Improved constraints for axion-like particles from 3-photon events at e^+e^- colliders

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October 30, 2023

QCD axion

- The **absence of CP violating effects in QCD**, leading to the unnaturally small value of the vacuum angle $\theta \lesssim 10^{-11}$, is known as the **strong CP problem** Phys. Rev. Lett. 124, 081803 (2020)

- Spontaneous breaking of Peccei-Quinn symmetry gives rise to a **new pseudoscalar particle** with a linear relation between mass m_a and coupling $g_{a\gamma\gamma}$ which **solves this problem** Phys. Rev. Lett. 40, 223 (1978); Phys. Rev. Lett. 40, 279 (1978)

- **Axion-photon coupling** is widely discussed. Experimental bounds in **MeV-GeV range** mostly from e^+e^- **colliders** Phys. Rev. Lett. 125, 161806 (2020); arXiv:2211.12699v3; and others

The results are upper limits on $|d_n|$.

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< 0.55	90	SEREBROV	2015
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< 0.63	90	[6] HARRIS	1999
< 0.97	90	ALTAREV	1996
< 1.1	95	ALTAREV	1992
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0.3 ± 4.8		PENDLEBURY	1984
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PDG data on neutron electric dipole moment, one of the most precisely measured θ-induced effects ($\vec{d} \sim \theta \cdot 10^{-16}$ e cm)

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„Cosmological pie" (by Martin Schmaltz)

Our aim is to:

- **Improve** upon previous analyses by also including the **ALP coupling to electrons**
- Significantly **extend the ALP search range** and impose **more stringent restrictions** on their couplings

Axion-like particle (ALP):

- Is an **axion generalization**, which appears in many **extensions of the SM**
- Has **mass-coupling relation unconstrained** with linear relation
- A promising **dark matter candidate**

Existing bounds from https://cajohare.github.io/AxionLimits

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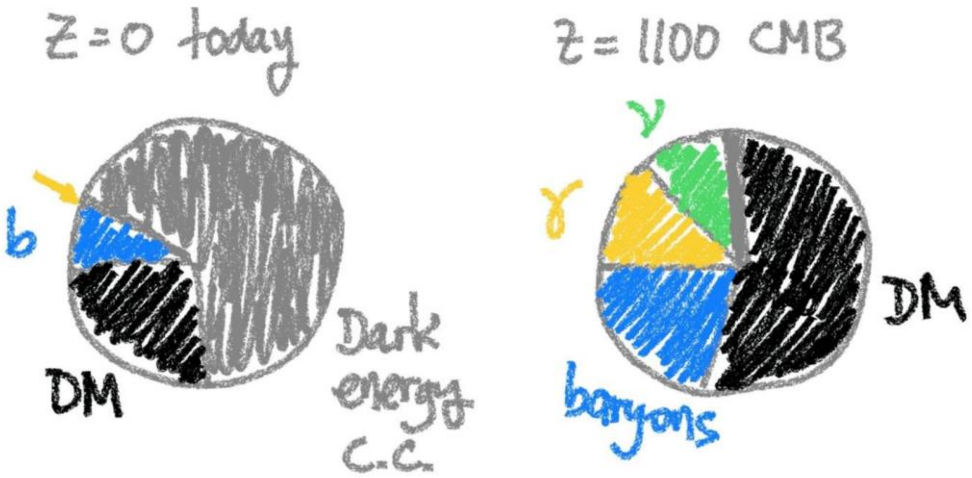

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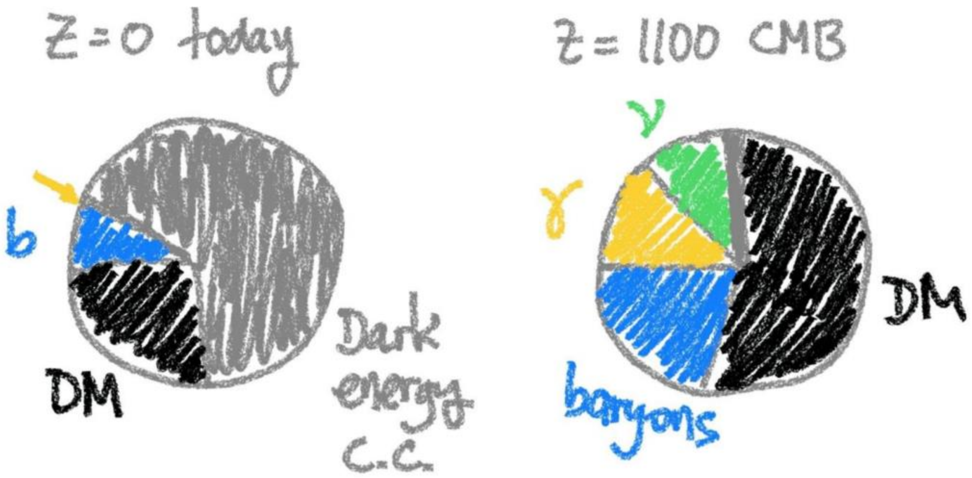

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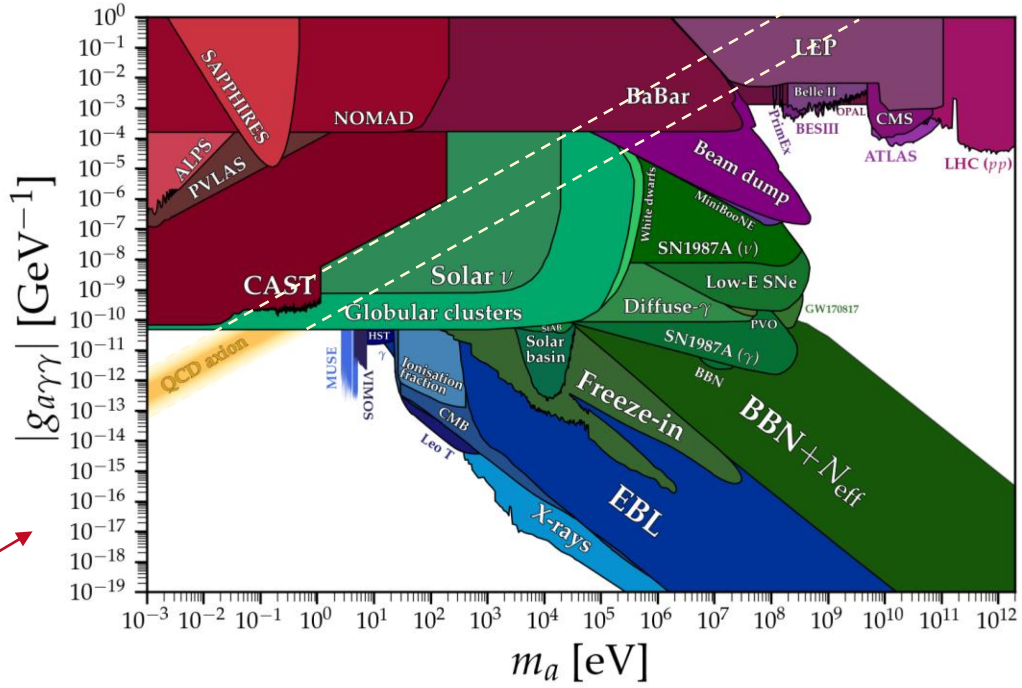

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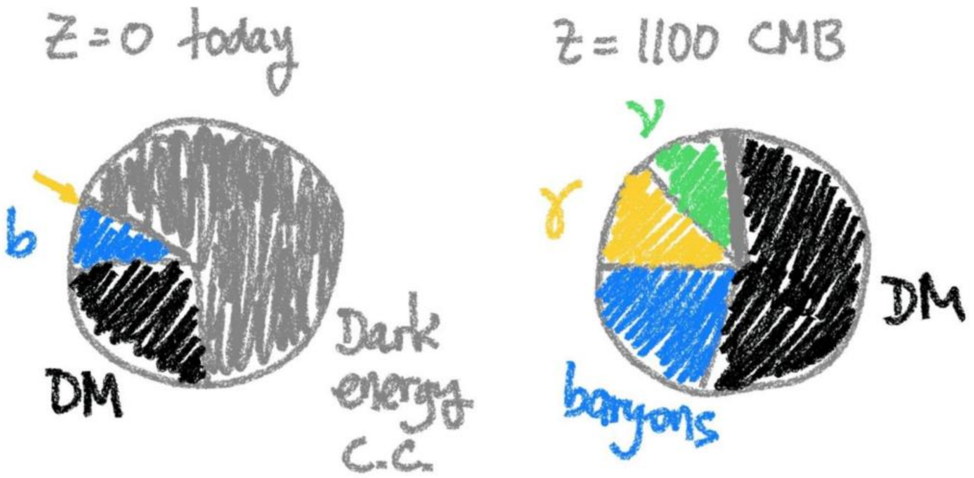

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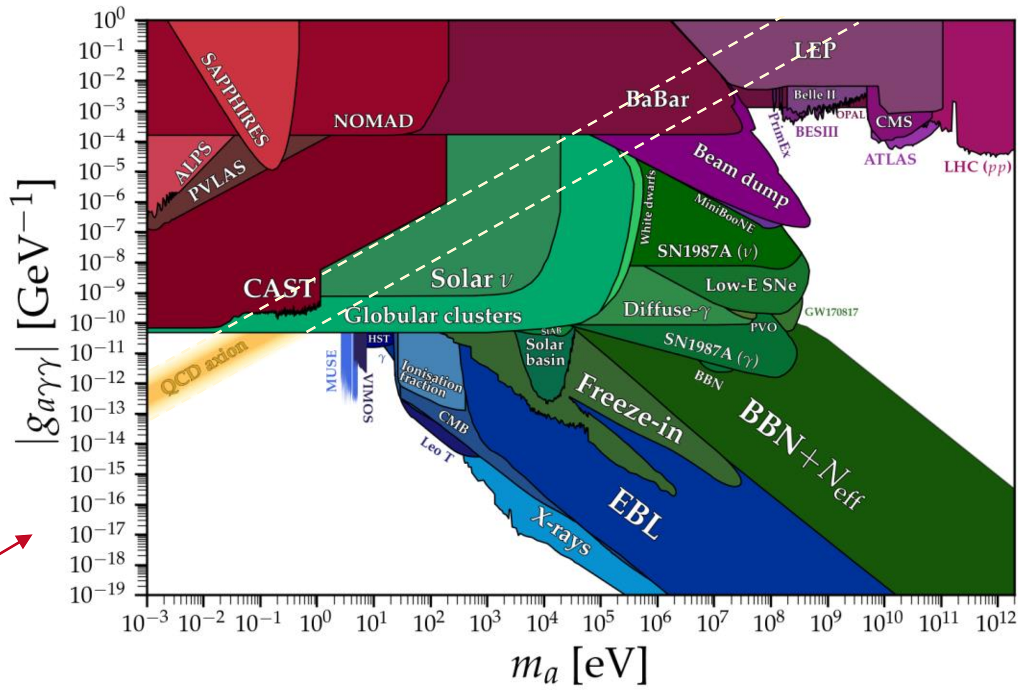

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In this work we assume that ALPs in the MeV to GeV mass range **couple predominantly to photons and electrons**, i.e., no enhanced impact to $(g-2)_\mu$

JHEP, 07:092, 2018

$$\Rightarrow \Gamma_{a\gamma\gamma} = \frac{g^2_{a\gamma\gamma} m_a^3}{64\pi}$$

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Dominant channel for lower-mass ALP!

In the absence of interaction with other fields, the total ALP decay width is assumed to consist of these two contributions

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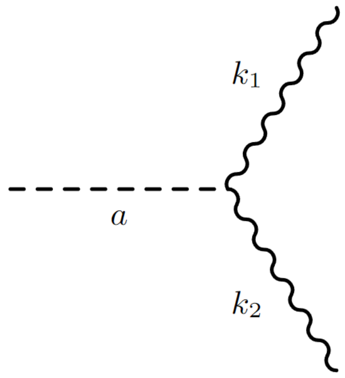

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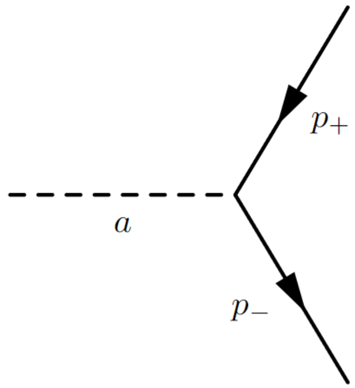

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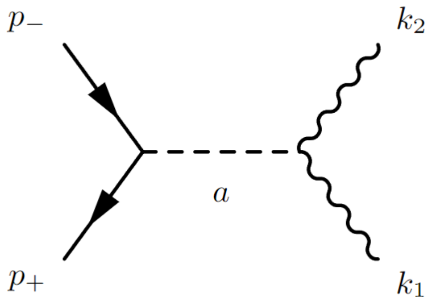
2- and 3-photon events

ALP contributes to 2-photon events through the single Feynman diagram:



However, it is **resonant** and thus has sensitivity only around $m_a^2 \approx s$

For a fixed collider energy, the process does **not provide constraints in a broad parameter space**

Thus, we proceed to 3-photon events

$$= i \frac{H_{e^+e^- \to \gamma^* \to a\gamma}(k_1)}{K_{23}^2 - m_a^2 + i m_a \Gamma_a} \times M_{a \to \gamma\gamma}(k_2, k_3) + \text{crossed}$$

Where the amplitude of $e^+e^- \to a\gamma_i$ is given by:

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And the amplitude of ALP decay to a photon pair:

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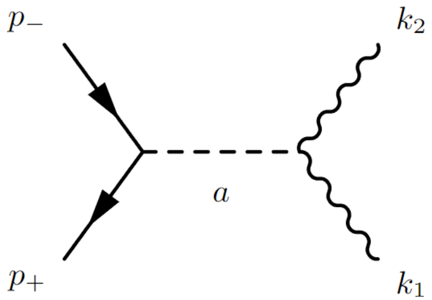

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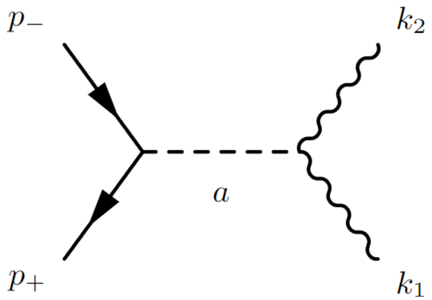

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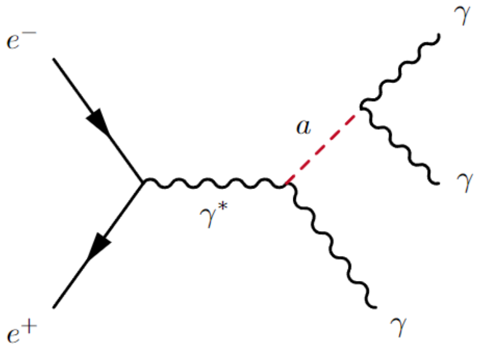

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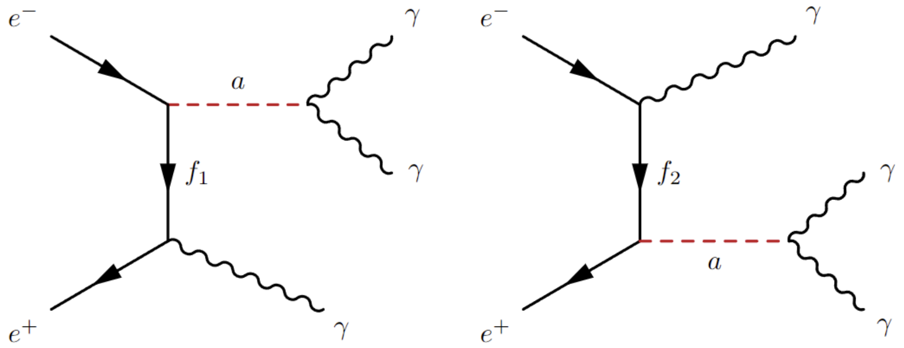
The next contribution arises **from ALP-electron coupling**:



$$= i\frac{H_{e^+e^-\to a\gamma,1}(k_1) + H_{e^+e^-\to a\gamma,2}(k_1)}{K_{23}^2 - m_a^2 + im_a\Gamma_a} \times M_{a\to\gamma\gamma}(k_2, k_3) + \text{crossed},$$

where $H_{e^+e^-\to a\gamma,j}(k_i)$ denote amplitudes for the corresponding $2 \to 2$ process

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With the internal electron momenta:

$$l_i = k_i - p_+, \quad f_i = p_- - k_i$$

Note: no interference between this set of diagrams and diagrams from the previous slide

Background analysis

General assumption: ALPs are very long-lived particles ⇒ decay width $\boldsymbol{\Gamma_a} \ll$ **exp. resolution** (interference is suppressed):

$$\frac{1}{(p_a^2 - m_a^2)^2 + (m_a \Gamma_a)^2} \to \frac{\pi}{m_a \Gamma_a} \delta\left(p_a^2 - m_a^2\right)$$

Due to the resonant behavior of the amplitude, one photon is always emitted with a fixed energy:

$$\omega = \frac{4E^2 - m_a^2}{4E}$$

Signal detection strategy: a narrow peak in the photon energies distribution, or a narrow peak in the squared mass distribution $m_{\gamma\gamma}$

Total $e^+e^- \to \gamma\gamma\gamma$ **cross section** has three terms:

$$\sigma_{ALP+B} = \sigma_{ALP} + \sigma_B + \sigma_{int}$$

- The dominant background: **QED 3-photon** annihilation

Aimed sensitivity is then:

$$\frac{\sigma_{ALP}}{\sigma_{QED}} = \frac{N}{\sqrt{L \cdot \sigma_{QED}}}$$

- N – the number of standard deviations that determines whether or not a fluctuation is considered as a signal ($N = 2 \Leftrightarrow 95\%$ c.l.)
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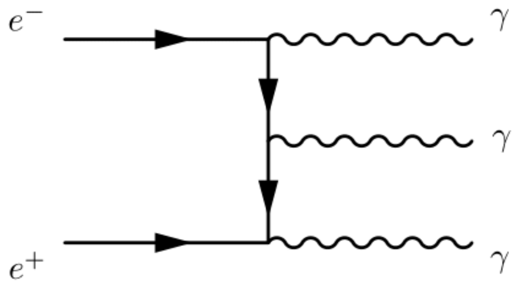

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Distributions

- In the 2018 data run Belle II achieved an integrated luminosity of 445 pb^{-1}, which was used for the ALP searches

Phys. Rev. Lett. 125, 161806 (2020);

- LO QED 3-photon distributions for the softest, middle and hardest photons in this kinematics are shown below:

Angular distribution

Energy distribution

Angular distributions of a photon which **accompanies the ALP**

Angular distributions of a photon **produced from ALP decay**

- In contrast to the ALP-related process, which exhibits a rather uniform angular distribution, the QED three-photon annihilation is characterized by an **enhanced angular distribution** in both the forward and backward directions.
- The presence of a distinct peak in the photon energy distribution would serve as an **indication** of ALP creation

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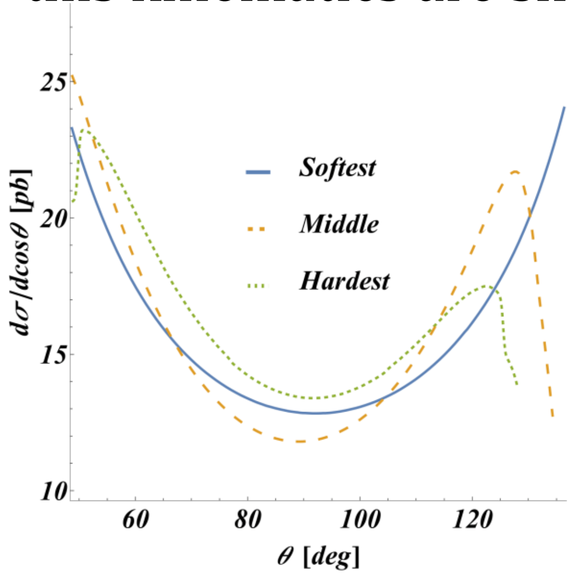

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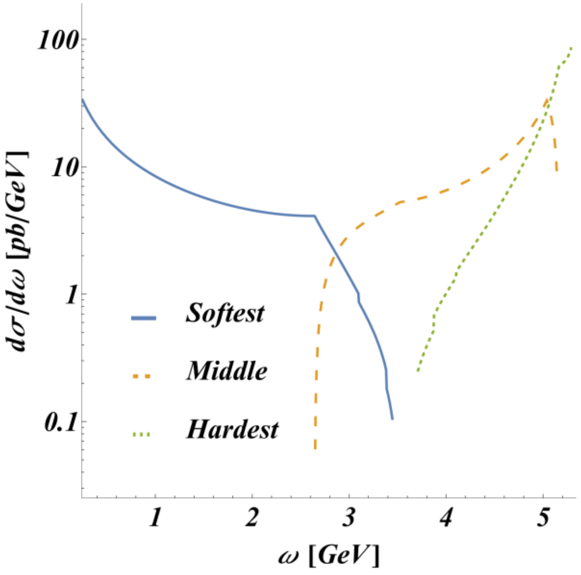
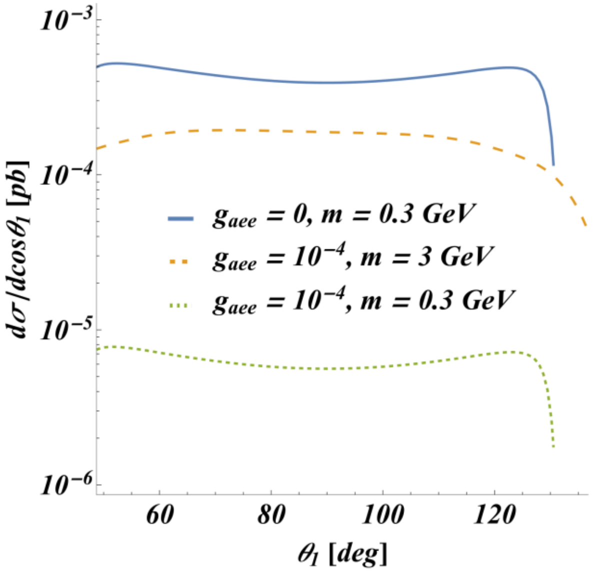
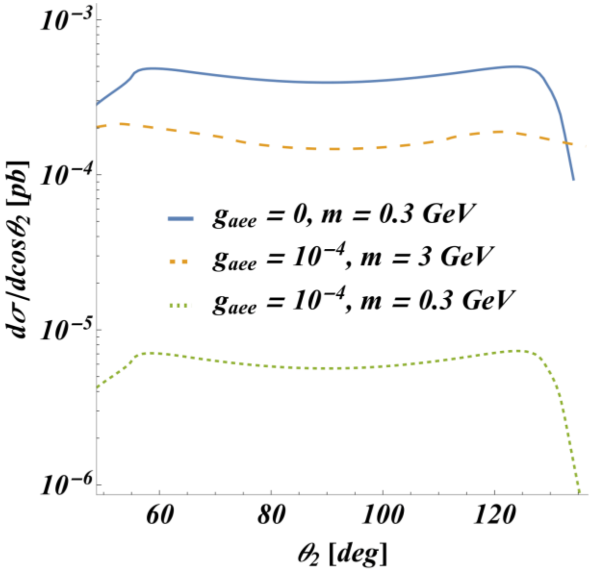


Energy distribution



Angular distributions of a photon which **accompanies the ALP**



Angular distributions of a photon **produced from ALP decay**

- In contrast to the ALP-related process, which exhibits a rather uniform angular distribution, the QED three-photon annihilation is characterized by an **enhanced angular distribution** in both the forward and backward directions.

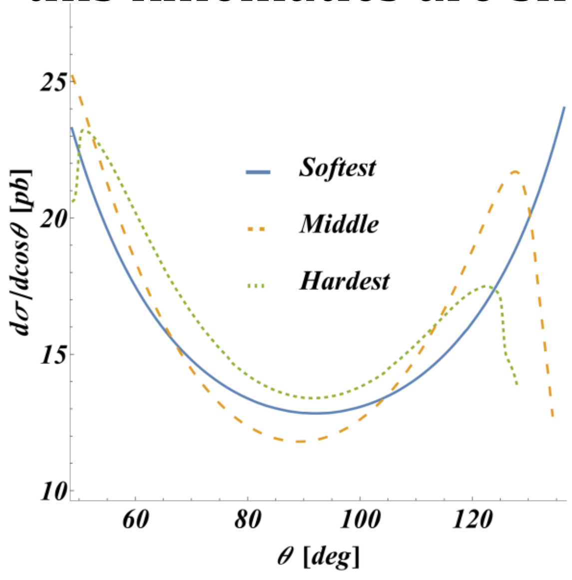
- The presence of a distinct peak in the photon energy distribution would serve as an **indication** of ALP creation

Distributions

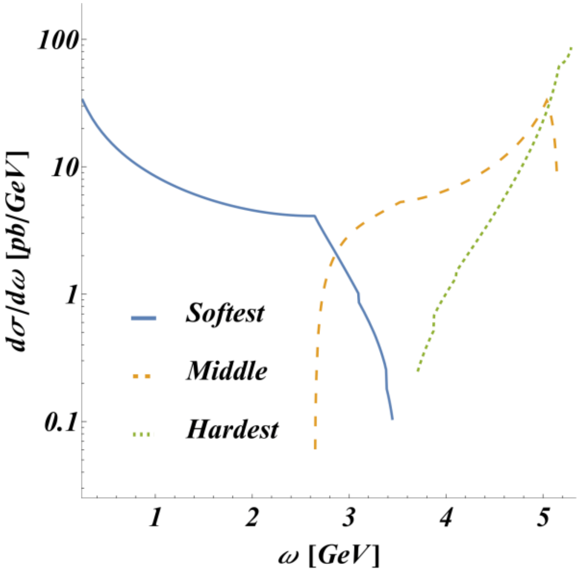
- In the 2018 data run Belle II achieved an integrated luminosity of 445 pb^{-1}, which was used for the ALP searches

  Phys. Rev. Lett. 125, 161806 (2020);

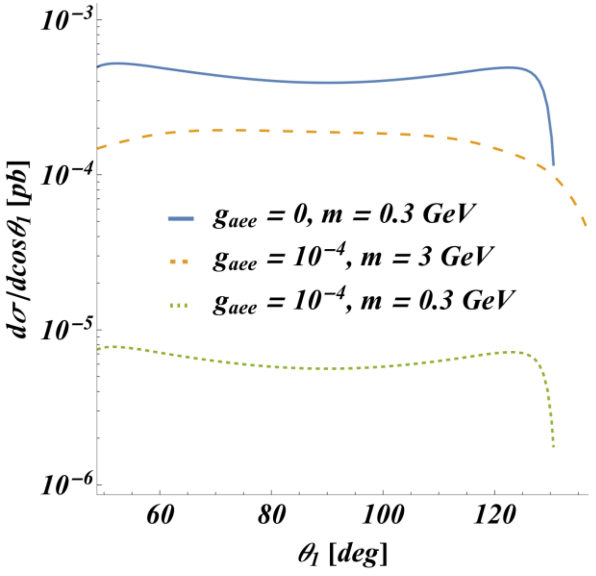
- LO QED 3-photon distributions for the softest, middle and hardest photons in this kinematics are shown below:



Angular distribution



Energy distribution



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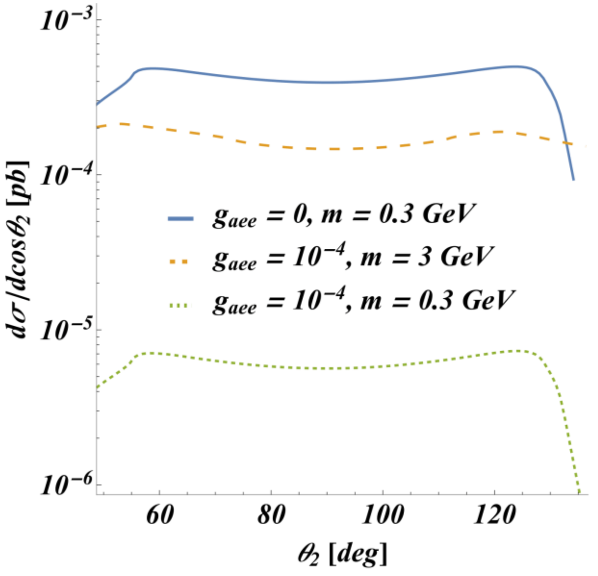

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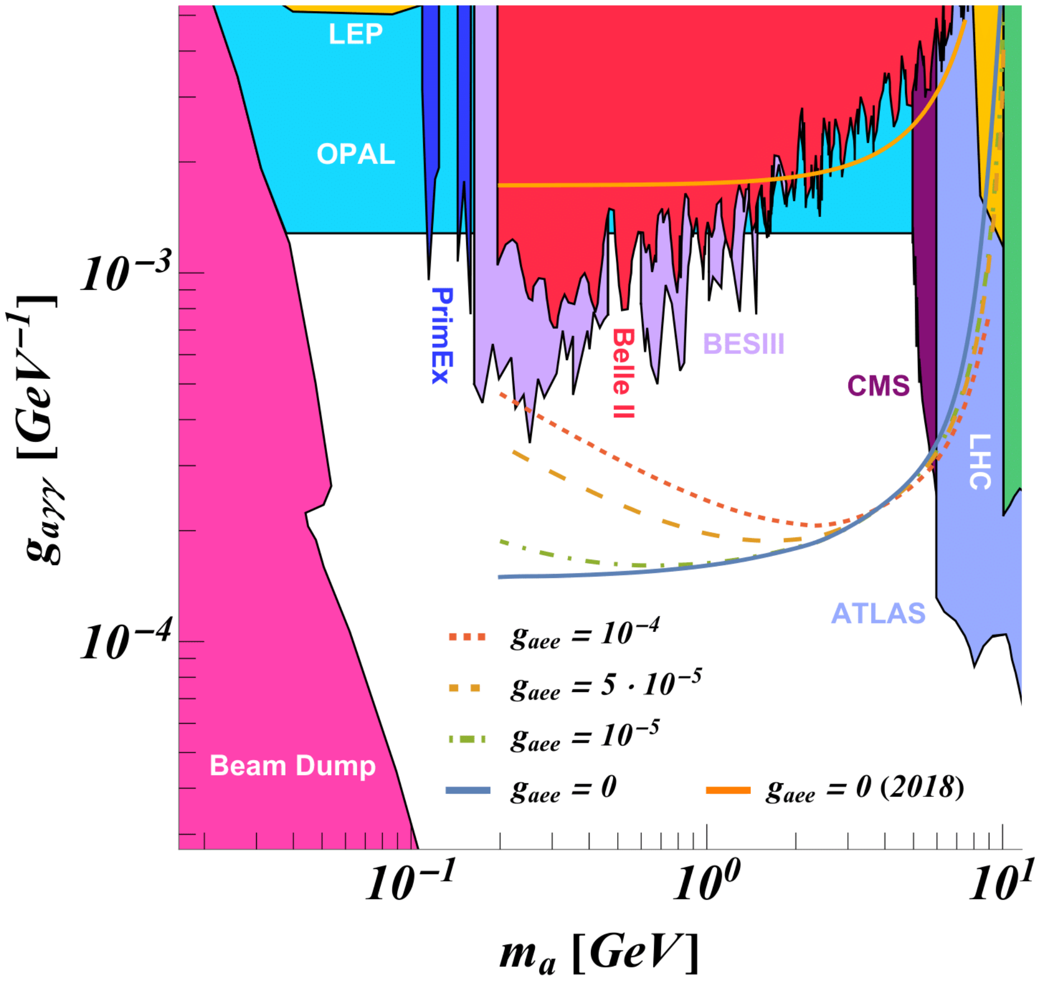
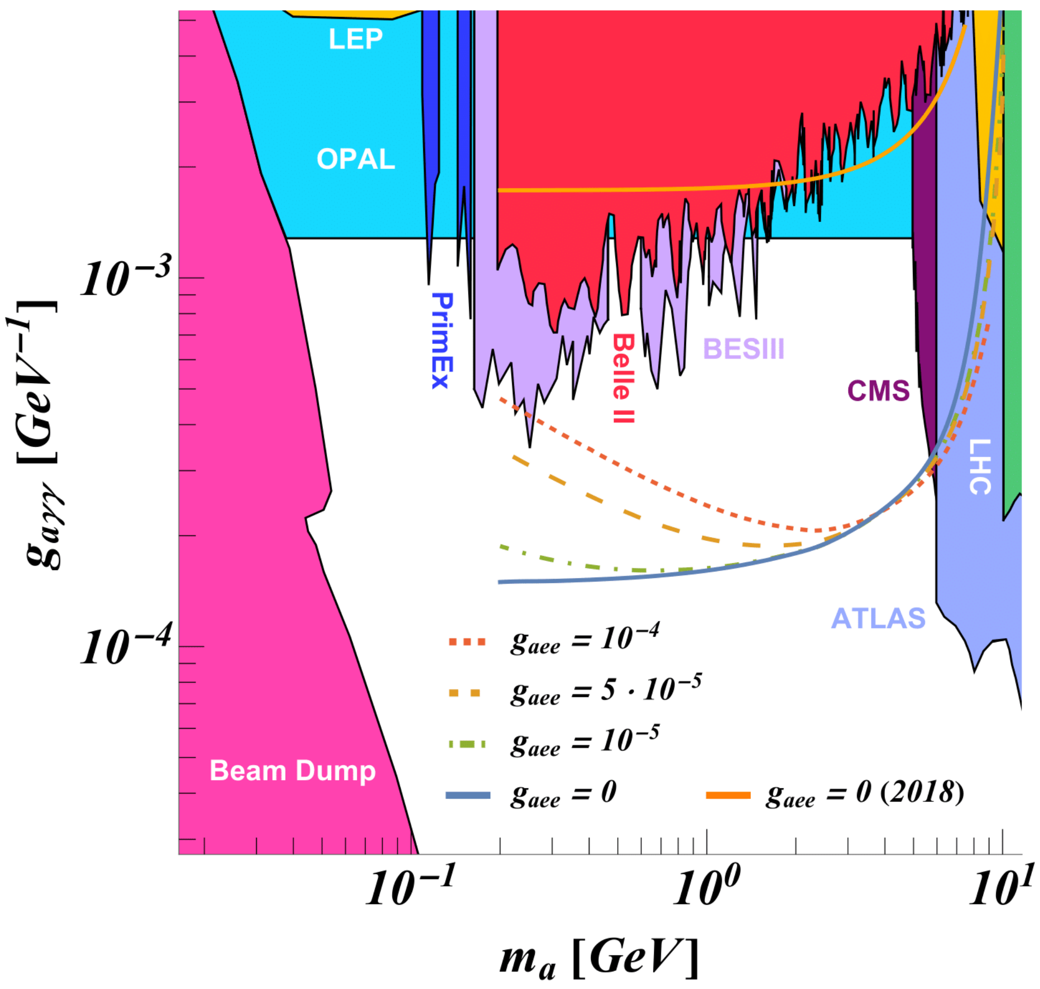


Belle II constraints for $g_{a\gamma\gamma}$ based on the 2018 data set of 445 pb^{-1} and projected results for 50 ab^{-1} of integrated luminosity – improvement by an order of magnitude

- A **good agreement** in the higher ALP mass region ($m_a \gtrsim 2$ GeV)
- In the lower mass region the invariant mass of a photon pair also becomes low (two photons travel in a very narrow cone with each other, oppositely to the third photon)
- This produces very asymmetric kinematics and the **QED background** becomes **suppressed**
- The assumption $g_{aee} = 0$ generally leads to an overestimated $g_{a\gamma\gamma}$ limit, which may be incorrect if the ALP has other decay channels besides the 2-photon mode

Results



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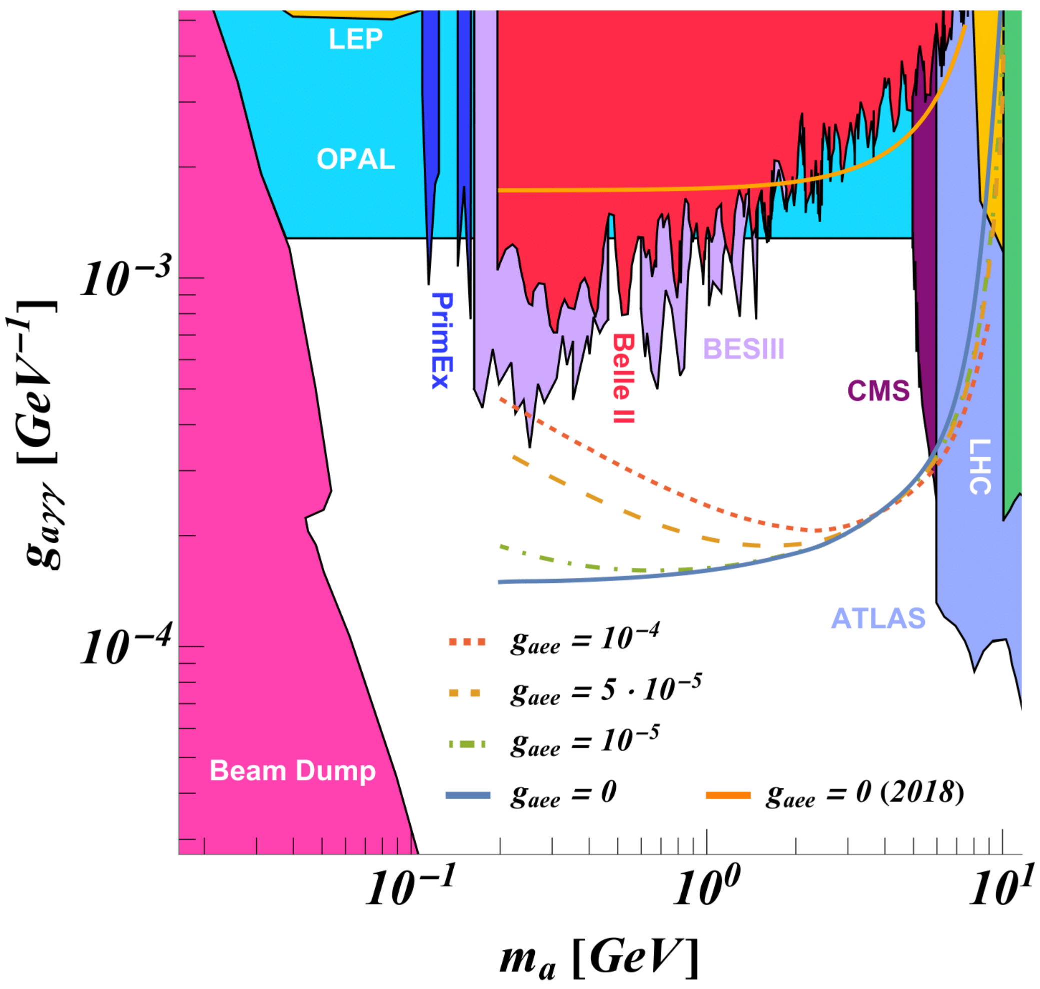

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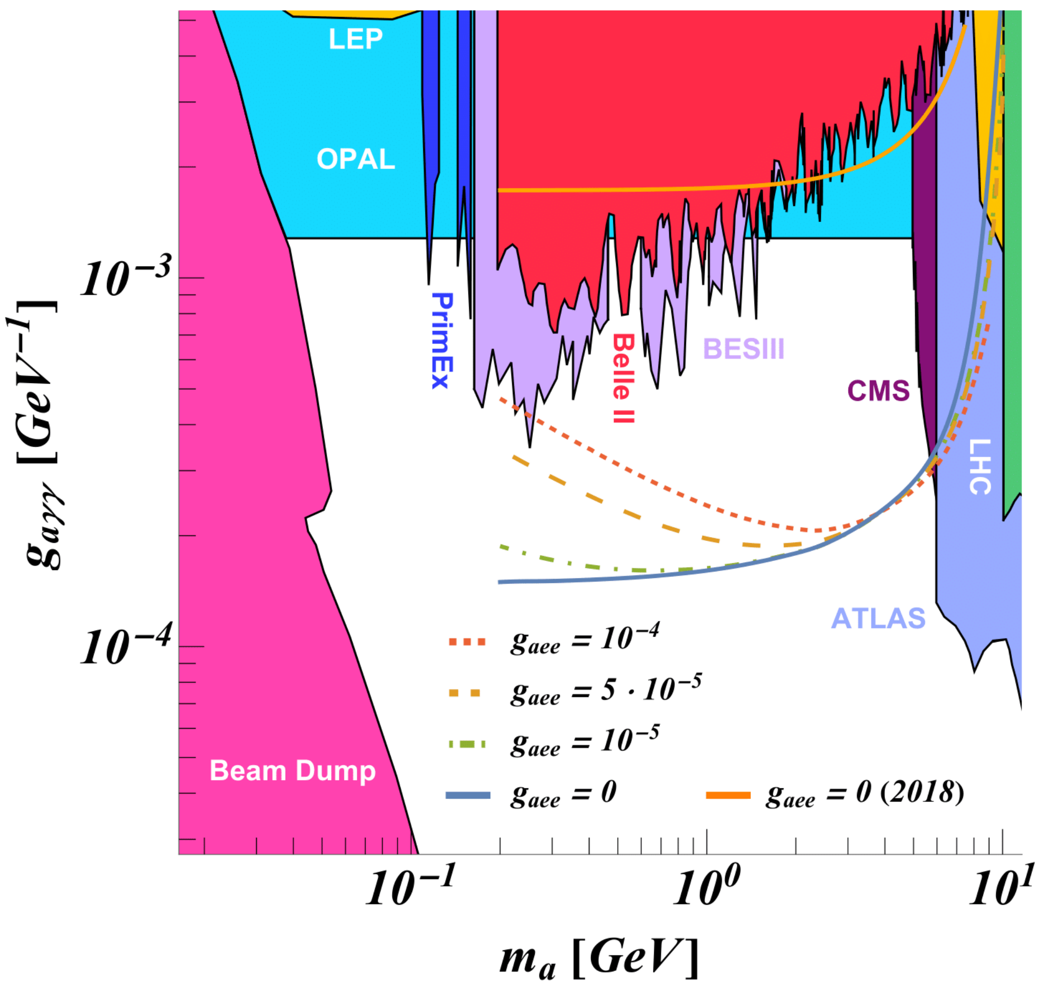

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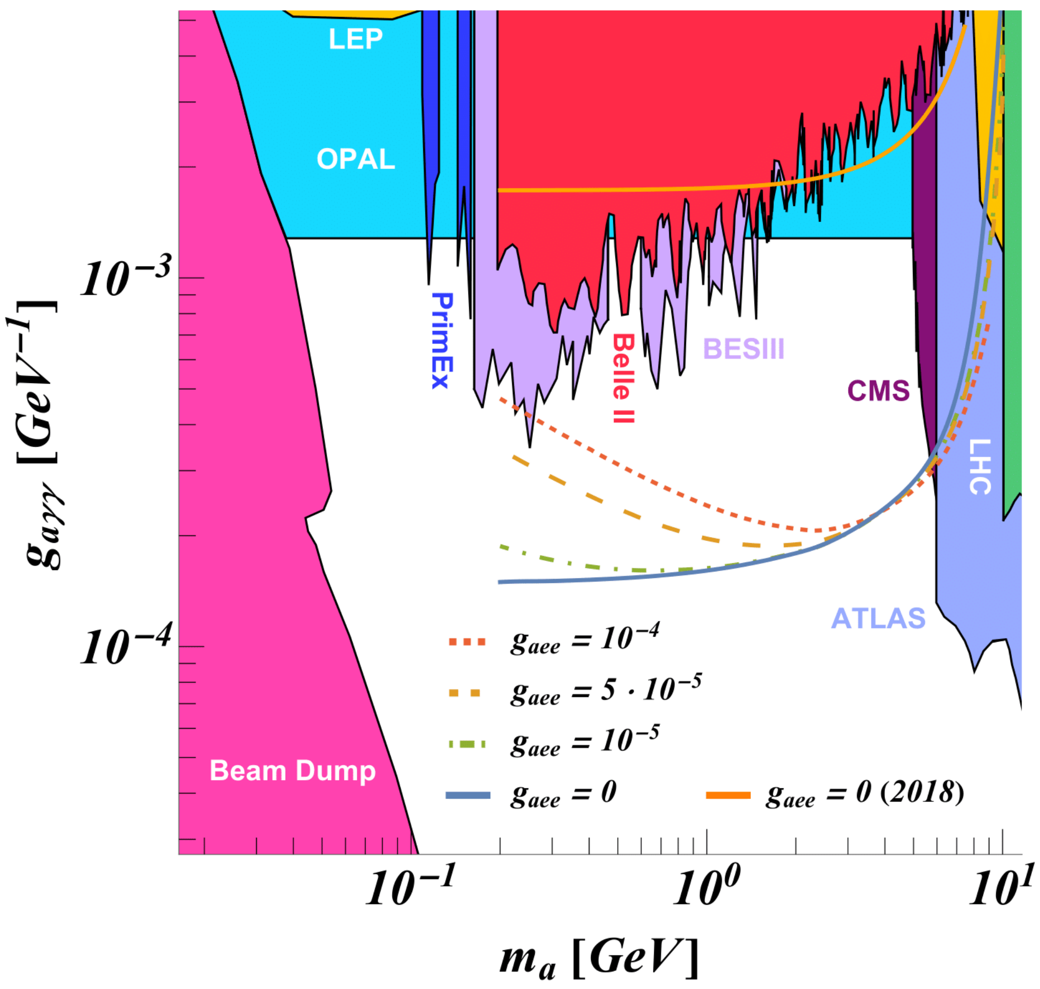

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Conclusion

The contributions of ALP states to $e^+e^- \rightarrow \gamma\gamma\gamma$ annihilation were calculated:

- New constraints acquired for ALPs in the MeV to GeV mass range, which can be effectively applied in e^+e^- colliders

- Tested on existing data for Belle II kinematics and projected for the forthcoming data collection with the integrated luminosity of 50 ab^{-1}

- Narrowed down the search area for potential ALPs and constrained the possible solution of the strong CP problem in the MeV to GeV mass range

There is **still some room for improvement**, e.g. more sophisticated background analysis? Investigation of the $(g-2)_\mu$ impact and limitations?

For more details see arXiv: 2309.15106 [hep-ph]

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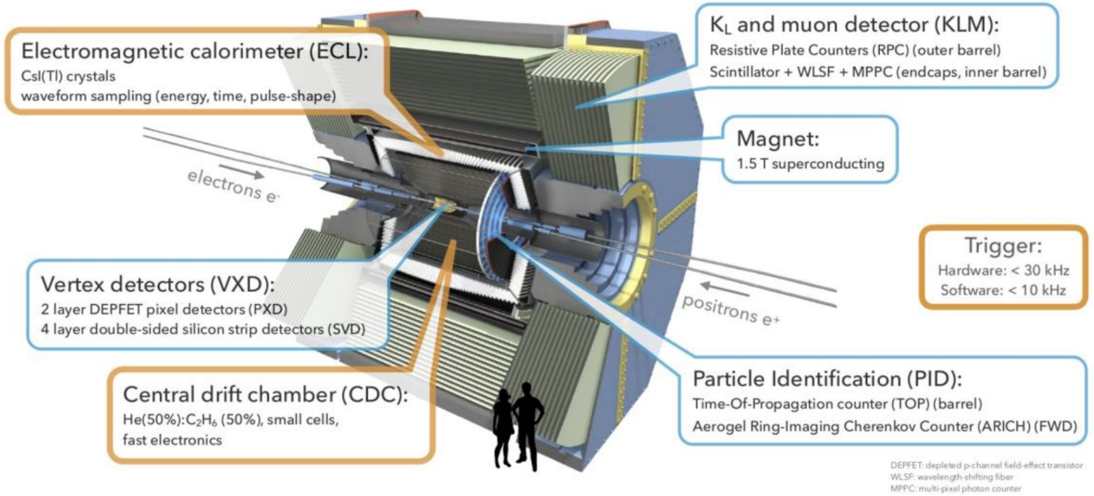
Thank you very much for your attention!

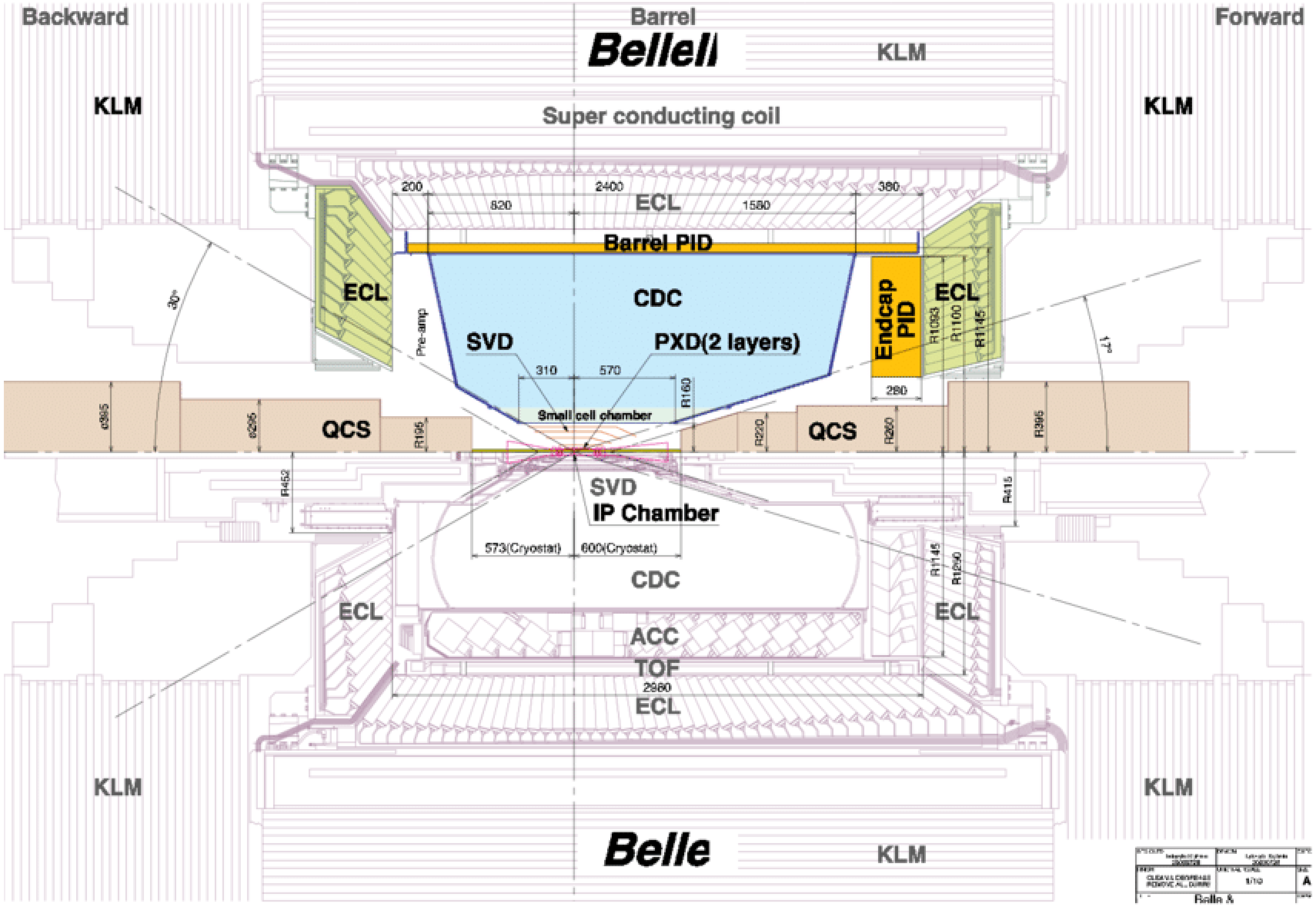
I wish you a good time during EINN conference and hope to see you during the poster session!

Belle 2

- Belle 2 is an **asymmetric** collider, electron and positron have energies 7 GeV and 4 GeV. This requires a **boost** with a relative velocity $\beta = 0.27$ to the CMS frame
- For **2018** analysis we require **three resolved photons** with energies higher than 0.65 GeV in the center-of-momentum frame as a criteria
- These requirements are slightly different from those used in the Belle II 2018 report, where the selection of photons with energies above 0.65 GeV for $m_a > 4$ GeV and 1 GeV for $m_a \leq 4$ GeV in the lab frame was performed
- The difference is negligible since $g_{a\gamma\gamma}$ is sensitive to $\sigma_{QED}^{-1/4}$
- The region $\boldsymbol{37.3° < \theta < 123.7°}$ provides the best energy resolution, avoiding regions close to detector gaps, and offers the lowest beam background levels – used for both 2018 and projected analyses
- Following the work of M. J. Dolan and others, we set the photon energy selection threshold of 0.25 GeV in the CMS frame for projected curves



Belle 2



Backward
Barrel
Forward
BelleII
KLM
KLM
KLM
Super conducting coil
200
2400
380
820
ECL
1580
Barrel PID
ECL
CDC
ECL
Endcap PID
Pre-amp
SVD
PXD(2 layers)
R1093
R1100
R1145
30°
17°
310
570
R160
280
Small cell chamber
QCS
QCS
R195
R220
R260
R396
R452
R415
SVD
IP Chamber
573(Cryostat)
600(Cryostat)
CDC
ECL
ECL
R1145
R1290
ACC
TOF
2980
ECL
KLM
KLM
Belle
KLM