SEARCH FOR AN AXION-LIKE PARTICLE IN $B^{\pm} \to K^{\pm}a, a \to \gamma\gamma$ AT *BABAR*

Steve Nguyen on behalf of BABAR Collaboration

June 11, 2021

WIN2021

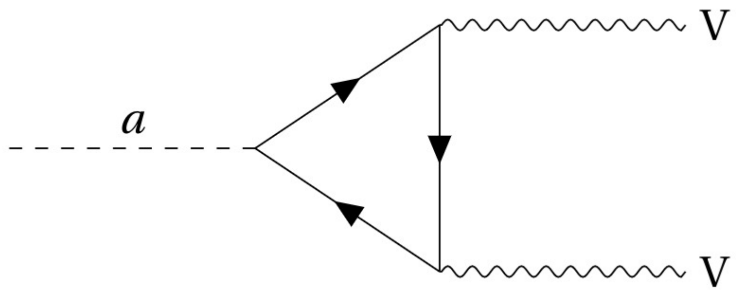
HARVEY MUDD COLLEGE

Zoom discussion: see link on Indico, available in **Flavor and Precision Physics Panel 1** at 8:30am CT, June 11.

R. Peccei, H. Quinn, PRL 38 (1977); S. Weinberg, PRL 40 (1978); F. Wilczek, PRL 40 (1978); P. Graham, D. Kaplan, S. Rajendran, PRL 115 (2015)

AXION-LIKE PARTICLES

$$\mathcal{L} = -\frac{g_{aV}}{4} a V_{\mu\nu} \tilde{V}^{\mu\nu}$$

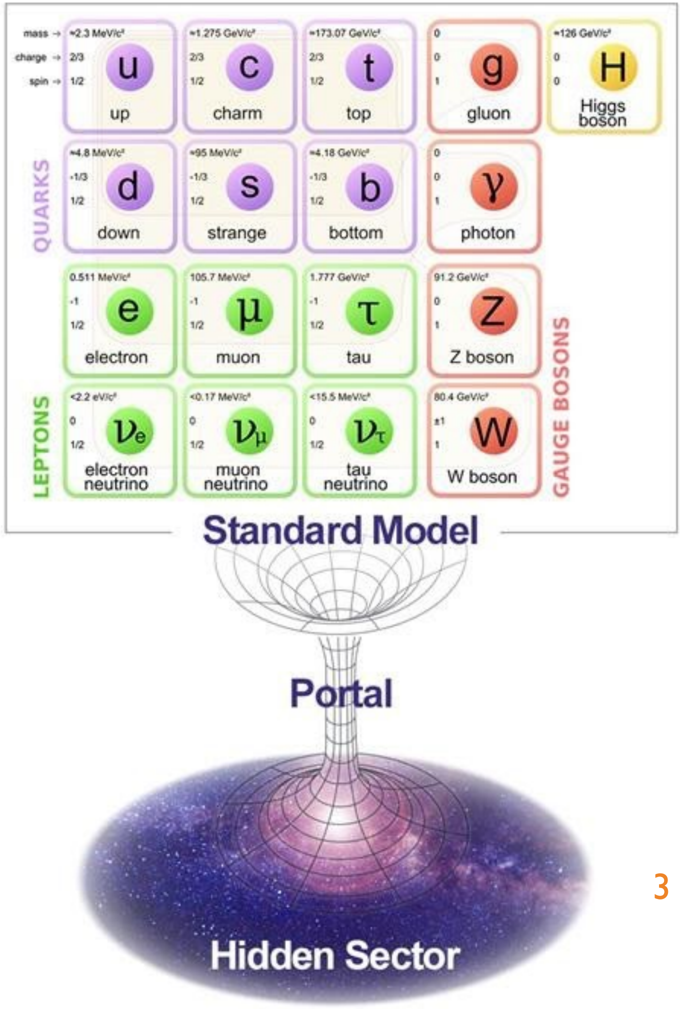


- The low-mass pseudo-Goldstone bosons which arises from the breaking of an anomalous (chiral) global symmetry is referred as Axion-Like particles (ALPs).
- ALPs can be found in many models of physics beyond the SM such as supersymmetric theories and string theory.
- ALPs can couple to the gauge fields in a manner proportional to the gauge anomaly.

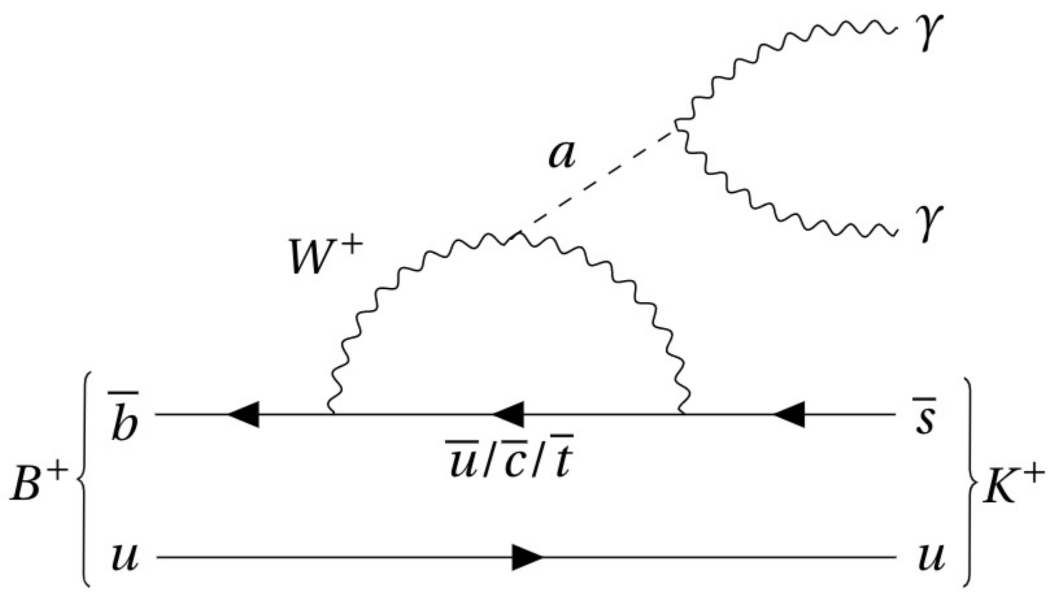
Y. Nomura, J. Thaler, PRD 79 (2009); Physics Beyond Colliders Report, JPG 47 (2020), and references therein.

ALPS AND PORTAL TO THE HIDDEN SECTOR

- ALPs can naturally have any mass, which arise from explicit symmetry breaking.
- The coupling strength of the ALP is inversely proportional to the scale of spontaneous symmetry breaking ($g_{aV} \sim 1/f$)
- ALPs are ideal candidates to act as mediators to the hidden sector via the so-called "axion portal."



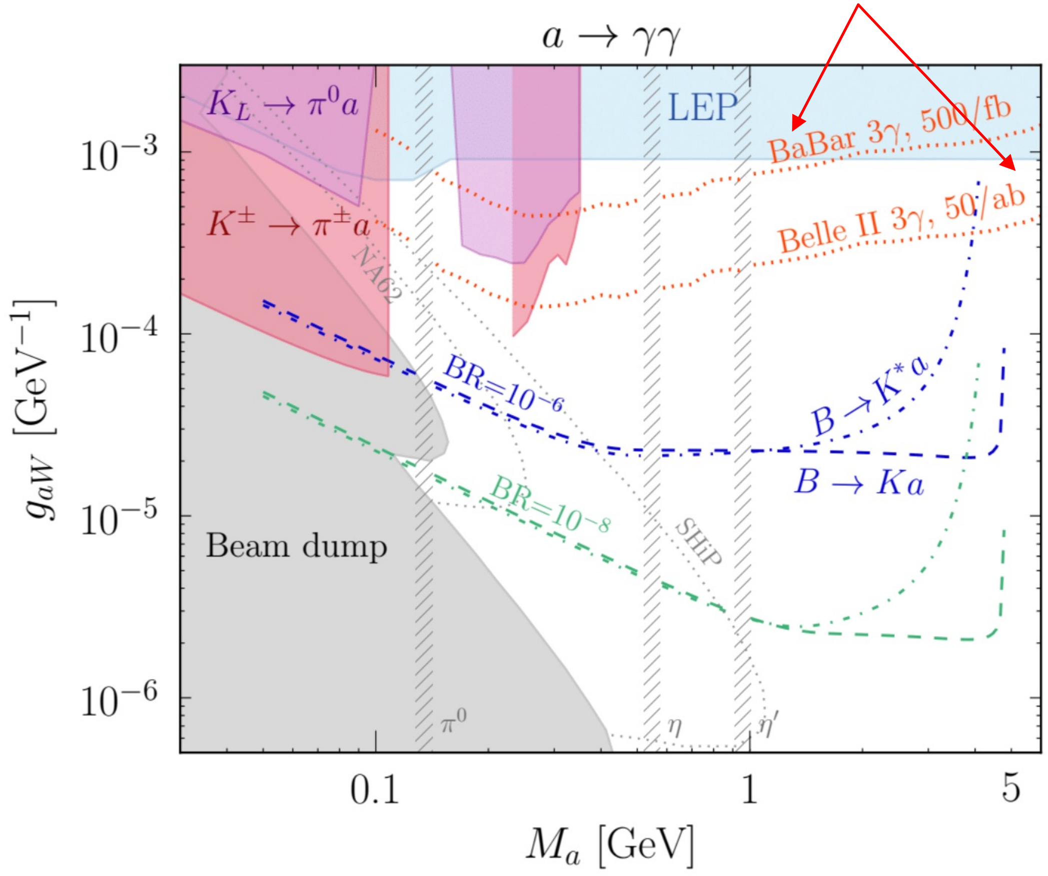
ALPS IN B MESON DECAY



- The phenomenology of the ALP coupling to photons is well studied.
- The SM photon is a linear combination of the hypercharge and SU(2) gauge fields, thus ALP coupling to photons also implies that ALP **can** couple to $W^{\pm}/Z$ bosons.
- The SM flavor-changing meson decay is of the same order as ALP production in the weak interaction.

ALPS IN B MESON DECAY

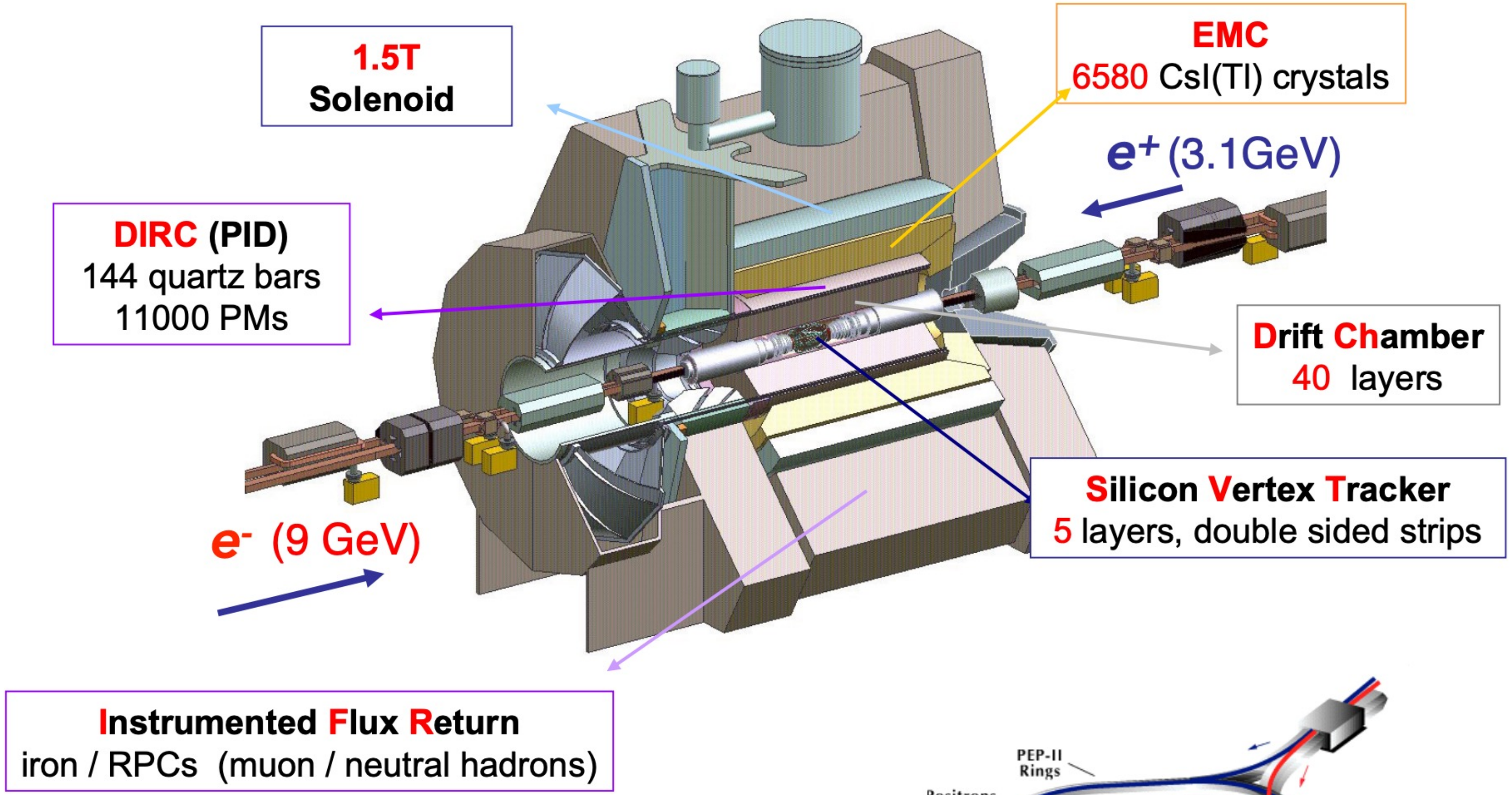
projected search for ALP coupling to photons



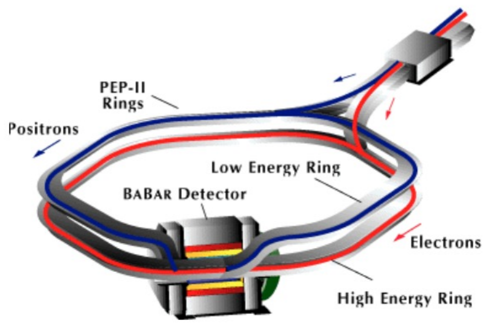
- $B^\pm \to K^\pm a, a \to \gamma\gamma$ decay is fully reconstructible and has very low background (dominated by the continuum QCD and $B\bar{B}$ processes, with QED backgrounds subdominant).
- $a \to \gamma\gamma$ dominates with $\mathrm{BR}(a \to \gamma\gamma) \simeq 100\%$ for $m_a \ll m_{W^\pm}$.
- This is the **first search** for ALPs in this channel.

BABAR EXPERIMENT

- Low energy asymmetric $e^{-}e^{+}$ collider.
- $\Upsilon(4S)$ are produced at very high rate which then decay into a pair of charged B-mesons.
- Luminosity of 424 fb^{-1}, which corresponds to 2.4×10^{8} pairs of charged B-mesons.



1999-2008



SUMMARY OF THE ANALYSIS AND STRATEGY

- We perform a blind analysis on 8% of the data to avoid bias before applying the method to the full data.
- We search for a narrow peak in the resulting di-photon invariant mass spectrum from $B^{\pm} \to K^{\pm}a, a \to \gamma\gamma$ for $0.1 \text{ GeV} < m_a < 4.78 \text{ GeV}$.
- To account for the irreducible backgrounds around π^0, η, and η' we exclude the ALP hypothesis masses in their peaking intervals: $0.1 - 0.175$ GeV, $0.45 - 0.63$ GeV, and $0.91 - 1.01$ GeV.
- The irreducible background $B^{\pm} \to K^{\pm}\gamma\gamma$ has a very small branching fraction ($\sim 10^{-7}$).

SUMMARY OF THE ANALYSIS AND STRATEGY

- We train Boosted Decision Trees (BDTs) to separate signal events from backgrounds.

- We extract the signal by scanning the di-photon invariant mass spectrum for ALP candidate peak that pass our selections.

- We measure the signal branching fractions (BFs) of $B^{\pm} \to K^{\pm}a, a \to \gamma\gamma$ for ALP mass in range of $0.1 \text{ GeV} < m_a < 4.78 \text{ GeV}$.

- For $m_a < 2.5 \text{ GeV}$, ALPs can be long lived, and we additionally determine signal BFs for $c\tau = 1, 10, 100 \text{ mm}$ for $0.1 \text{ GeV} < m_a < 2.5 \text{ GeV}$.

MONTE CARLO SIMULATIONS

- **Signal Monte Carlo (MC) events** are generated with EVTGEN, promptly decaying samples for 24 ALP mass points $(0.1 - 4.78\ \mathrm{GeV})$, long-lived samples for 16 ALP mass points $(0.1 - 2.5\ \mathrm{GeV})$. 30000 signal events are generated at each mass point.

- **MC Backgrounds** are samples generated and weighted to data luminosity:
  - $e^-e^+ \to q\bar{q}\ (q = u, d, s, c)$ (JETSET)
  - $e^-e^+ \to B\bar{B}$ (EVTGEN)

    } Predominant
  - $e^-e^+ \to e^-e^+(\gamma)$ (BHWIDE)
  - $e^-e^+ \to \mu^-\mu^+(\gamma), \tau^-\tau^+(\gamma)$ (KK with TAUOLA)

    } QED - Subdominant

- **The detector response simulation** based on GEANT4.

SELECTIONS

- **Pre-selections:** Suppress non-B background by cut on
  - $|\Delta E| = \left|E_{beam,CM} - E_{B,CM}\right| < 0.3\ \text{GeV}$
  - $5.0\ \text{GeV} < m_{ES} = \sqrt{\left(\frac{\frac{s}{2} + \vec{p}_B.\vec{p}_i}{E_i}\right)^2 - p_B^2} < 5.4\ \text{GeV}$
  - Kinematic fit required the di-photon and $K^{\pm}$ originated from the $B^{\pm}$ candidates using beam spot, beam energy constraint, and $B^{\pm}$ mass constraint.

SELECTIONS

- **Train Boosted Decision Trees (BDTs)** on MC for the two predominant backgrounds:
  - $e^-e^+ \rightarrow q\bar{q}\ (q = u, d, s, c)$
  - $e^-e^+ \rightarrow B\bar{B}$
- We train and test the BDT classifier using ROOT TMVA algorithm.
- We train our BDTs using the Gradient Boosting method.

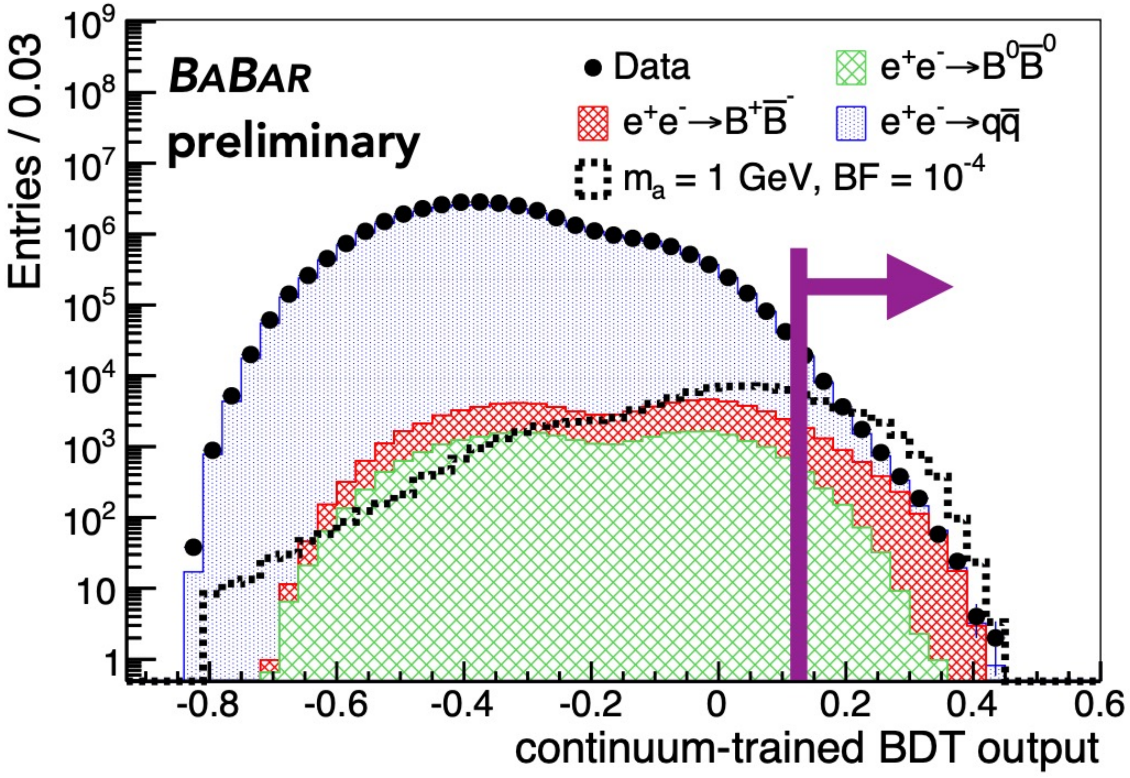
SELECTIONS

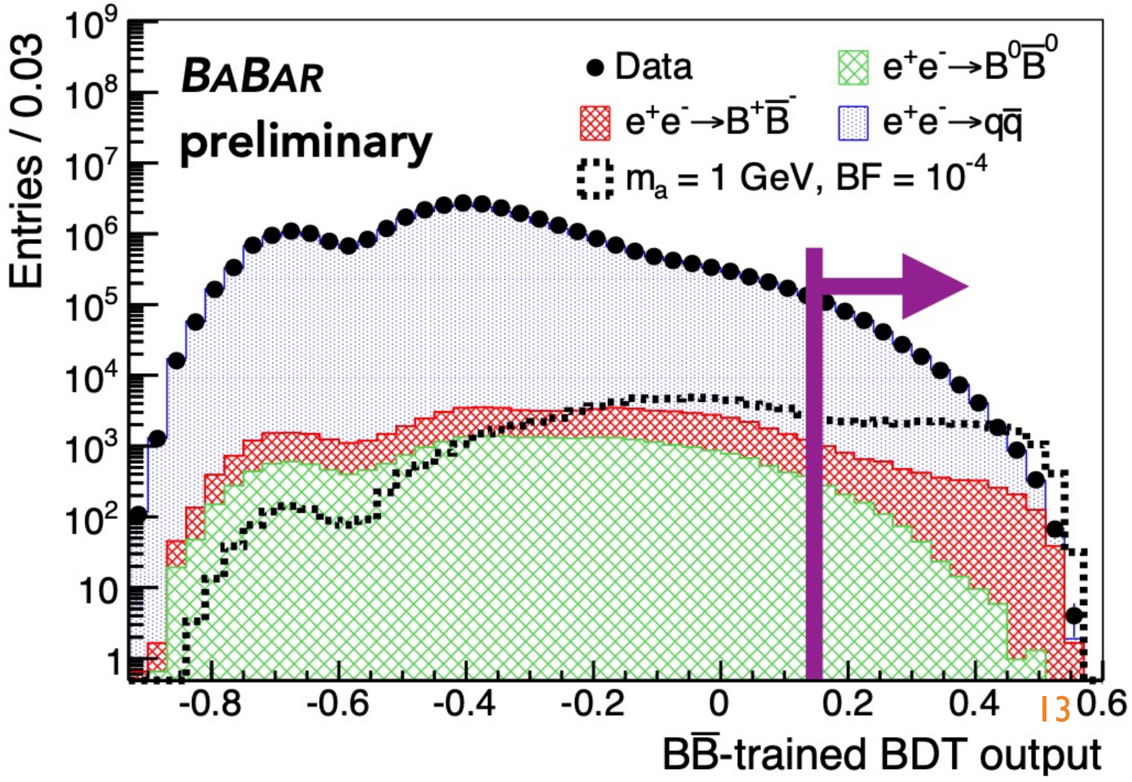
We use 13 training variables:

- Beam-energy substituted mass m_{ES}
- Helicity angle of a daughter photon with highest energy
- Difference between beam energy and $B^{\pm}$ energy in CM frame ΔE
- Kaon helicity angle
- Invariant mass of all tracks and neutral clusters except $B^{\pm} \to K^{\pm}a$ candidate
- Number of neutral clusters in event
- Maximum K PID selector
- Cosine of angle between sphericity axes of $B^{\pm}$ candidate and rest of event (ROE)
- 2^{nd} Legendre moment of ROE, calculated relative to $B^{\pm}$ thrust axis
- Maximum of a daughter photon energies
- Difference between π^0, η, or η' mass and the reconstructed mass from a pair of a and non-a daughter photons

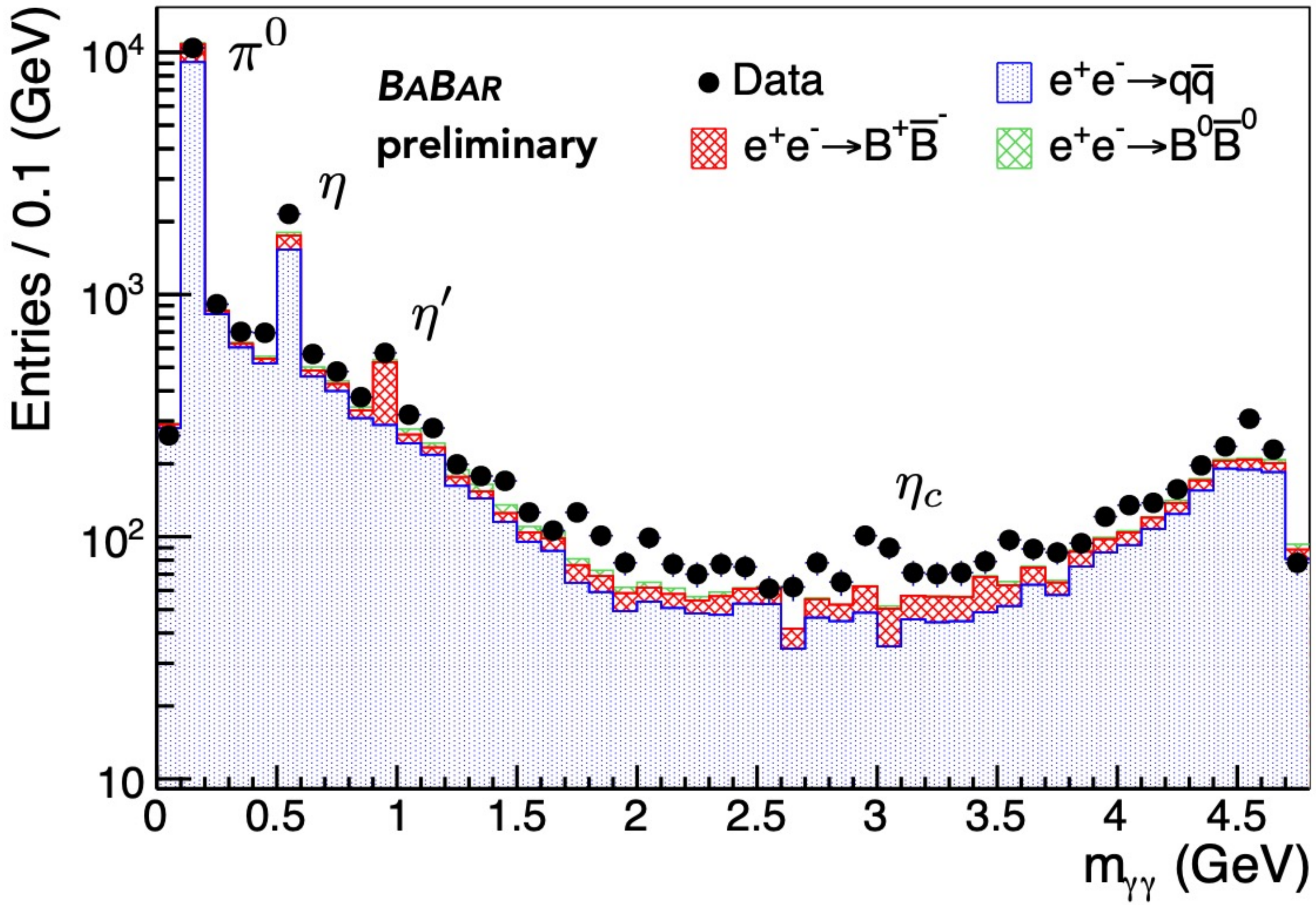
SELECTIONS

Final cut on BDTs classifier: We found the optimal pair of selection is ≥ 0.13 for the continuum-trained BDT, and ≥ 0.15 for the $\mathrm{B\overline{B}}$-trained BDT for all signal masses.





DI-PHOTON MASS SPECTRUM



- The peaking of background correspond with π^0, η, η' masses.
- 2.6σ local signal significance at η_c mass, consistent with the world average BF of $B^{\pm} \to K^{\pm}\eta_c, \eta_c \to \gamma\gamma$.
- Set conservative limits on ALP at this mass η_c by assuming all events are signal.

SIGNAL RESOLUTIONS

- We fit the signal MC distribution with a double-sided Crystal Ball function and take the parameter σ of the Gaussian component as the resolution.
- We construct a linear interpolation of signal histogram between adjacent signal points.
- Comparing data and MC of $B^{\pm} \rightarrow K^{\pm}h \; (h = \pi^{0}, \eta, \eta')$ validates the signal resolutions within 3%.
- We also derive signal efficiency for MC which are approximately 30% over most of the mass range.

SIGNAL EXTRACTION

- We determine the step size between 476 hypothesis mass points by the signal resolution excluding masses near π^0, η, η':
  - $100\ \mathrm{MeV} < m_a < 175\ \mathrm{MeV}$: $\boldsymbol{\pi^0}$
  - $450\ \mathrm{MeV} \leq m_a \leq 630\ \mathrm{MeV}$: $\boldsymbol{\eta}$
  - $0.91\ \mathrm{GeV} \leq m_a \leq 1.01\ \mathrm{GeV}$: $\boldsymbol{\eta'}$
- We extract the signals by a series of unbinned maximum likelihood fits.
- The fit windows are symmetric with half-width ranging from $\pm(30 - 70)\sigma$ (where σ is the signal width) depending on the mass and the proximity to peaking π^0, η, η'.

SIGNAL EXTRACTION

- The likelihood function includes contribution from the signal, continuum background, and peaking background.

- We derive **signal PDFs** from MC and linearly interpolate between simulated masses.

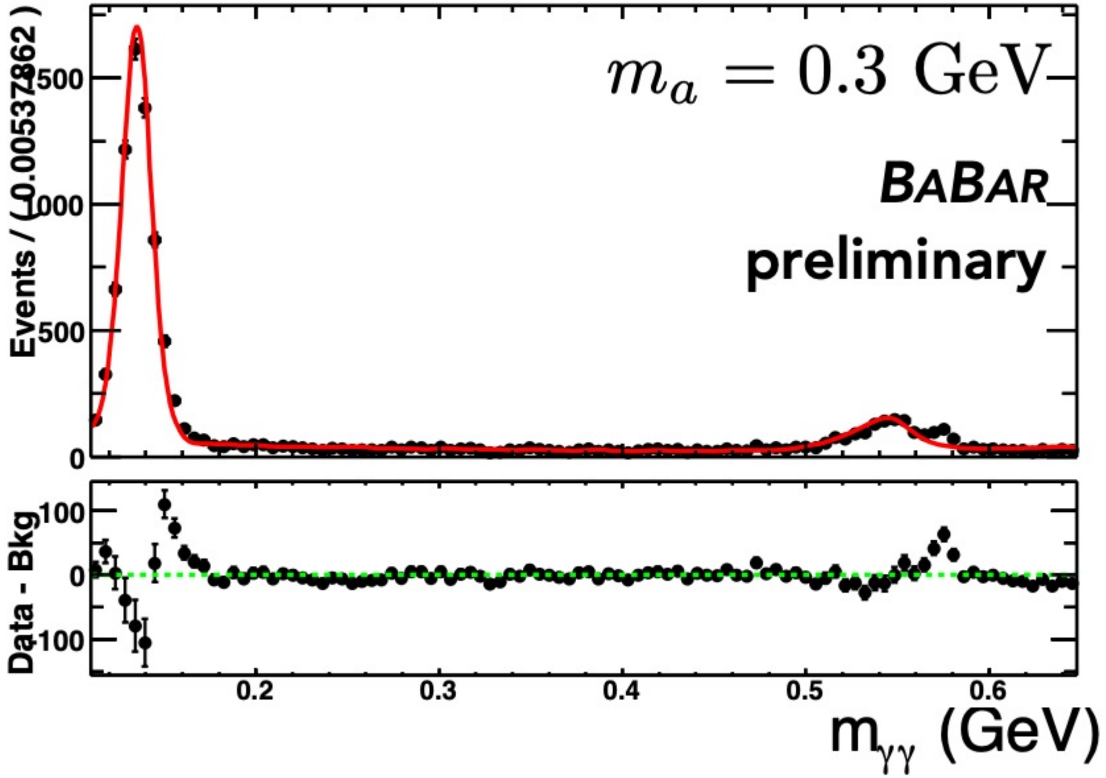
- Continuum **background PDFs**:

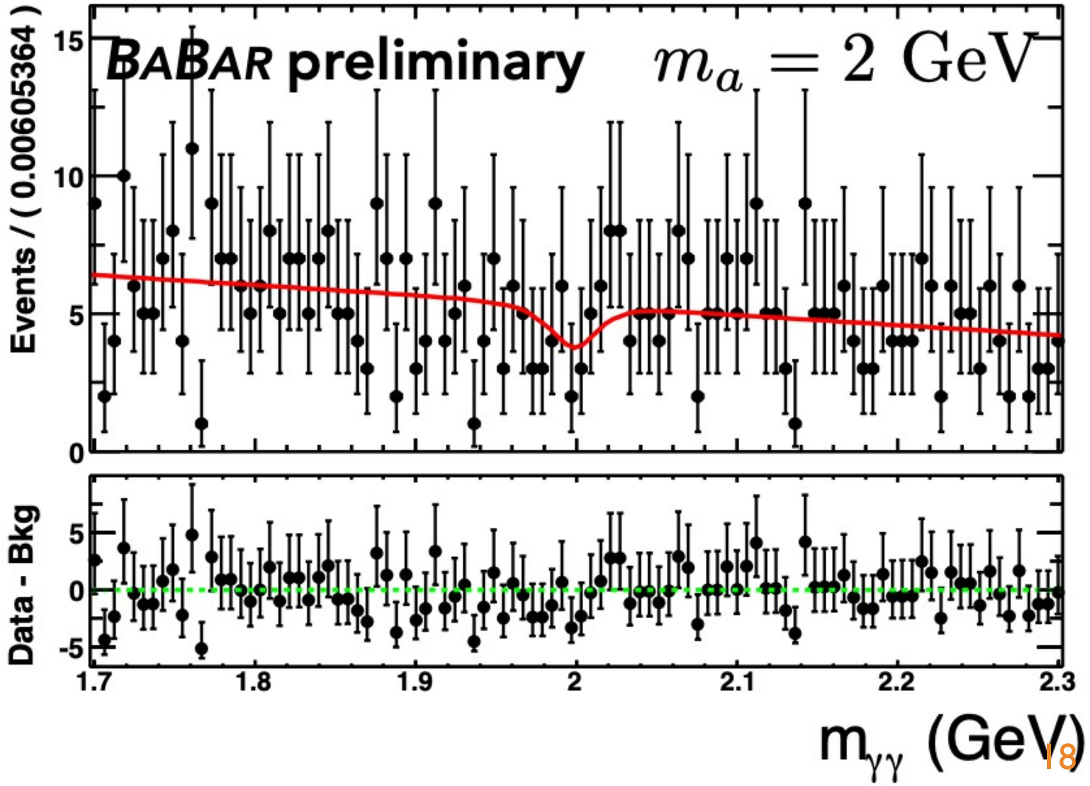
  - For $m_a < 1.35\ \mathrm{GeV}$, we use a second-order Chebyshev polynomial

  - For $m_a \geq 1.35\ \mathrm{GeV}$, we use a first-order Chebyshev polynomial.

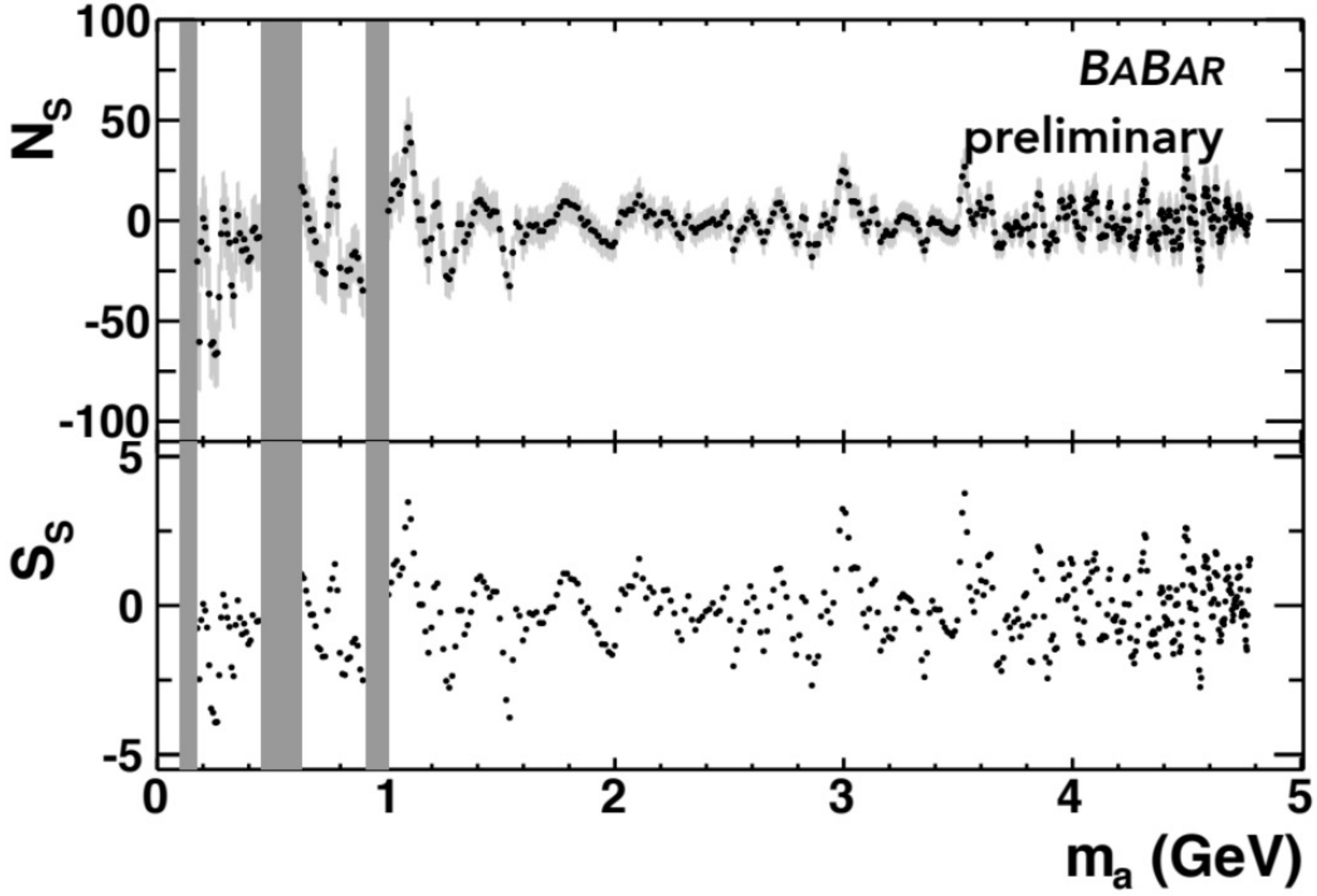
- Each **peaking resonance PDF** is modeled as a sum of a signal template and a broader Gaussian distribution with parameters fixed to fits in MC — this component arises from continuum production of meson resonance that is broadened because of kinematic fit.

SIGNAL YIELD: SAMPLE FITS





SIGNAL YIELD: SIGNAL EVENTS AND LOCAL SIGNIFICANCE.



- Most significant excess $< 1\sigma$ after including trial factors to account for look-elsewhere effect.
- No significant signal observed.

SYSTEMATIC UNCERTAINTY

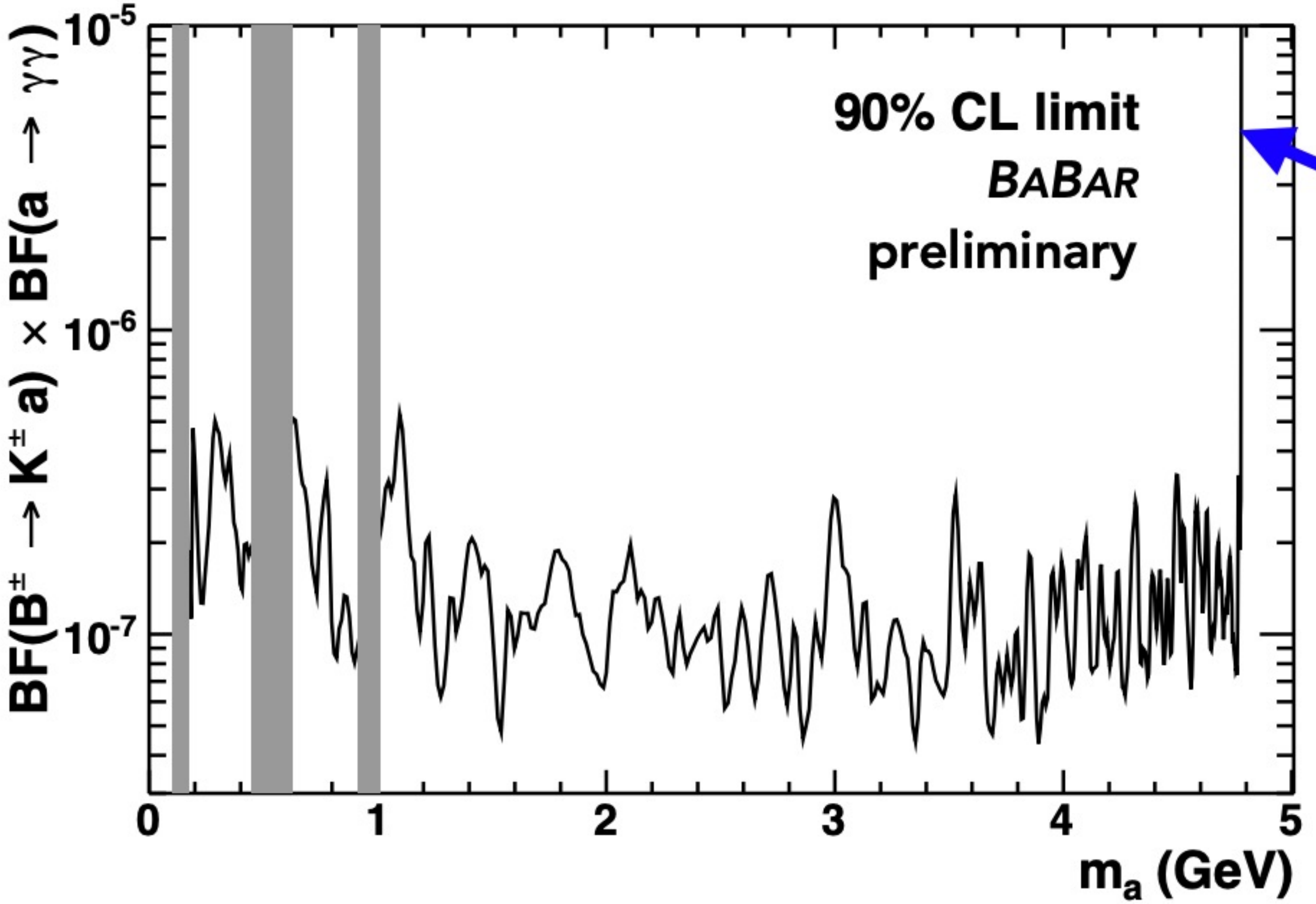
- Assess uncertainty on signal yield from fit by varying order of polynomial for continuum background (3^{rd} order for $m_a < 1.35\ \mathrm{GeV}$, constant at higher mass), varying shape of peaking background within uncertainties, and using next-nearest neighbor for interpolating signal shape.
  - Dominate total uncertainty for some masses in vicinity of π^0 and η.
- Systematic uncertainty on signal yield from varying signal shape width within uncertainty is on average 3% of statistical uncertainty.
- 6% systematic uncertainty on signal efficiency, derived from data/MC ratio in vicinity of η'.
- Other systematic effects are negligible by comparison, including the limited signal MC statistics and luminosity.

BRANCHING FRACTION

- We derive Bayesian limits on the branching fraction at the 90% CL.
  - Taking the flat prior for non-negative values branching fraction.
  - We convolve the likelihood function with a Gaussian distribution with standard deviation equal to the total systematic uncertainty.

$$\mathrm{Br}(B^{\pm} \to K^{\pm} a) = \frac{N_{\mathrm{best-fit}}}{2\sigma_{B^+B^-}\mathcal{L}_{\mathrm{int}}\varepsilon_{\mathrm{sig}}},$$

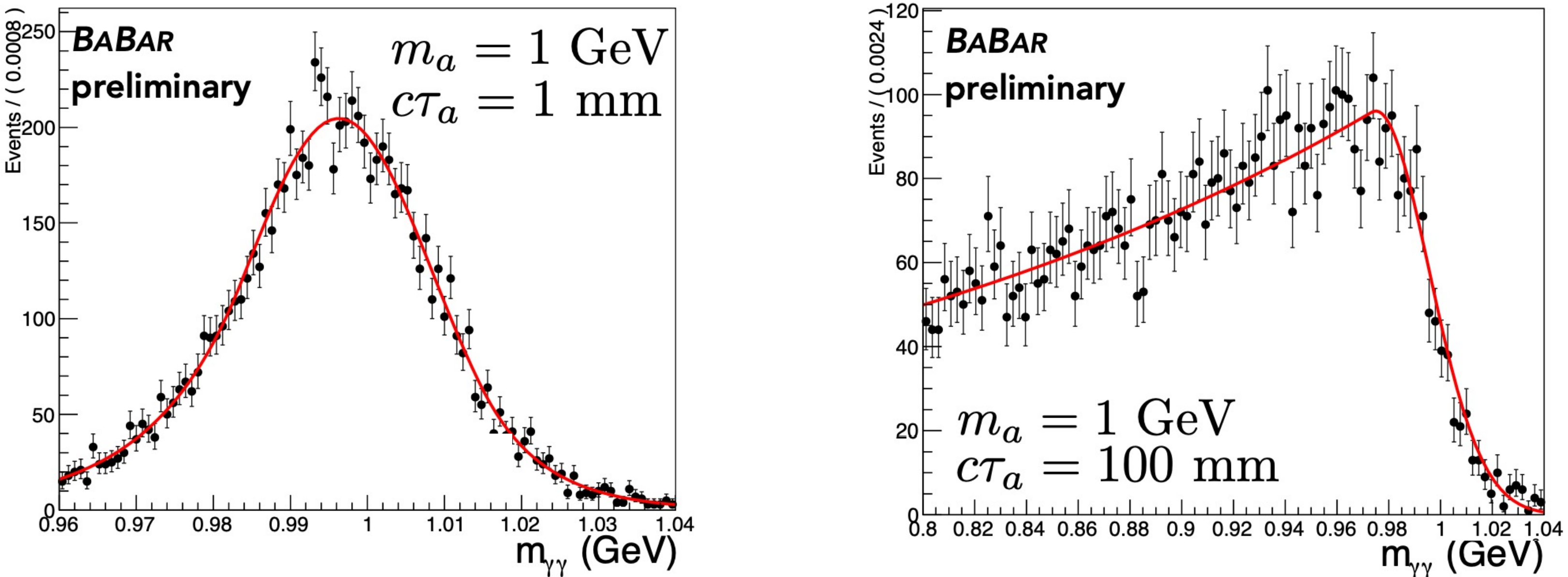
BRANCHING FRACTION LIMIT



$m_a > m_B - m_K$

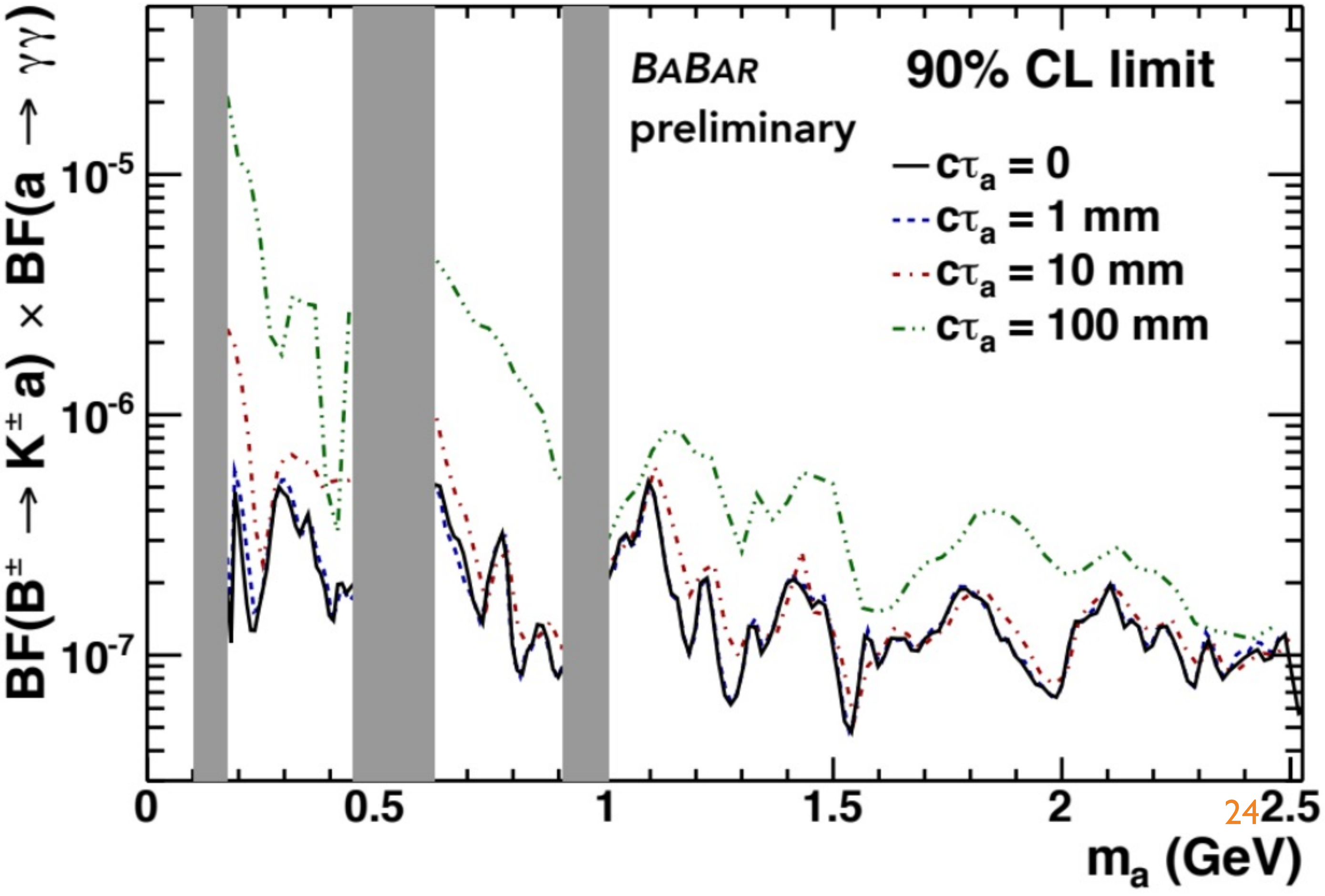
LONG-LIVED ALPS

- For $m_a < 2.5\ \mathrm{GeV}$, we probe couplings for which ALP becomes long-lived.
- Re-do the analysis with lifetime of $c\tau = 1, 10, 100\ \mathrm{mm}$ using single-sided Crystal Ball function to model the resolution. → Bias in reconstruction of signal mass.
- We do not re-optimize; we rather assess the sensitivity.



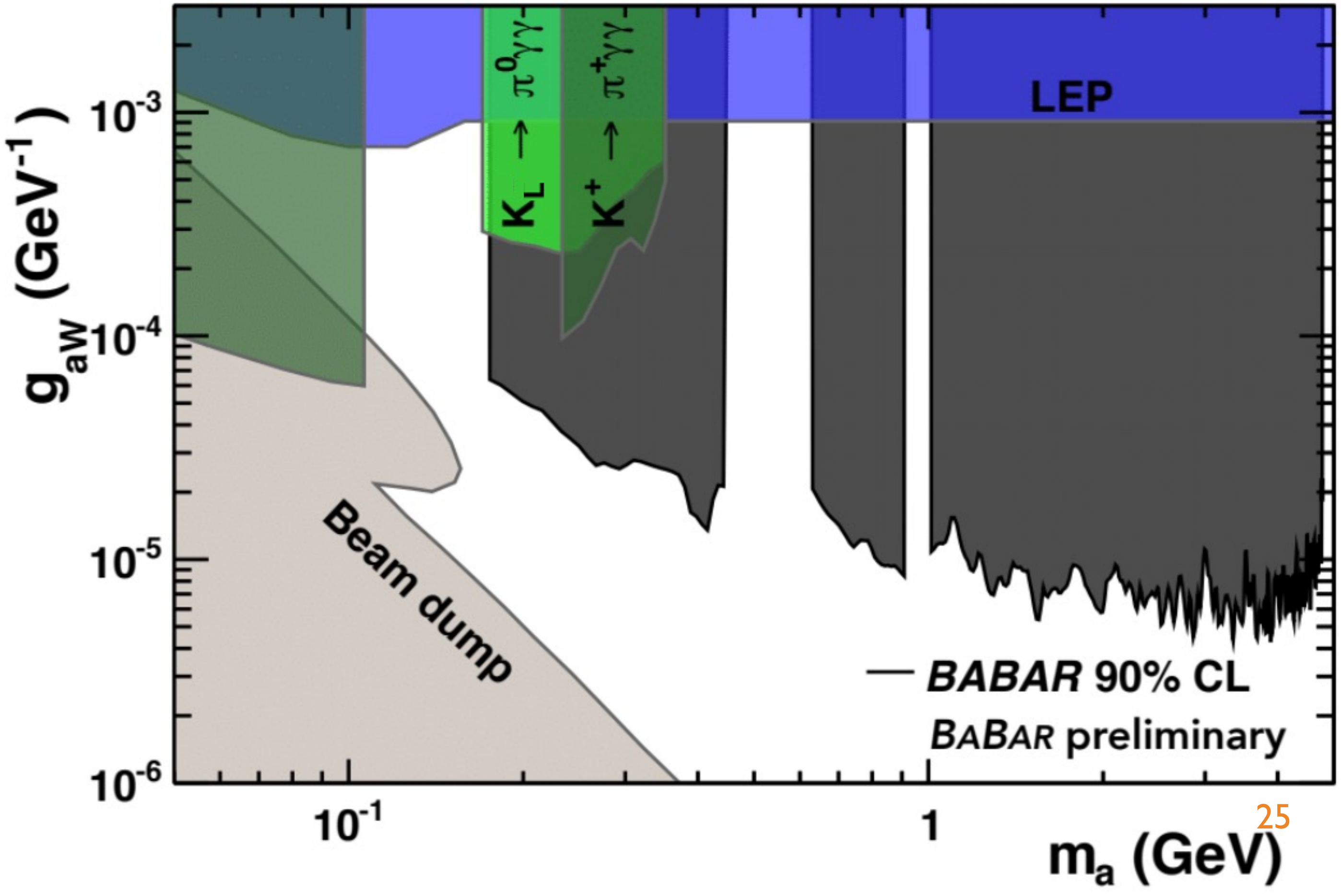
LONG-LIVED ALPS

- Background shape and window width systematic are larger; others stay the same.
- No significant signal found; We derive the upper limit of BFs at the 90% CL.



ALP COUPLING CONSTRAINTS

- We use the derived limit on BF as a function of lifetime to set limit on g_{aW}.
- Improve limit on ALP coupling by over 2 orders of magnitude for many masses!



CONCLUSION

- This is the **first search** for ALPs in $B^{\pm} \to K^{\pm}a, a \to \gamma\gamma$ decay.
- No significant signal found.
- New 90% CL constraints on ALP coupling with W boson are derived which are **over 2 order of magnitude stronger** than existing constraints.
- Flavor-changing mesons decays are proven to be a good channel to look for ALPs.
- Data from **BABAR** experiment promises further contributions to the search for hidden sector.
- **Zoom discussion:** see link on Indico, available in **Flavor and Precision Physics Panel 1** at 8:30 am CT, June 11.