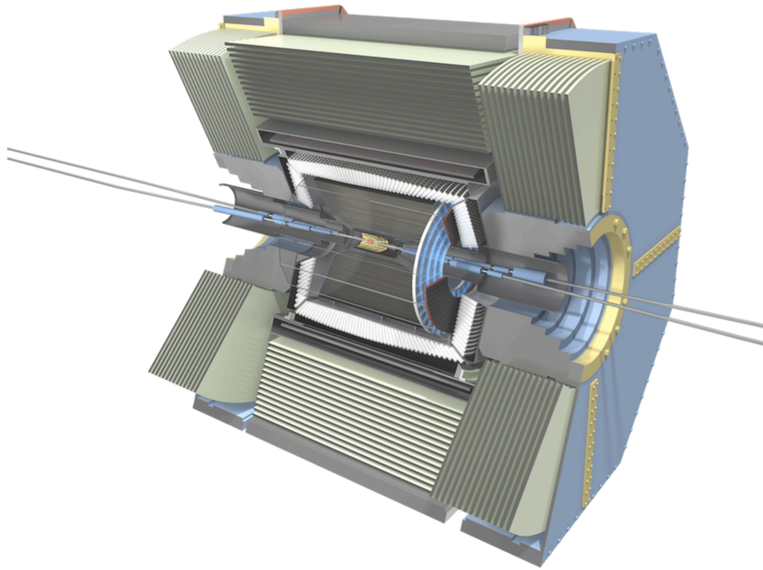
Searches for axions & ALPs at B factories



2023 February 17th, NePSi 23

Michael De Nuccio [they/them]
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Overview

- B factories
- Axions & ALPs @ B factories
- Recent searches for axions/ALPs

Introduction

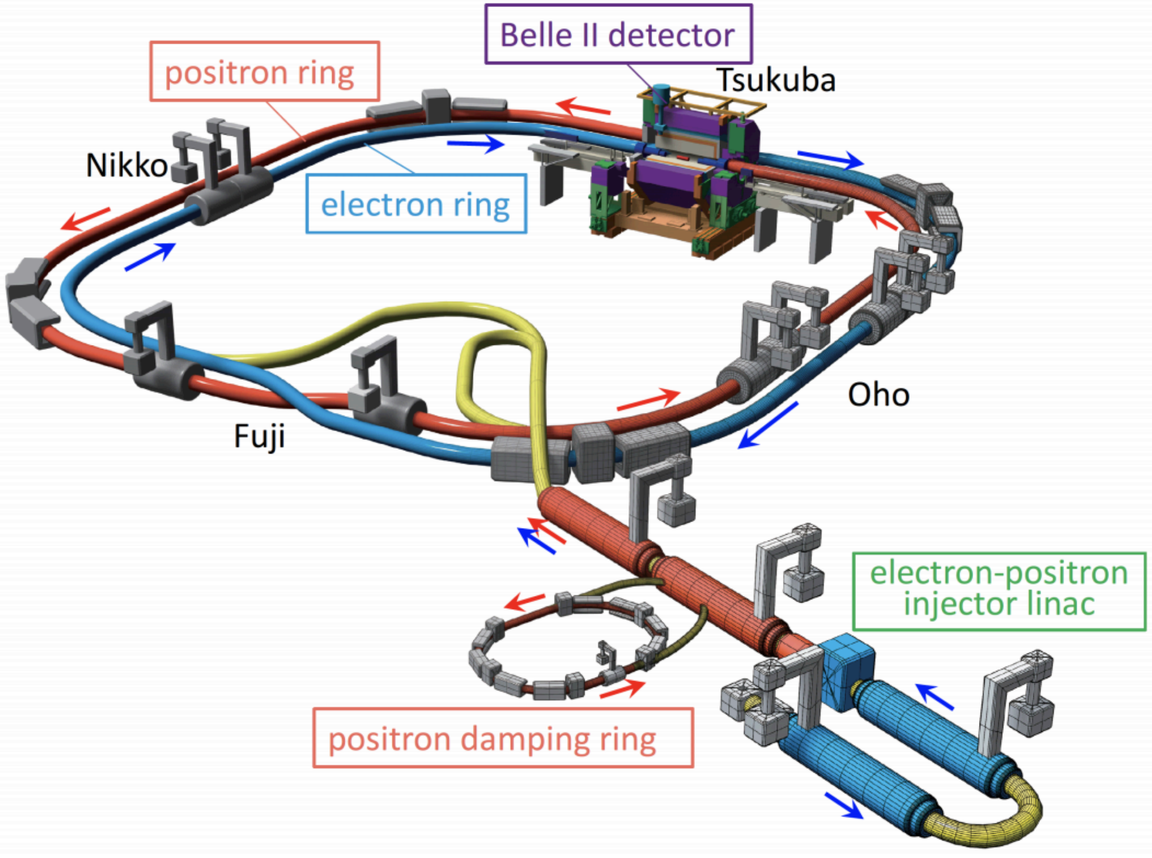
B factories

- First-generation B factories:
  - **BaBar:** @SLAC, on PEP-II, 1999-2008
    - $\mathscr{L} \approx 420\ \text{fb}^{-1} \approx 0.4\ \text{ab}^{-1}$
  - **Belle:** @KEK, on KEKB, 1999-2010
    - $\mathscr{L} \approx 710\ \text{fb}^{-1} \approx 0.7\ \text{ab}^{-1}$
- Second-generation B factory:
  - **Belle II:** @KEK, on SuperKEKB, 2018-onward
    - 30x instantaneous luminosity (target)
    - $\mathscr{L} \approx 50\ \text{ab}^{-1}$ total luminosity (target)
    - Updated detectors and triggers

B factories

- **B factory:** produce a lot of B mesons
- **Asymmetric e^+e^- collider**
  @ $\Upsilon(4S)$ energy = 10.58 GeV

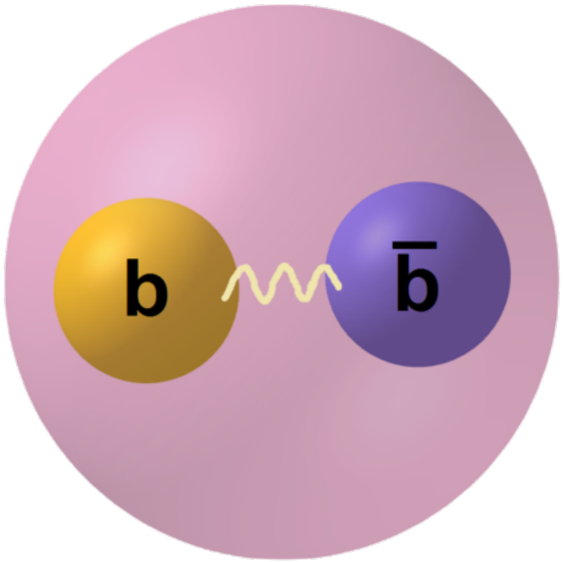
SuperKEKB as an example



SuperKEKB Collider, Nucl. Instrum. Meth. A 907 (2018) 188

B factories

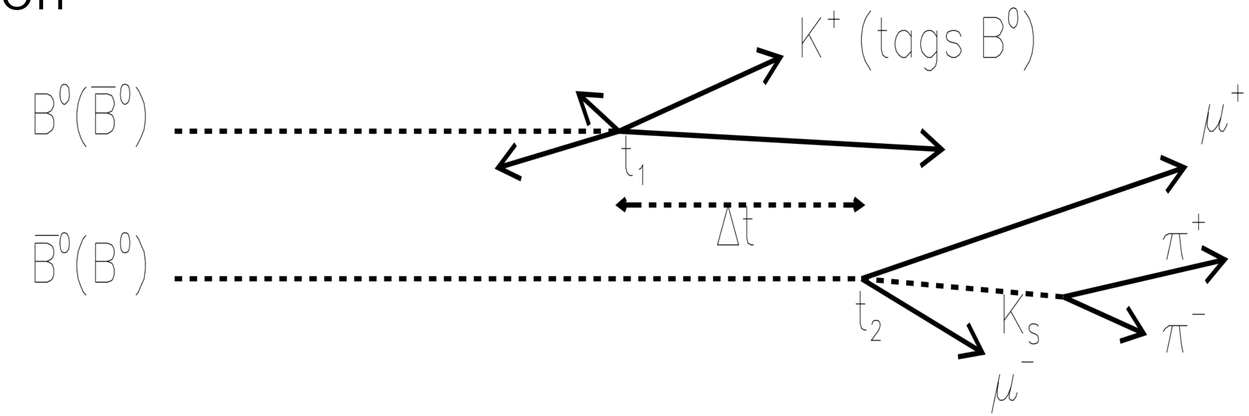
- **B factory:** produce a lot of B mesons
- **Asymmetric e^+e^- collider**
  @ $\Upsilon(4S)$ energy = 10.58 GeV
- Why the $\Upsilon(4S)$?
  - Bottomonium: $b\bar{b}$ resonance
  - Just enough mass to decay into two B mesons
    - $m(\Upsilon(4S)) = 10.58 \text{ GeV} > 2m(B) = 2 \times 5.28 \text{ GeV} = 10.56 \text{ GeV}$
    - $B\bar{B}$ pair (charged or neutral) almost at rest in the centre-of-mass reference frame



Hoa112008 (Wikipedia)

B factories

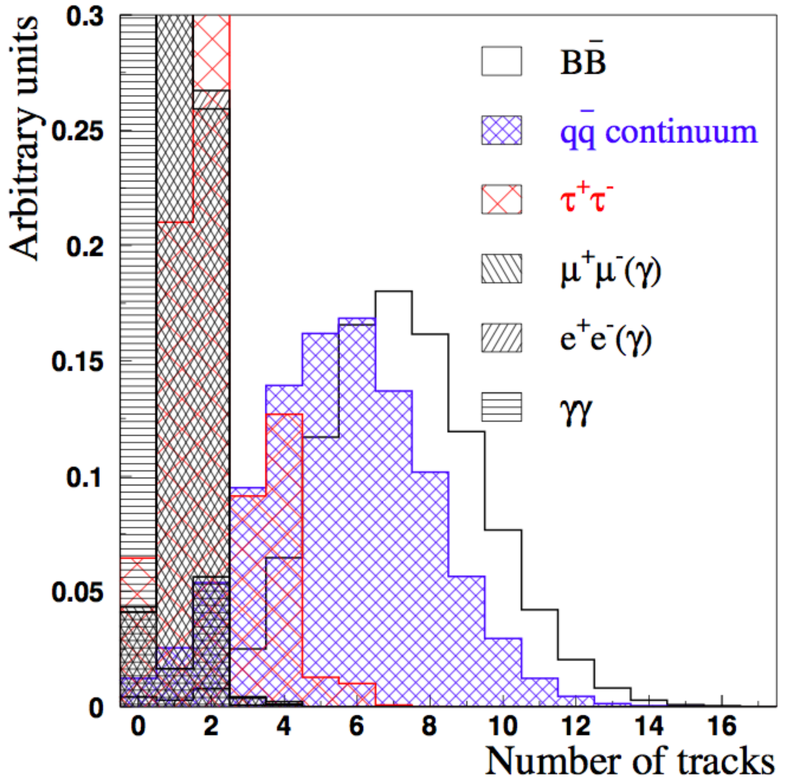
- **B factory:** produce a lot of B mesons
- **Asymmetric e^+e^- collider**
  @ $\Upsilon(4S)$ energy = 10.58 GeV
- Asymmetric?
  - In beam energy:
    - $E(e^+) = 4$ GeV
    - $E(e^-) = 7$ GeV
  - To enhance separation of the two B mesons
  - Allows study of time-dependent CP violation



BaBar & Belle The Physics of the B Factories - Eur. Phys. J. C 74 (2014) 3026

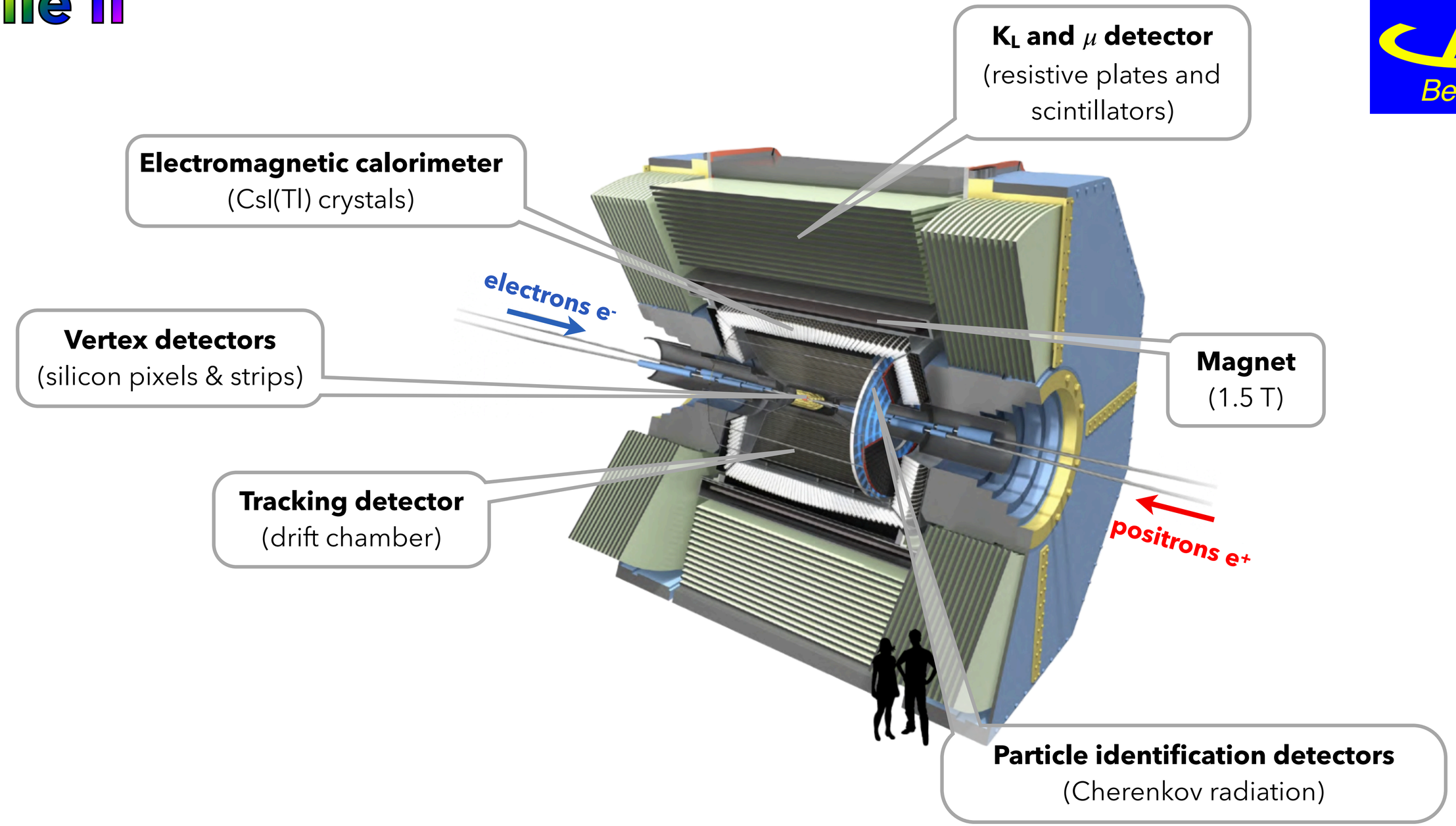
B factories

- **B factory:** produce a lot of B mesons
- **Asymmetric e^+e^- collider**
  @ $\Upsilon(4S)$ energy = 10.58 GeV
- Why e^+e^- colliders?
  - High signal-over-bkg ratio
  - **Clean environment**
    - Few charged tracks (6~11 vs 300~7000 of e.g. ATLAS)
  - Dedicated **triggers for low-multiplicity** events (down to 1 particle)
    - Only Belle II and late BaBar
  - Almost-**hermetic detector**
  - **Initial state is exactly known** ⟹ kinematic constraints



BaBar & Belle The Physics of the B Factories - Eur. Phys. J. C 74 (2014) 3026

Belle II



Belle II official website

Axions & ALPs at B factories

- **B factories** have amazing features for **dark/new physics searches**
  - Clean environment
  - Hermetic detector
  - Initial state is exactly known
  - Low-multiplicity triggers
- Can explore **higher masses** than other classes of axions/ALPs experiments and **lower masses** than LHC-like experiments
- Despite the nominal focus being B physics, efforts towards **beyond-SM physics**
  - Also about **axions/ALPs**!

SPOILER!!!

None of the following searches found any evidence! :(

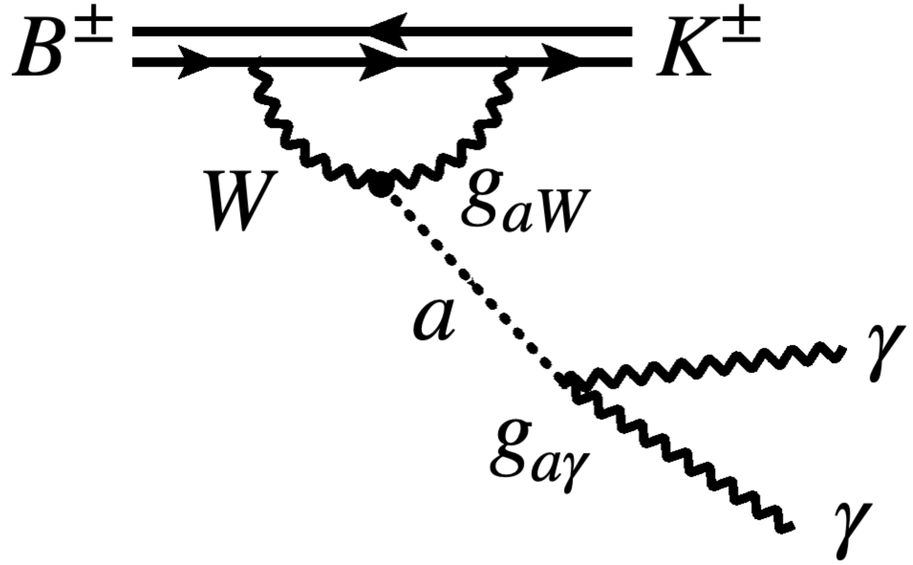
All set **upper limits** (ULs)

Axion-Like Particles in B decays:

$$B \to Ka, a \to \gamma\gamma$$

ALPs in B decays: $B \to Ka$, $a \to \gamma\gamma$

- ALPs: often investigated their coupling to gluon and γ
- Here: **coupling to** $W^{\pm}$
- $B^{\pm} \to K^{\pm}a, a \to \gamma\gamma$
- Also study non-prompt decay, i.e. lifetime $c\tau \neq 0$
- **First** search for visibly decaying ALPs coming from Bs
- $\mathscr{L}$ = 424 fb^{-1}
  - On $\Upsilon(4S)$ resonance
  - 8% used to optimize search strategy, then excluded
- Range: $\sim 0.18 < m_a < m_{B^+} - m_{K^+} \approx 4.8$ GeV

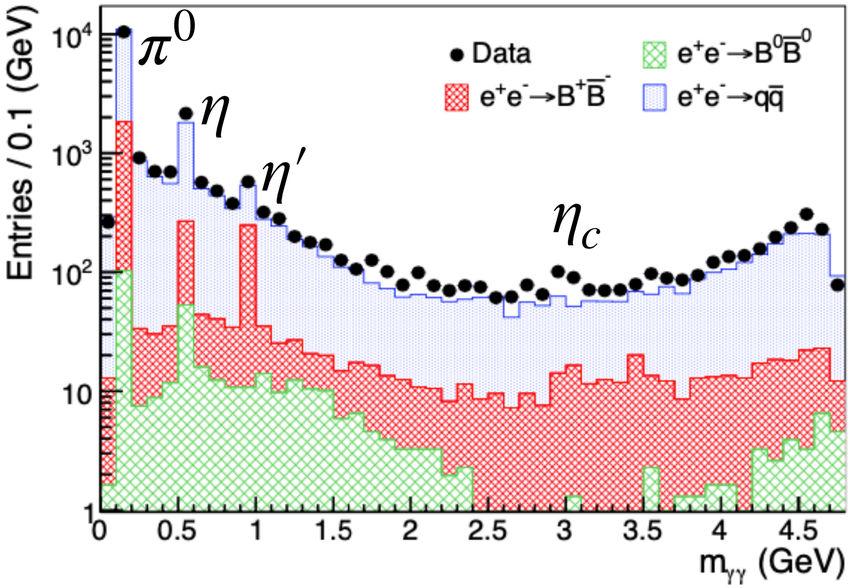


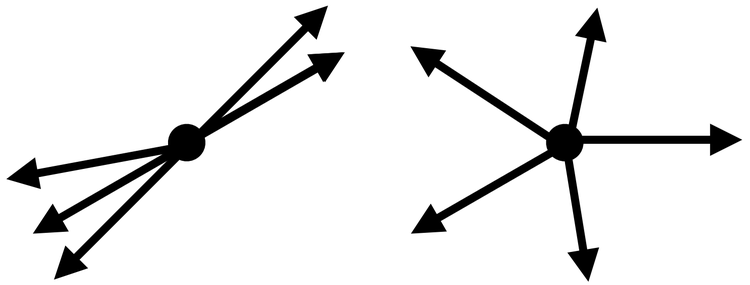
(I worked on this during my master!)

BaBar Phys. Rev. Lett. 128, 131802 (2022)

ALPs in B decays: $B \to Ka$, $a \to \gamma\gamma$

- **Signal:**
  - 1 track + 2 γ summing to $m(B)$
- **Backgrounds:**
  - $e^+e^- \to q\bar{q}$ $(q = u, d, c, s)$: **continuum**
    - Dominant background
  - $e^+e^- \to B\bar{B}$
    - Peaking, vetoed: $B^\pm \to K^\pm h^0$, $h^0 \to \gamma\gamma$ $(h^0 = \pi^0, \eta, \eta')$
    - Peaking, small, not modeled: $B^\pm \to K^\pm \eta_c$, $\eta_c \to \gamma\gamma$
- **2 BDTs**: vs continuum and vs $B\bar{B}$
  - 13 variables, including event-shape ones
  - For signal: training on combo of m_a to uniform in $m(\gamma\gamma)$

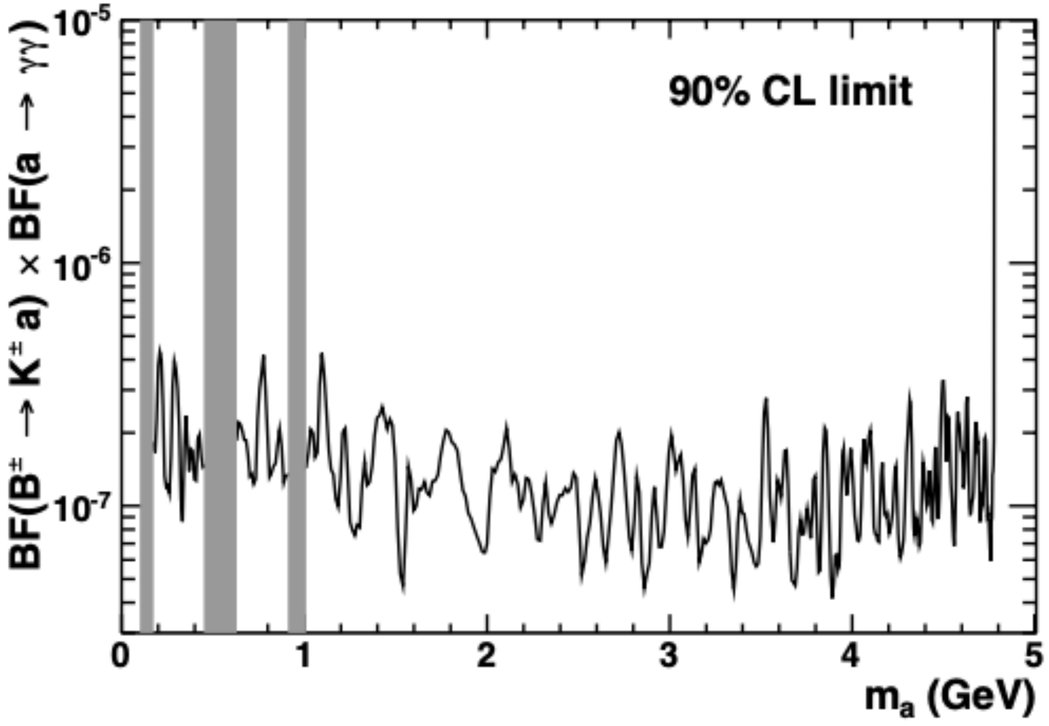


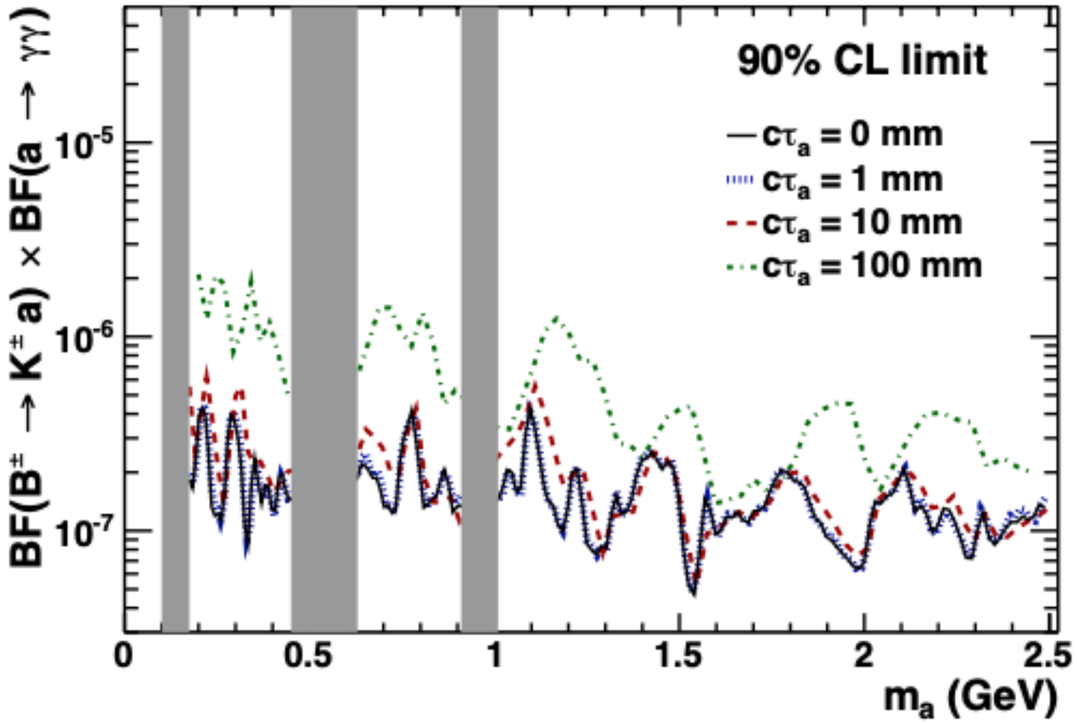


BaBar Phys. Rev. Lett. 128, 131802 (2022)

ALPs in B decays: $B \to Ka$, $a \to \gamma\gamma$

- **Peak hunt: fit on m(γγ)** of peaking signal over bkg (except π^0, η, η')
  - Signal = KDE (Kernel Density Estimator)
  - Background = 1st-order polynomial + template & resonance peaks
- **Re-performed** the upper limit extraction for **non-zero lifetimes**
  - cτ = 1, 10, 100 mm (⟹ small mass and coupling)

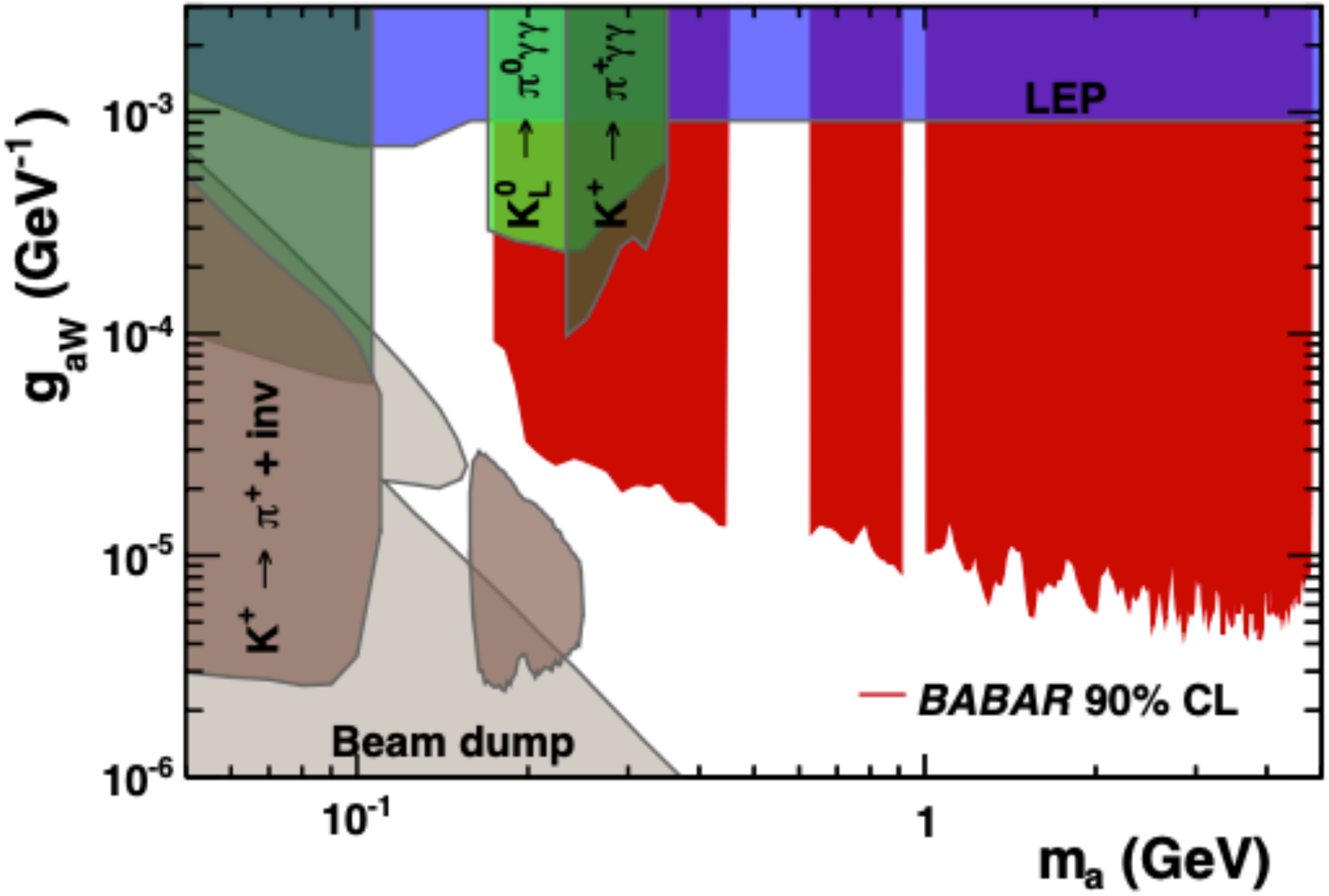




BaBar Phys. Rev. Lett. 128, 131802 (2022)

ALPs in B decays: $B \to Ka$, $a \to \gamma\gamma$

- **Peak hunt: fit on m(γγ)** of peaking signal over background
- 90% CL UL on g_{aW}**: improving previous constraints** by >O(100)



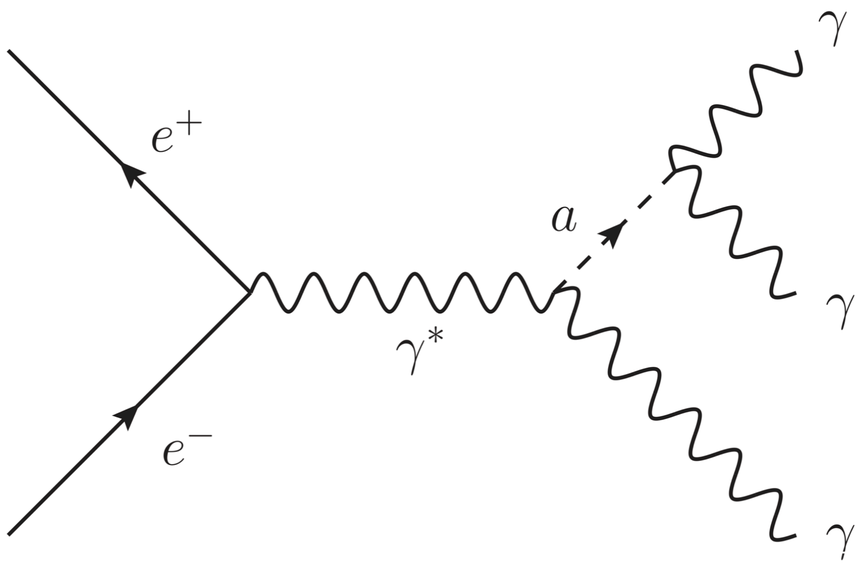
BaBar Phys. Rev. Lett. 128, 131802 (2022)

ALPs in ee collisions:

$$ee \to \gamma a,\ a \to \gamma\gamma$$

ALPs in ee collisions: ee→γa, a→γγ

- $\mathbf{e^+e^- \to \gamma a,\ a \to \gamma\gamma}$
  - Photophilic ALP
- Parameters: mass $\mathbf{m}_a$ and coupling $\mathbf{g}_{a\gamma\gamma}$
- Pushing to **low masses is difficult**
  - $\gamma\gamma$ from ALP merge & π^0 peak
  - Can be addressed in second iteration
- $\mathscr{L}$ = 0.445 fb^{-1}
  - Just preliminary data for calibration and tuning
- Range: $0.2 < m_a < 9.7$ GeV

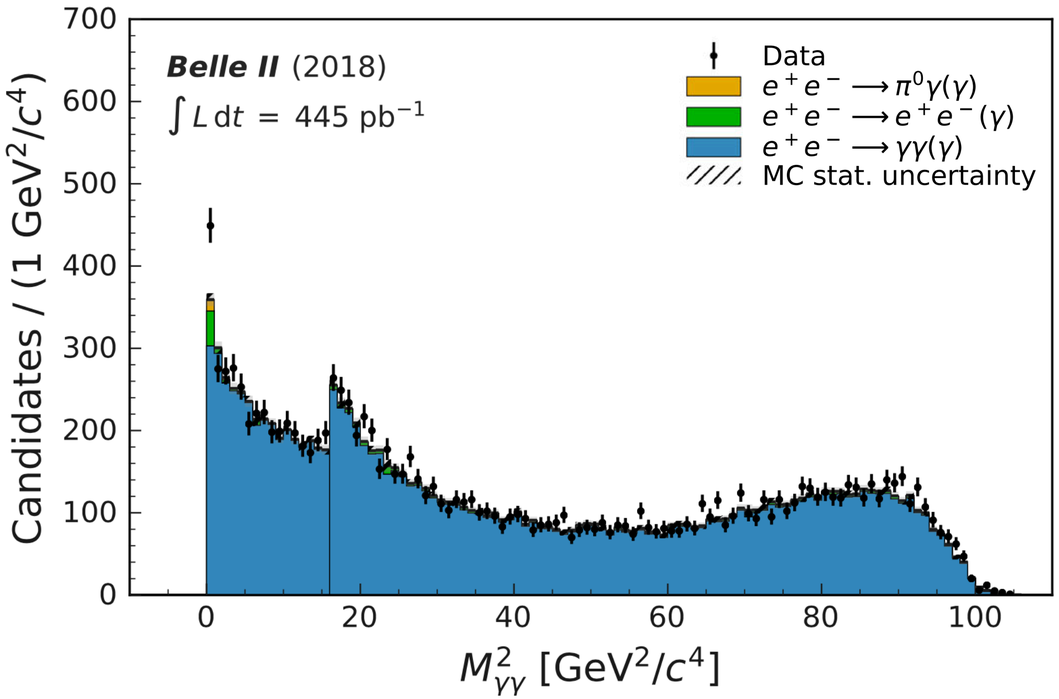


(this was my PhD research topic!)

Belle II Phys. Rev. Lett. 125, 161806 (2020)

ALPs in ee collisions: ee→γa, a→γγ

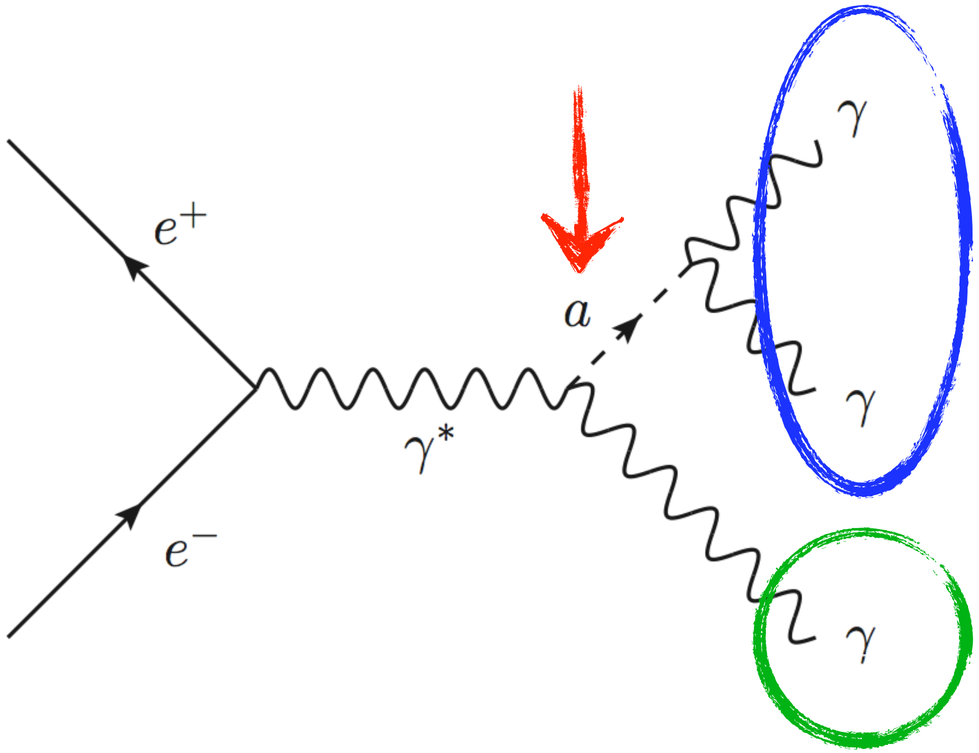
- **Signal**:
  - 3-photon final state, no missing E nor tracks
- **Backgrounds**:
  - $e^+e^- \to \gamma\gamma(\gamma)$
  - $e^+e^- \to ee(\gamma)$
  - $e^+e^- \to h^0\gamma,\ h^0 \to \gamma\gamma\ (h^0 = \pi^0, \eta, \eta')$
- **Selection**: multi-dimensional **rectangular cut(s)**
  - **Future** possibility: **Neural Network** particularly for low mass
- Peak hunt over $m^2(\gamma\gamma)$ (or m^2_{recoil}): peaking signal over smooth bkg



Belle II Phys. Rev. Lett. 125, 161806 (2020)

ALPs in ee collisions: ee→γa, a→γγ

- Peak hunt over $m^2(\gamma\gamma)$ (or m^2_{recoil}): peaking signal over smooth bkg
- **Mass** of ALP candidate can be **computed in two ways**:



Better resolution for **low** ALP masses

Diphoton mass

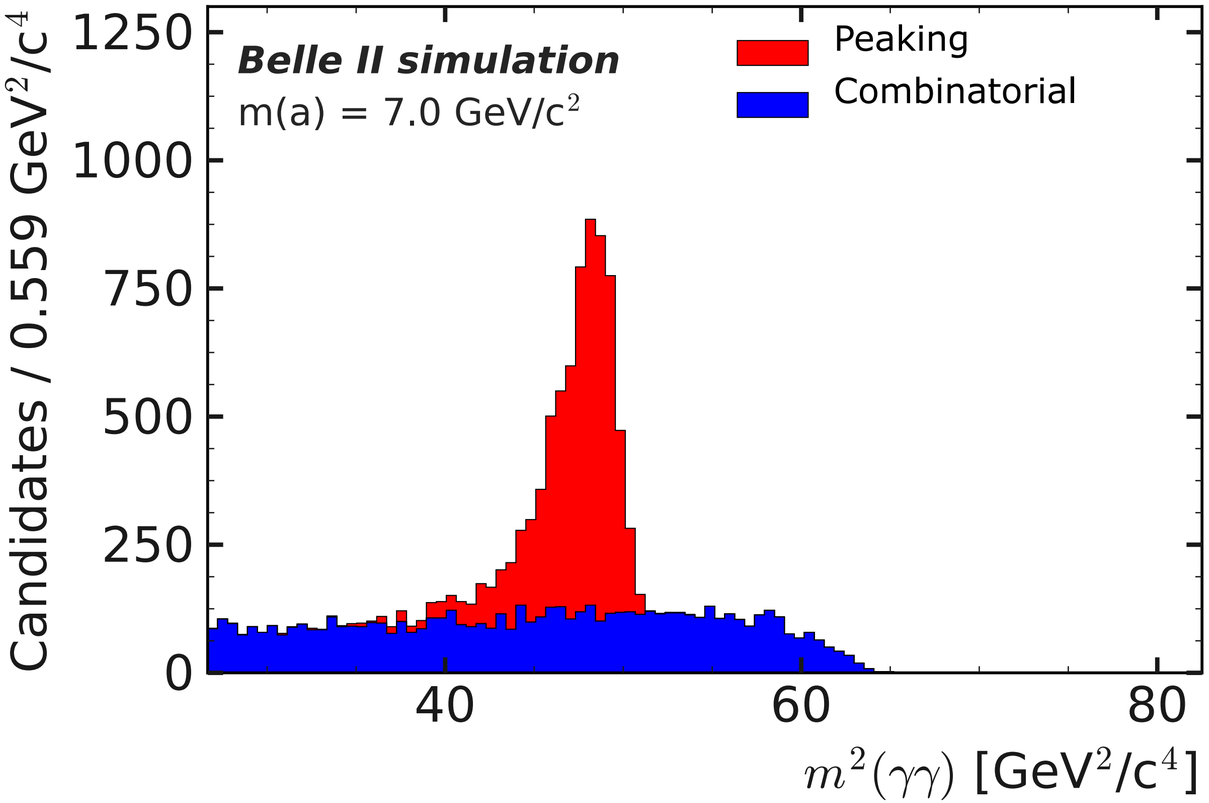
Recoil mass:
3-body system and
knowledge of initial state

Better resolution for **high** ALP masses

Belle II Phys. Rev. Lett. 125, 161806 (2020)

ALPs in ee collisions: ee→γa, a→γγ

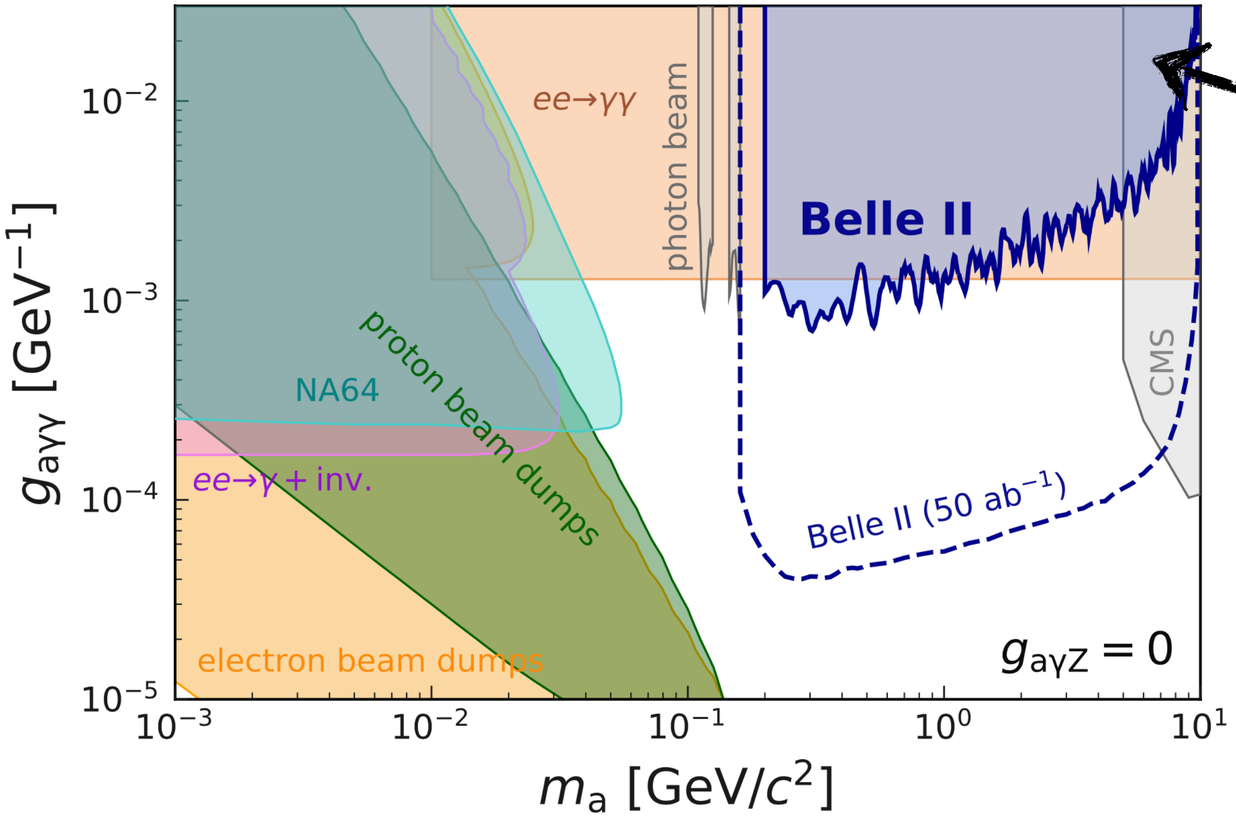
- Peak hunt over $m^2(\gamma\gamma)$ (or m^2_{recoil}): peaking signal over smooth bkg
- 1 event ⟹ 3 candidates
- **Signal** events:
  - 1 real ALP ⟹
    peaking component (Crystal Ball)
  - 2 fake combinations ⟹
    combinatorial component (KDE)



Belle II Phys. Rev. Lett. 125, 161806 (2020)

ALPs in ee collisions: ee→γa, a→γγ

- **95% CL UL** on $g_{a\gamma\gamma}$
- Already competitive with **preliminary data** (we now have x1000 data)
- Belle II has a **unique area of sensitivity**



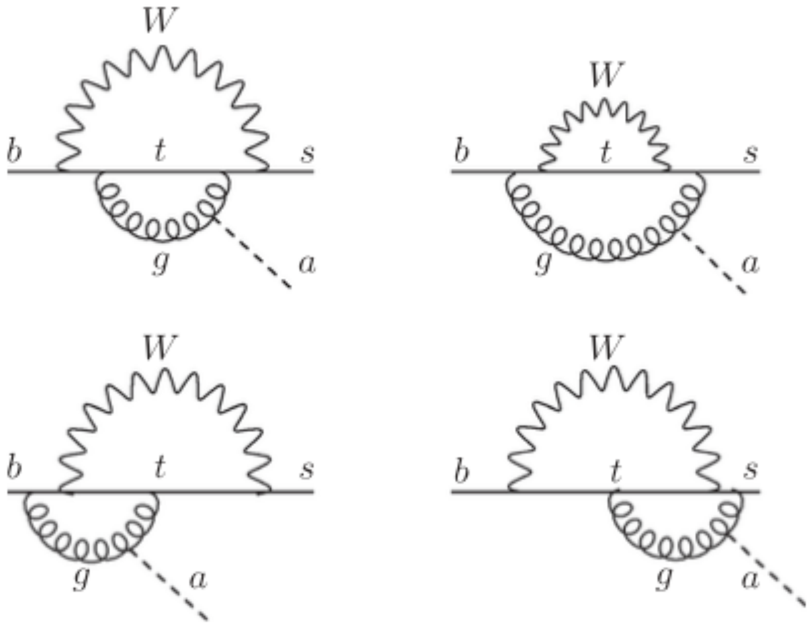
Belle II Phys. Rev. Lett. 125, 161806 (2020)

Heavy QCD axion in $b \to s$ transitions

Heavy QCD axion in $b \to s$ transitions

- For Peccei-Quinn (or QCD) axions: $m_a f_a \simeq m_\pi f_\pi$ (mass and decay constant)
  - $f_a \gtrsim$ O(TeV) $\Leftrightarrow m_a \lesssim$ O(keV) already largely excluded by experiments
- $m_a f_a \simeq m_\pi f_\pi$ not necessarily true if m_a has non-QCD contributions
  - **Heavy QCD axion**: $m_a > m_\pi f_\pi / f_a$
  - Coupling to SM mostly to gluons (2-loop)
- Is being **searched for at Belle II**
  - Sadly can't show you any results yet, as analysis is ongoing
  - General overview & projections (and stay tuned!)

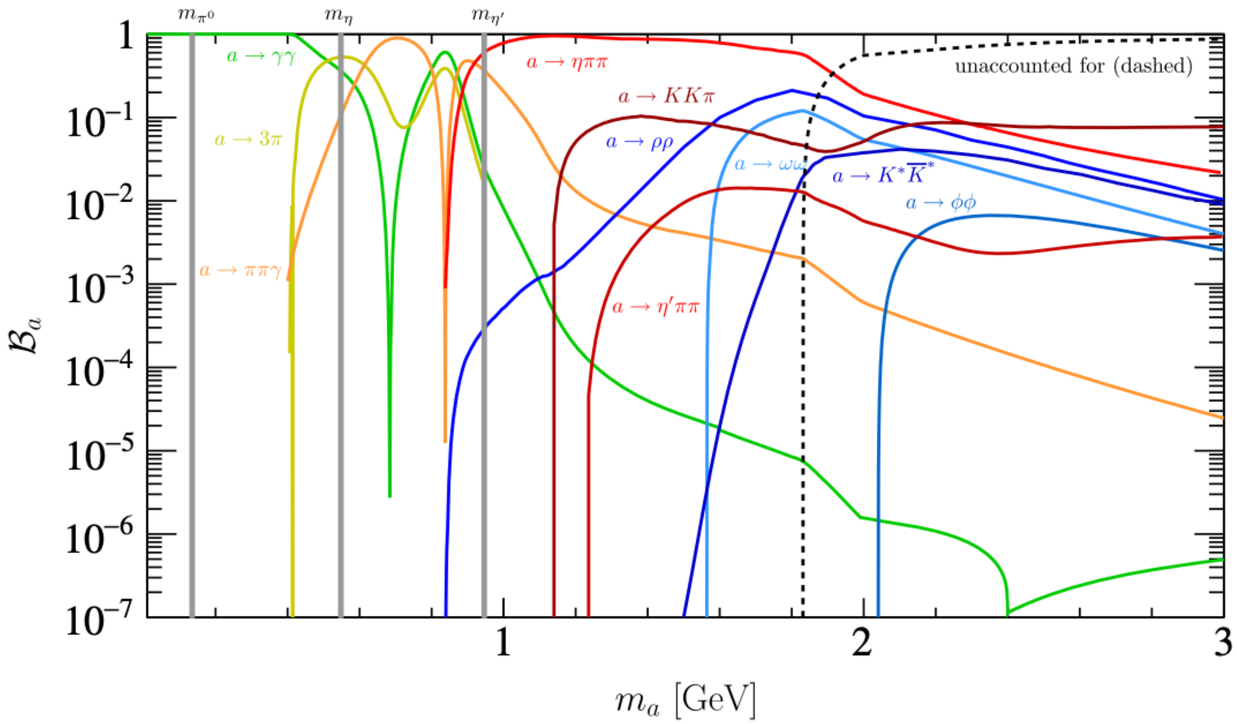
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{\alpha_s}{8\pi}\frac{a}{f_a} G^a_{\mu\nu}\tilde{G}^{a\mu\nu} + \frac{1}{2}(\partial_\mu a)^2 - \frac{m_a^2}{2}a^2$$

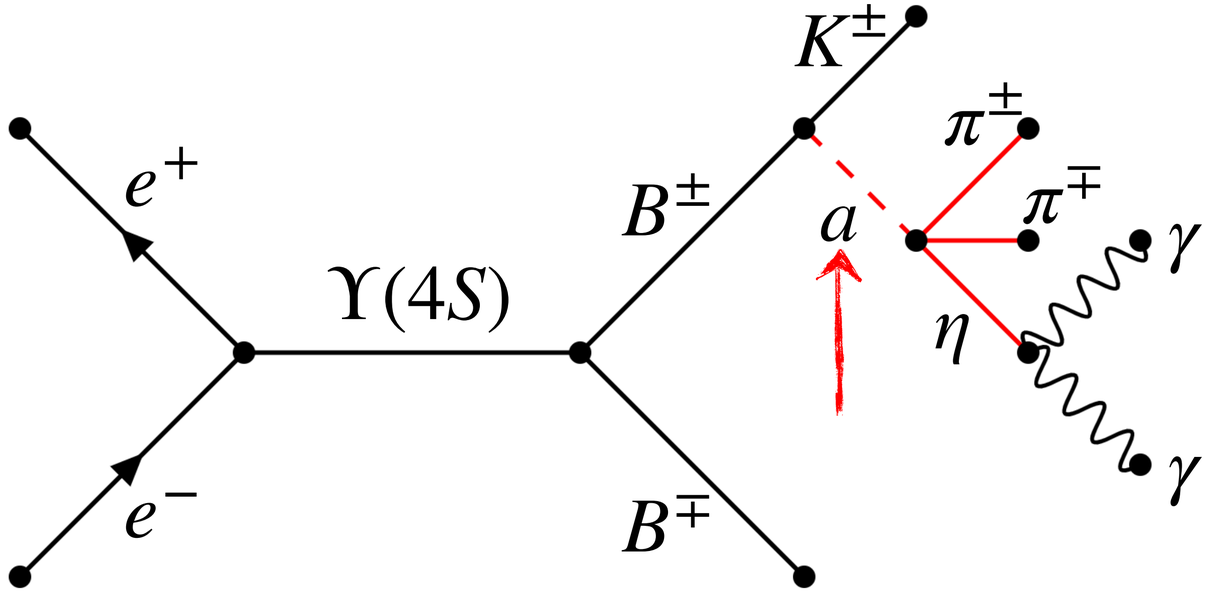


Chakraborty, Kraus, Loladze, Okui, Tobioka Phys. Rev. Lett. 104, 055036 (2021)

Heavy QCD axion in $b \to s$ transitions

- For $f_a \sim$ O(TeV), $m_a \lesssim 400$ MeV already explored (and excluded, obv)
- For $m_a \gtrsim 400$ MeV, poorly/not explored
- **Promising channel** to explore this region is $B^+ \to K^+ a$
- Axion decay under study in Belle II: $a \to \eta\pi^+\pi^-$
- Range: $0.7 \lesssim m_a \lesssim 3$ GeV

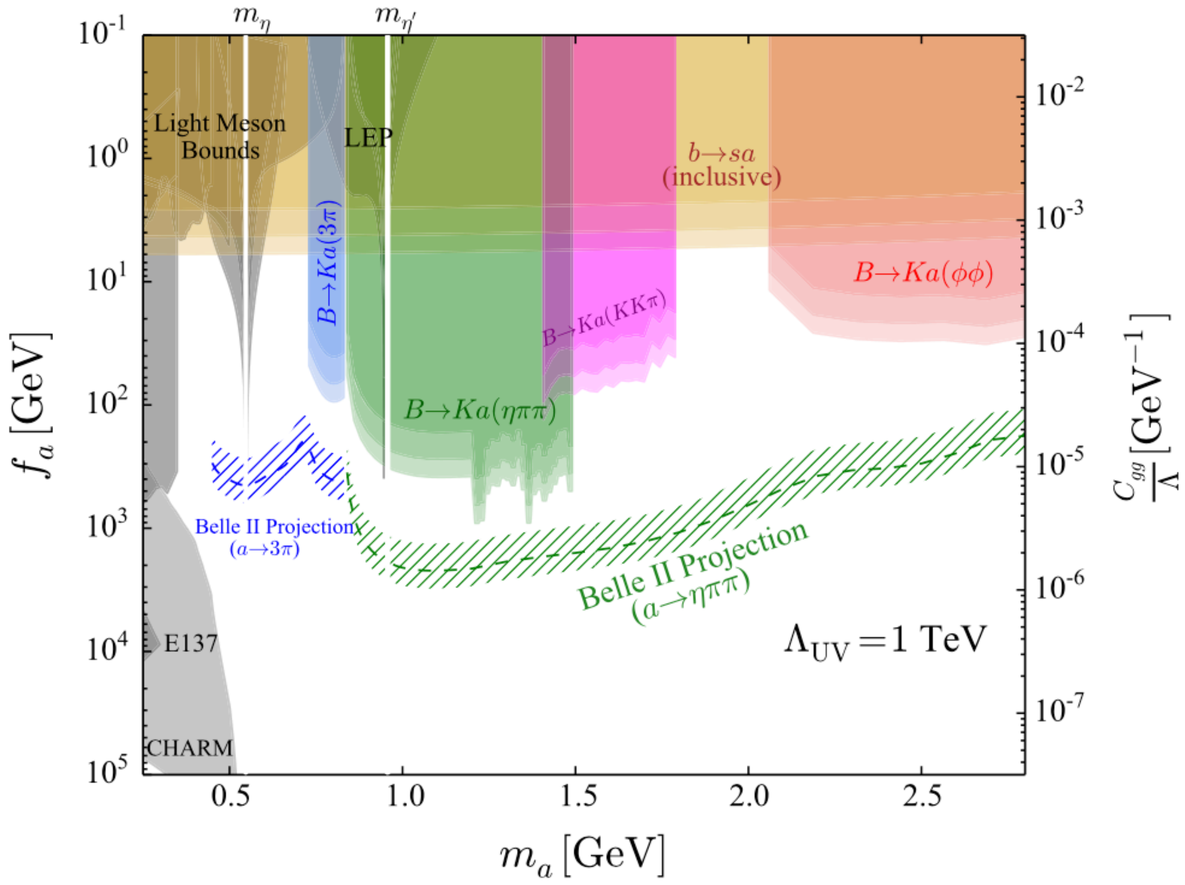




Aloni, Soreq, Williams Phys. Rev. Lett. 123, 031803 (2019)

Heavy QCD axion in $b \to s$ transitions

- Colored regions: **recast** from PDG and previous searches at **Belle and BaBar**
- **Projections for 50 ab^{-1} @ Belle II** by extrapolating bkg from BaBar search and requiring signal < 2 std dev

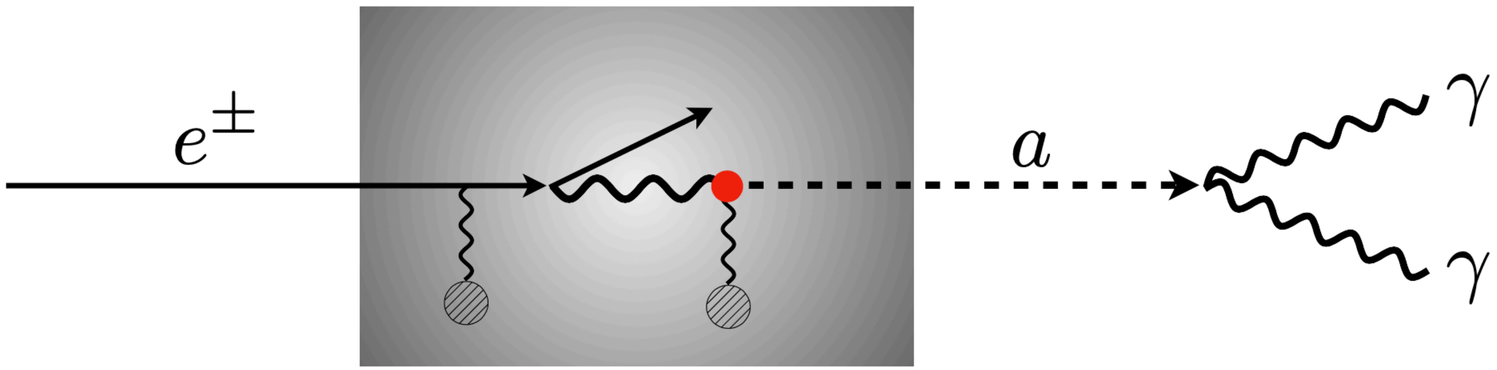


Chakraborty, Kraus, Loladze, Okui, Tobioka Phys. Rev. Lett. 104, 055036 (2021)

Search for ALPs with e^+e^- beams at KEK Linac

Search of ALPs with e^+e^- beams at KEK Linac

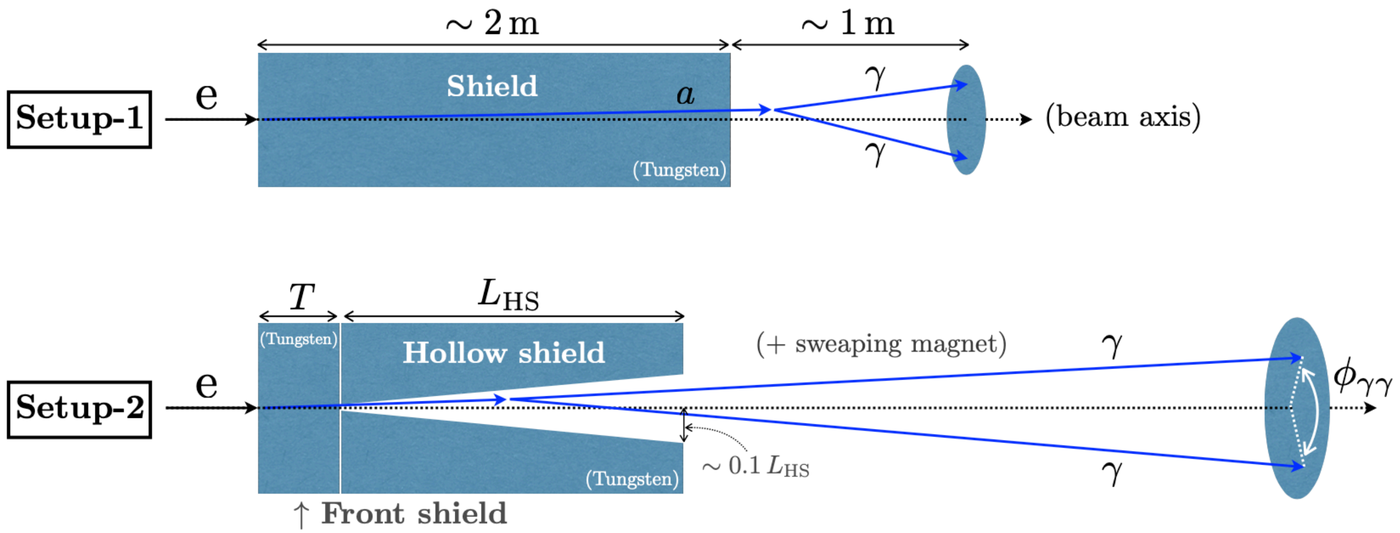
- **Fixed-target experiment**: "halfway" between dump experiments and colliders
  - Explore shorter lifetimes than the former, but longer than the latter
- $e^{\pm}$ onto tungsten target →
  Bremsstrahlung γ →
  Primakoff conversion into ALPs →
  ALP decays into $\gamma\gamma$ →
  detect these two photons
- Under approval procedure

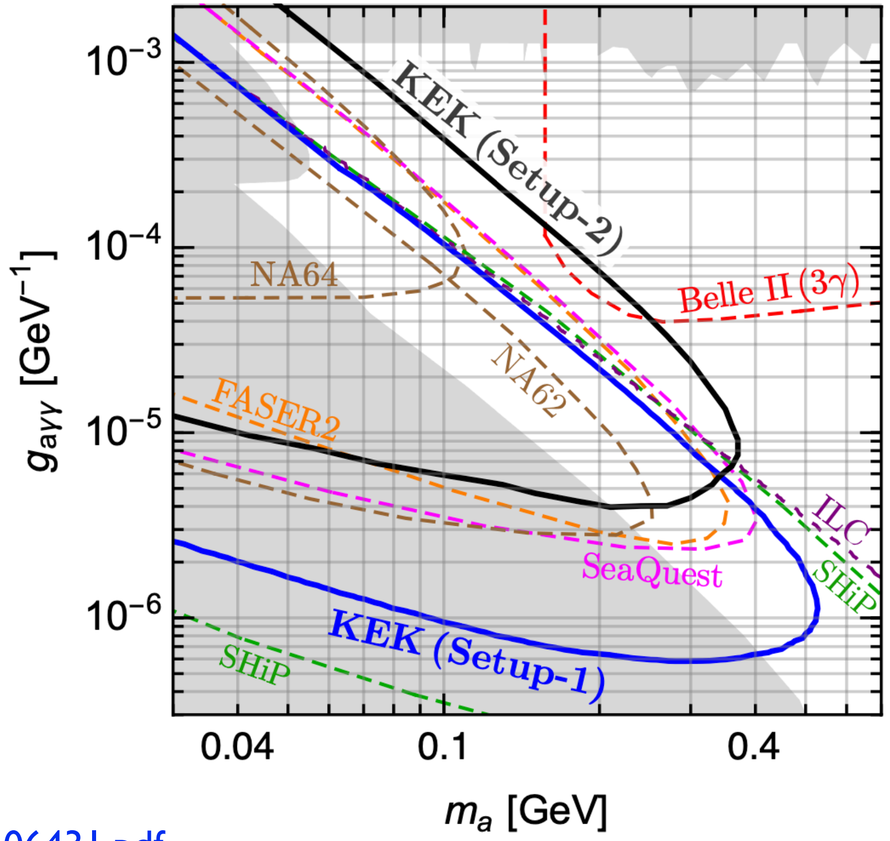


Ishikawa, Sakaki, Takubo https://arxiv.org/pdf/2107.06431.pdf

Search of ALPs with e^+e^- beams at KEK Linac

- Two experimental setups explored:
  - **Setup 1** (almost-zero bkg): 2 m shield, 1 m decay volume, 4 GeV e^+ beam
  - **Setup 2** (non-zero bkg): 20 cm shield, hollow shield, sweeping magnet, 7 GeV e^- beam
- Both can explore uncharted regions; Setup 2 has competition not even from planned exps





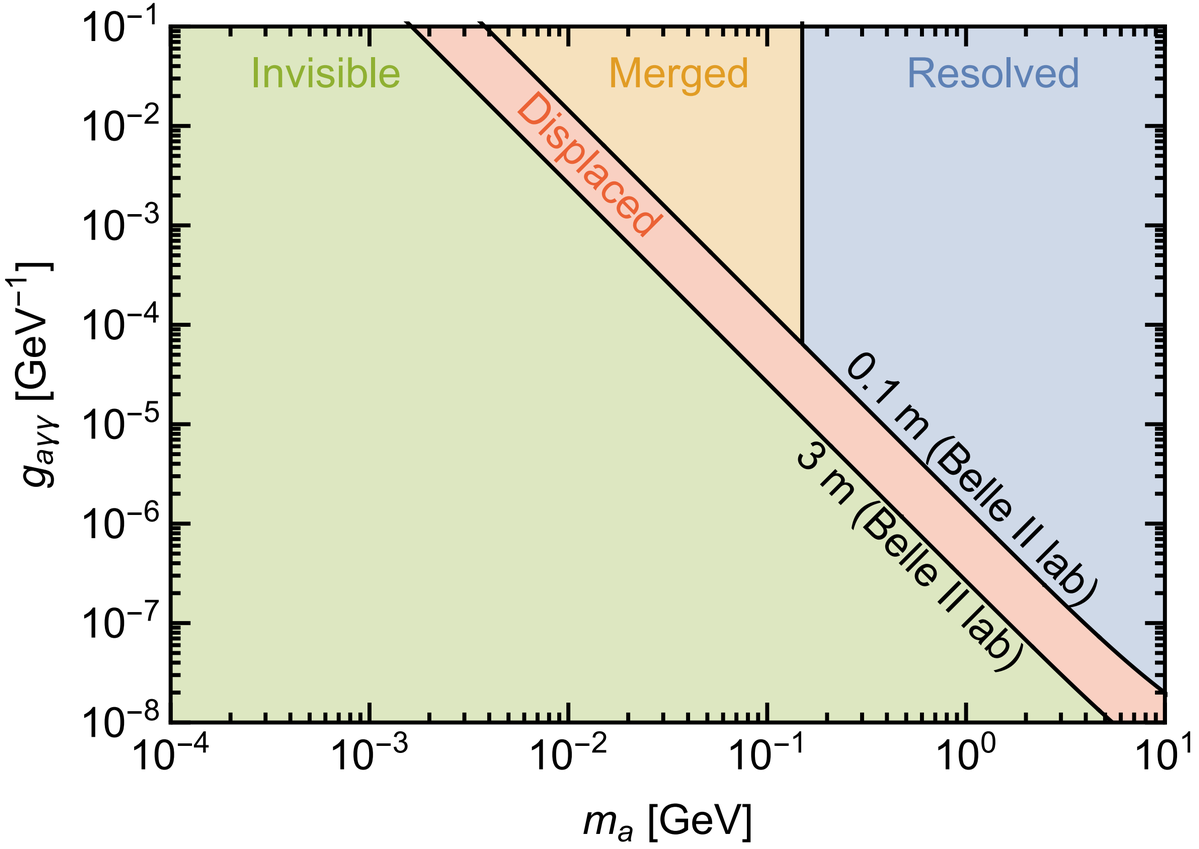
Ishikawa, Sakaki, Takubo https://arxiv.org/pdf/2107.06431.pdf

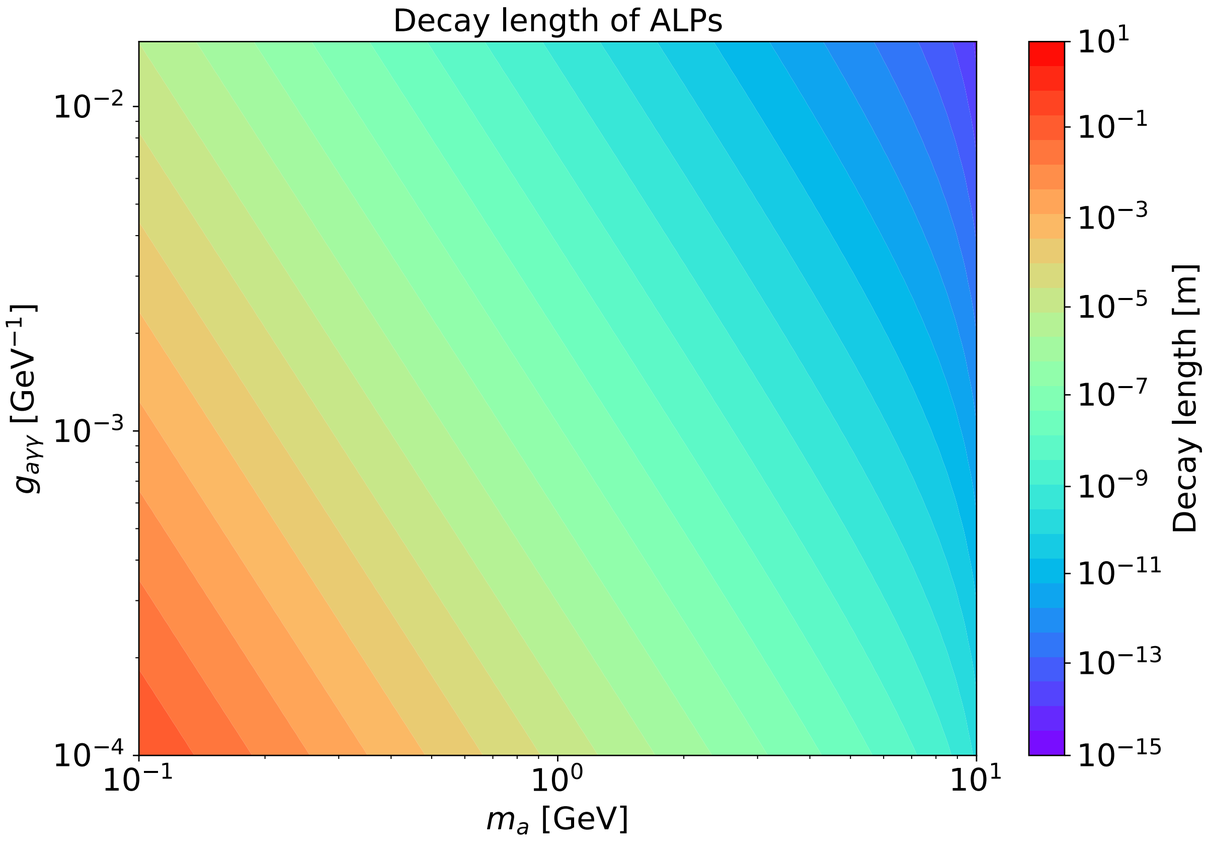
Summary

Summary

- Axions and ALPs searches at B factories are a relatively new territory
- But we are **already competitive** at “intermediate” masses
  - ALPs coupling to W
  - Photophilic ALPs
  - Heavy QCD axions
  - Fixed target
  - (and more)
- **0.1~10 GeV** is our domain
- Stay tuned for more results!

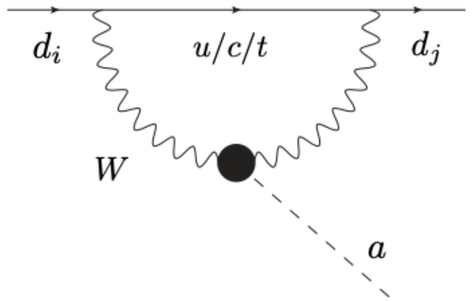
Backup

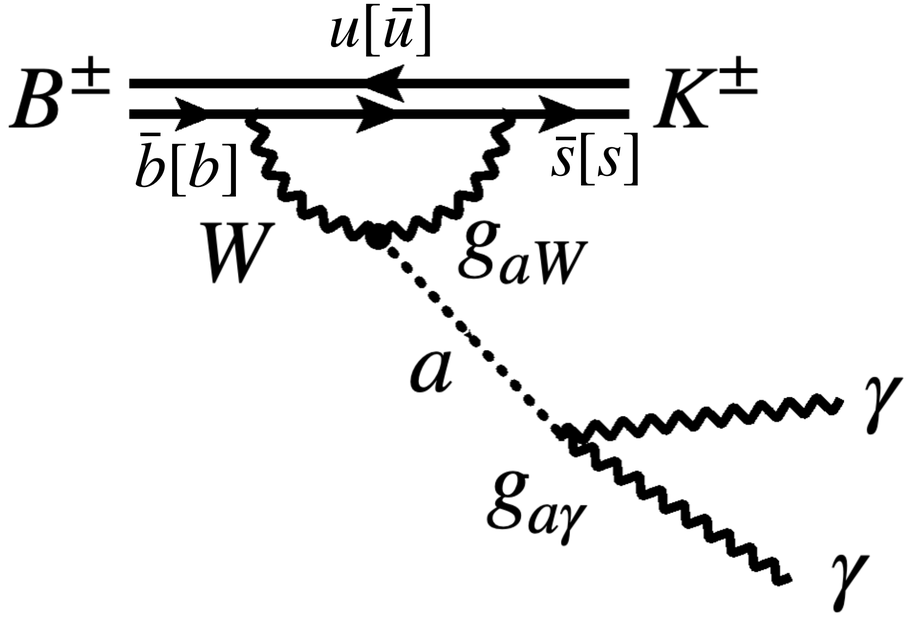




Left plot from: Dolan, Ferber, Hearty, Kahlhoefer, Schmidt-Hoberg, JHEP 1712 (2017) 094

ALPs in B decays: $\mathbf{B \to Ka}, \mathbf{a \to \gamma\gamma}$





Phys. Rev. Lett. 128, 131802 (2022)

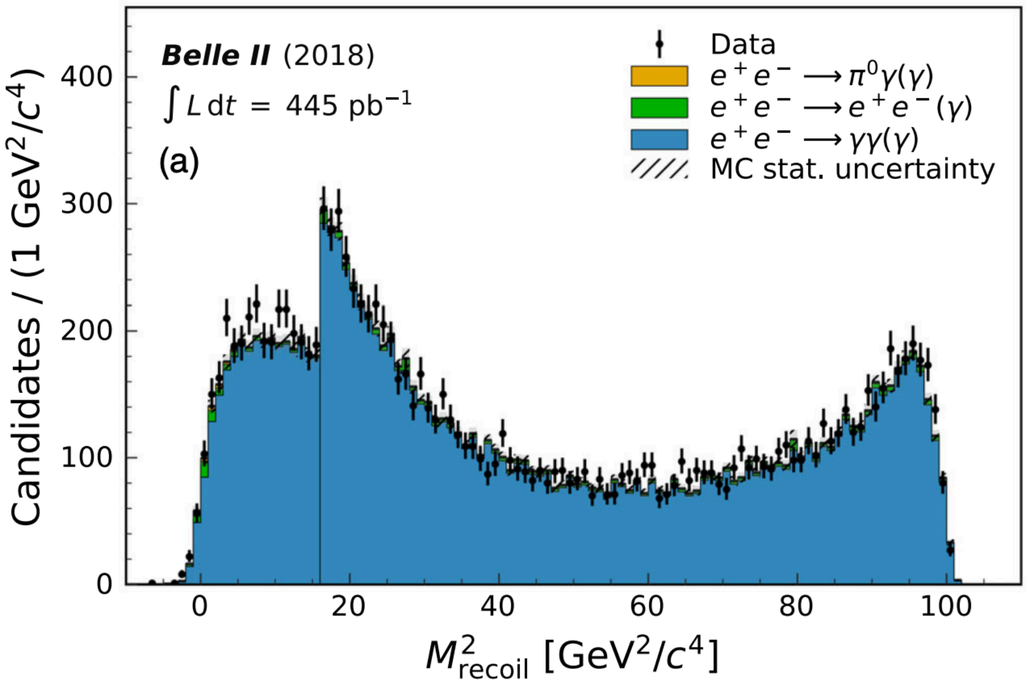
ALPs in ee collisions: $\mathbf{ee \to \gamma a,\ a \to \gamma\gamma}$

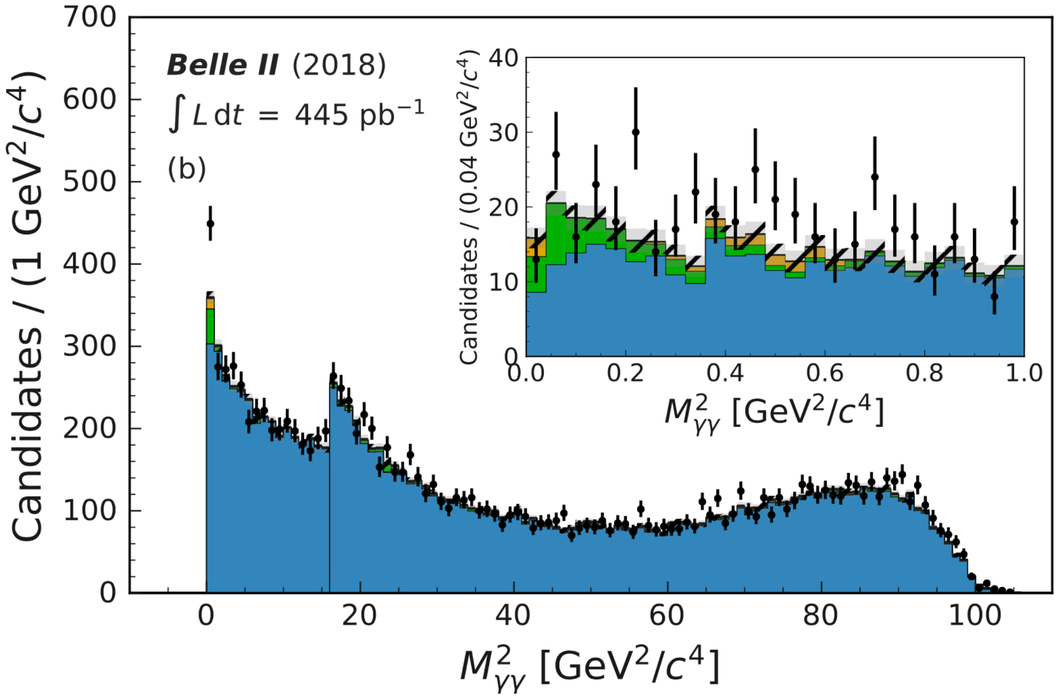
MC validation

- Check goodness of MC simulation and reconstruction

- **10%** preliminary random **unblinding**
- Simulated **extraction** with radiative **Bhabha**
- **Sideband** in $m_{\gamma\gamma\gamma}$
- Studies on **2-γ events** & radiative Bhabha

ALPs in ee collisions: $ee \to \gamma a,\ a \to \gamma\gamma$





Belle II Phys. Rev. Lett. 125, 161806 (2020)

Heavy QCD axion in $b \to s$ transitions

- exclusive final states a → 3π, φφ, KKπ, and ηππ, use a paper to calculate corresp branching fractions for axion decay, data-driven approach
  - a → 3π: Belle analysis of B->K omega, recasted
  - B → Kφφ: BABAR, 2sigma max above data seen per bin (and axions width much smaller than bin)
  - B → Ka(→ KKπ): BaBar, as before but per 2 bins because bins smaller than before; eff and cuts corrections
  - a→ηππ: as above (same babar article, same approach), except mass cut (just took weakest and extend)
- projections for B2, for a → ηππ and a → 3π searches
  - extrapolate continuum bkg from babar analysis above, then require signal < 2 std dev
  - as above, but with the Belle's a → 3π bkg

Phys. Rev. Lett. 104, 055036 (2021)

Searches for Higgs/ALPs at BaBar

- https://inspirehep.net/files/0ee7332fb6d26302eb8359d0db1ee85e
- Generic searches for scalar into invisible/tautau/mumu