-1}) or early Phase 3 [O(*10-100 fb*$^{-1}$)] data sets:



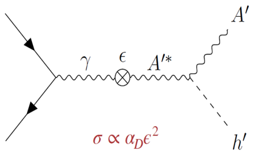
- **Invisible Z′ ($L_\mu - L_\tau$)**



- **Axion-like particles**



- **Invisible dark photon**



- **Dark Higgsstrahlung**

Z’ to invisible

Z’ to invisible

A bit of Theory

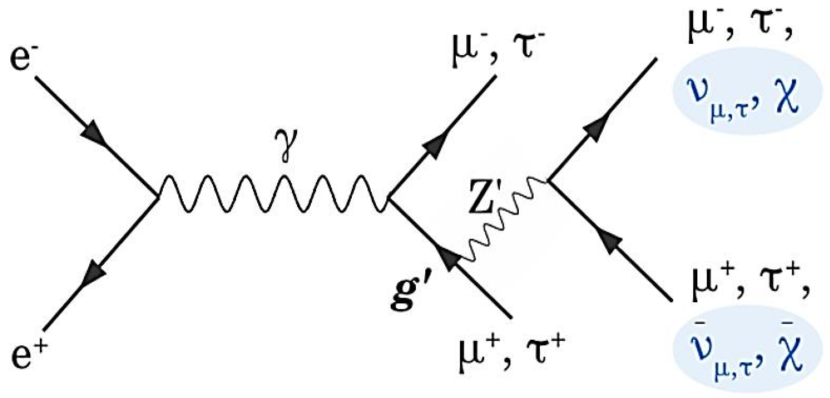
Shuve et al. (2014), arXiv:1403.2727
Altmannshofer et al. (2016) arXiv 1609.04026

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)

$$e^+e^- \to \mu^+\mu^-Z'$$
$\hookrightarrow$ **invisible**

Z’ to invisible

Experimental signature

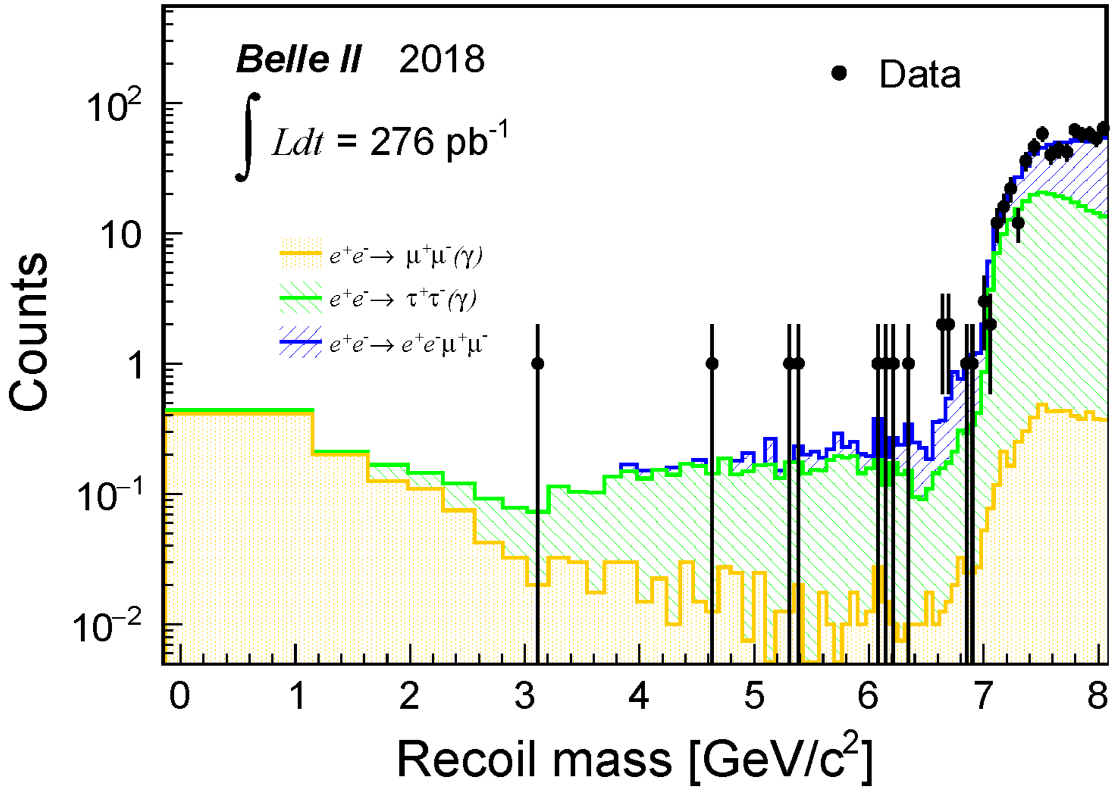
Looking for:

- 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:

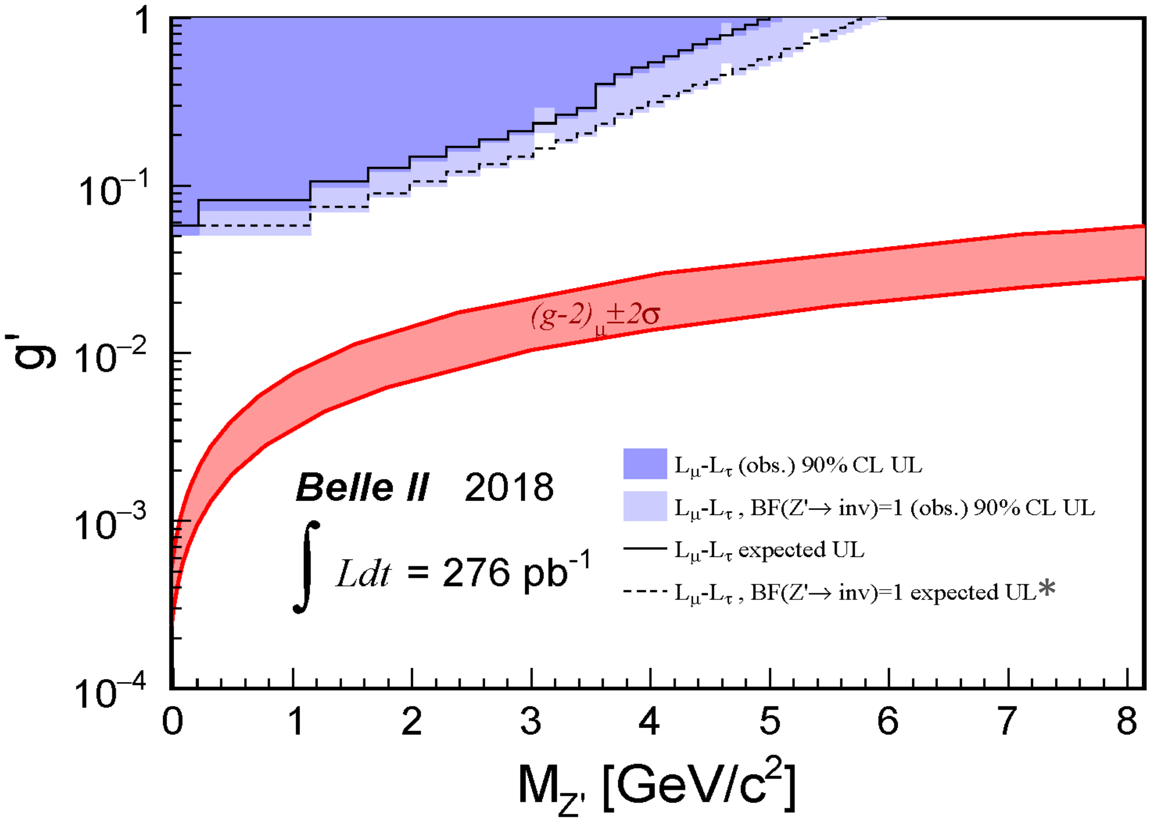
$$e^+e^- \rightarrow \mu^+\mu^-(\gamma);$$
$$e^+e^- \rightarrow \tau^+\tau^-(\gamma), (\tau \rightarrow \mu\nu\nu);$$
$$e^+e^- \rightarrow \mu^+\mu^-e^+e^-;$$



Measurement performed with data collected during Phase 2.
Only 276 pb^{-1} usable due to trigger conditions for 2 track events.

Z’ to invisible

g’ Upper Limit



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

90% CL upper limit on the cross section and then translated in terms of the *g’* coupling constant.

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

Submitted to PRL arXiv:1912.11276

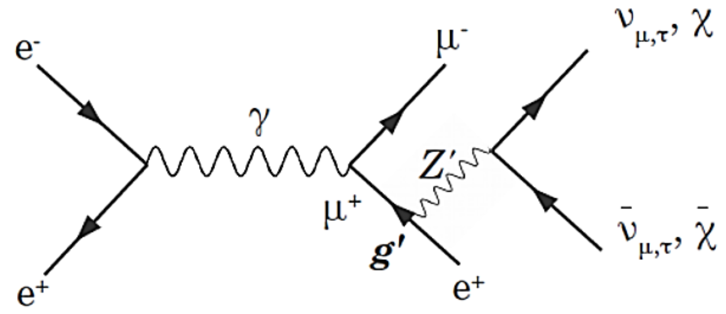
List of systematic uncertainties

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

Z' to invisible

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

Results for a LFV Z'

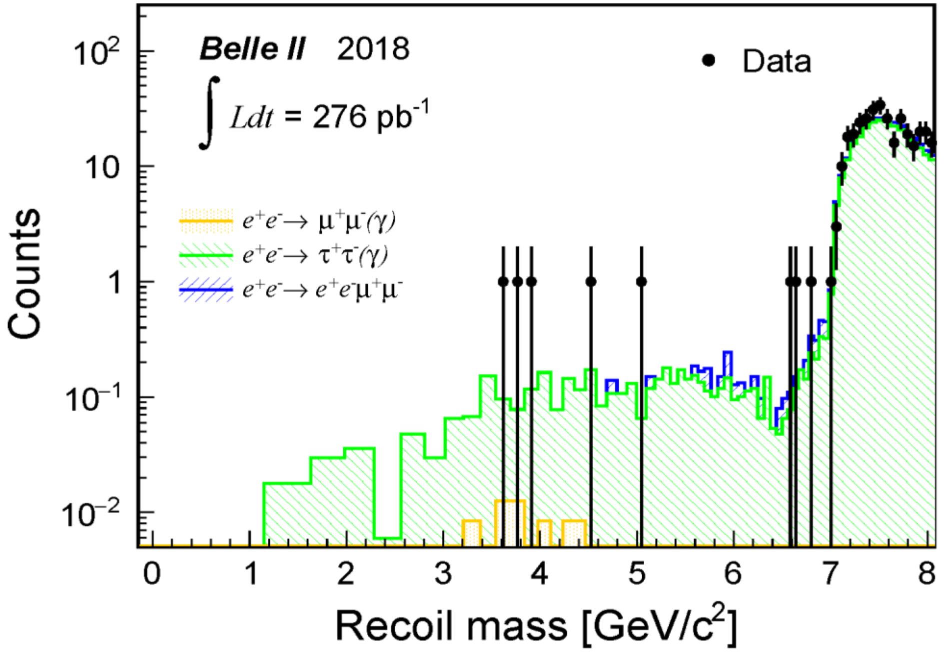


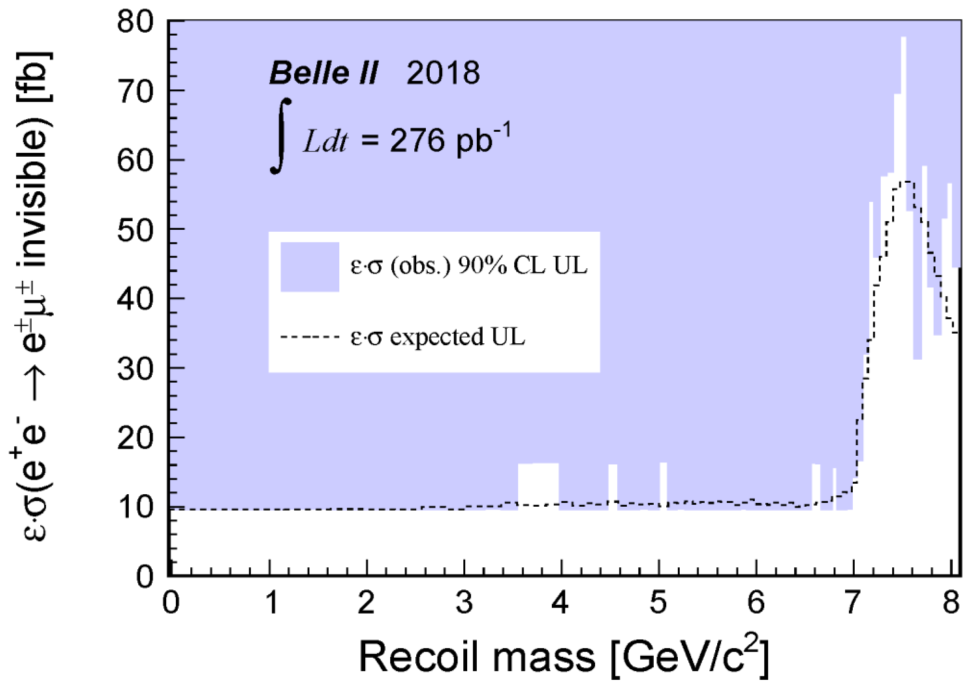
$$\mathbf{e^+e^- \to e^+\mu^- Z'; Z' \to invisible}$$

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

Model independent search with same analysis selection criteria of the Z' to invisible search.

Submitted to PRL (same publication of the 'Standard' Z')





Axion Like Particles

Axion Like Particles

[JHEP 1712 (2017) 094 arXiv:1709.00009]

A bit of theory

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

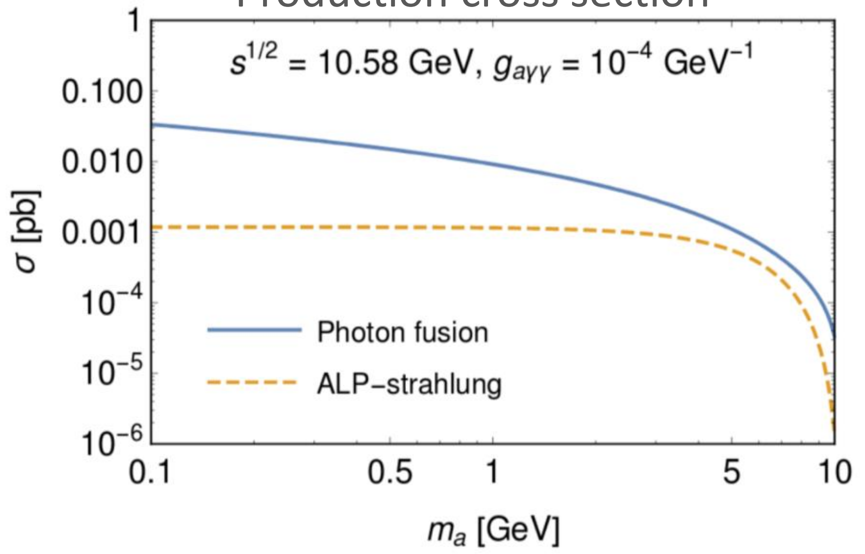
$$\mathcal{L} \supset -\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

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

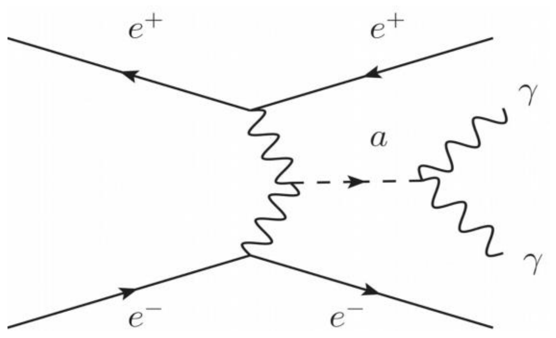
Focus on coupling to photons. Two possible production processes:

- *Photon fusion*
- ***ALP-strahlung***

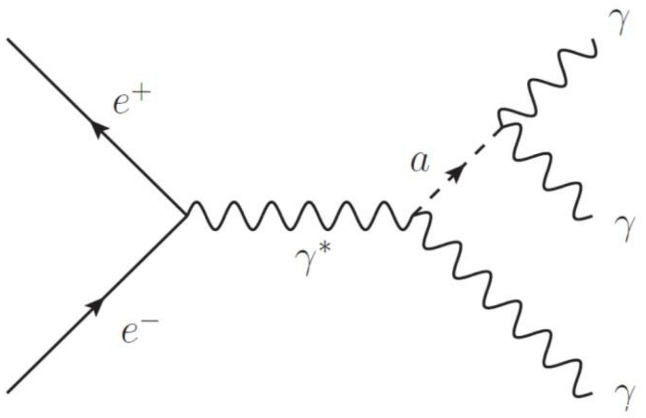
Production cross section



Photon fusion



ALP-strahlung



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

No results at B-factories yet

Axion Like Particles

Experimental signature

First exploring photon coupling $g_{a\gamma\gamma}$ in **ALP-strahlung**

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

ALPs can also decay to DM;

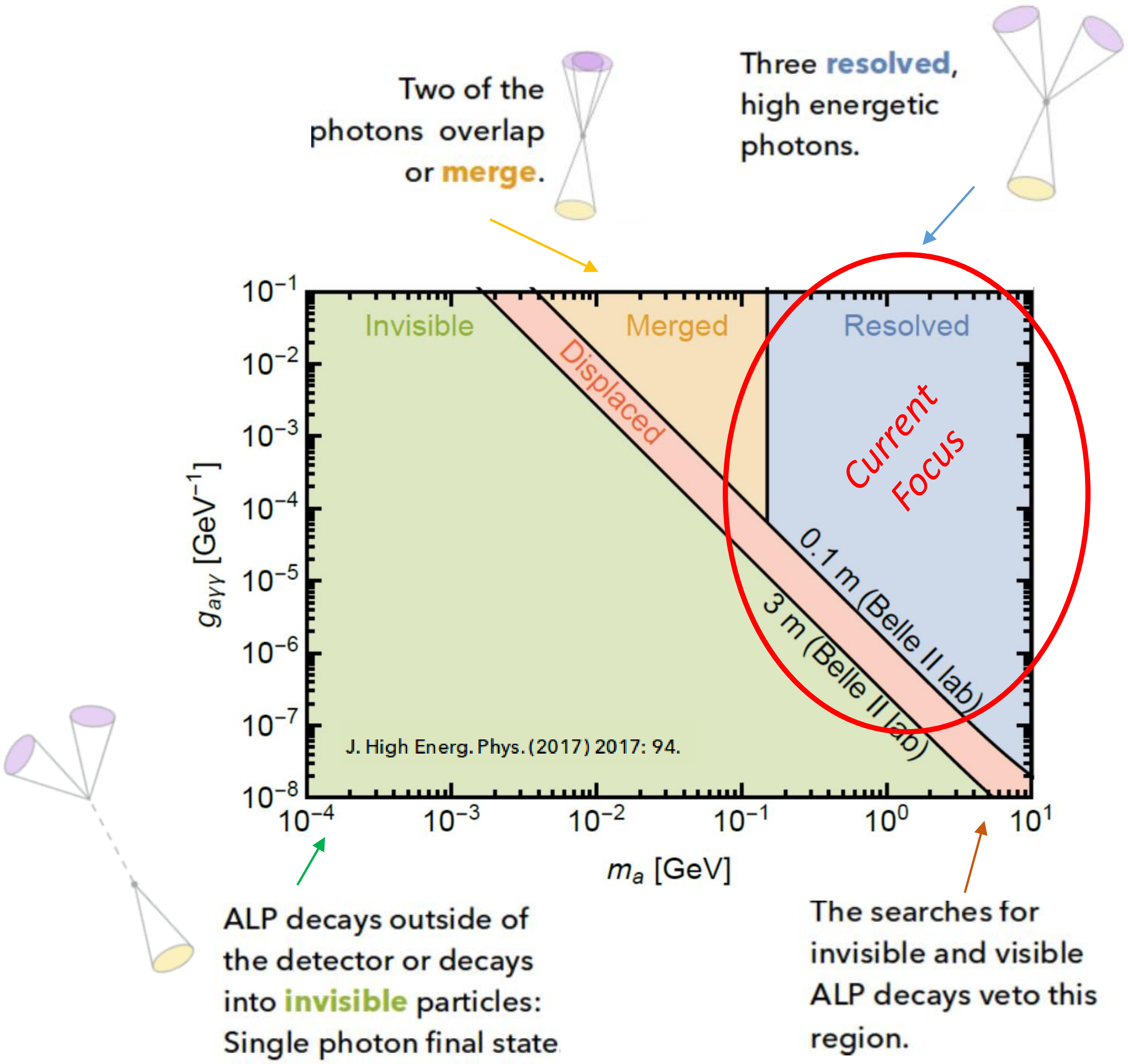
$$\tau \sim 1/g_{a\gamma\gamma}^2 M_a^2$$

Final state:

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

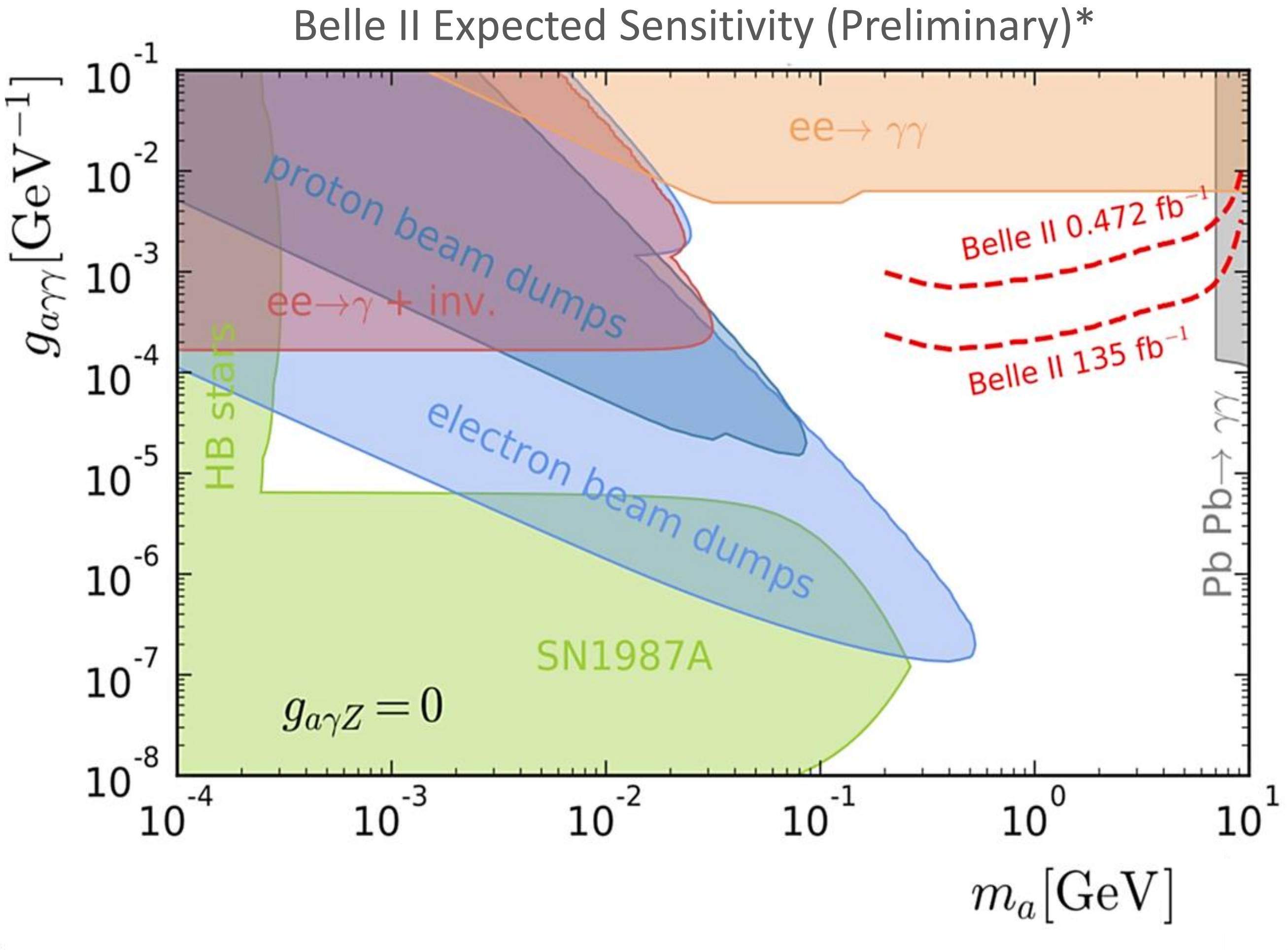
Background:

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



Axion Like Particles

Expected sensitivity



Belle II can be competitive with Phase2 dataset ($\sim$500pb^{-1}).

Measurement to be finalized very soon

*No systematics.
Only (dominant) ee→γγγ background included
135fb^{-1} assumes no γγ trigger veto in the barrel

Dark Photon

Dark Photon to invisible

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

A bit of theory

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

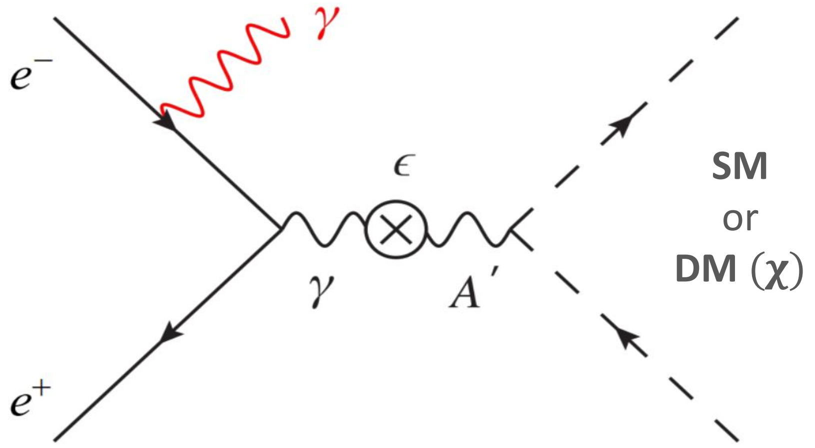
$$\mathcal{L} \supset \epsilon g_D A'_\mu J^\mu_{\mathrm{EM}}$$

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

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

$m_x > \frac{1}{2}\mathrm{m}_{A'} \to$ A' visible decays to SM particles;

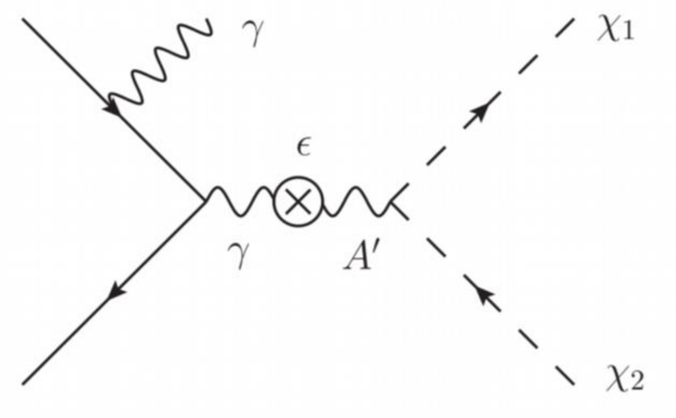
$m_x < \frac{1}{2} m_{A'} \to$ A' invisible decays to LDM;



First exploring the invisible decay: $e^+e^- \to \gamma_{ISR}A' \to \gamma_{ISR}\, \chi\bar{\chi}$

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:

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

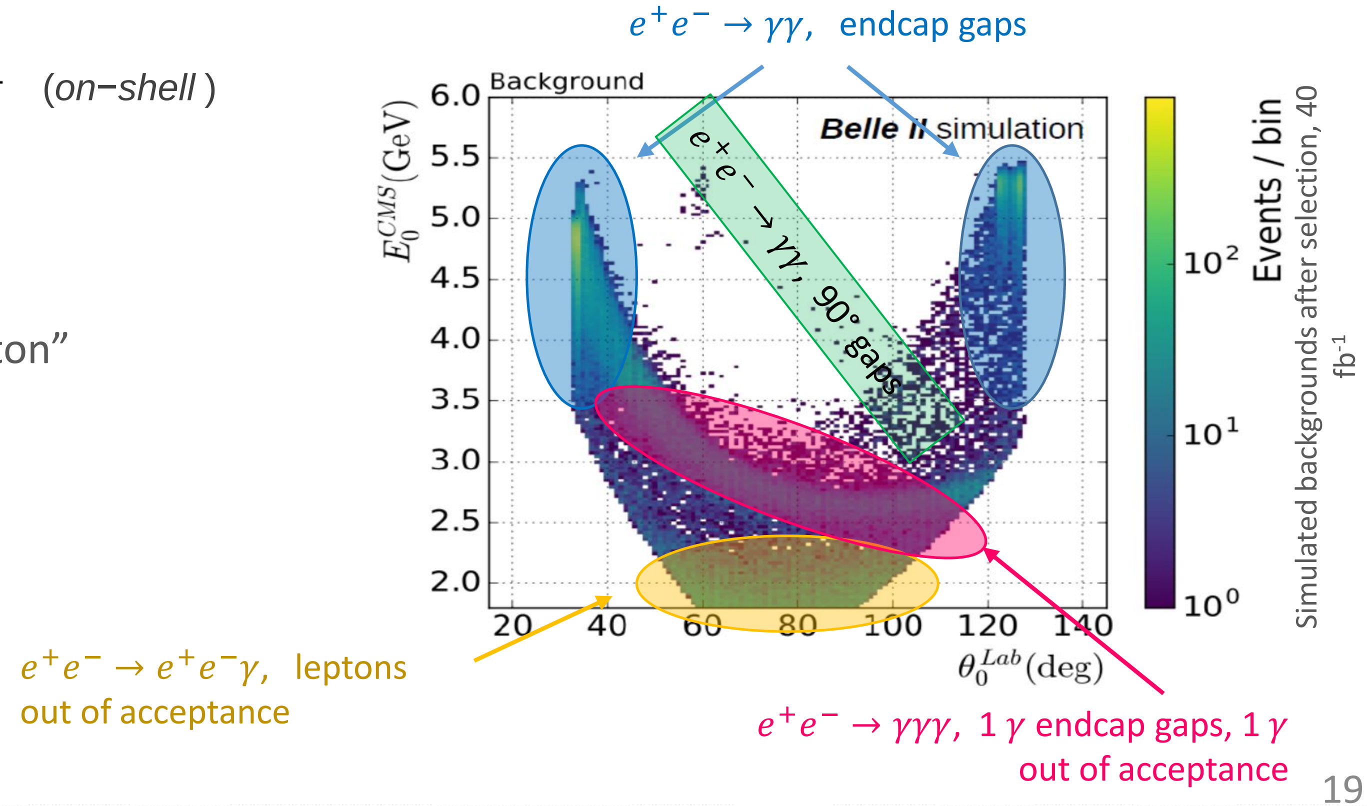
Needs a special **single photon trigger**

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

Discriminant variables: E_{CMS} vs. polar angle of “single photon”

SM backgrounds:

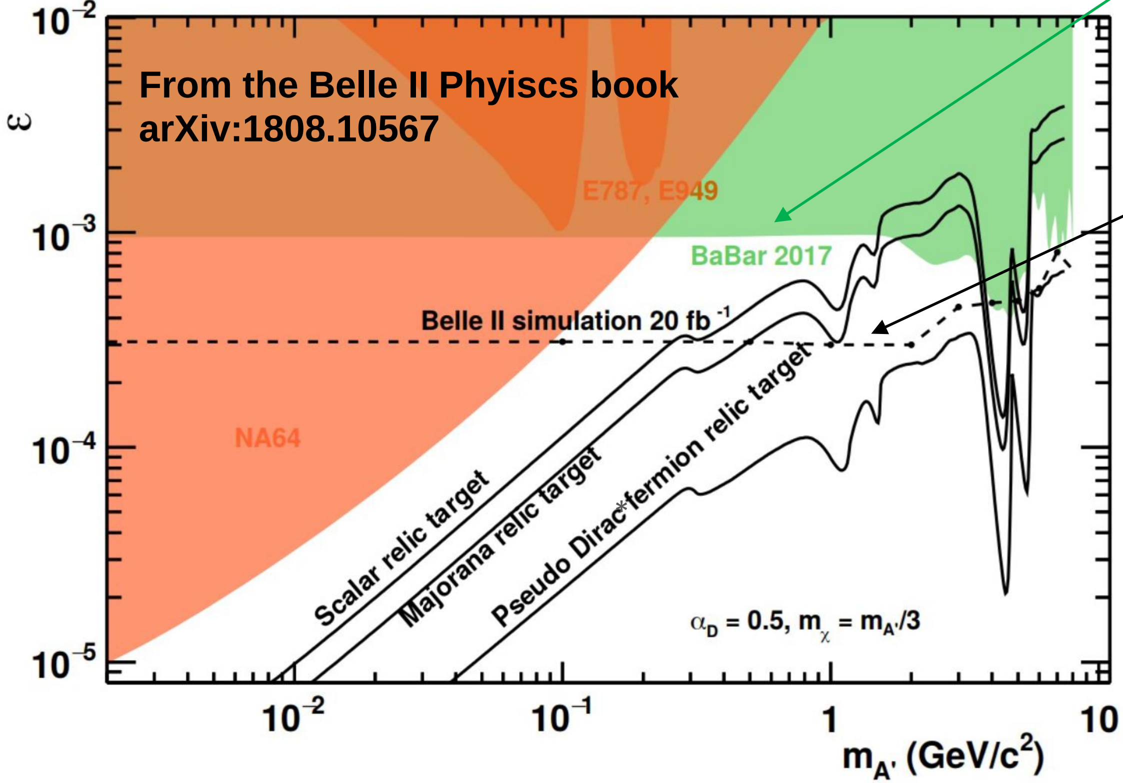
- $ee \to \gamma\gamma(\gamma)$
- $ee \to ee(\gamma)$
- Cosmics



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 early Phase 3 dataset (~ 20 fb^{-1}).

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

General remarks

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

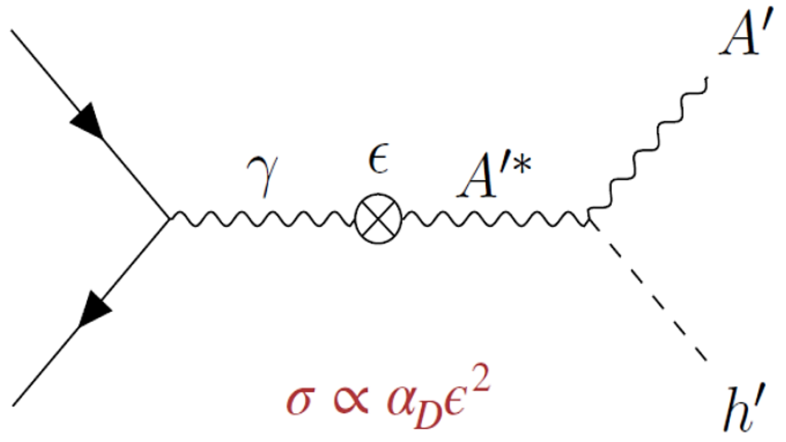
In a minimal scenario: a single dark photon A’ and a single dark Higgs boson h’.

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.

Focus on $m_{h'} < m_{A'}$ case:

- 2 charged particle in the final state plus missing energy.
- First looking at muon final state.



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

$$\hookrightarrow \mu^+\mu^-$$

Signal:

- A peak in the *Recoil mass vs. Di-muon mass* phase space.

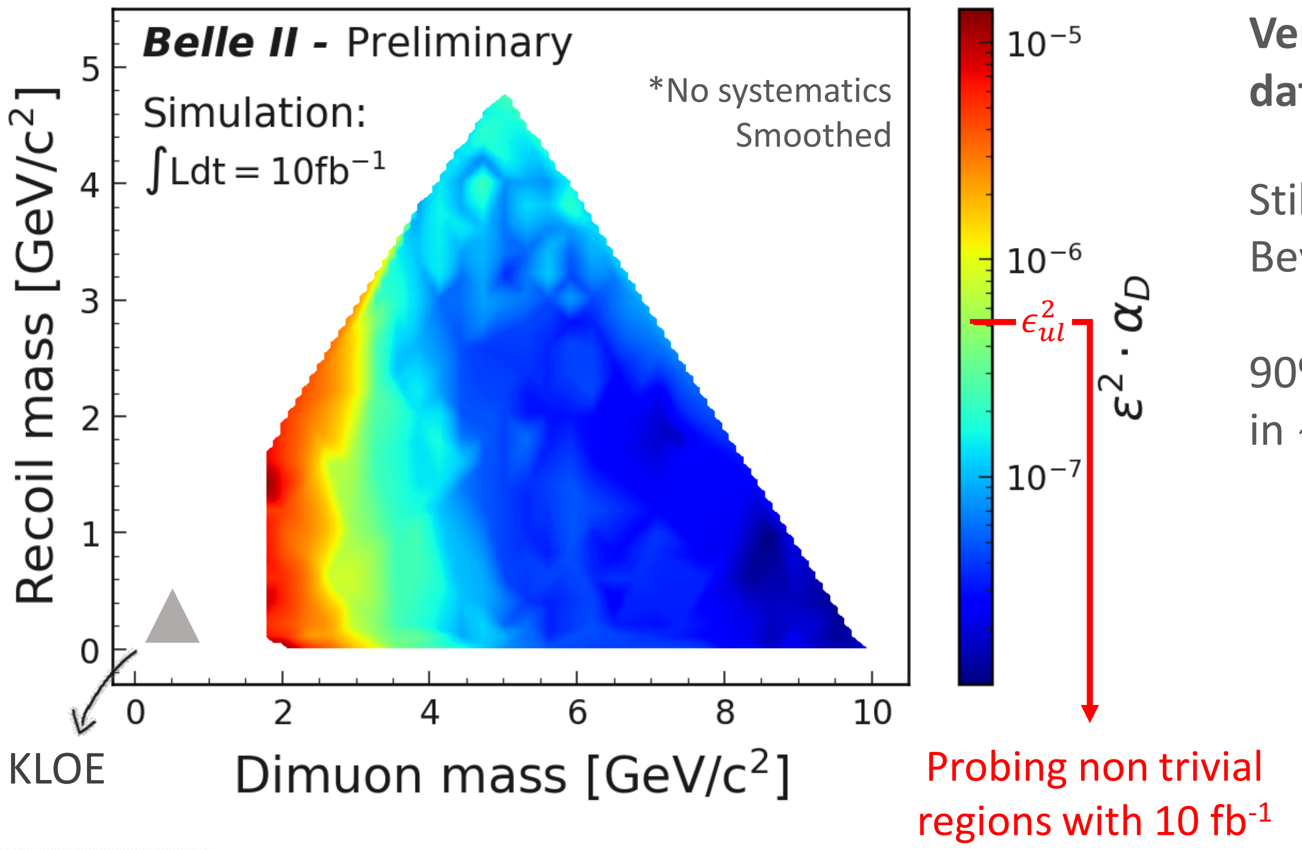
Background:

- Everything with 2 particles identified as muons and missing momentum: $\mu\mu\gamma$, $\tau\tau\gamma$, $ee\mu\mu$, $\pi\pi\gamma$

Dark Higgsstrahlung

Expected sensitivity

Belle II Expected Sensitivity (Preliminary)*



Very promising results even with early Phase 3 dataset (~10 fb^{-1}).

Still unconstrained region in $\epsilon^2 \, \alpha_D$.
Beyond the KLOE coverage.

90% C.L. UL on ϵ^2 in Dark Photon searches lies in $\sim 5 \cdot 10^{-7}$ regime.

Conclusions

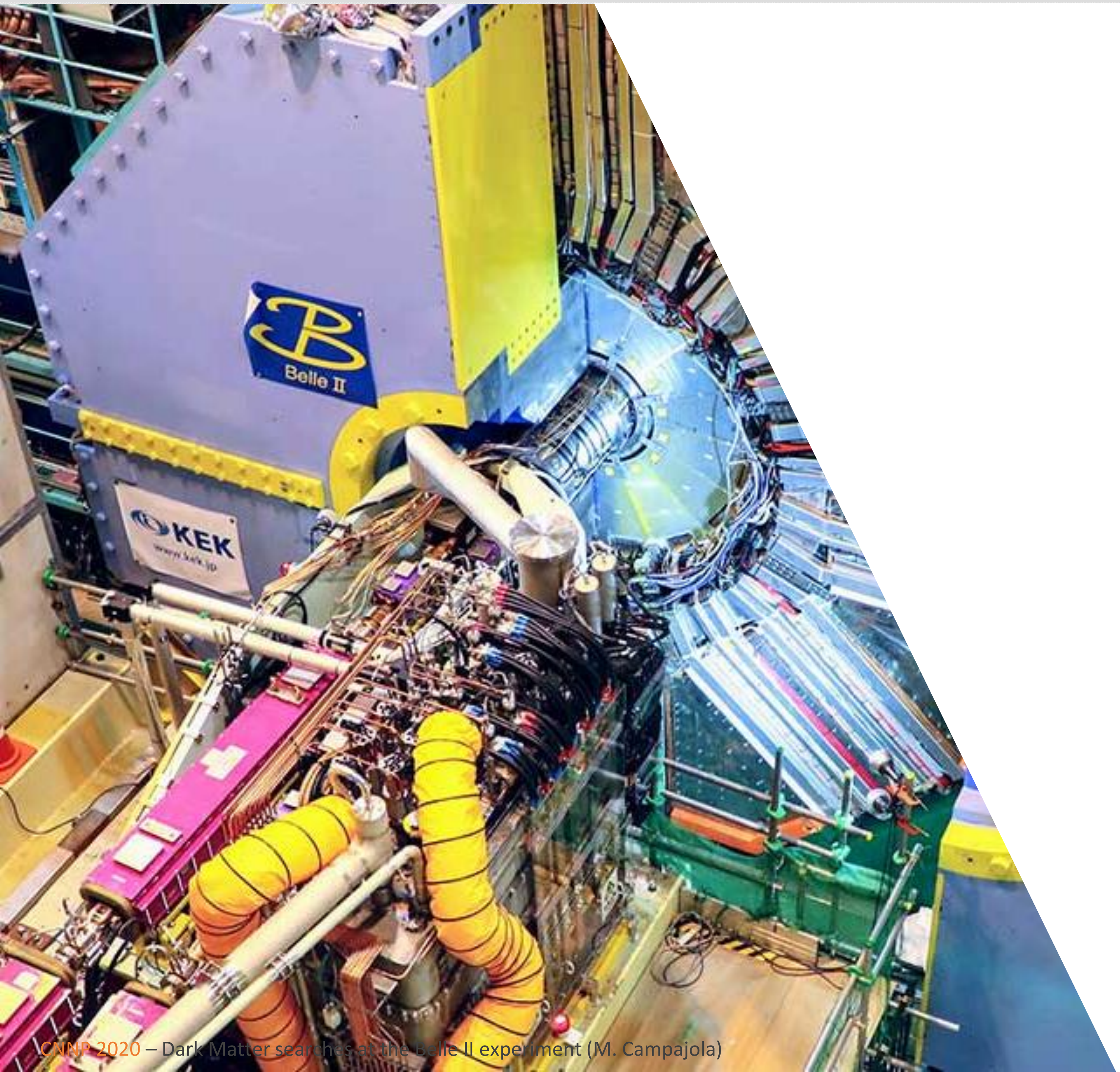
- Although designed mainly for B-physics, the **Belle II experiment** has a broad and active program to explore the ***Dark Sector Physics***;
- It started operations in 2018 (Phase 2). Successful commissioning of the machine and 0.5fb^{-1} of data collected;
- Phase 3 started physics data taking on March 2019. Up to now ~ 10 fb^{-1} collected.

- First result with early data are coming:
  - ***Z' to invisible*** search with the Phase 2 data close to publication.
  - **ALPs search** with Phase 2 data to be finalized very soon;
  - **invisible A':**
  - **Dark Higgsstrahlung:**

  → good prospects even with early Phase 3 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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Belle II

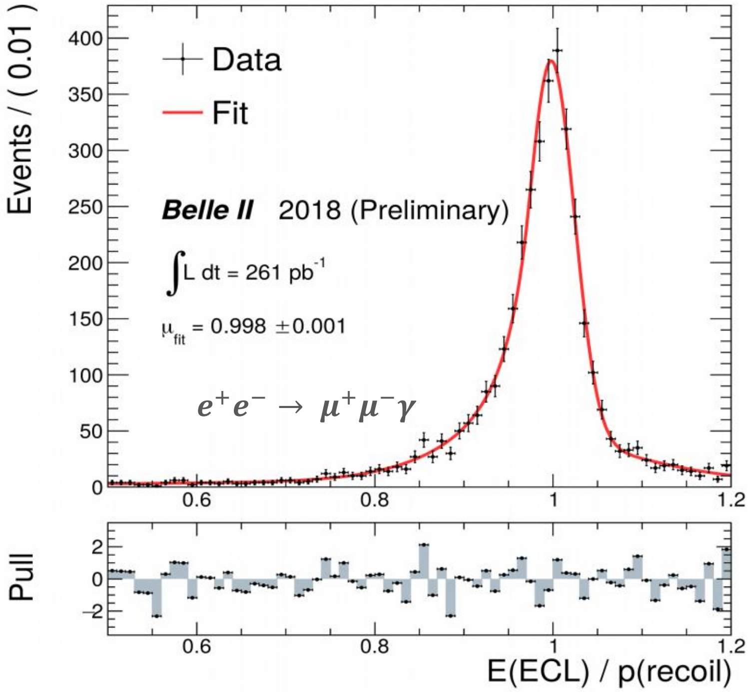
Spare

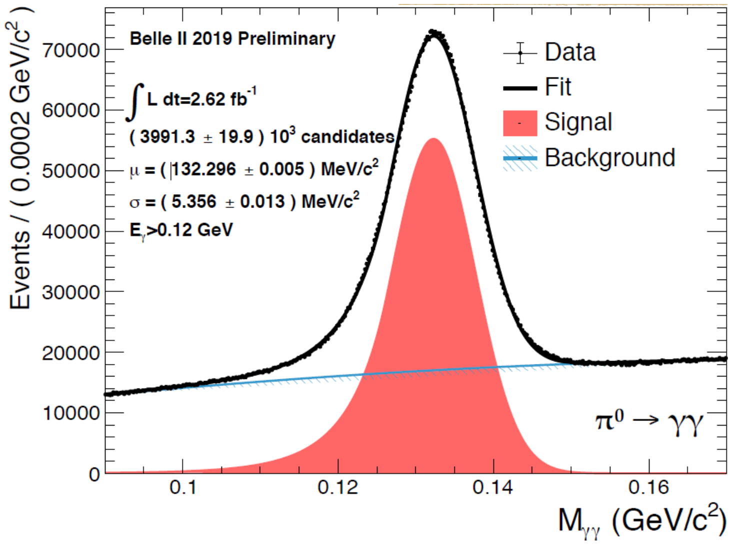
Others Dark Sector searches

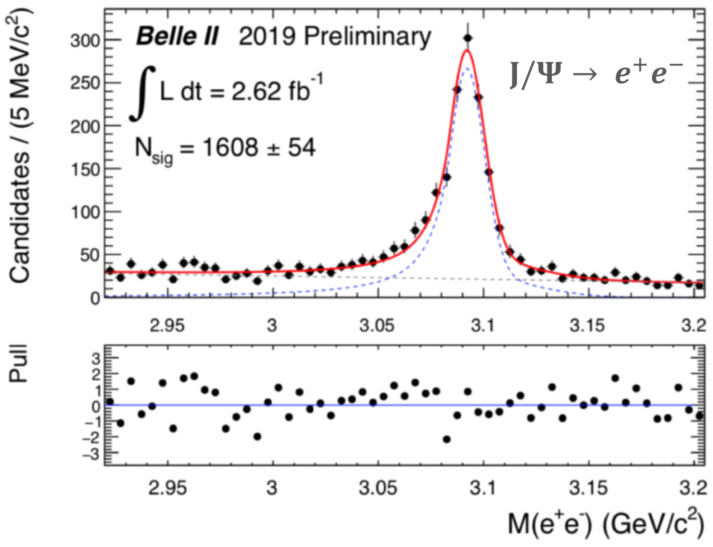
- Visible dark photon decays
- Off-shell dark photon decays
- Muonic dark force: $e^+e^- \rightarrow \mu^+\mu^- Z',\ Z' \rightarrow \mu^+\mu^-$
- Magnetic monopoles with small magnetic charges
- Long-lived particles (LLPs)

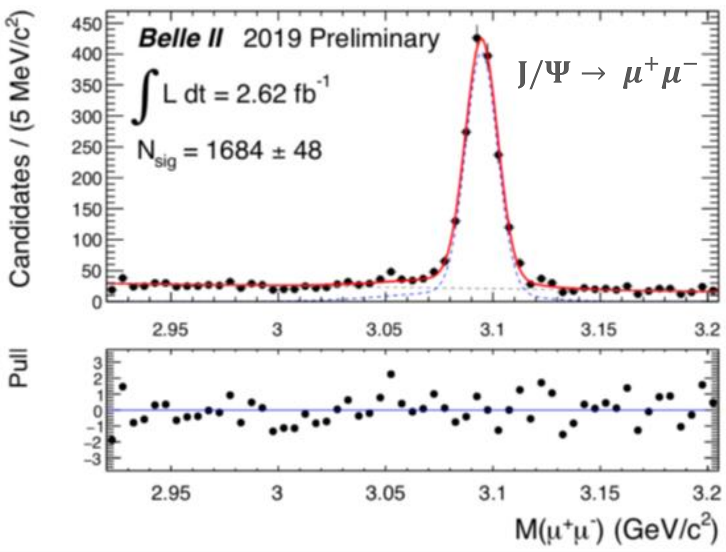
Spare

Belle II performances snapshots



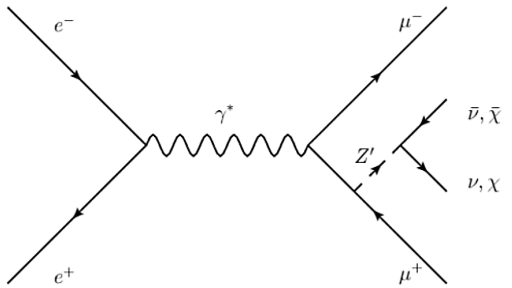


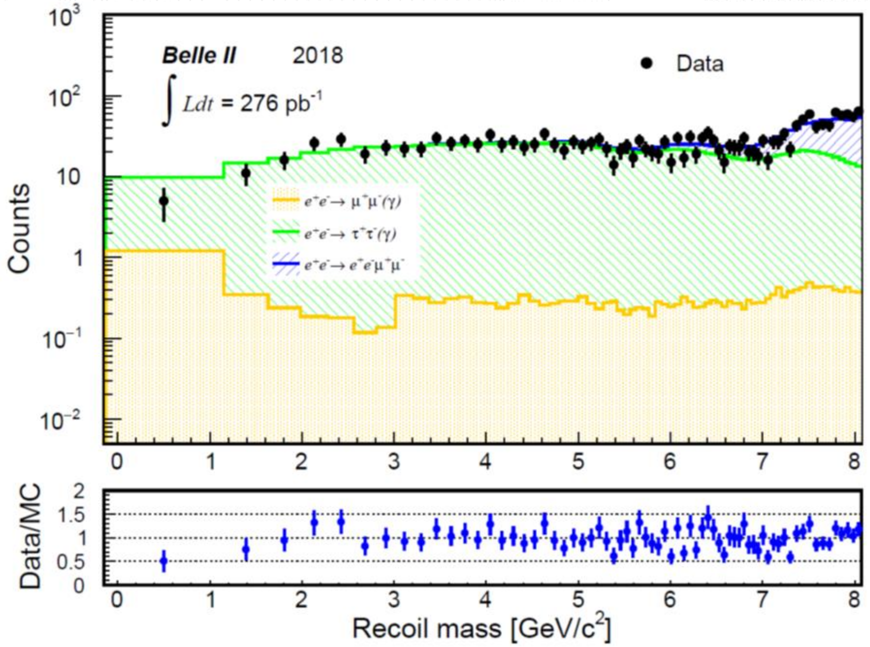




Spare

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;