The Axion Quest

20th Rencontres du Vietnam

Quy Nhon, Vietnam 08/08/2024

ALP searches at e^+e^- colliders

Marcello Campajola

on behalf of the Belle II, BaBar and BESIII collaborations

Marcello Campajola
Università di Napoli 'Federico II' and INFN Napoli
marcello.campajola@na.infn.it

New physics landscape

Models

Should new physics be light and weakly coupled?

These seem like independent requirements, but in some cases they're not.

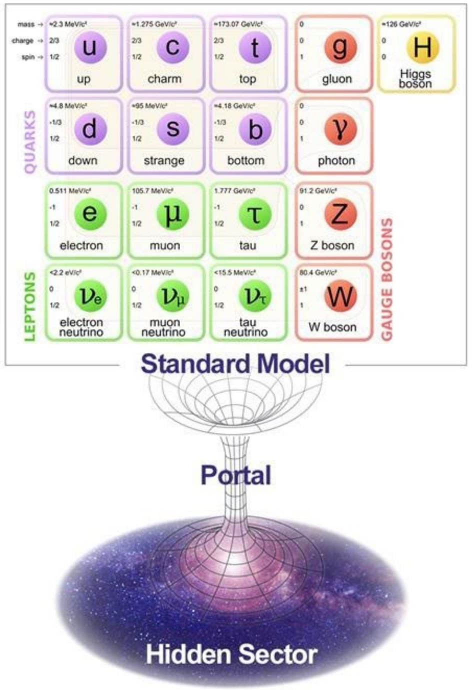
Beyond-SM theories in which a global UV symmetry is spontaneously broken predict pseudo-Goldstone bosons known as **Axion-like particles (ALPs):**

- ***they are naturally light compared to the weak scale;***
- ***their coupling strength is inversely proportional to the scale of spontaneous symmetry breaking.***

ALPs could be the only light remnant of a heavy new physics sector:

- symmetries in a dark sector, compact extra dimensions, ….

ALPs proposed as a mediators between the dark sector and ordinary matter and they could be cold dark matter candidates themselves.



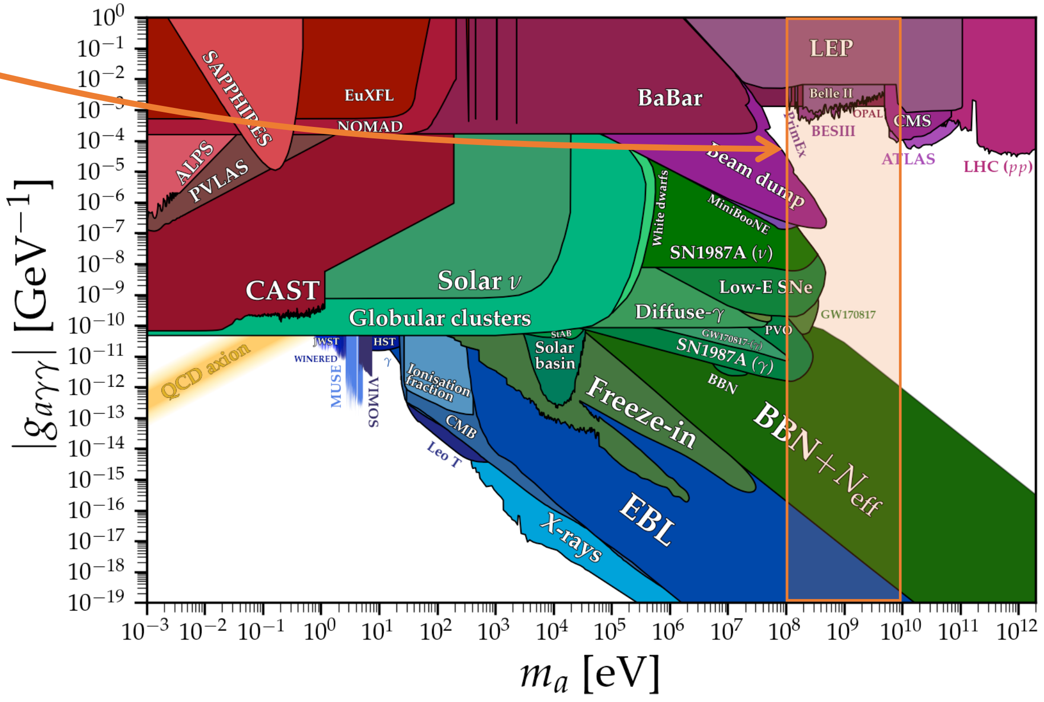
ALPs searches at e^+e^- colliders

Motivations

Lot of bounds on ALPs coupling to fermions and bosons… but still gaps in the ALP mass range from 100 MeV to roughly 10 GeV:

- out of the reach of beam dump and LHC experiments;

ALP coupling to photons



https://cajohare.github.io/AxionLimits/

ALPs searches at e^+e^- colliders

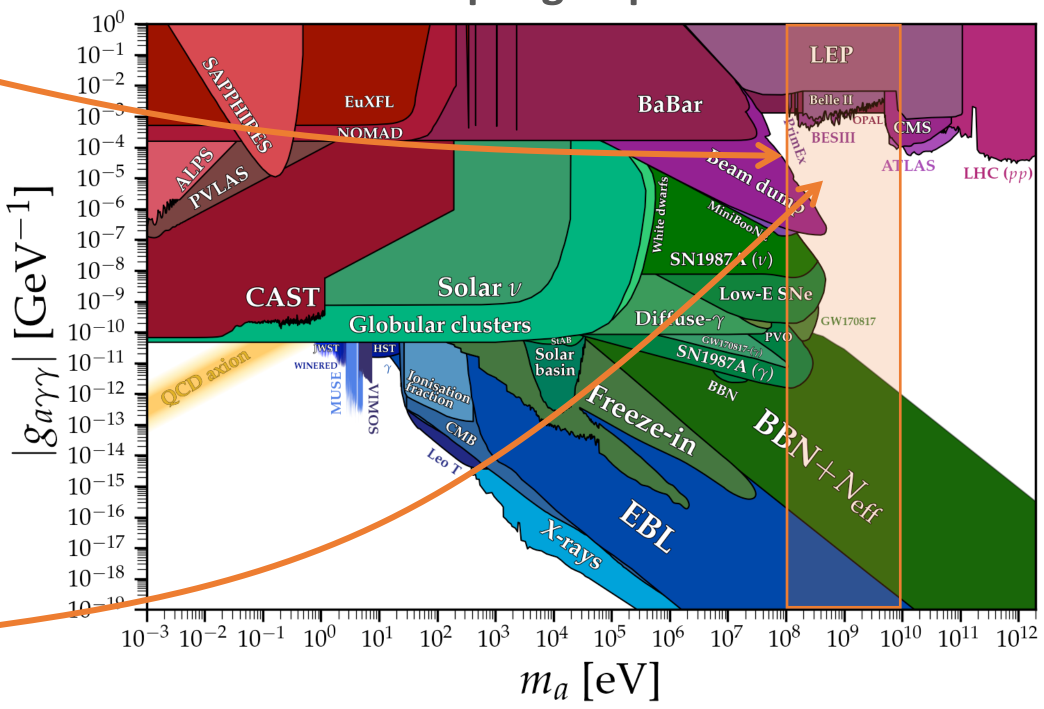
Motivations

Lot of bounds on ALPs coupling to fermions and bosons… but still gaps in the ALP mass range from 100 MeV to roughly 10 GeV:

- out of the reach of beam dump and LHC experiments;

e^+e^- low energy colliders can probe a wide variety of ALPs signatures in the MeV-GeV range, complementing other techniques and experimental approaches

ALP coupling to photons



https://cajohare.github.io/AxionLimits/

experiments and datasets

B-factory experiments

Overview

Asymmetric e^+e^- colliders optimized for the production of B meson pairs;

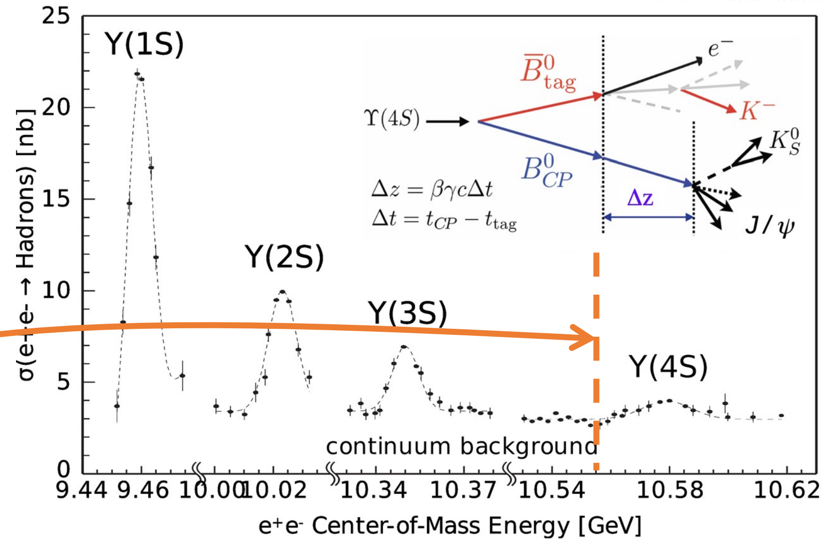
Collision at Υ(nS) resonances, mainly Υ(4S) → 10.58 GeV:

- just above the production threshold of $B\bar{B}$ (10.56 GeV);
  - BR(Υ(4S) → BB) > 96%;
- $B\bar{B}$ pair (charged or neutral) almost at rest in the CMS frame;

Asymmetric beam energies: e.g. 9.0/3.0 GeV (e^-/e^+) (BaBar):

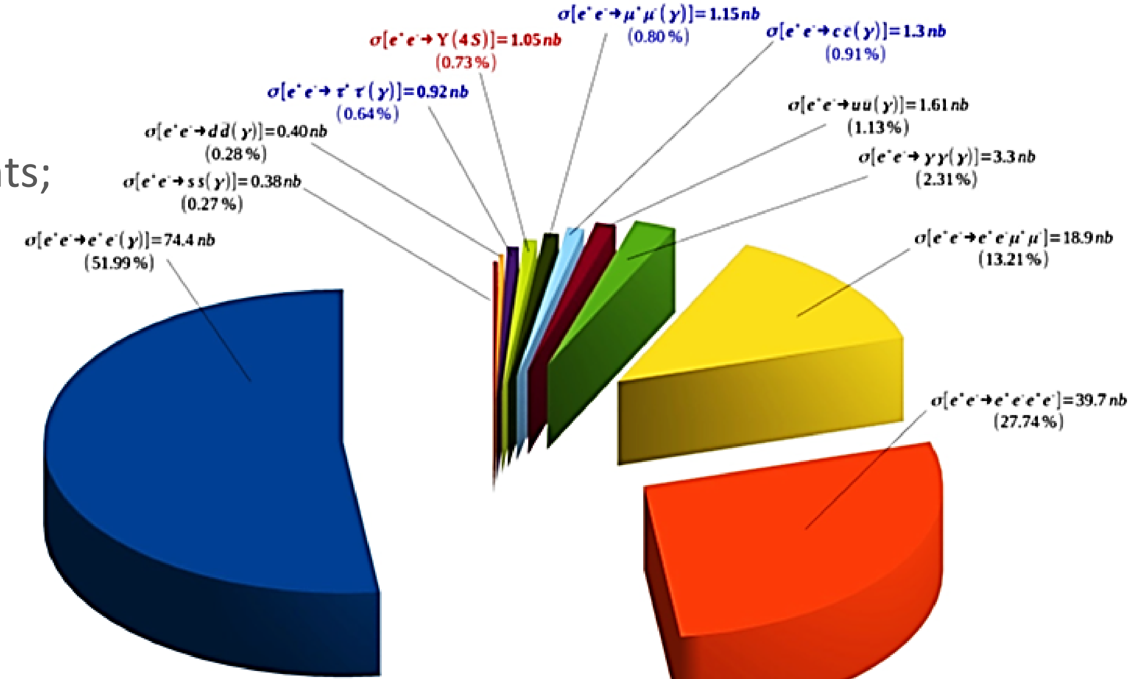
- Boosted $B\bar{B}$ pairs for CP-violation time-dependent measurements;

Large instantaneous luminosity: > 10^{34} cm^{-2} s^{-1} ;



Not just $B\bar{B}$ production:

- **rich charm, τ, quarkonium and low-multiplicity program;**

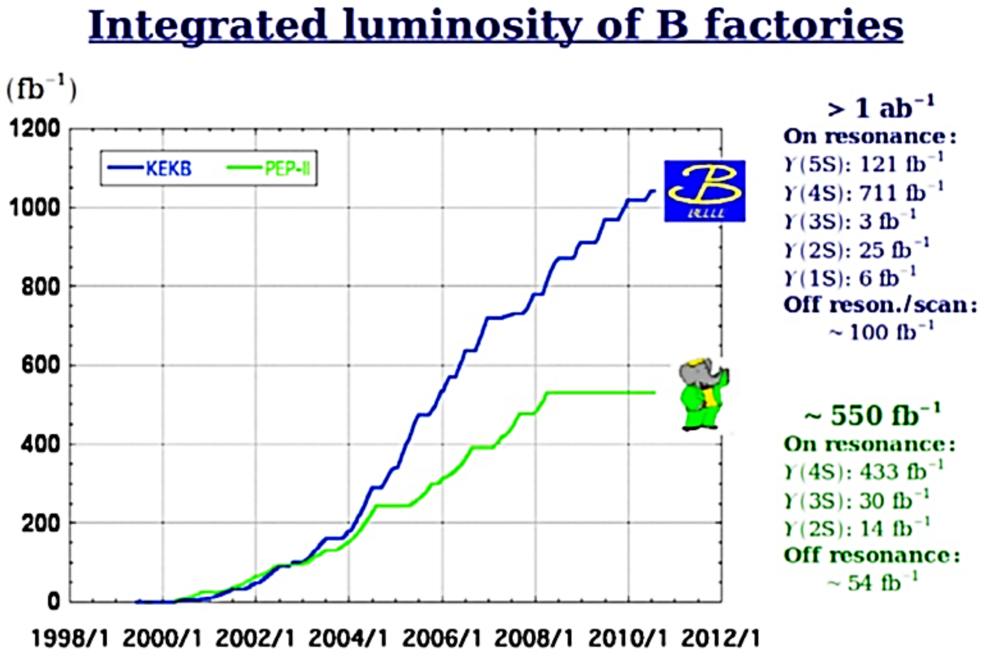


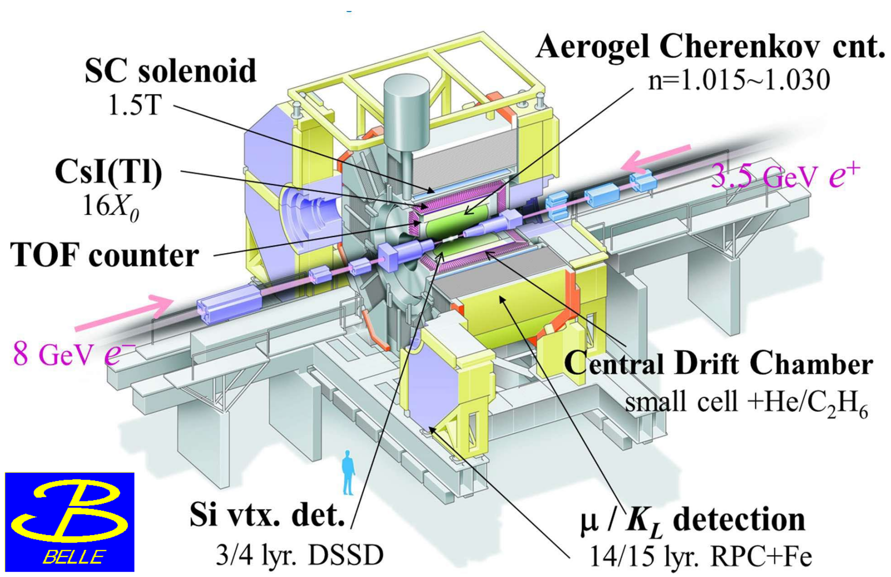
cross sections pie

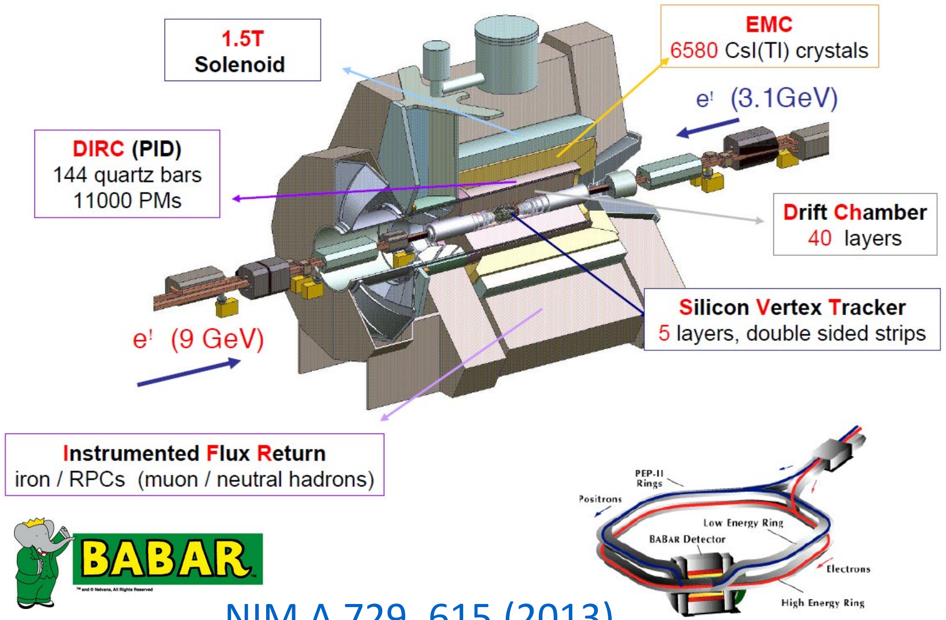
B-factory experiments

First generation

- **Belle@KEKB,** KEK (JP), 1999-2010, 711 fb^{-1} at Υ(4S);
- **BaBar@PEP-II,** SLAC (USA), 1999-2008, 462 fb^{-1} at Υ(4S);
  - More than 1 billion of B meson pair;
  - Confirmed CP Violation in the B section;
  - Precision measurement of the CKM matrix, and exotic particles;







NIM A 729, 615 (2013)

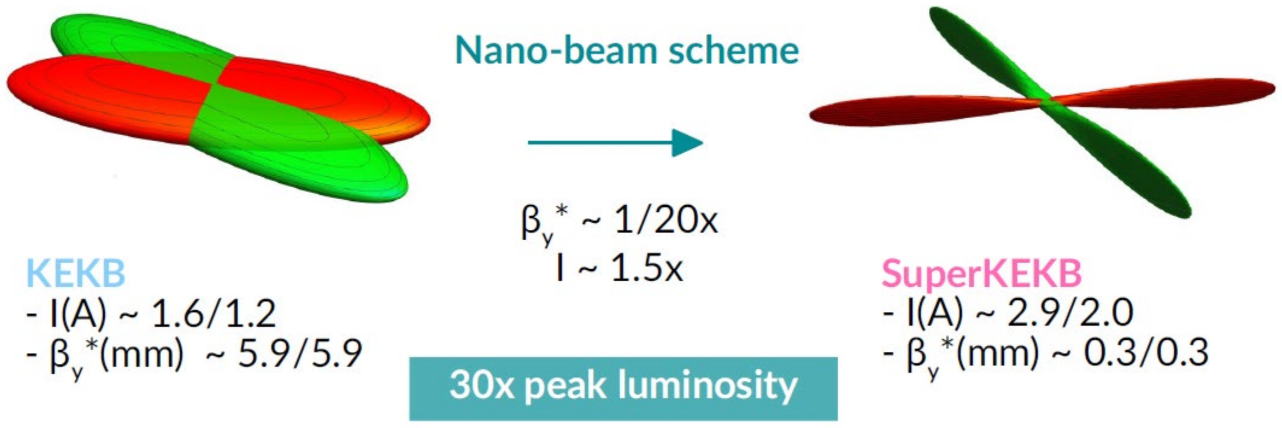
SuperKEKB & Belle II

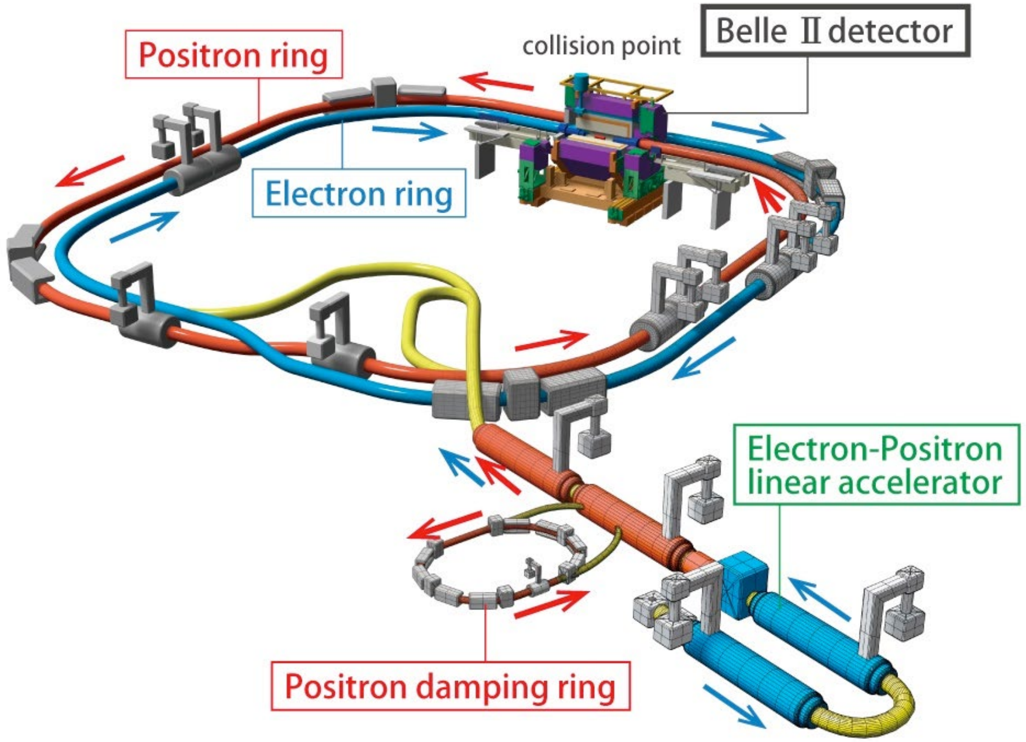
A 2nd generation B-factory

SuperKEKB is a 2nd generation asymmetric e^+e^- collider at the Y(4S) energy located at Tsukuba (Japan).
Major upgrade of KEKB.

- Target word highest instantaneous luminosity: 6×10^{35} $cm^{-2}s^{-1}$ (x30 KEKB/Belle):
  - 1.5x higher beam currents;
  - 20x smaller beam spot (''nano beam scheme'' [1]);

KEKB beams **SuperKEKB nanobeams**





[1] P. Raimondi et al., arXiv:0709.0451

SuperKEKB & Belle II

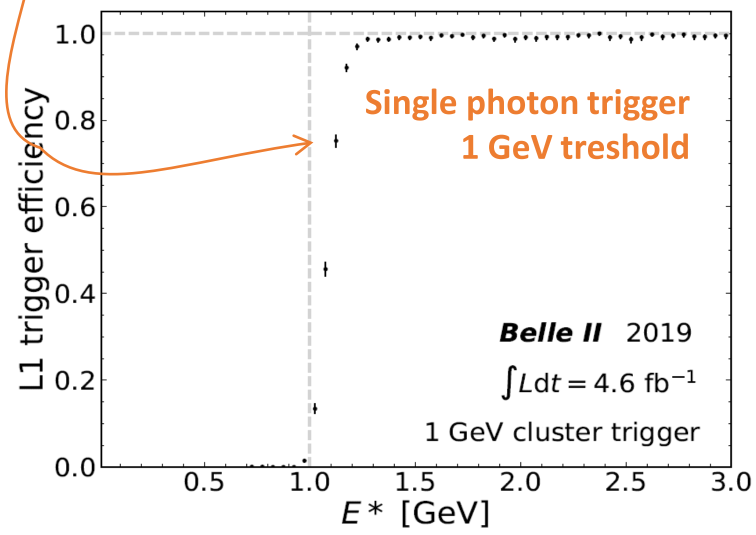
Detector overview

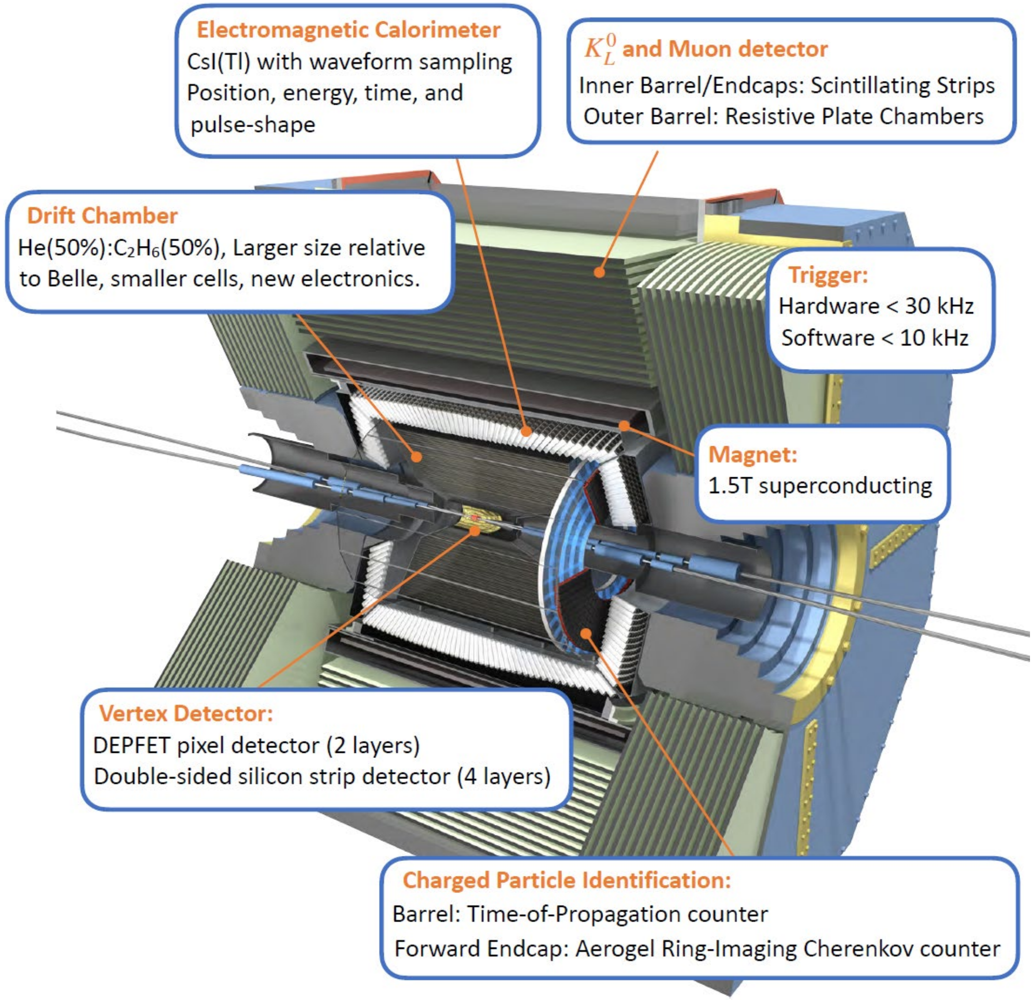
[Prog. Theo. Exp. Phys. 12 (2019)]

General purpose detectors, hermetic, with vertex detectors and particle identification.

Major upgrade of Belle@KEKB:

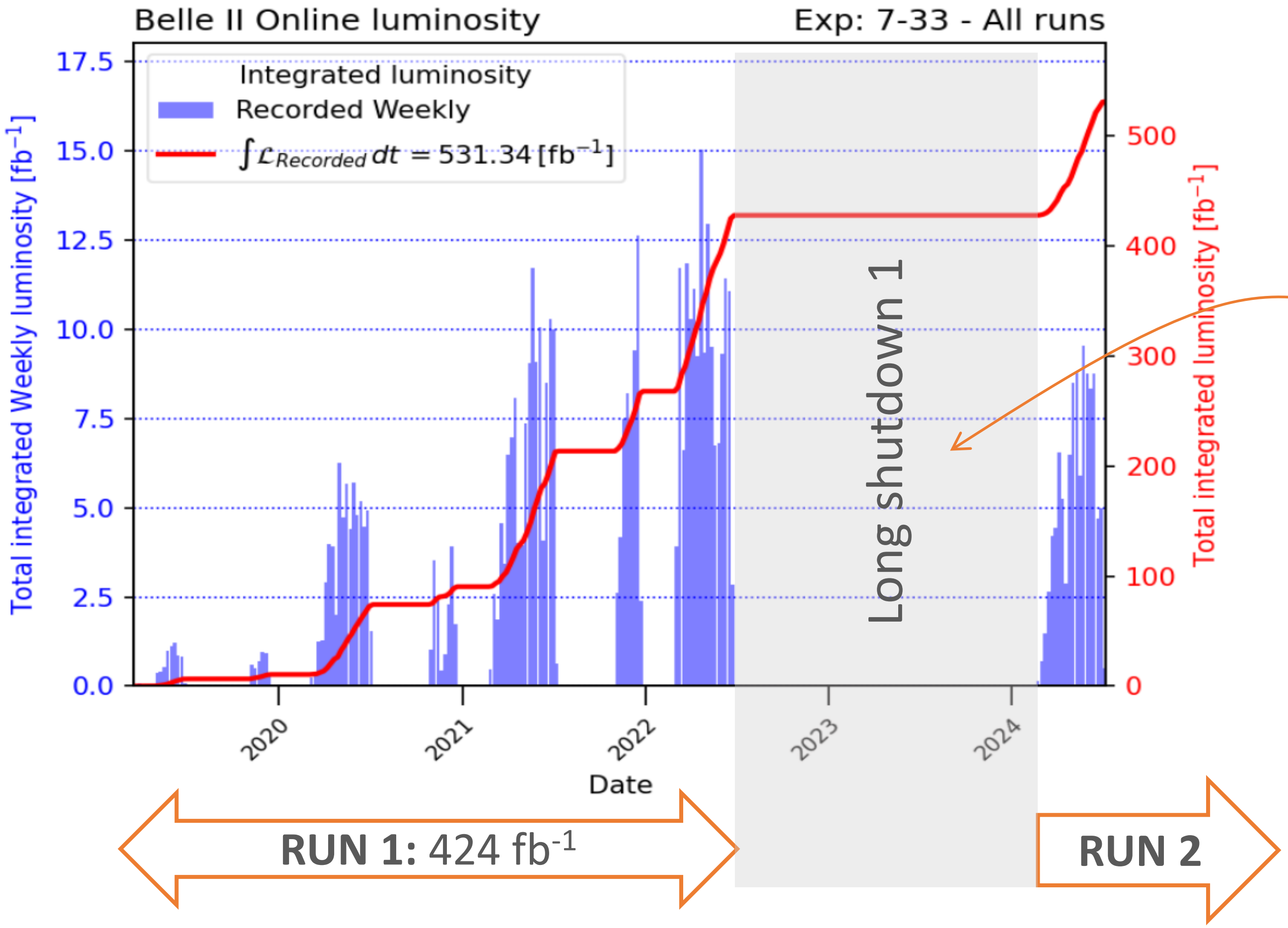
- Better resolution, particle identification and capability to cope with higher background;
- **Special low multiplicity triggers makes Belle II dataset world-unique:**
  - e.g. single photon, single muon, single track;





SuperKEKB & Belle II

Schedule



- **Data-taking from 2018;**
- **Achieved world record instantaneous luminosity: 4.7×10^{34} cm^{-2}s^{-1}**
- **Long shutdown 1 (2022-2024)**
  - detector improvements – mainly installation of full two-layer pixel detector (PXD2);
  - accelerator improvements, e.g., non-linear collimators to combat beam background;
- **Restarted collision in Feb 2024. So far collected 531 fb^{-1} (RUN 1 + 2);**
- **Target dataset: 50 ab^{-1}**

BESIII

A charm factory

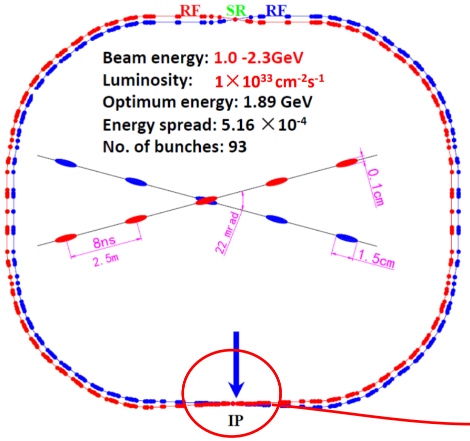
BESIII runs at BEPCII accelerator in Beijing:

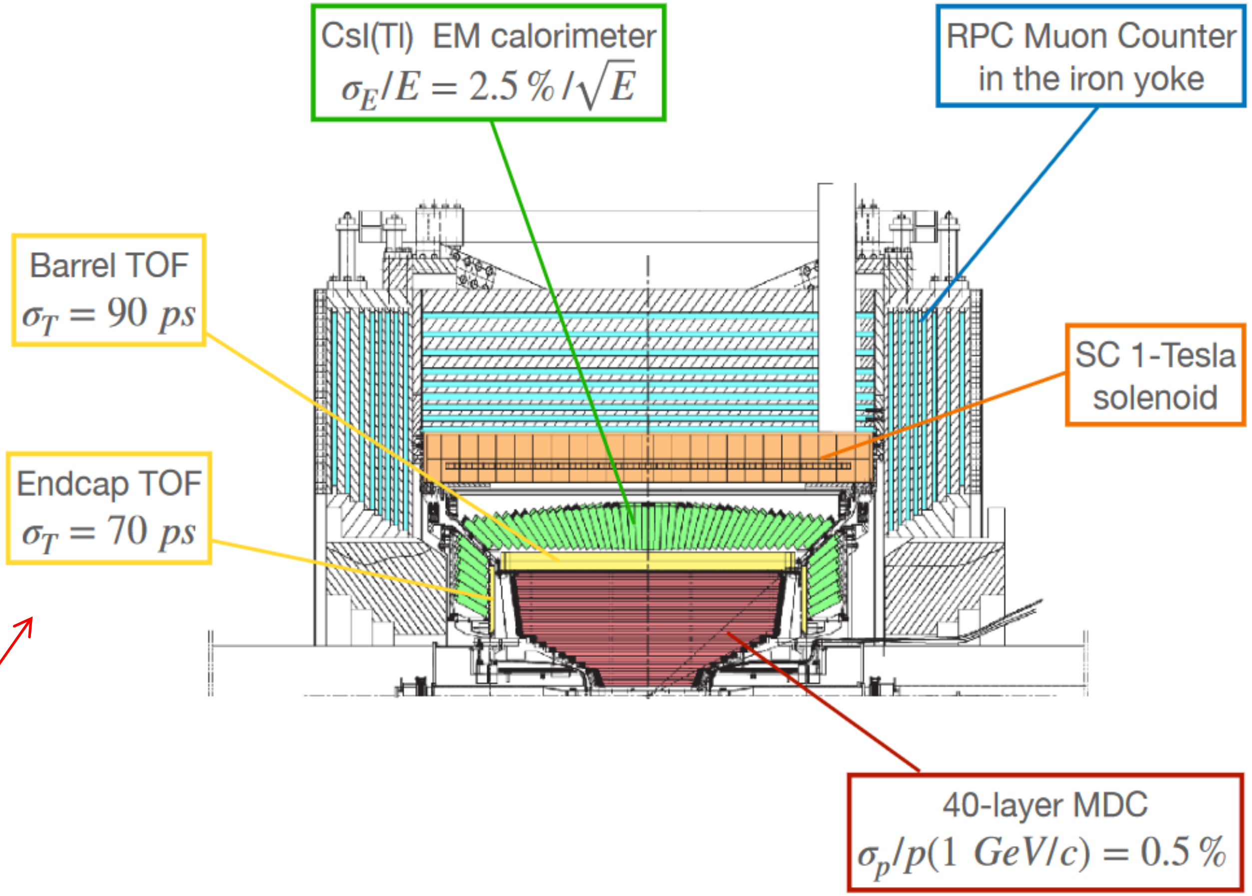
- experiment at a **symmetric e^+e^- collider around the tau-charm** pair threshold (**2-4.6 GeV**).

Physics data taking ongoing since 2009:

- Achieved peak luminosity of $\sim 1 \times 10^{33}$ cm^{-2} s^{-1}
- **Collected the largest data samples of 10 billion J/ψ, 2.7 billion ψ(3686) on threshold in the world;**

Beijing Electron–Positron Collider II





NIMA 614, 345 (2010)

ALPs searches at e^+e^- colliders

Merit factors

- High luminosity;
- Well defined initial state → kinematic constraints;
- Little/no pile-up and clean environment (few charged tracks);
- Hermetic detector coverage (almost 4π);
- Good missing energy reconstruction → signature of invisible particles;
- Excellent PID;
- Displaced vertex identification (@ Bfactories);
- Inclusive trigger for multi-track (N>3) hadronic events, and dedicated triggers for low-multiplicity searches;

Despite the nominal focus being B, charm or tau physics, excellent sensitivities for **beyond-SM physics searches also including ALPs.**

ALP signatures in e^+e^- colliders

ALPs searches at e^+e^- colliders

Production mechanisms

ALPs can couple to SM fermions or bosons.

- The most general (*dim*=5) Lagrangian:

$$\mathcal{L}_{\rm eff}^{D\le 5} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}a^2 + \frac{\partial^\mu a}{f}\sum_F \bar{\psi}_F \boldsymbol{c}_F \gamma_\mu \psi_F + c_\phi \frac{\partial^\mu a}{f}(\phi^\dagger i D_\mu \phi + \text{h.c.})$$
$$+ c_{GG}\frac{\alpha_s}{4\pi}\frac{a}{f}G^a_{\mu\nu}\tilde{G}^{\mu\nu,a} + c_{WW}\frac{\alpha_2}{4\pi}\frac{a}{f}W^A_{\mu\nu}\tilde{W}^{\mu\nu,A} + c_{BB}\frac{\alpha_1}{4\pi}\frac{a}{f}B_{\mu\nu}\tilde{B}^{\mu\nu}\,.$$

explicit mass term
couplings to fermions
coupling to the Higgs current
coupling to gluons
coupling to $SU(2)_L$ gauge bosons
coupling to hypercharge

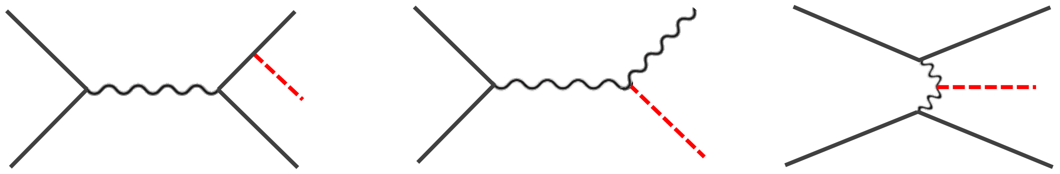
ALPs can possibly be produced/probed in a variety of modes

ALPs searches at e^+e^- colliders

Search strategy

direct production

$$e^+e^- \to X_{Dark} X_{SM}$$

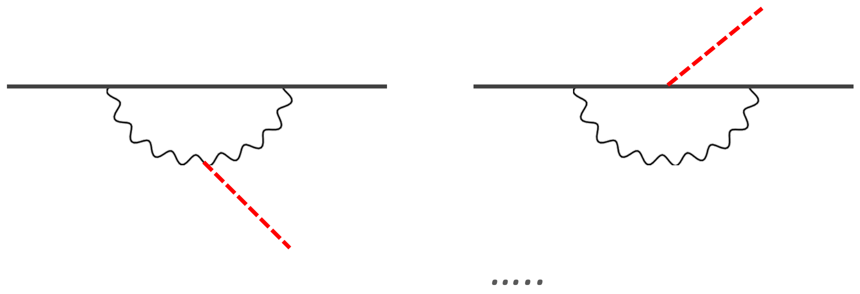


Directly produced in SM particle collisions (e.g. photon fusion, ALP-strahlung)

- **probe mediator masses up to $\sqrt{s}$;**

decay production

$$B/D/\tau/\ldots \to X_{Dark} X_{SM}$$



Produced in mesons (*B, tau* or other) decay

- **probe mediator masses up to respective meson mass;**

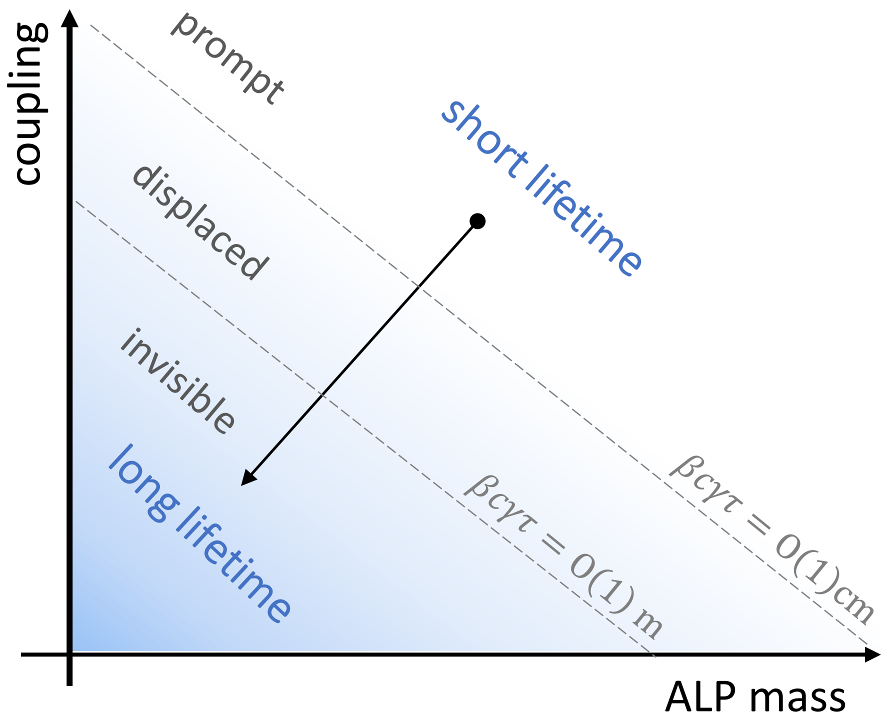
ALPs searches at e^+e^- colliders

Decay signatures

Different decay modes depending on kinematically allowed final states, favored coupling, etc.

Life-time is an additional player:

- proportional to some inverse power of the coupling and of the mediator mass;
- long lived particles can decay inside the detector and leave traces of displaced decay products or they transverse the detector and are reconstructed as missing energy from the remainder of the event:
  - decay-length < O(1)m: **displaced decay vertices**;
  - decay-length > O(1)m: **decay outside the detector (invisible);**



ALPs searches at e^+e^- colliders

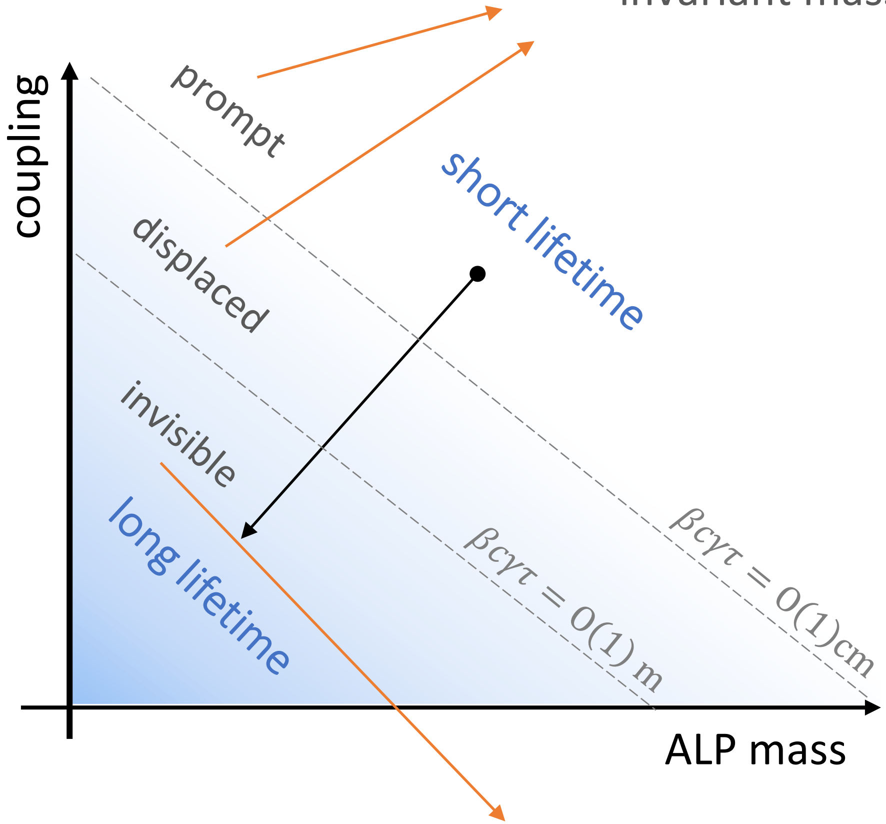
Decay signatures

Different decay modes depending on kinematically allowed final states, favored coupling, etc.

Life-time is an additional player:

- proportional to some inverse power of the coupling and of the mediator mass;
- long lived particles can decay inside the detector and leave traces of displaced decay products or they transverse the detector and are reconstructed as missing energy from the remainder of the event:
  - decay-length < O(1)m: **displaced decay vertices**;
  - decay-length > O(1)m: **decay outside the detector (invisible);**

bump in the decay produts invariant mass



same signature as decay to DM ⟺ missing energy signature

ALP searches at e^+e^- colliders

Talk overview

This talk will review (recent) dedicated searches for Axion-like particles at BABAR, Belle II and BESIII:

BESIII:

- $\psi(3686) \rightarrow \pi^+\pi^-$ J/ψ, J/ψ → γ a, a →γγ PLB 838, 137698 (2023)
- J/ψ → γ a, a →γγ arXiv:2404.04640 (2024)

BaBar:

- B → K a, a →γγ PRL 128, 131802 (2022)

Belle II:

- B → K a, a →x^+x^- PRD 108, L111104 (2023)
- τ → l a, a → invisible PRL 130, 181803 (2023)
- e^+e^- → μ μ a, a → τ τ PRL 131, 121801 (2023)

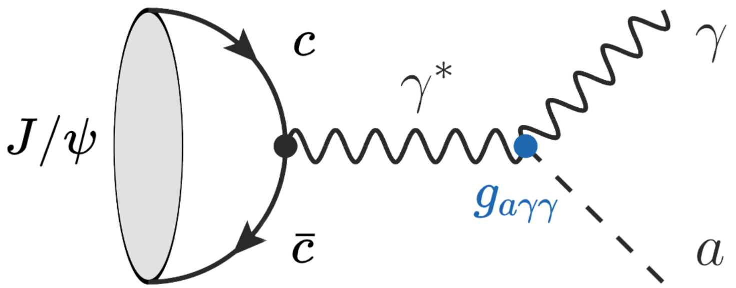
ALPs in J/ψ decays

Overview

Search for ALPs that predominantly couple to γ gauge boson

@ BESIII: search for $J/\psi \to \gamma a, a \to \gamma\gamma$ decay with J/ψ obtained from $\psi(3686) \to \pi^+\pi^- J/\psi$;

- $\pi^+\pi^-$ used to tag J/ψ and probe ALPs resonant production;
- Using a data sample of 2.7 x 10^9 $\psi(3686)$ events corresponding to one billion of J/ψ; Phys. Lett. B 838, 137698 (2023)

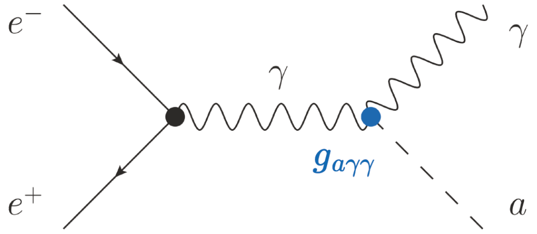


assumed negligible coupling to charm quark

@ BESIII: brand new search for ALPs in untagged J/ψ decays:

- **$J/\psi \to \gamma a, a \to \gamma\gamma$ with a data sample of 10 x 10^9 J/ψ events on threshold;**
  - 3 gamma final state;
  - No charged tracks;
  - Peak in the digamma mass spectrum;

Same final state of ALP-strahlung
Its contribution subtracted from the signal yield.



ALPs in J/ψ decays

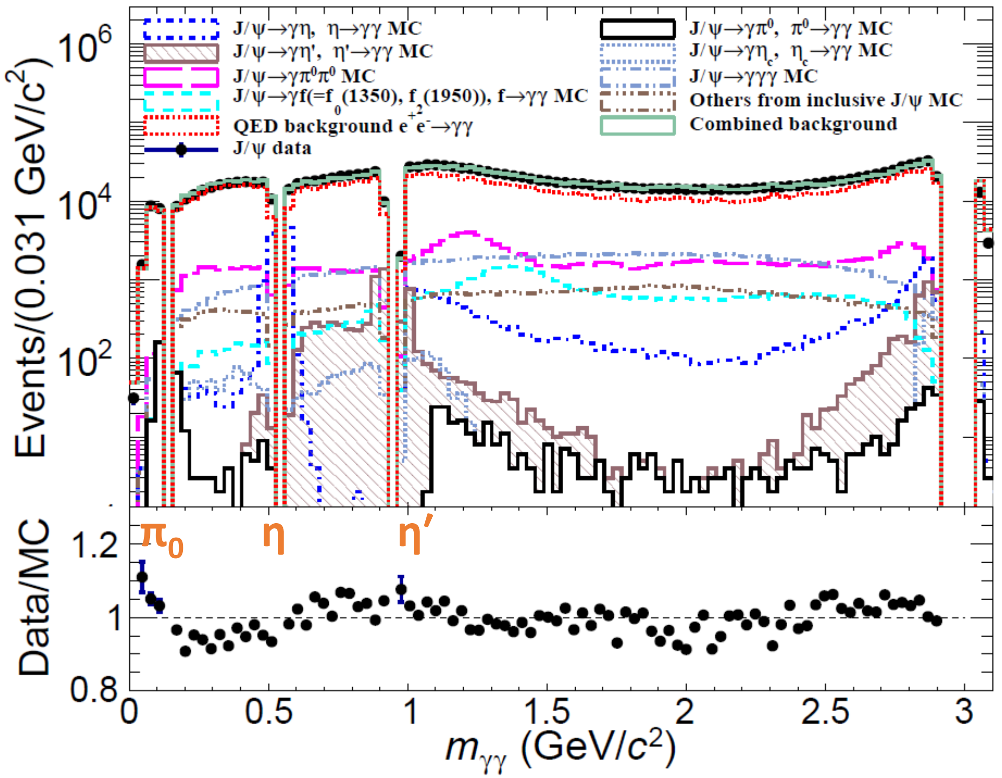
Strategy

Main background from:

- pseudoscalar meson production $J/\psi \rightarrow \gamma P$ with P = {π^0, η, η′};
- $e^+e^- \rightarrow \gamma\gamma(\gamma)$;
  - data-driven prediction from continuum data at a center of mass energy below J/ψ threshold;

Signal extraction:

- Unbinned maximum likelihood fits to the $M_{\gamma\gamma}$ distribution;
- Scan in steps of 1 MeV for m_a<1.5 GeV, 2 MeV above;
- Likelihood function includes signal and backgrounds;
  - peaking background mass regions excluded and used to validate the signal extraction procedure;



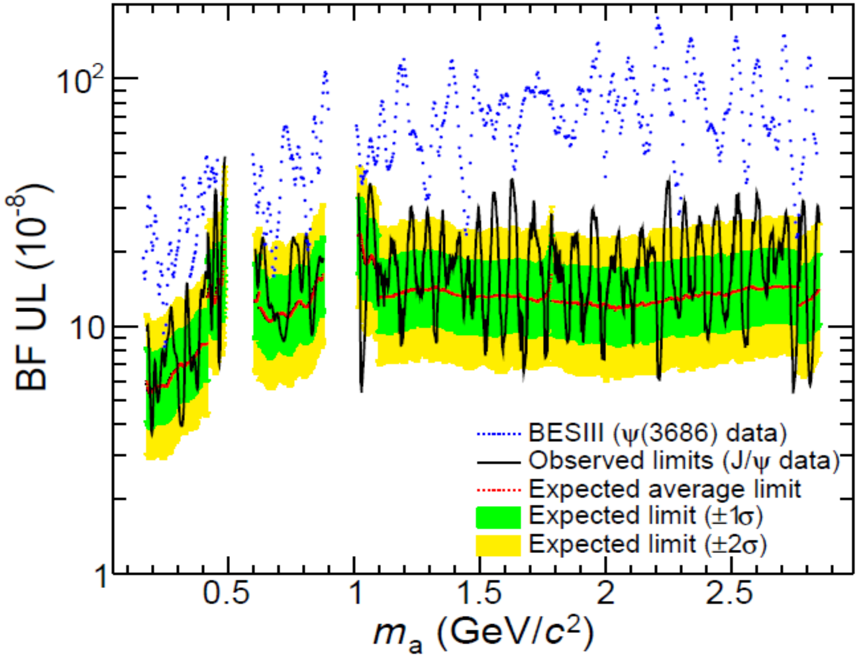
ALPs in J/ψ decays

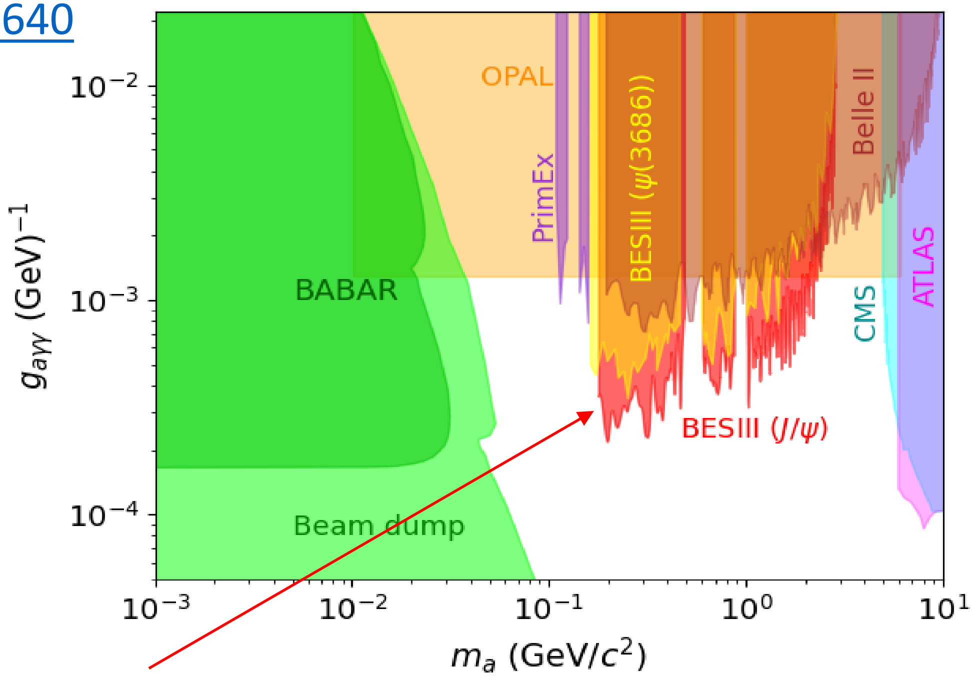
Results

No significant ALP signal observed (maximum global significance 1.6 σ)

- Upper limits at the 95% C.L. on the product branching fraction BF(J/ψ → γa) × BF(a → γγ), and on the coupling of ALP to a photon pair ($g_{a\gamma\gamma}$)

Accepted by PRD(L)
[arXiv:2404.04640](https://arxiv.org/abs/2404.04640)





most stringent to date for 0.18 ≤ m_a ≤ 2.85 GeV

ALPs in B-meson decays

Overview

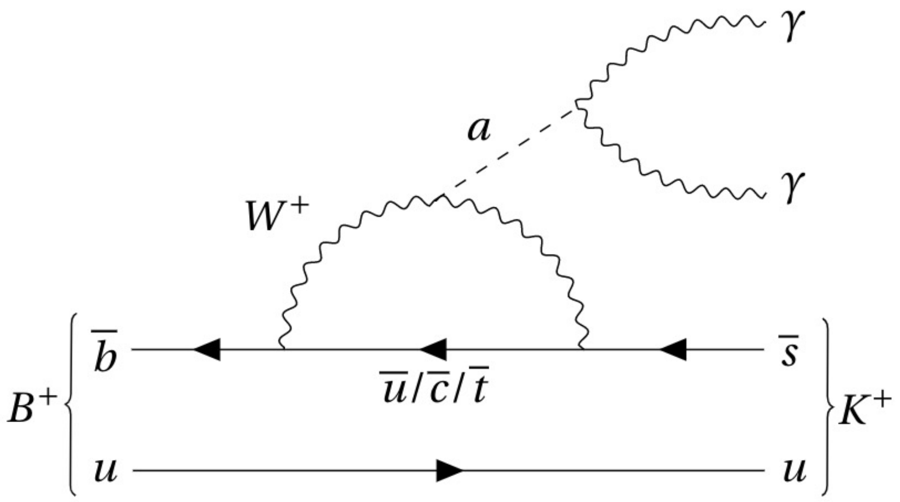
Search for ALPs that predominantly couple to electroweak gauge bosons in flavor changing neutral current (FCNC) B decays:

- FCNC are extremely suppressed in the SM → perfect testbed to search for ALP emission by $W^{\pm}$ boson;
    - The SM FCNC B meson decay is of the same order as ALP production in the weak interaction;

@ BaBar: search for ALP in B → K a decays, exploiting b → s transition

- Signal $B^{\pm}$ reconstructed combining a pair of photons with a track identified as a kaon;
- Look for narrow peak in di-photon invariant mass spectrum;

Note: ALP lifetime becomes important at low masses and couplings ($\tau \sim 1/m_a^3 g_{aW}^2$) → long-lived ALP



$a \to \gamma\gamma$ dominates

$BR(a \to \gamma\gamma) \simeq 100\%$ for $m_a \ll m_{W^{\pm}}$

ALPs in B-meson decays

Analysis strategy

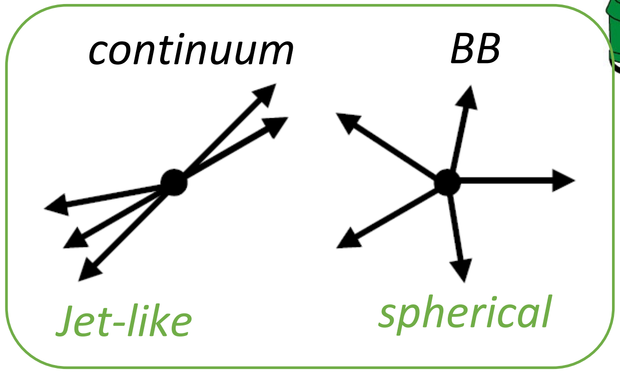
Background rejection:

- Invariant mass and total energy constrained to the nominal B mass and measured c.m. beam energy for continuum rejection;
- 2 BDTs to separate signal from the continuum QCD and BB processes (13 variables, including event-shape ones);
    - Background dominated by the continuum QCD, BB processes subdominant;
    - Peaking backgrounds observed at π^0, η, and η';

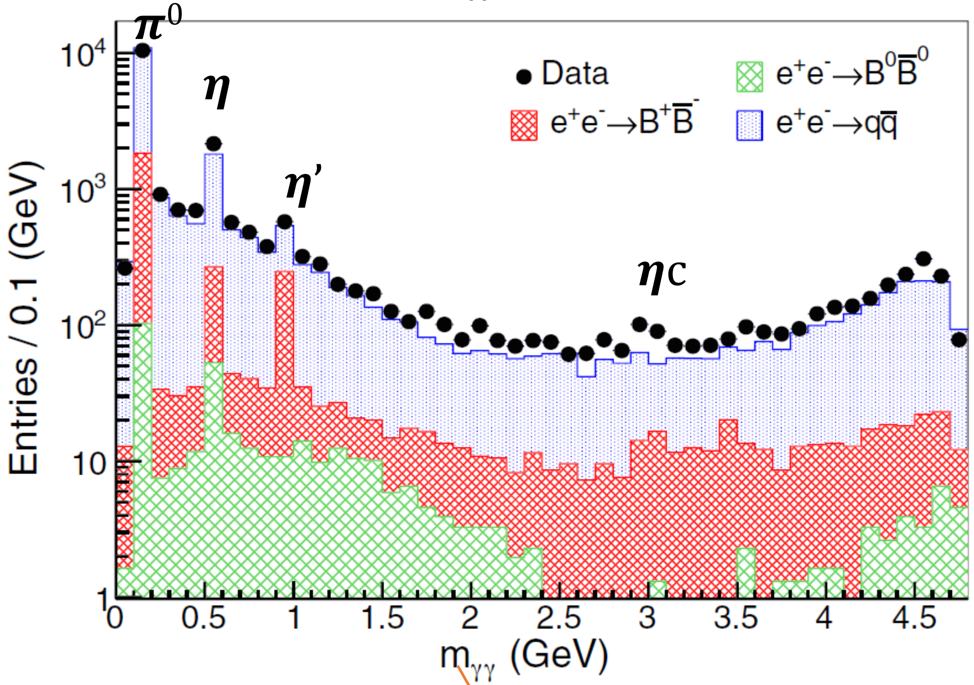
Signal extraction:

- Apply kinematic fit to improve axion mass resolution;
- Scan $m_{\gamma\gamma}$ in steps of signal mass resolution (~ 8 – 14 MeV);
- Fit signal peak over smooth background away from low energy resonances;
    - explored range 0.1 GeV < m_a < m_B-m_k = 4.78 GeV;

Event topology



Final $m_{\gamma\gamma}$ mass distribution



$m_a = m_{\gamma\gamma}$ distribution

ALPs in B-meson decays

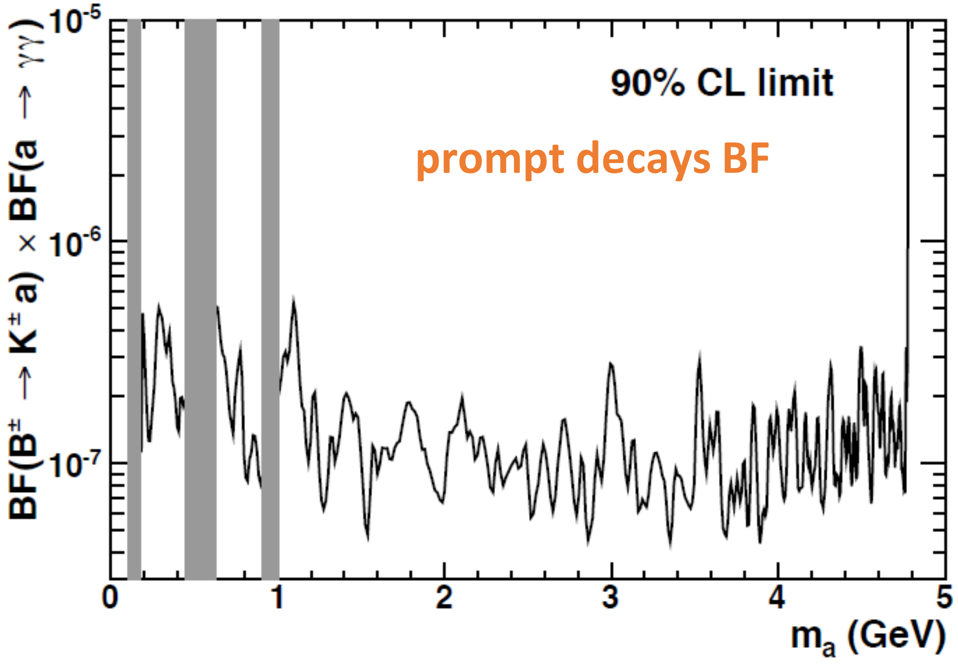
Results

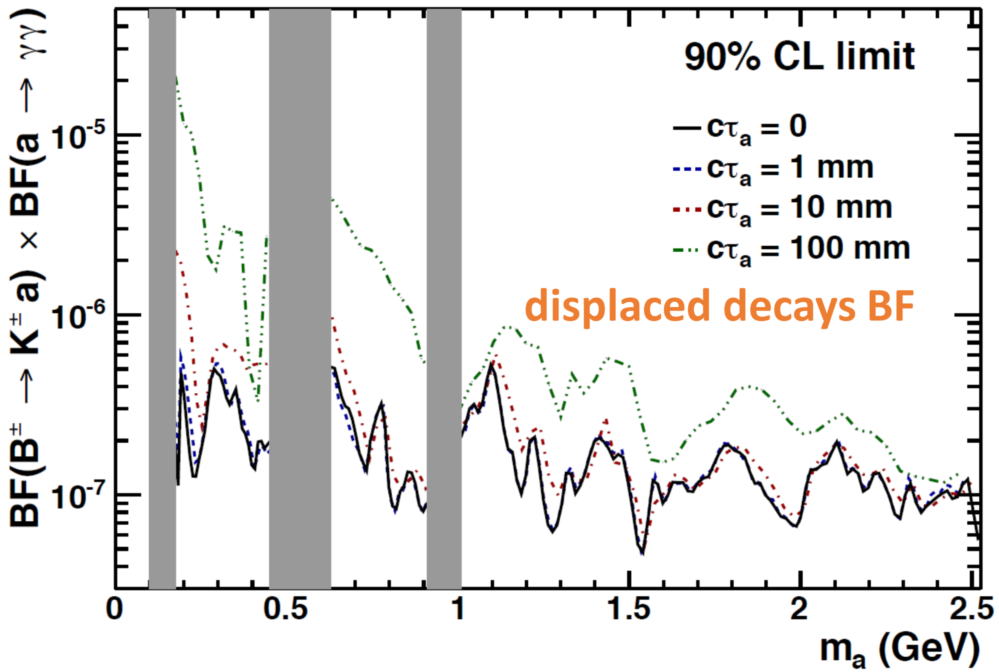
No signal in 424 fb^{-1} of data (largest global significance $\sim 1\sigma$);

- **90% C.L. upper limits on the BF:**
  - **for m_a < 2.5 GeV also provide displaced decay results;**
    - displaced vertex not reconstructed, but ALP resolution degraded;

$\tau \sim 1/m_a^3 g_{aW}^2$

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





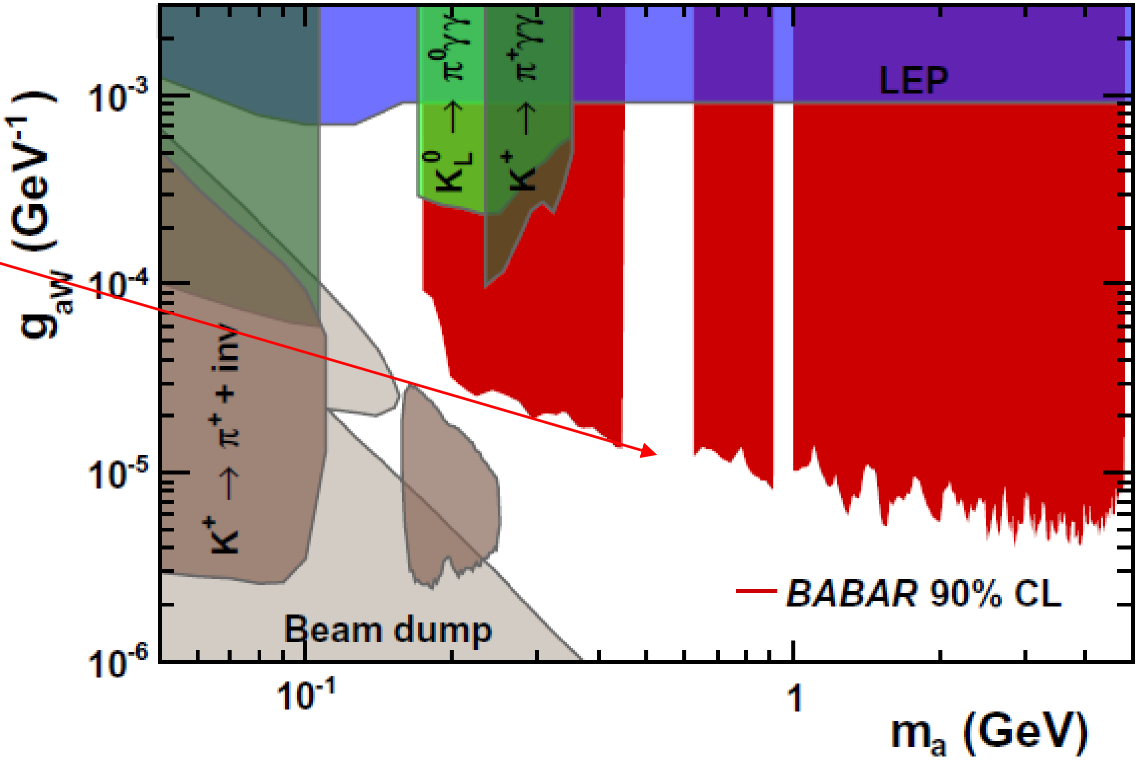
ALPs in B-meson decays

Results

No signal in 424 fb^{-1} of data (largest global significance $<1\sigma$);

- **90% C.L. upper limits set on the g_{aW} coupling constant**
  - **First search for visibly decaying ALPs produced in B meson decays;**
  - **Limits on g_{aW} improved up to two order of magnitudes over a large mass range;**

90% CL upper limits on coupling g_{aW}

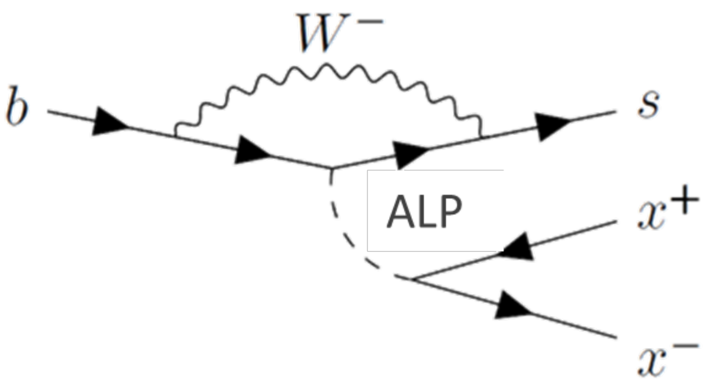


Phys. Rev. Lett. 128, 131802 (2022)

Long-lived ALP in B-meson decays

Overview

Search for ALPs that predominantly couple to fermions in FCNC B decays;

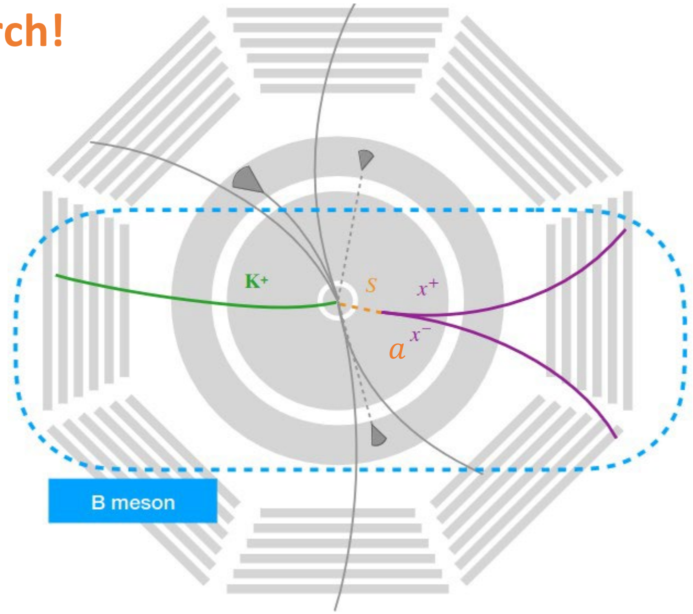


@ Belle II:

- search for a long-lived ALPs produced in b to s transitions:
  - $B^+ \to K^+ a;$
  - $B^0 \to K^{*0}(\to K^+\pi^-)\ a;$

  followed by a decay into opposite charged tracks ($ee, \mu\mu, \pi\pi, KK$) from a **displaced vertex;**
  - probe lifetimes between $10^{-5} < c\tau < 4\,\mathrm{m}$

First Belle II long-lived particle search!



transverse view of the Belle II detector

Strategy:

- Search for a bump in the invariant mass of tracks coming from a displaced vertex;
- Displaced vertex distance from interaction region > 0.05 cm;
  - displaced vertex -> low backgrounds;

Long-lived ALP in B-meson decays

Strategy

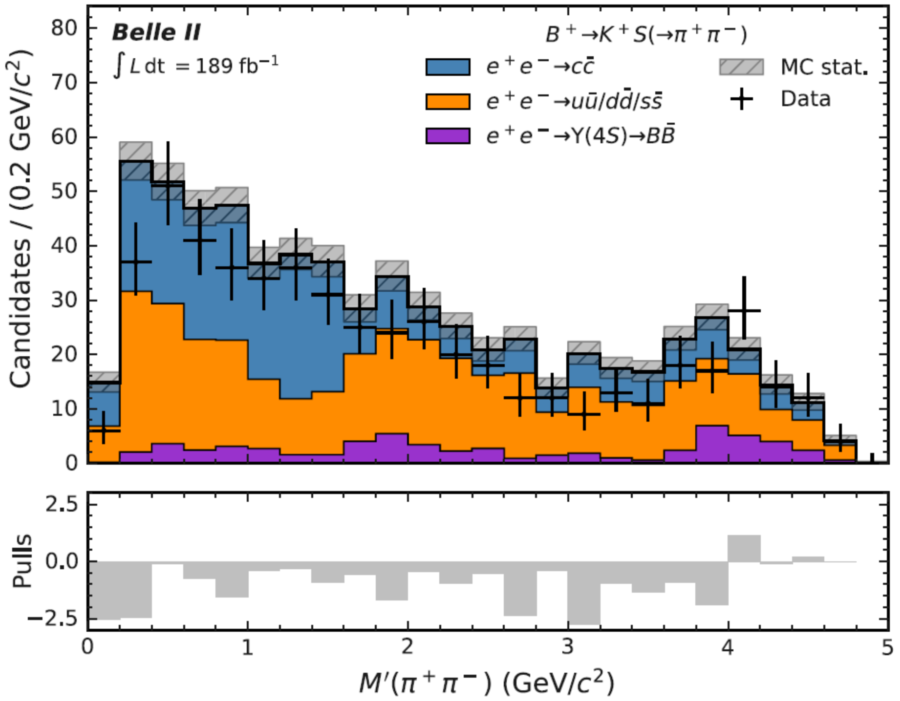
Background rejection:

- For continuum rejection:
  - invariant mass and total energy constrained to the nominal B mass and measured c.m. beam energy;
  - event shape variables;
- SM long-lived K_S^0 mass region vetoed and used to evaluate long-lived particle performance (efficiencies, shapes, particle identification);
- Further peaking backgrounds (ϕ, J/ψ) suppressed by tighter displacement selection;

Signal extraction:

- Search for a bump in the reduced invariant mass of tracks coming from a displaced vertex. Scan in step of half resolution (2 to 10 MeV);
  - using the reduced mass simplify the modeling of the signal width close to kinematic thresholds;
- Background determined directly in data (robust against un-modelled non-peaking background);

mass spectrum for pion channel



$$M'(x^+x^-) = \sqrt{M^2_{a\to x^+x^-} - 4m_x^2}$$

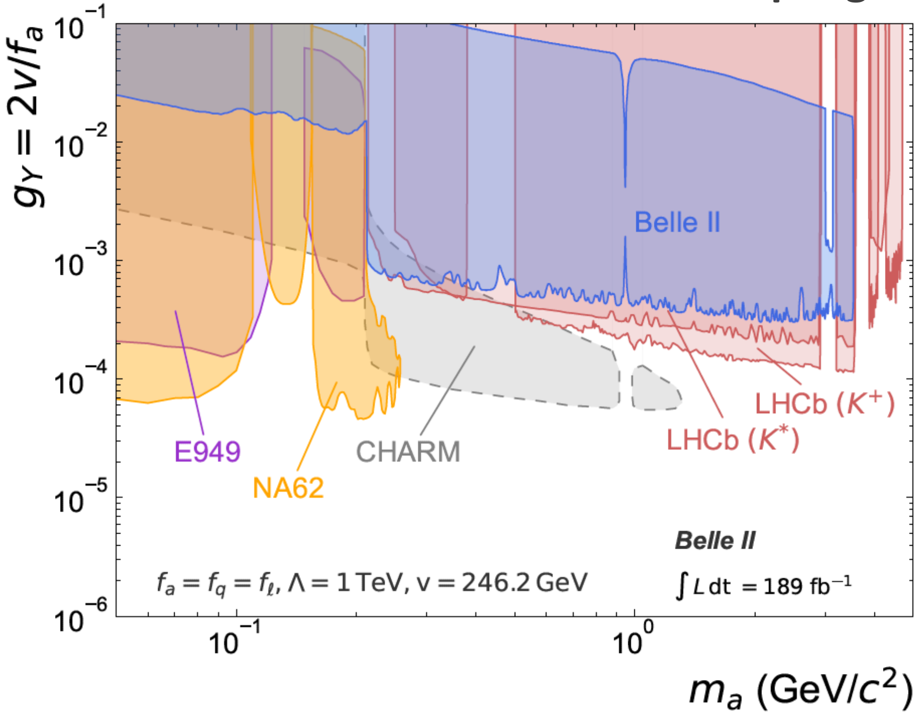
Long-lived ALP in B-meson decays

Results

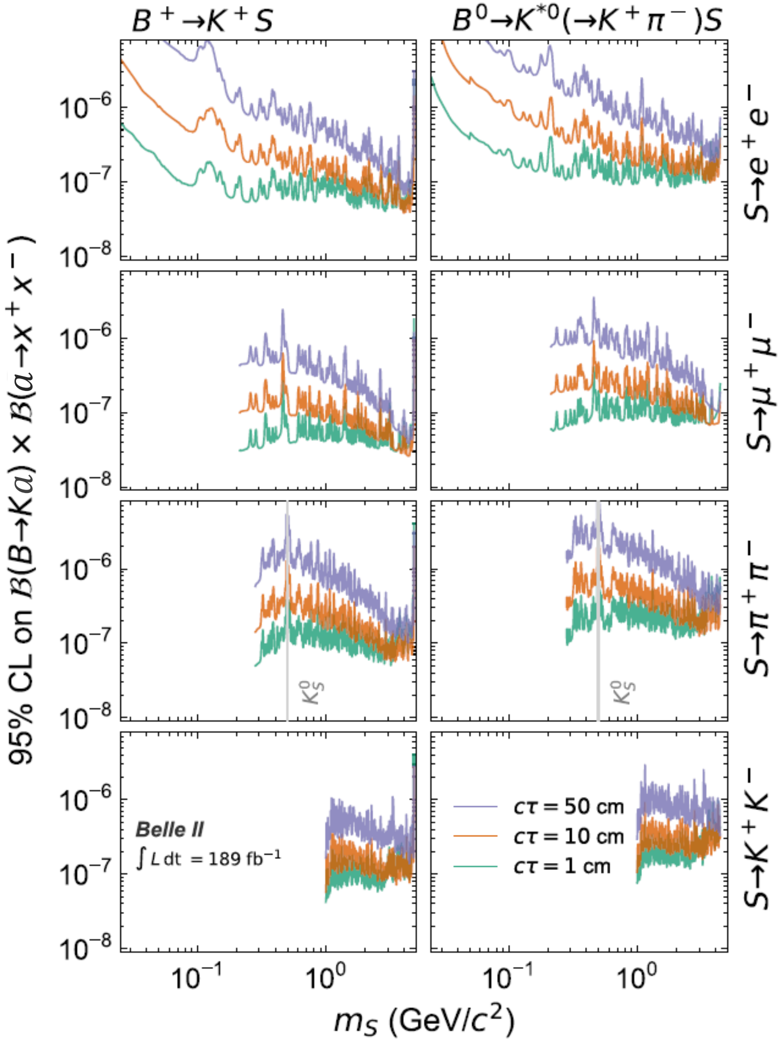
No significant excess observed in 189 fb^{-1} (largest global significance <1σ);

- **First model-independent limits on BR to exclusive hadronic final states;**
- 95% UL on the coupling to fermions;

95% UL on the ALP-fermion coupling



Phys. Rev. D 108, L111104 (2023)



Invisible ALP in LFV τ decays

Overview

τ decays to new LFV bosons a decaying invisibly predicted in many models:

- **possible ALPs candidates [1]**

@ Belle II search for the process:

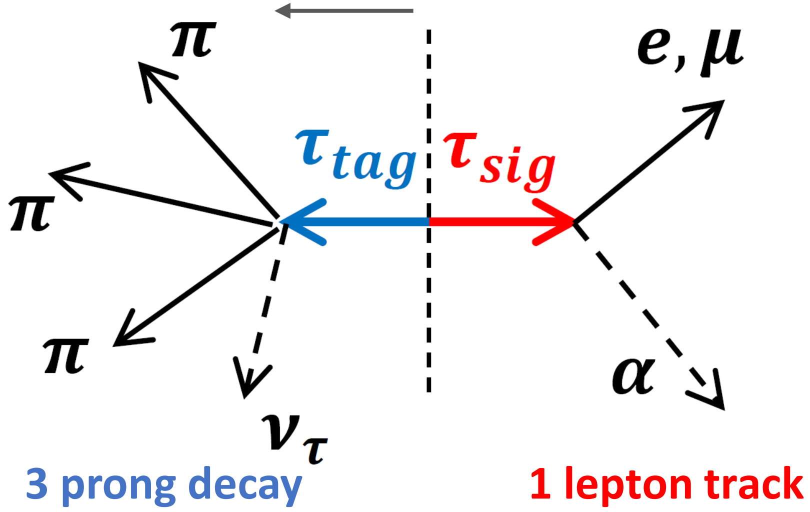
$e^+e^- \rightarrow \tau_{sig} (\rightarrow l a)\ \tau_{tag} (\rightarrow 3\pi\nu)$, with l = e, μ

- **unique probe of lepton flavor violating ALPs**

Analysis in brief:

- three tracks on the tag side, one track on the signal side (l=e or l=μ);
- Signal extraction exploit the shape differences:
  - *2-body* decay for signal (peaking in some kinematics features) over *3-body* decay of irreducible background $\tau \rightarrow l\nu\nu$;

$$\vec{T} = max\left(\sum_i \frac{\vec{p_i}\cdot\hat{T}}{|p_i|}\right)$$



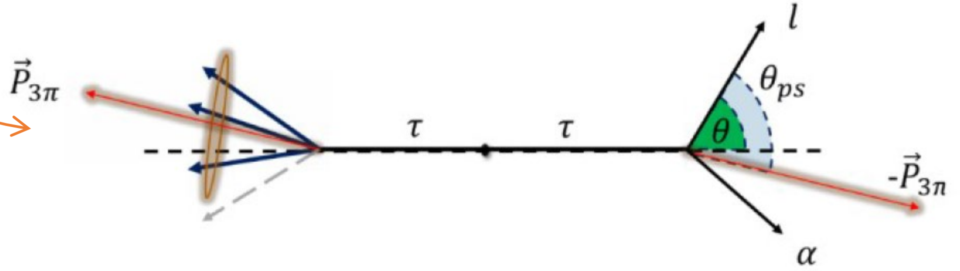
[1] M. Bauer, et al. Phys. Rev. Lett. 124, 211803 (2020)

Invisible ALP in LFV τ decays

Strategy

Shape differences more prominent in the τ_{sig} rest frame:

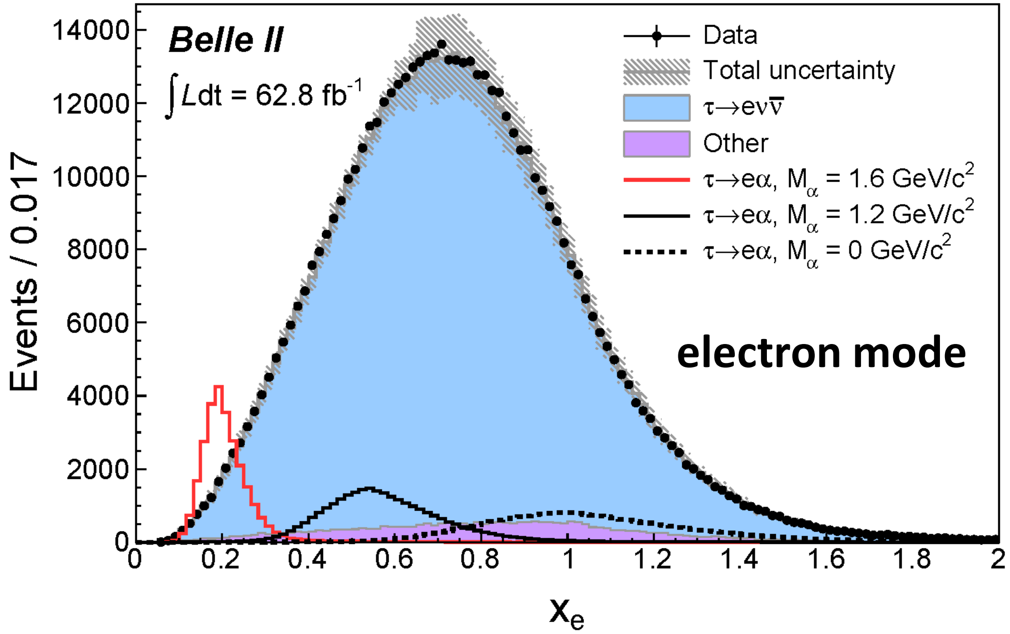
- approximate τ_{sig} pseudo-rest frame as $E_{sig} \sim \sqrt{s}/2$ and $\hat{p}_{sig} \approx -\vec{p}_{\tau_{tag}} / |\vec{p}_{\tau_{tag}}|$

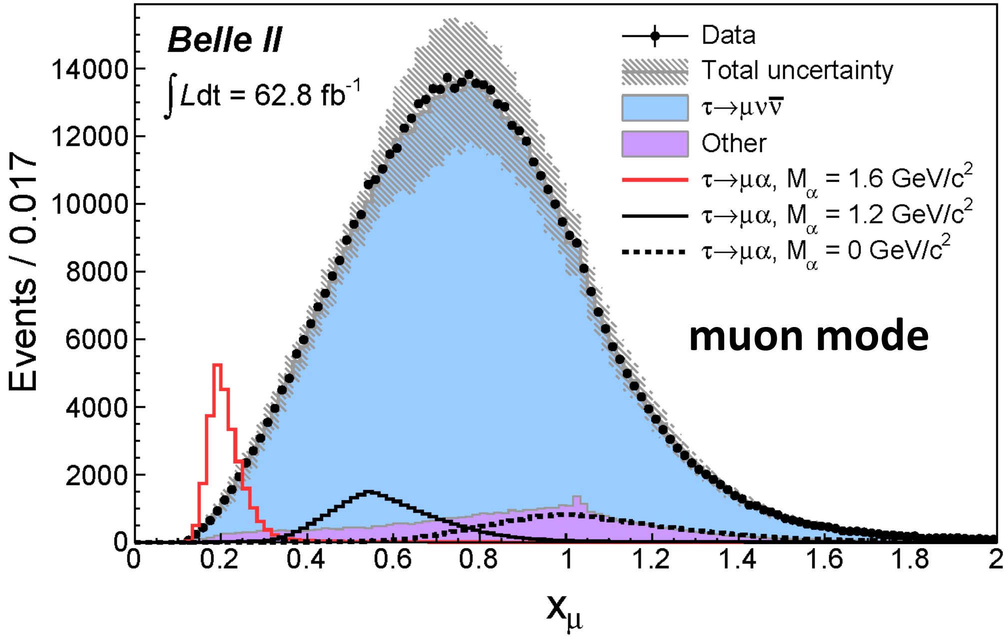


Signal/background discriminating variable:

- **normalized lepton energy x_l** ⇨ $x_l \equiv \frac{E_l^*}{m_\tau c^2/2}$

Signal extraction: fit a peak above broad spectrum from $\tau \to l\nu\nu$





Invisible ALP in LFV τ decays

Results

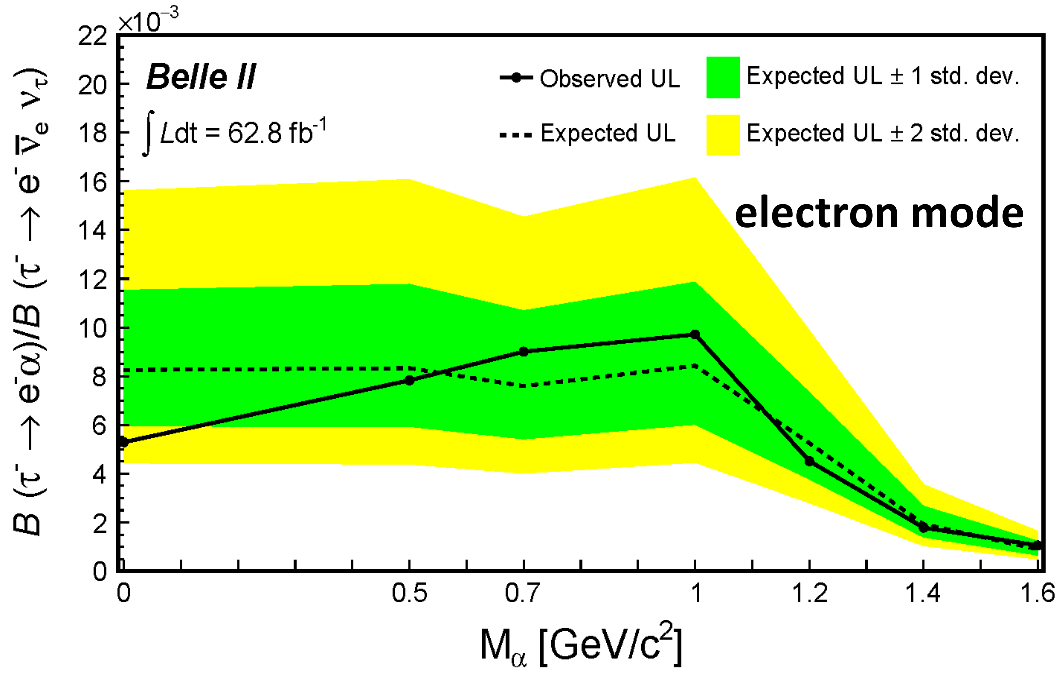
[1] ARGUS Collaboration, Z. Phys. C 68, 25 (1995)

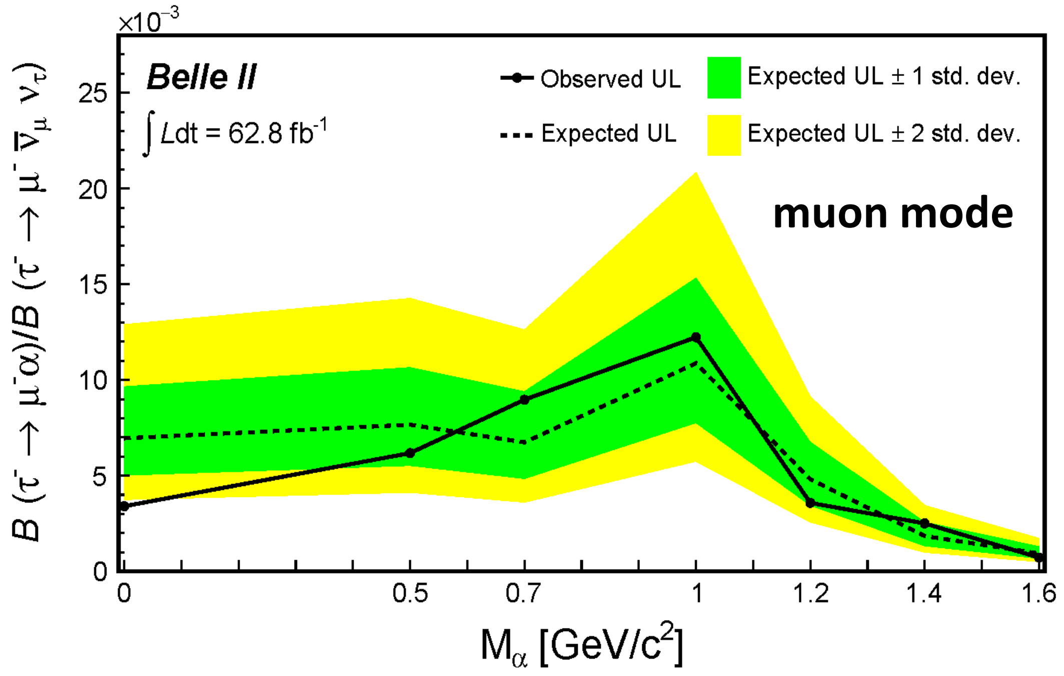
No significant excess in 62.8 fb^{-1}.

95% CL upper limits on BF ratios of BF($\tau_{sig} \rightarrow l\alpha$) normalized to BF($\tau_{SM} \rightarrow l\nu\nu$);

- **2-14 times tighter limits on the previous Argus results [1];**

PRL 130, 181803 (2023)





Search for ALP $\rightarrow \tau^+\tau^-$ decays

Overview

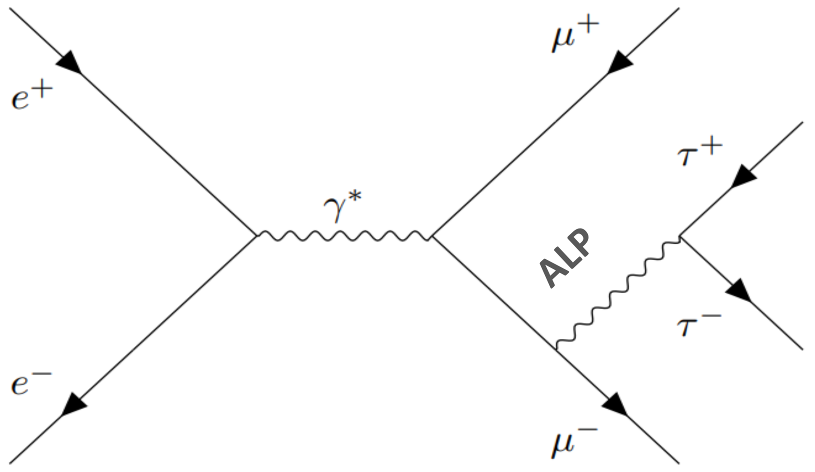
Search for ALP with predominantly lepton coupling.

@ Belle II: search for a ALP in a di-tau resonance

$$e^+e^- \rightarrow \mu^+\mu^- a, \quad a \rightarrow \tau^+\tau^-$$

ττ system difficult to reconstruct
→ signature unconstrained

- Select taus decays to one-charged particle (+neutrals);
- Event signature is four tracks (2μ) with missing energy;
- Muons used to compute recoil mass (peaking for signal);

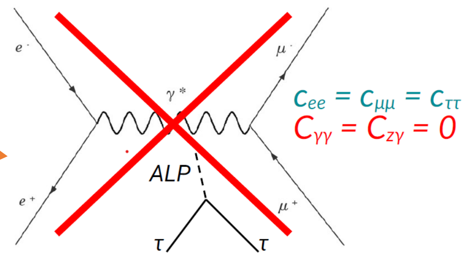


$$\Gamma(a \to \ell^+\ell^-) = \frac{m_a m_\ell^2}{8\pi\Lambda^2} \left|c_{\ell\ell}^{\text{eff}}\right|^2 \sqrt{1 - \frac{4m_\ell^2}{m_a^2}},$$

Decay to taus favoured above di-tau mass threshold;
Assumed no coupling to gauge bosons;

Analysis optimized for a Z' vector boson, but results re-cast for:

- Axion-like-particle with lepton couplings [1];
- Leptophilic scalar S [2];



[1] M. Bauer, M. Neubert, and A. Thamm, J. High Energy Phys. 2017, 44 (2017)
[2] B. Batell, N. Lange, D. McKeen, M. Pospelov, and A. Ritz, Phys. Rev. D 95, 075003 (2017)

Search for ALP $\rightarrow \tau^+\tau^-$ decays

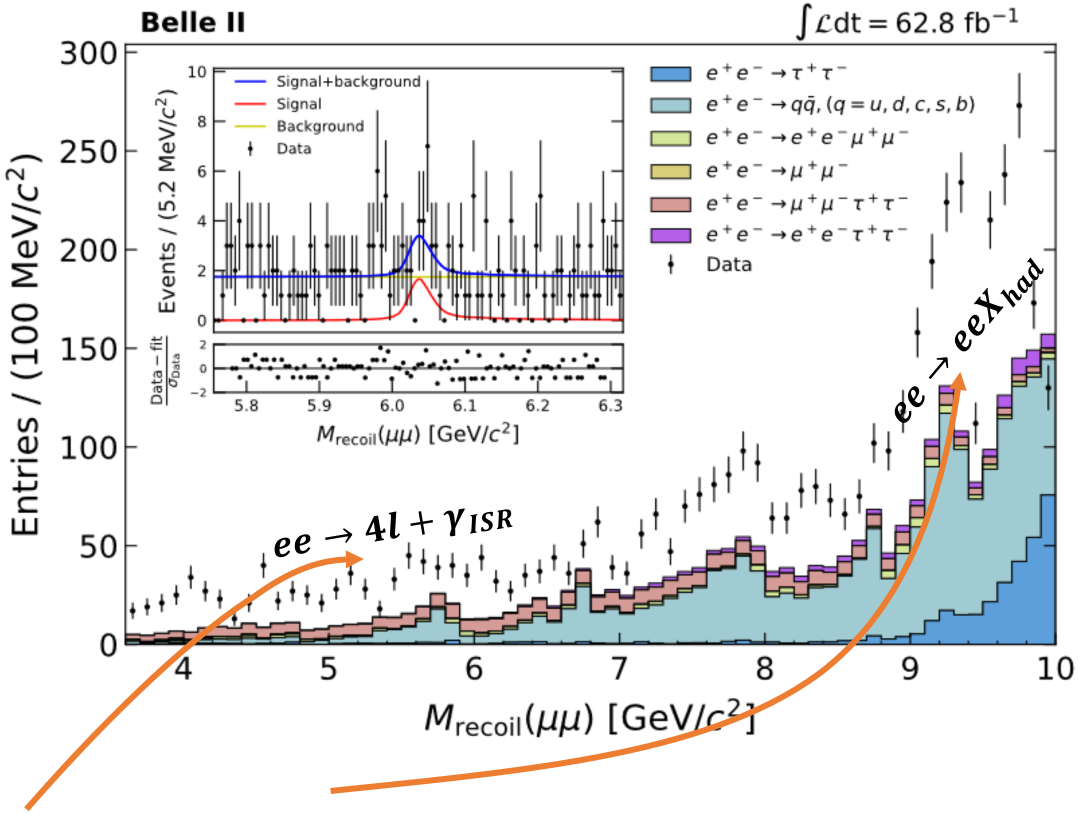
Strategy

Background rejection:

- 4 leptons background suppressed by M(4tracks) < 9.5 GeV/c^2;
- Neural network exploiting the presence of a resonance recoiling against the two tagging muons, final-state-radiation emission of the resonance;
- Main residual background components:
  - $\tau^+ \tau^- (\gamma)$
  - *q q (q = u, d, s, c, b)*
  - 4-lepton final states
  - $\mu^+ \mu^- \pi^+ \pi^-$
  - $e^+ e^- X_{had}$ (two-photon processes)

Signal extraction:

- Signal yield from a fit scan (in step of half m_a resolution) over M_{recoil} above a floating background (robust against un-modelled non-peaking background);



Data/simulation discrepancy from non-simulated/unmodeled processes: missing ISR, Xhad

Search for ALP → $\tau^+\tau^-$ decays

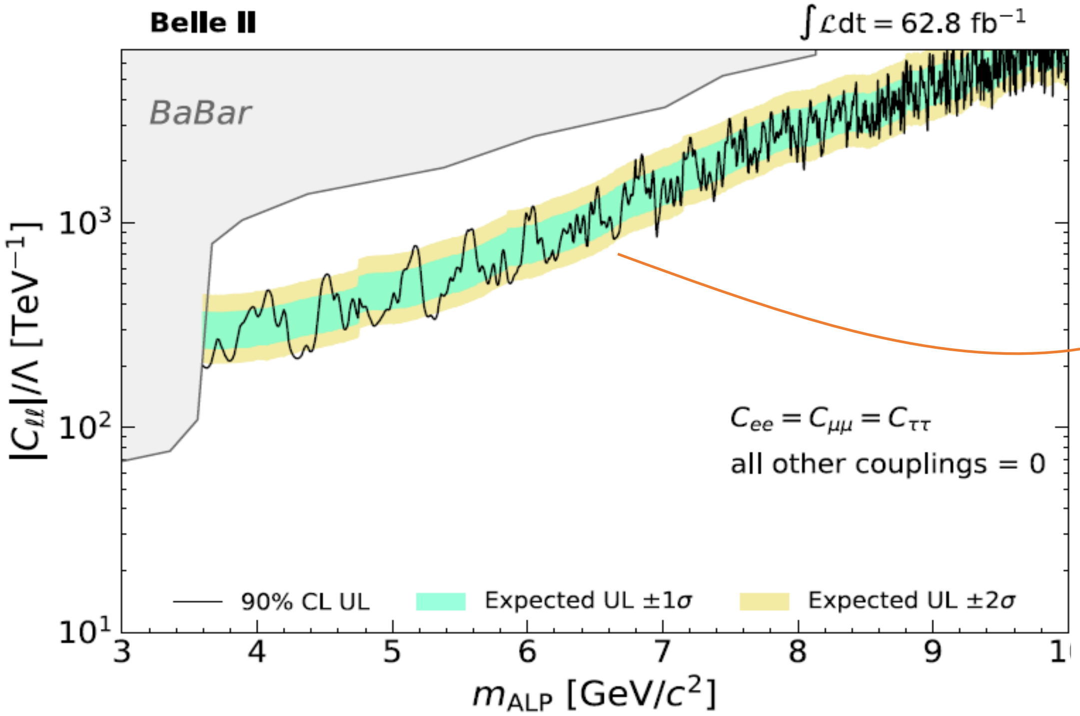
Results

No excess found with 63.3 fb^{-1} (maximum global significance 1.8 σ).

90% CL upper limits on the cross section **$\sigma(e^+e^- \to (X \to \tau^+\tau^-)\ \mu^+\mu^-) = \sigma(e^+e^- \to X\ \mu^+\mu^-)B(X \to \tau^+\tau^-)$**, with X = S, ALP, Z'

- Results translated to limits on ALP, leptophilic scalar S and Z' mediator couplings:

PRL 131, 121801 (2023)



First direct constraints for ALP → $\tau\tau$;

Conclusions

Result summary

It's a great time to explore physics beyond SM… many new theoretical possibilities opened, expecially in the dark sector.

High intensity e^+e^- low energy colliders provide unique opportunities to explore ALPs and often provide the best limits at the 100 MeV - 10 GeV mass scale.

Very active and diverse program of ALP searches at e+e- colliders. Results shown today on :

BESIII:

- $\psi(3686) \to \pi^+\pi^- J/\psi$, $J/\psi \to \gamma\, a$, $a \to \gamma\gamma$ PLB 838, 137698 (2023)
- $J/\psi \to \gamma\, a$, $a \to \gamma\gamma$ arXiv:2404.04640 (2024)

BaBar:

- $B \to K\, a$, $a \to \gamma\gamma$ PRL 128, 131802 (2022)

Belle II:

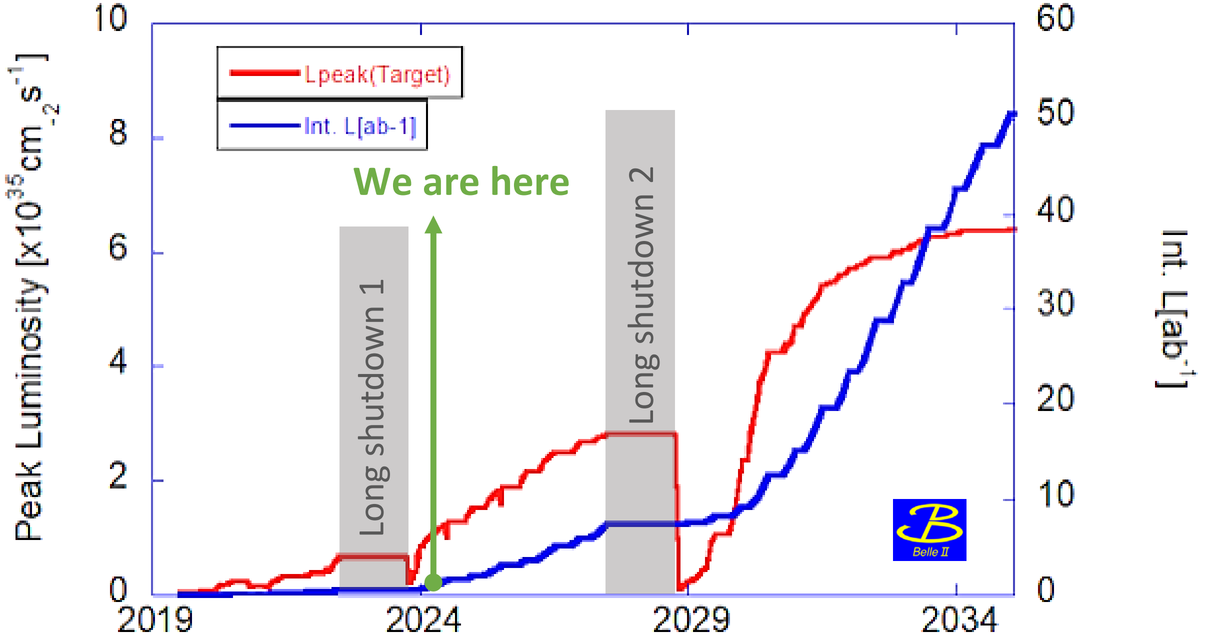
- $B \to K\, a$, $a \to x^+x^-$ PRD 108, L111104 (2023)
- $\tau \to l\, a$, $a \to$ invisible PRL 130, 181803 (2023)
- $e^+e^- \to \mu\,\mu\, a$, $a \to \tau\,\tau$ PRL 131, 121801 (2023)

Conclusions

Belle II perspectives

Luminosity projection @ Belle II

- So far collected 531 fb^{-1}
- In next years, will collect 100 times the current dataset:



- **more results with higher statistics and improved analyses:**
- as an example:
  - B $\rightarrow$ *h a*, *a* $\rightarrow$ *invisible*
  - B $\rightarrow$ *h a*, *a* $\rightarrow$ γγ

D. Marcantonio's talk Friday

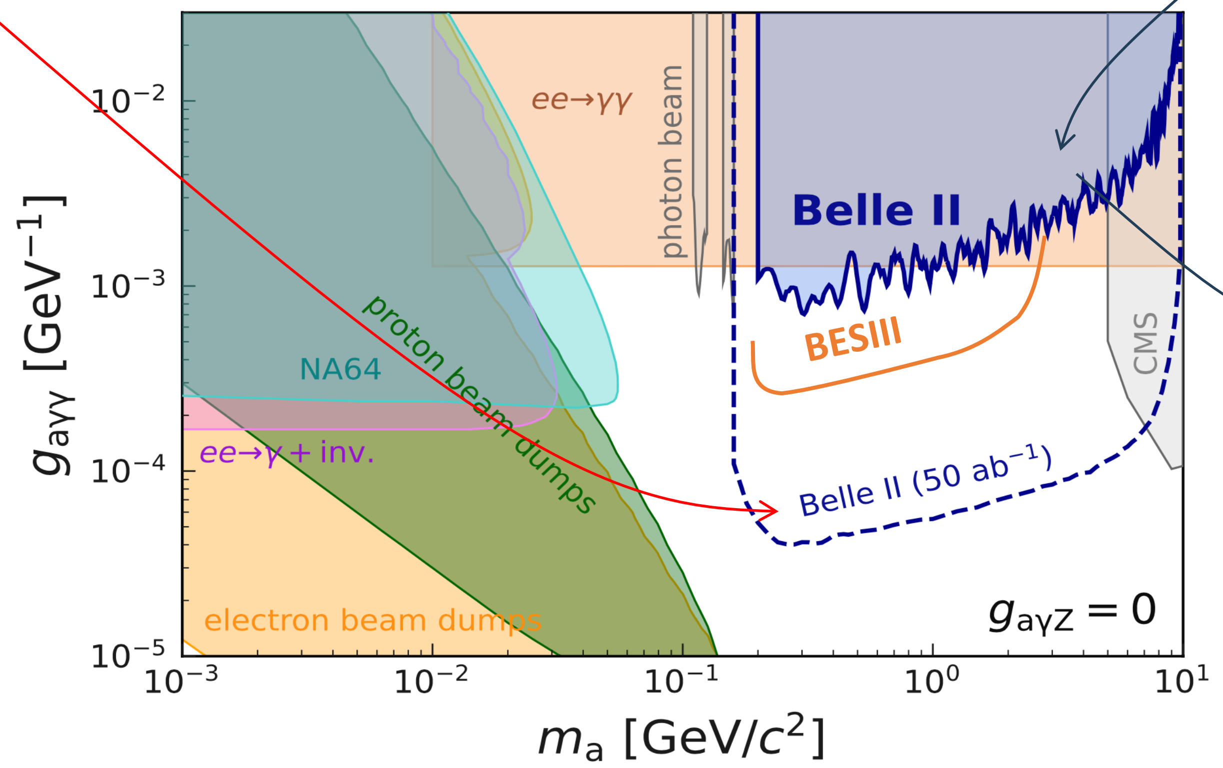
Conclusions

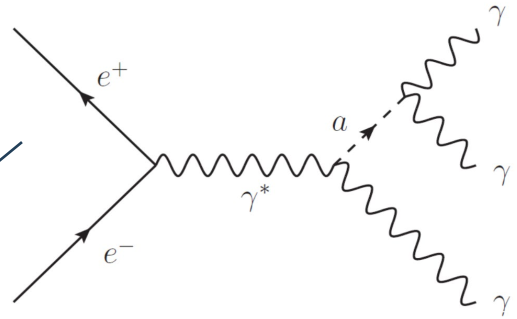
Belle II perspectives

Luminosity projection @ Belle II

- So far collected 531 fb^{-1}
- In next years, will collect 100 times the current dataset:
  - **The best is yet to come!**

ALP coupling to photon Belle II sensitivity





2018 pilot run (0.5 fb^{-1})
More in the backup

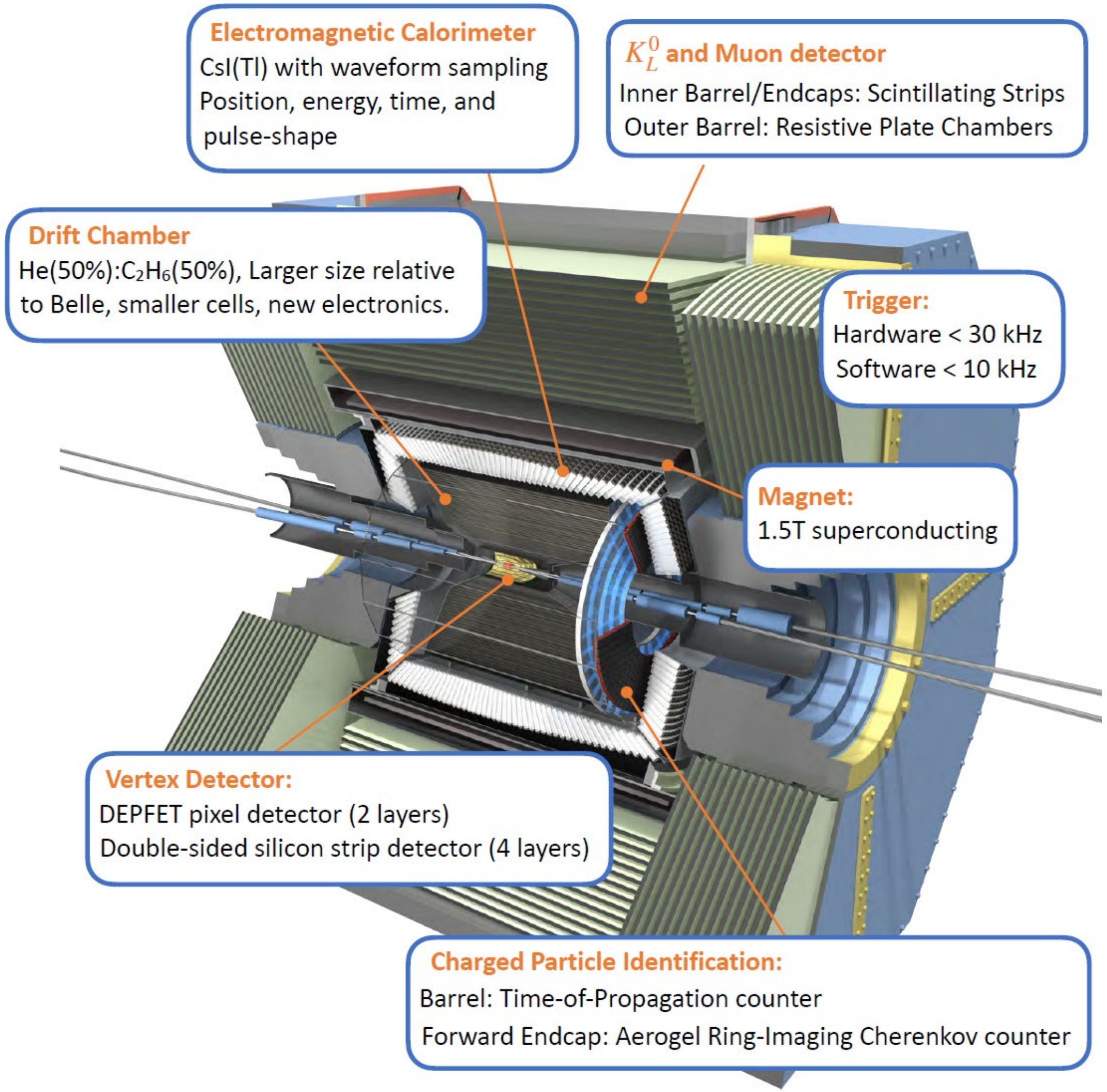
Spares

Belle II

Detector overview

Prog. Theo. Exp. Phys. 12 (2019)

- 15 µm vertexing resolution, excellent tracking.
- Hermetic detector makes full event reconstruction possible.
- Photon efficiency 90% above p > 1.5 GeV.
- Muon eff. 90% with 7% pion mis-ID. Electron eff. 86% with 0.4% pion mis-ID
- Kaon ID in full momentum range, eff. 90% with 6% pi(mis-ID.



Belle II

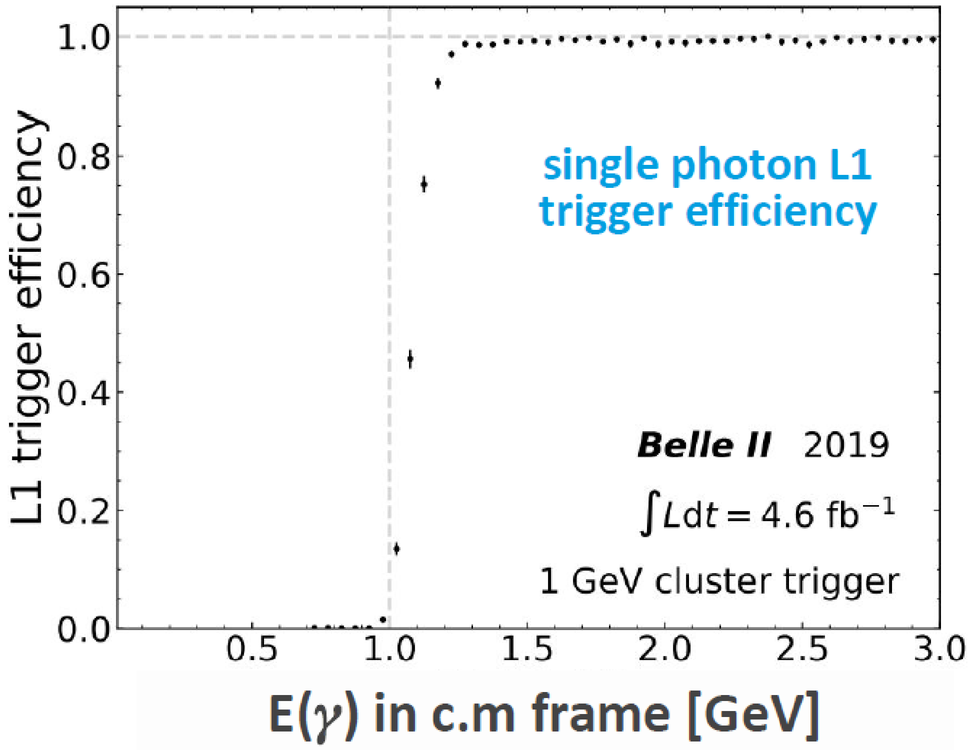
Trigger performances

essential for dark-sector and tau physics

- typical signatures include low-multiplicity of tracks, and energy deposits in EM calorimeter
- large background from radiative Bhabha and two-photon processes

some of the dedicated low-multiplicity triggers:

- single muon
  - combine drift chamber and muon detector information
- single track:
  - neural-net based hardware trigger
- single photon:
  - high efficiency for $E(\gamma) > 1$ GeV

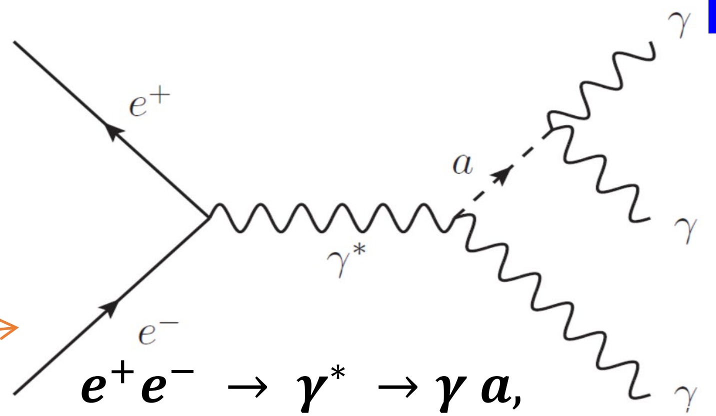


Belle II

Physics program

ALP-strahlung production

Overview



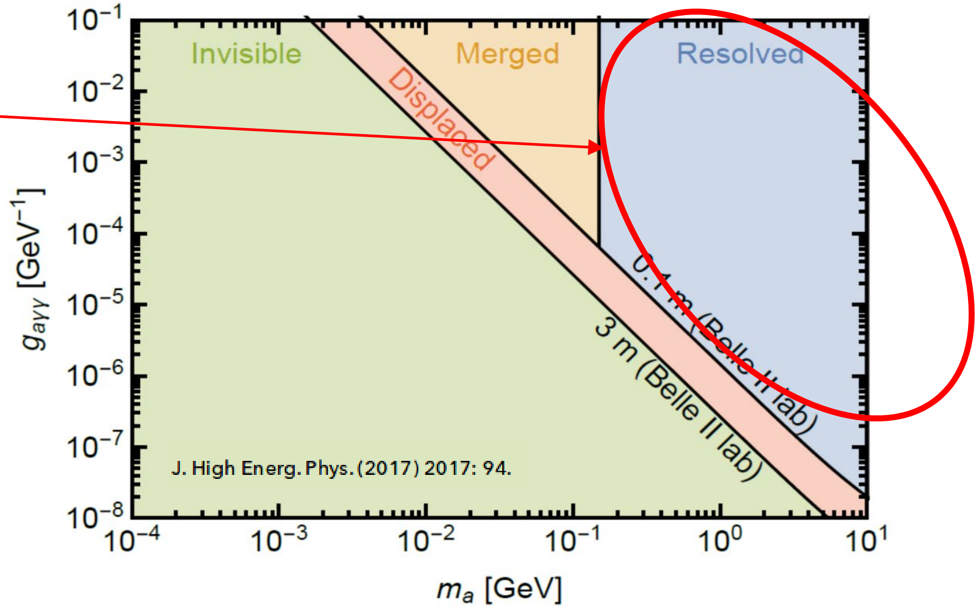
$e^+e^- \rightarrow \gamma^* \rightarrow \gamma\, a,$
$a \rightarrow \gamma\gamma$

Search for ALP coupling to photons via ALPs direct production:

- Photon fusion experimentally challenging due to the final-state boost;
- **ALPs-strahlung easier (this search);**
  - different topologies depending on $\mathbf{m_a}$ and $\mathbf{g_{a\gamma\gamma}}$

$\tau \sim 1/g^3_{a\gamma\gamma}M^2_a$

ALP-strahlung final state topology @ Belle II

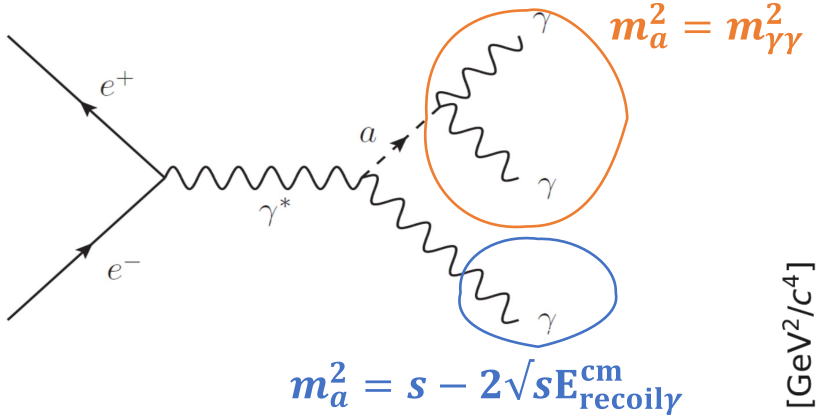


@Belle II: exploring the 3γ resolved final state;

- select events with:
  - 3γ that add up to the beam energy;
  - Zero tracks;
- look for a bump on di-photon (recoil) mass;
- Measurement performed with 2018 pilot run data (455 pb^{-1})

ALP-strahlung production

Strategy



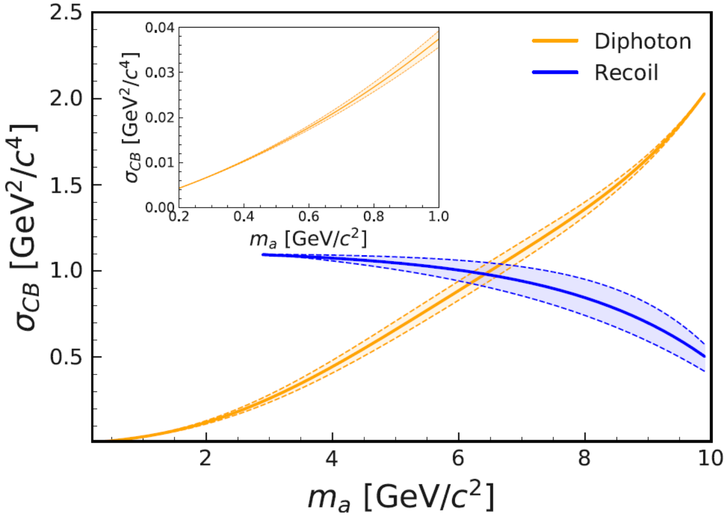
Backgrounds from QED:

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

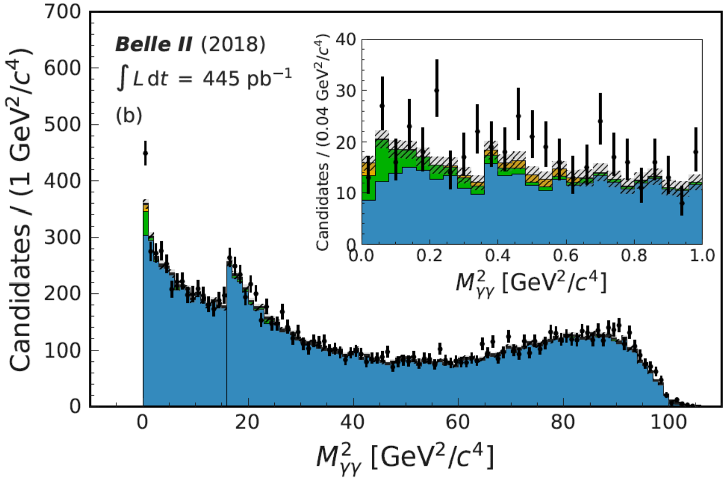
Signal extraction:

- Fit narrow peak over smooth background in step of half m_a resolution;
- Using either in the recoil mass (high m_a) or in di-photon mass (low m_a);
- Explored mass range $0.2 < m_a < 9.7$ GeV/c^2;
  - low masses difficult: merged photons and π^0;

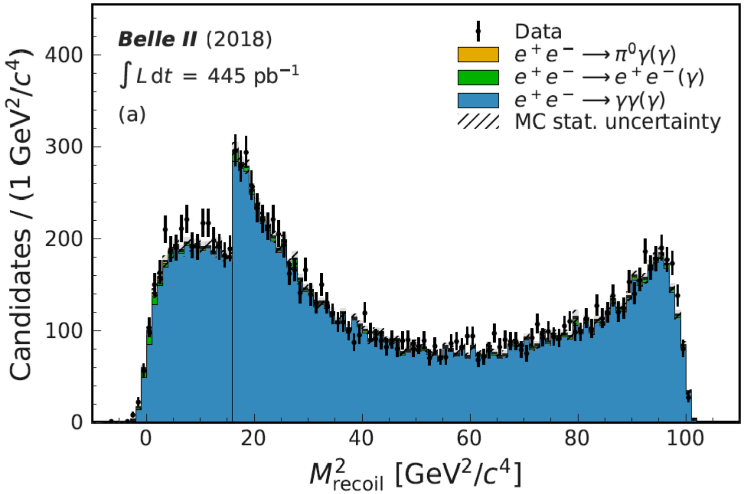
mass resolution



di-photon mass spectrum



recoil mass spectrum



ALP-strahlung production

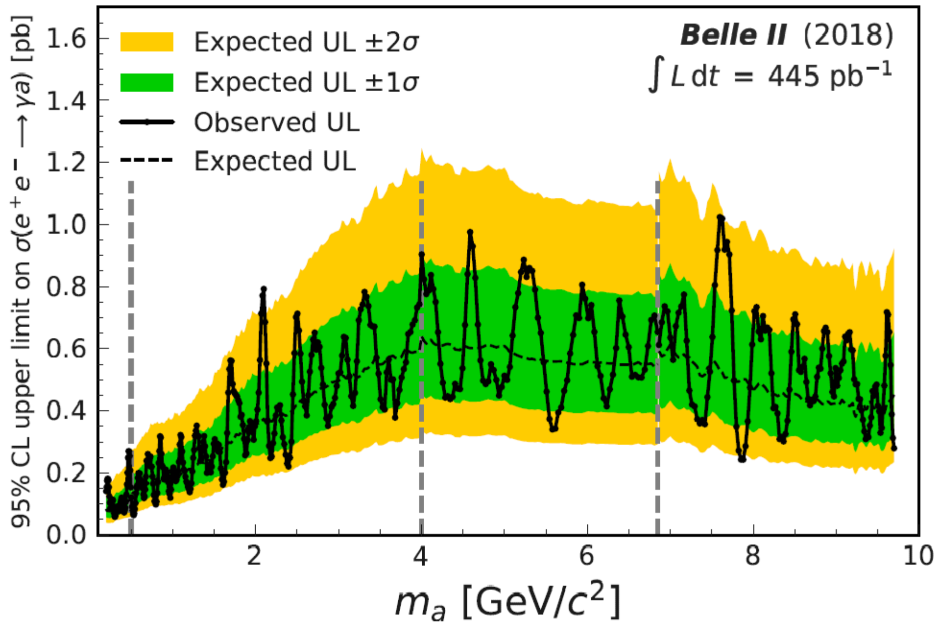
Results

No evidence for signal with 455 pb^{-1} of data;

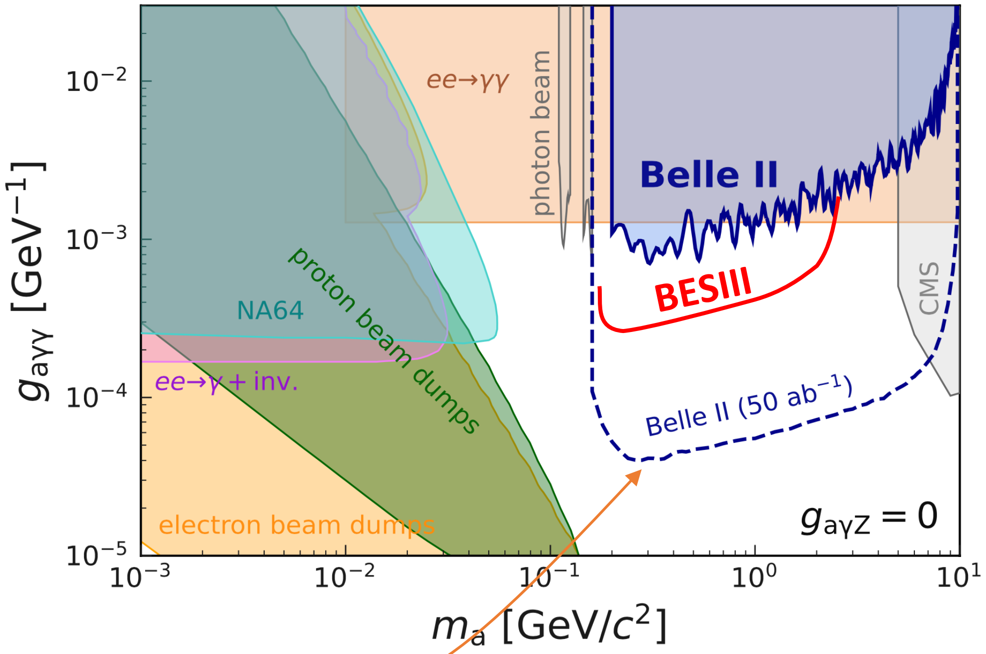
- **95% CL upper limit on the cross section and then translated in terms of the $g_{a\gamma\gamma}$ coupling constant.**

[PRL 125, 161806 (2020)](#)

cross-section upper limits



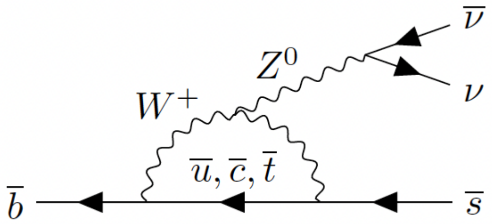
coupling upper limits



very interesting future prospects!

Evidence for $B^+ \to K^+\nu\nu$

Overview and strategy

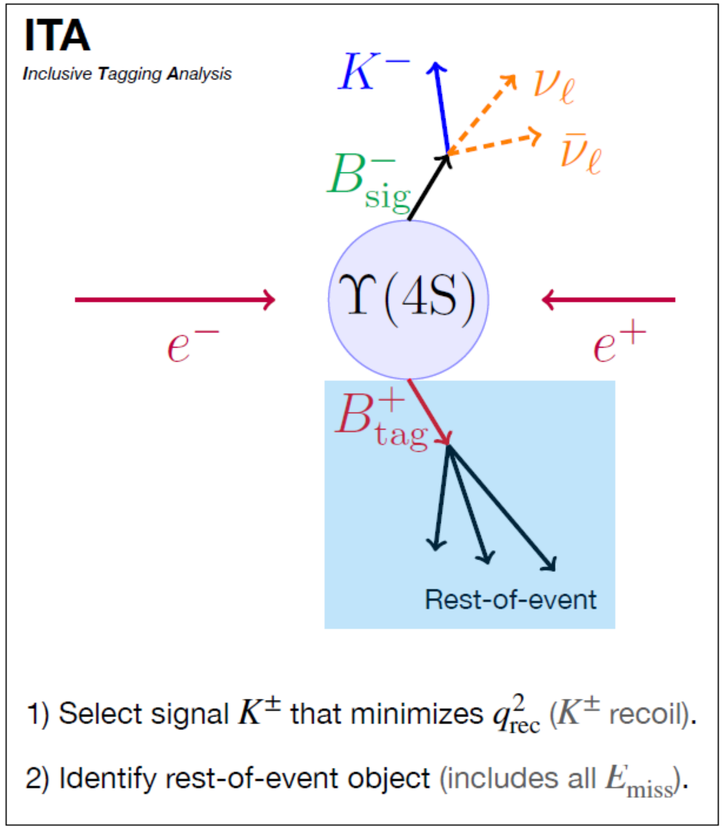


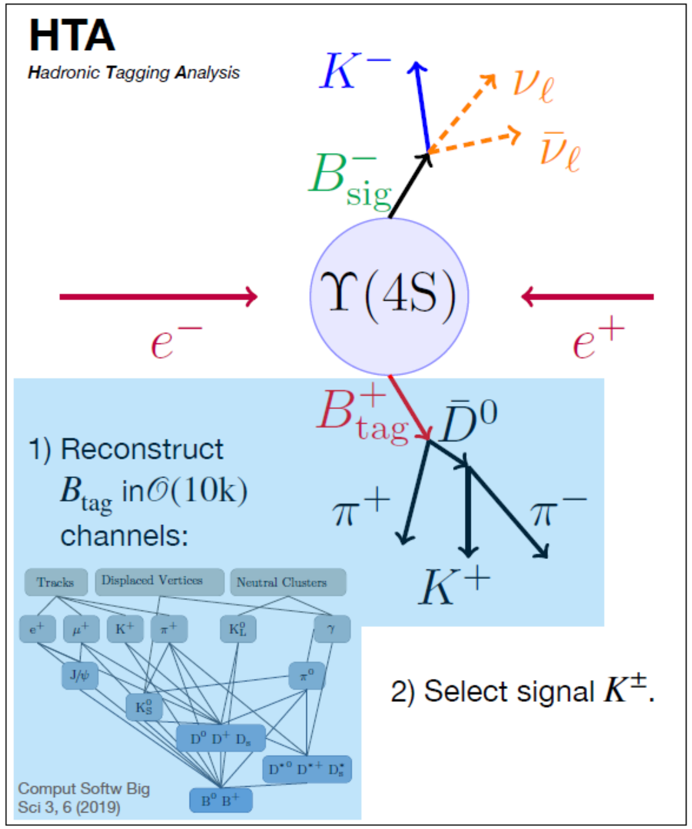
Reliable SM prediction, never observed before, possibly affected by NP (ALPs, dark scalars, Z’, leptoquarks…)

- Experimentally challenging for the 2 neutrinos in the final state;
- Used two complementary B tag approach:
    - low purity-high efficiency (0.8% - 8%)
    - its opposite (3.5% - 0.4%)

Strategy:

- Event selection by combining signal kaon, event topology, rest-of-event info in MVA classifiers
- Background from continuum, semileptonic B decays
- Signal efficiency and bkg estimation corrected and validated using a variety of control channels
- Closure test by measuring BF(B+→ □+K0)



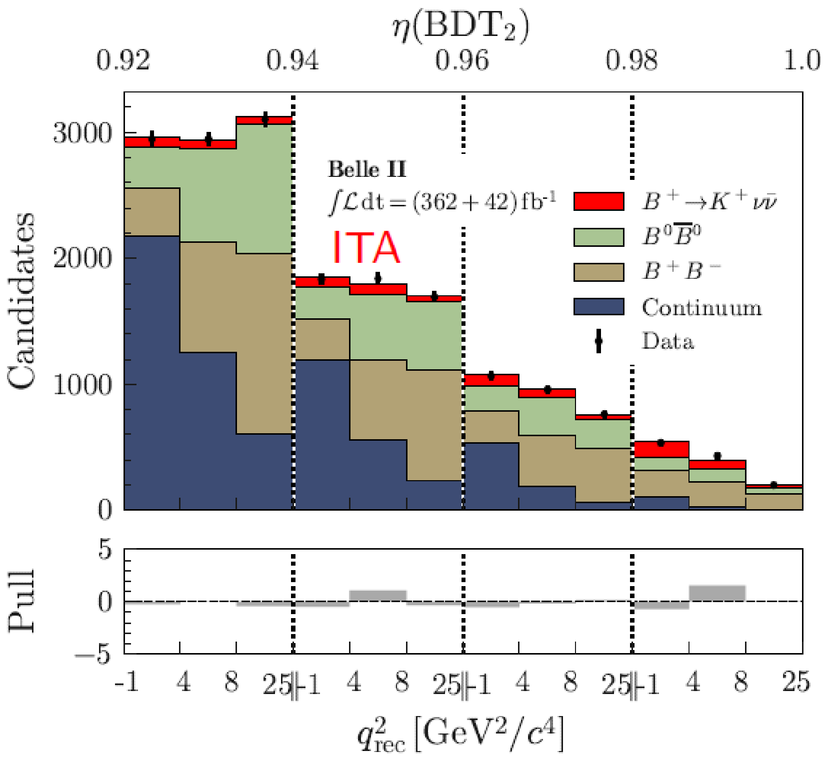


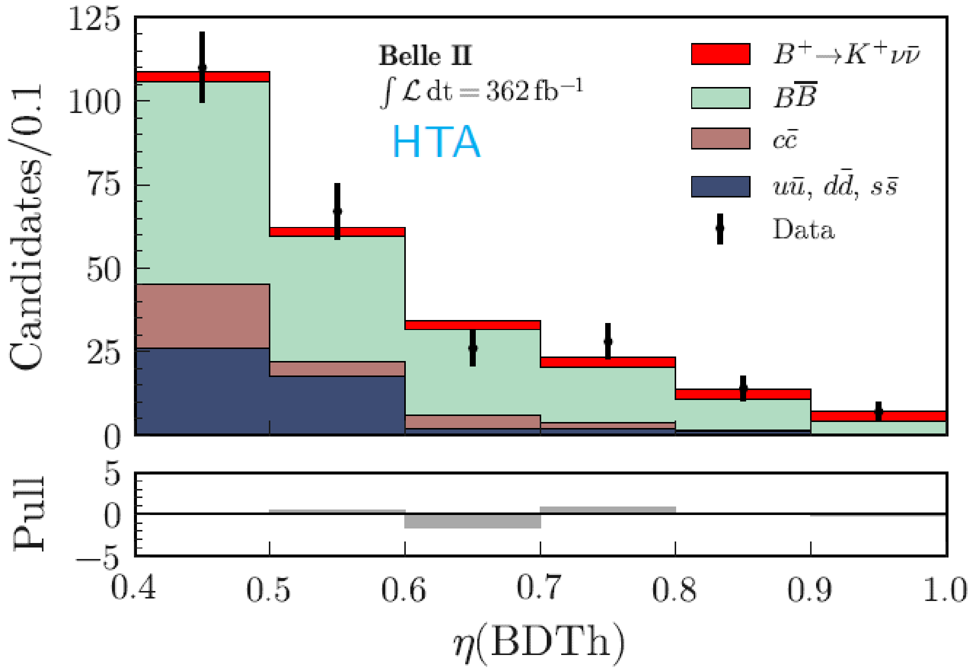
Evidence for $B^+ \to K^+\nu\nu$

Strategy

Perform binned maximum likelihood fit:

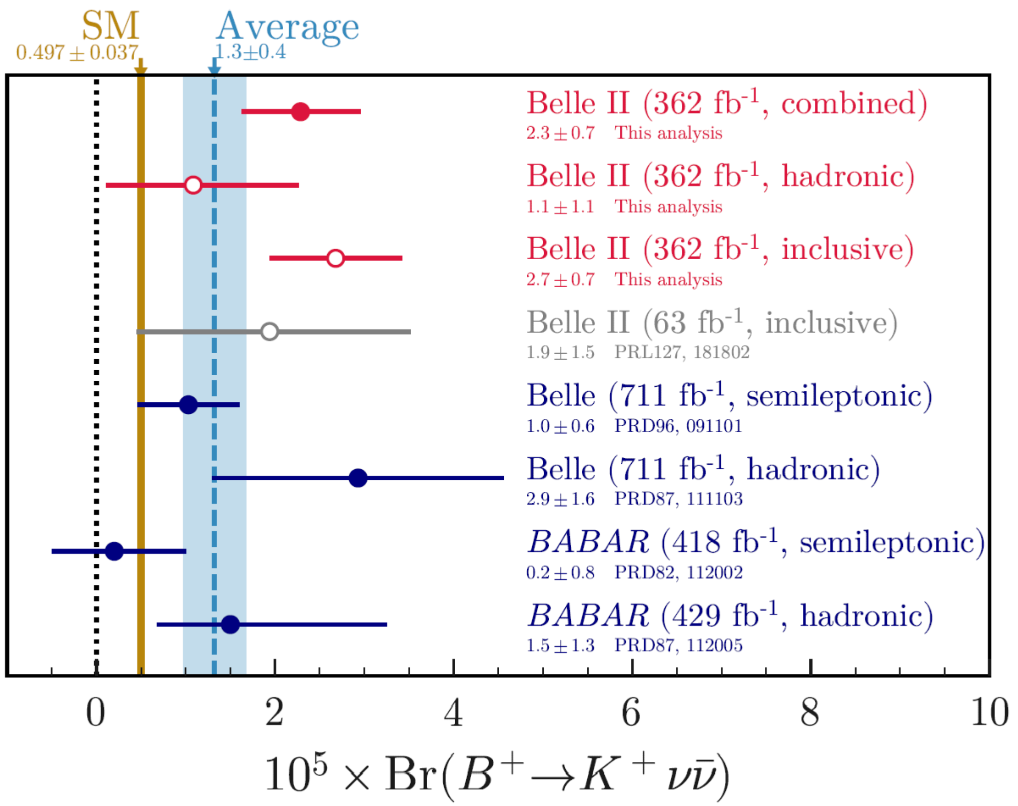
- Inclusive tag: in bins of q^2 and classifier output
- Hadronic tag: in bins of classifier output





Evidence for $B^+ \rightarrow K^+\nu\nu$

Results



ITA: $BF = (2.7 \pm 0.5 \pm 0.5) \times 10^{-5}$

HTA: $BF = (1.1^{+0.9+0.8}_{-0.8-0.5}) \times 10^{-5}$

Combined: $BF = (2.3 \pm 0.5^{+0.5}_{-0.4}) \times 10^{-5}$

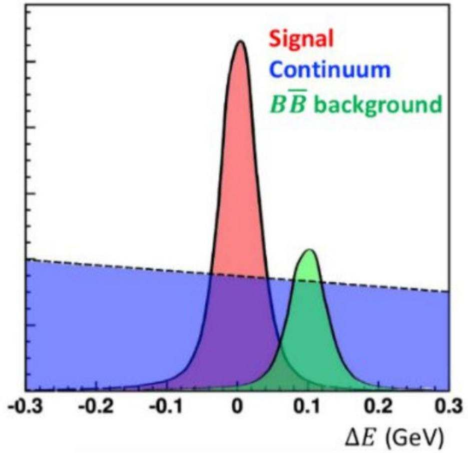
3.5 σ excess, 2.7 σ from SM

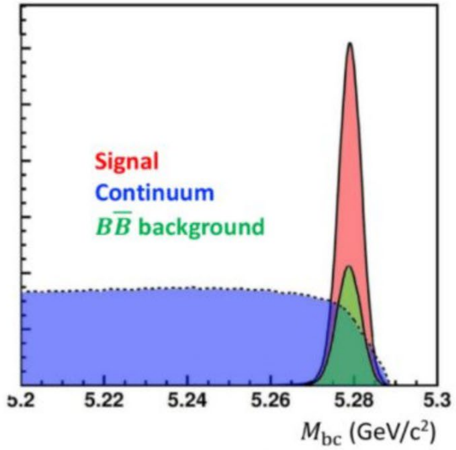
Belle II

Continuum rejection

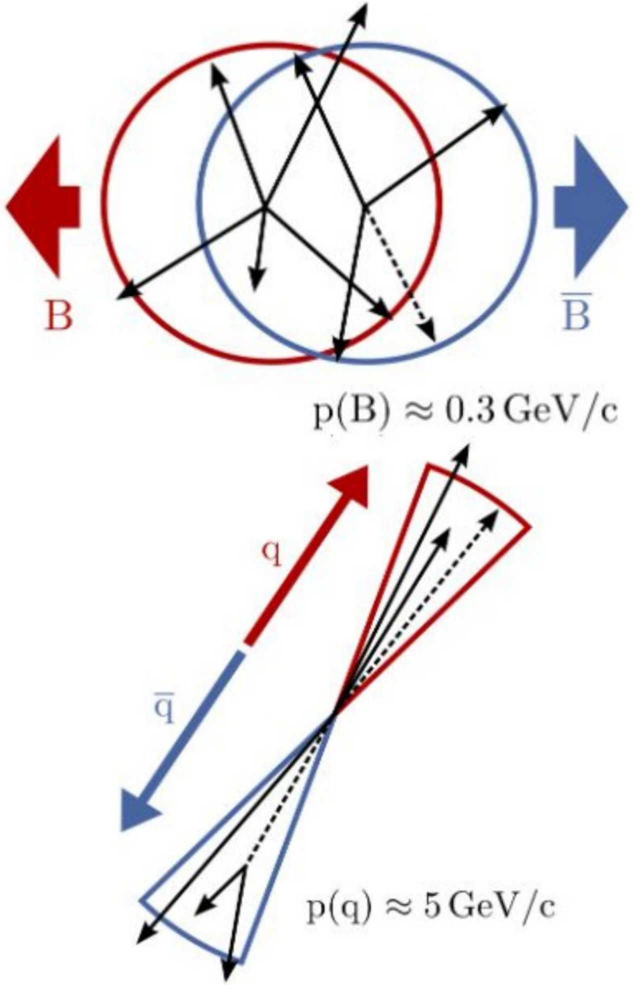
$$\Delta E = E_B^* - \sqrt{s}/2$$

$$M_{bc} = \sqrt{(\sqrt{s}/2)^2 - |\vec{p}_B^{*2}|}$$





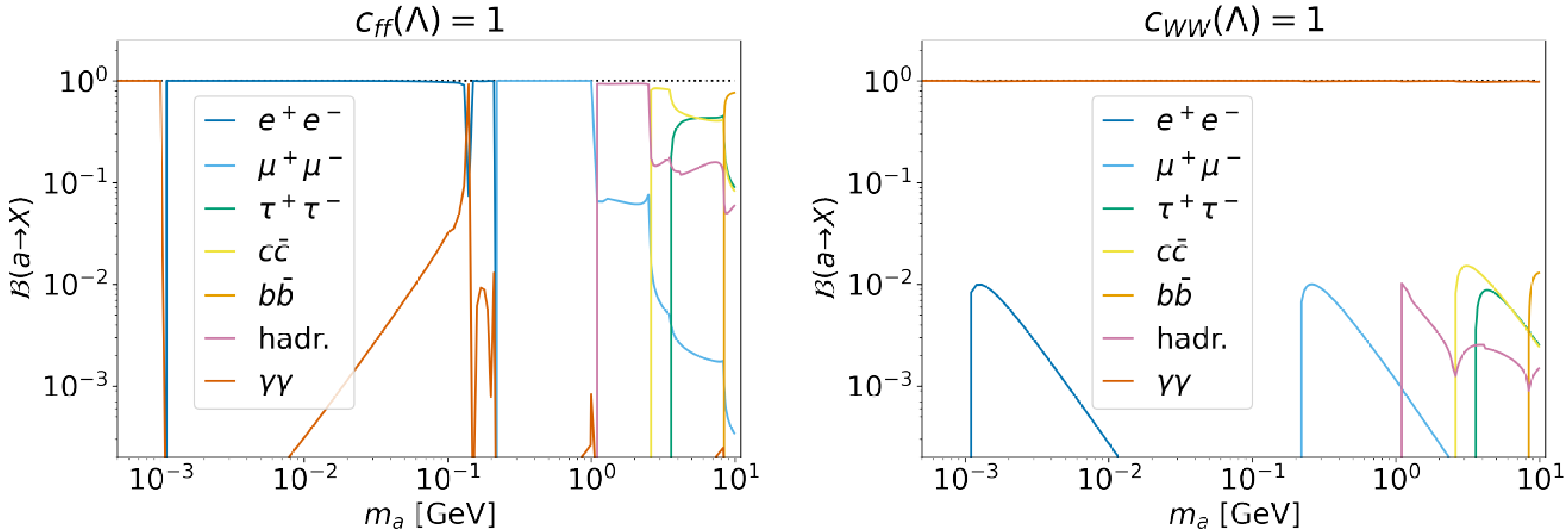
Expected ΔE = 0 **Expected M_{bc} = m_B**



Different event shape to separate B events from continuum background

ALP decay

BRs



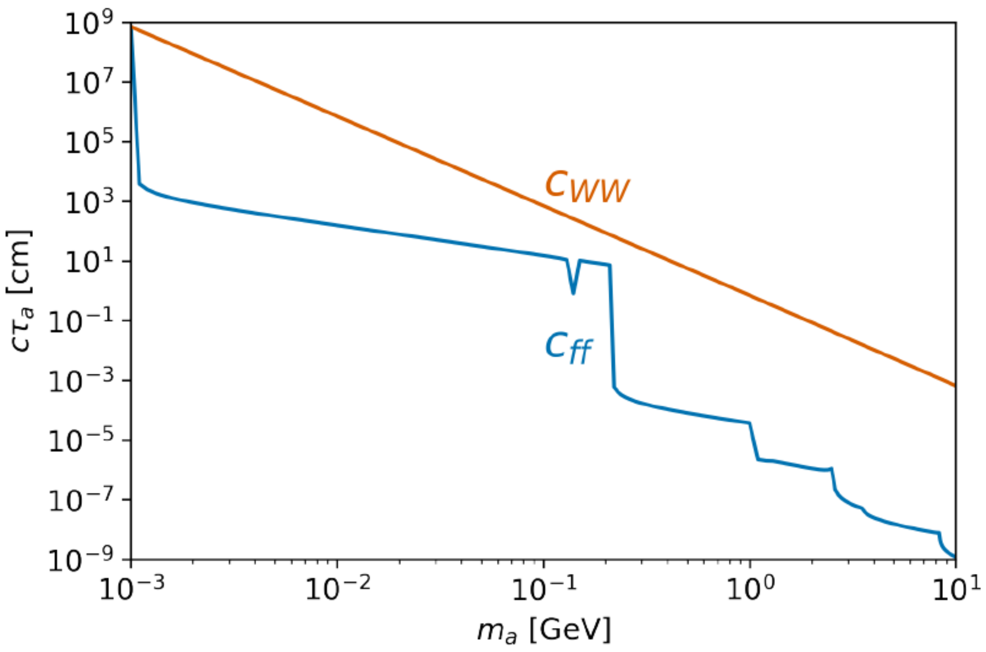
$$\Gamma_{a\to\ell\bar{\ell}} = 2\pi m_a \frac{\left|C_{\ell\ell}^{\text{eff}}(m_a)\right|^2 m_\ell^2}{\Lambda^2}\sqrt{1-\frac{4m_\ell^2}{m_a^2}}\,,$$

$$\Gamma_{a\to\gamma\gamma} = \frac{\alpha^2}{4\pi}\left|C_{\gamma\gamma}^{\text{eff}}(m_a)\right|^2 \frac{m_a^3}{\Lambda^2}$$

[Displaced or invisible? ALPs from B decays at Belle II, Ferber et al., 2023 (2023) 131]

ALP decay

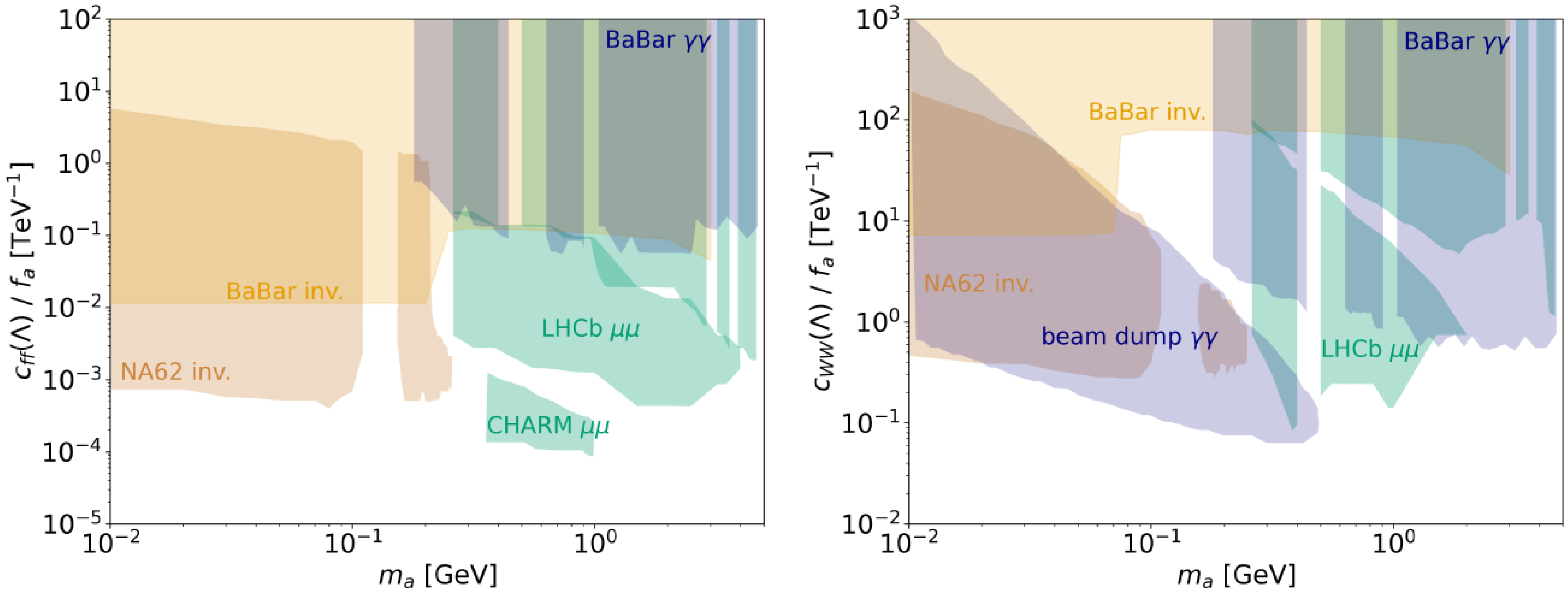
Lifetimes



[Displaced or invisible? ALPs from B decays at Belle II, Ferber et al., 2023 (2023) 131]

ALP couplings

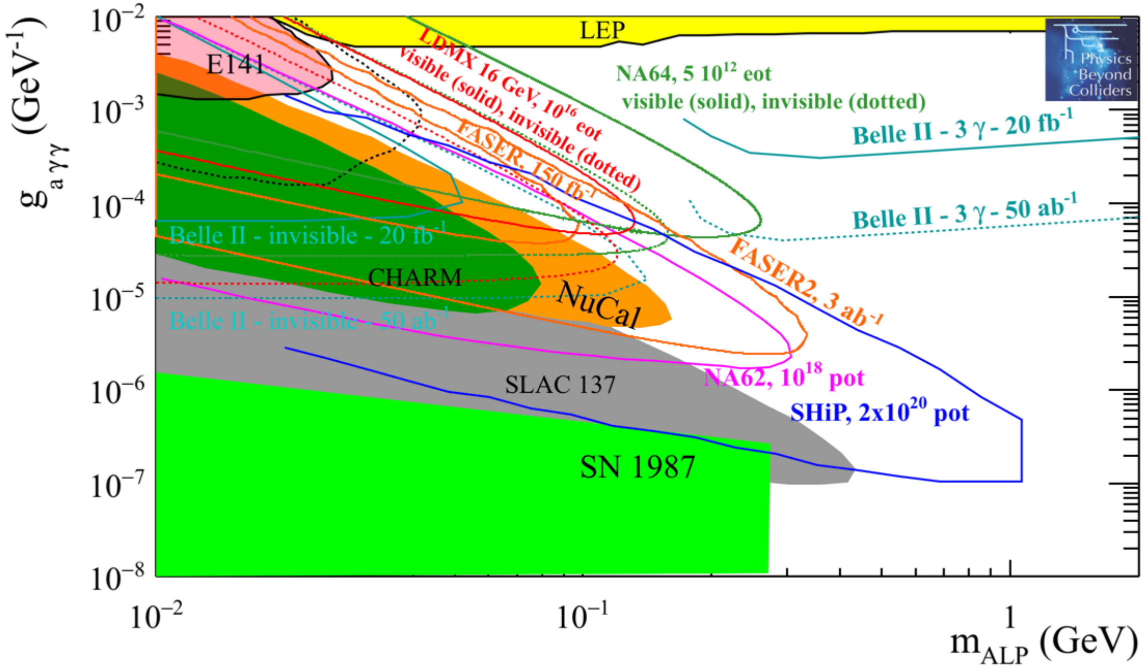
Upper limits

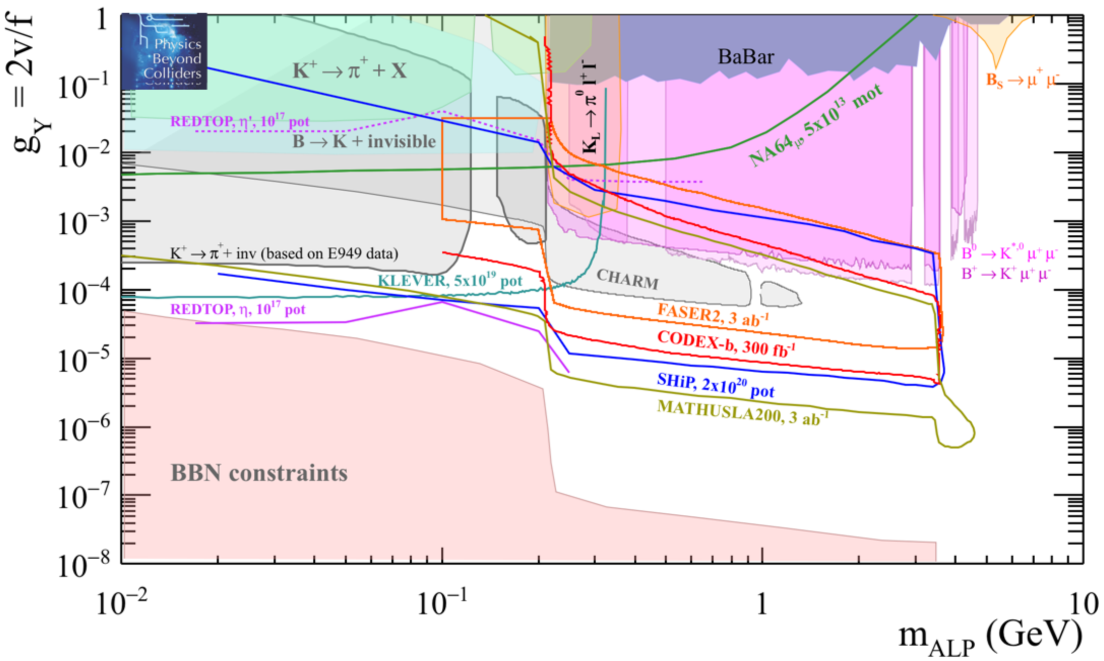


[Displaced or invisible? ALPs from B decays at Belle II, Ferber et al., 2023 (2023) 131]

ALP couplings

Upper limits





Beacham, James, et al. "Physics beyond colliders at CERN: beyond the standard model working group report." *Journal of Physics G: Nuclear and Particle Physics* 47.1 (2019): 010501.