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

HARVEY MUDD COLLEGE

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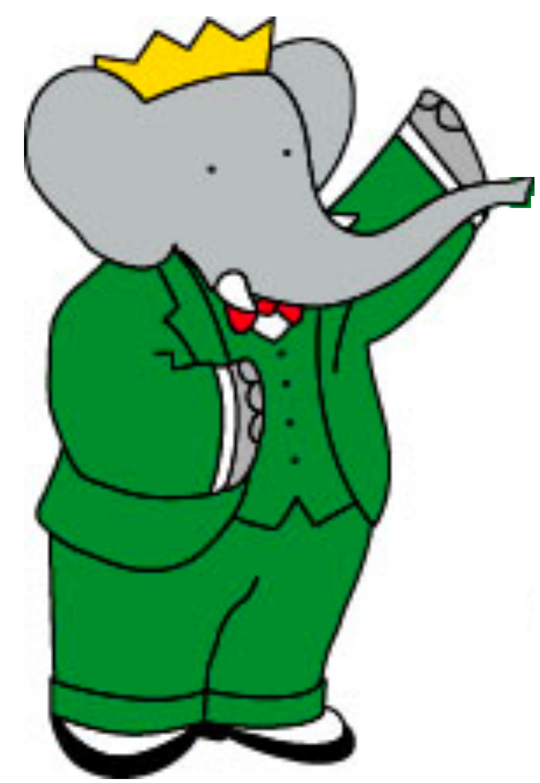
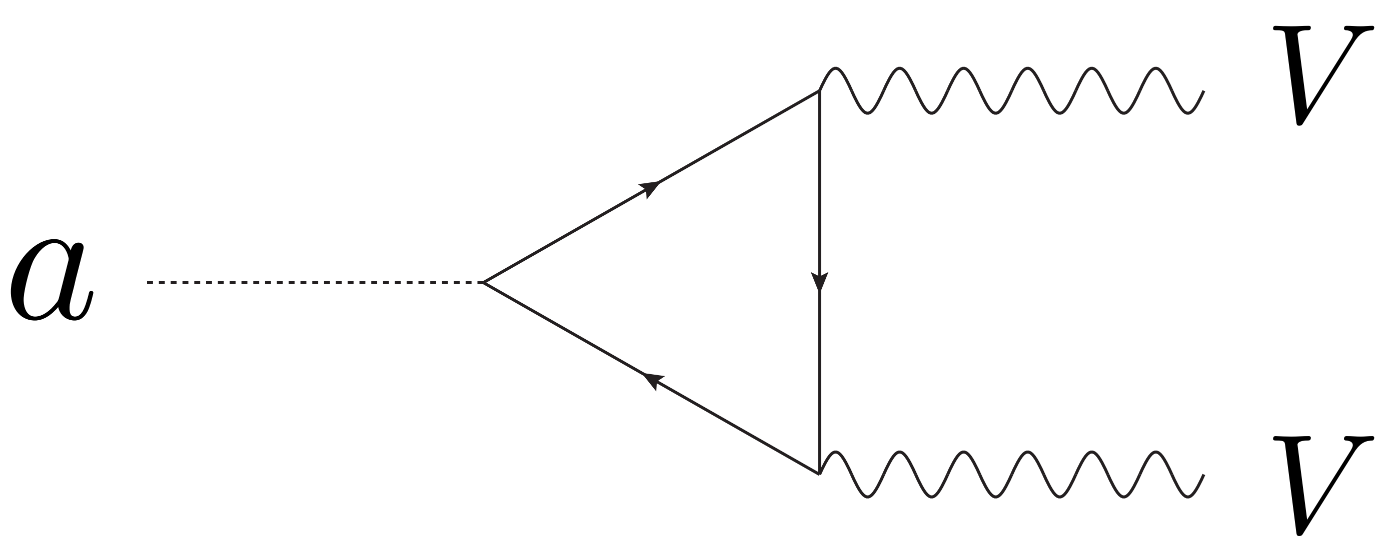


Zoom discussion: see link on Indico, available 19:45-20:45 CET

AXION-LIKE PARTICLES

- Axion-like particles (ALPs) are pseudoscalars that couple to pairs of gauge bosons, V
- They are pseudo-Goldstone bosons of an anomalous global symmetry

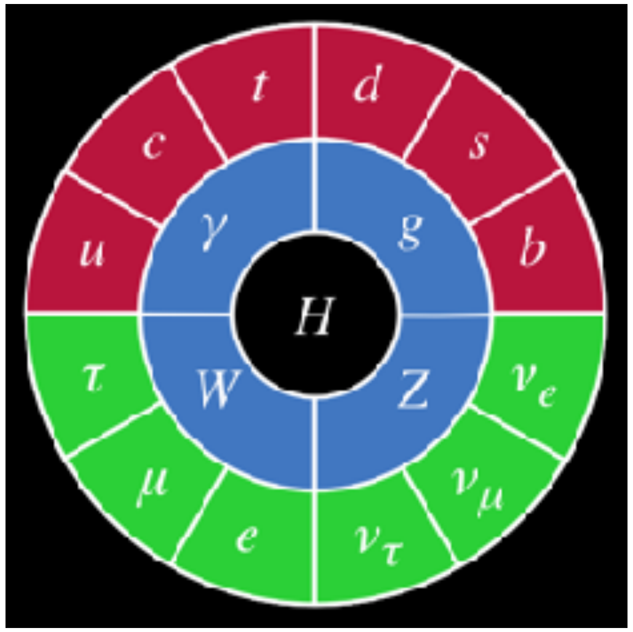


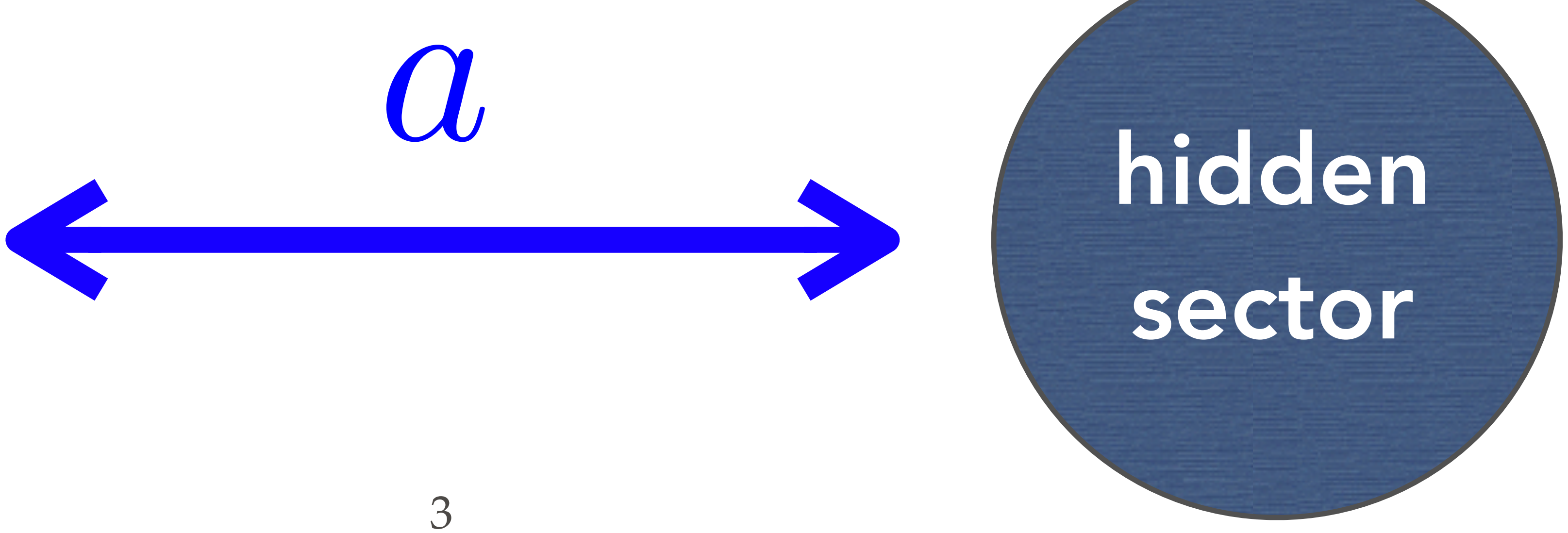
$$\mathcal{L} = -\frac{g_{aV}}{4}\, a\, V_{\mu\nu}\tilde{V}^{\mu\nu}$$

ALPS & HIDDEN SECTORS

- ALPs have several interesting properties:
  - Arise in string theory, supersymmetry, and other BSM models, including solutions to hierarchy, strong-CP problems
  - They are naturally light compared to the weak scale
  - They have non-renormalizable couplings that are suppressed by a high new physics scale $g_{aV} \sim 1/\Lambda$
- **"Axion portal"** to hidden sectors:

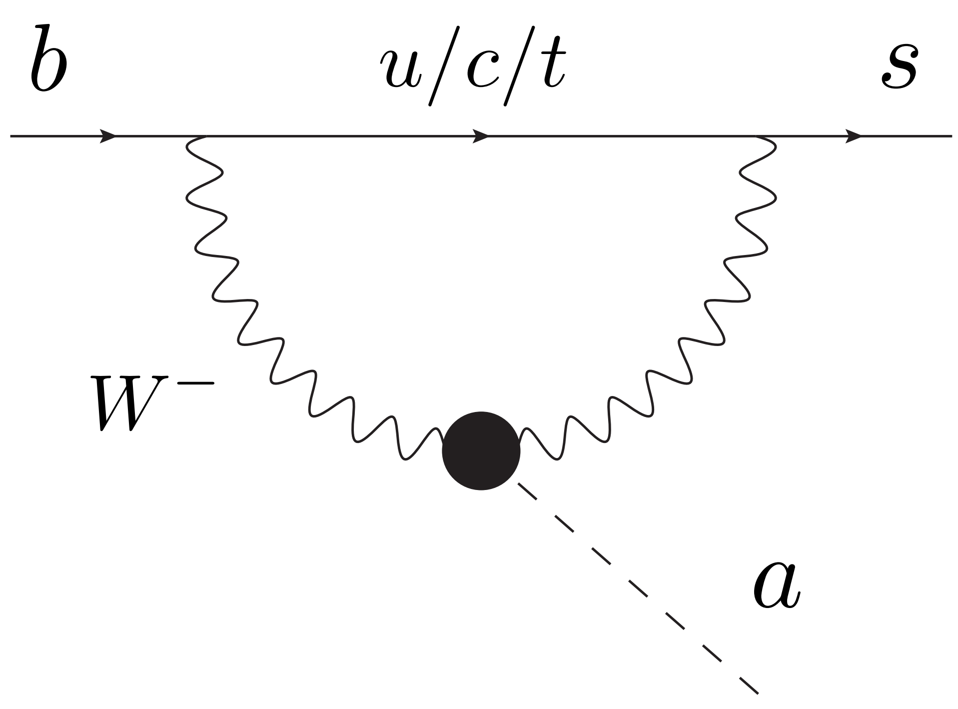
e.g., Y. Nomura, J. Thaler, PRD 79 (2009); Physics Beyond Colliders Report, JPG 47 (2020), and references therein

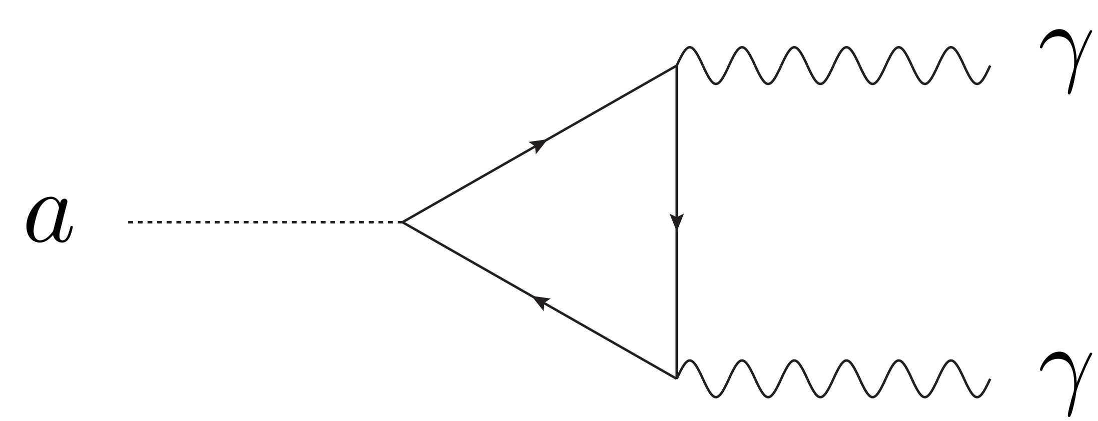




ALPS & MESON DECAYS

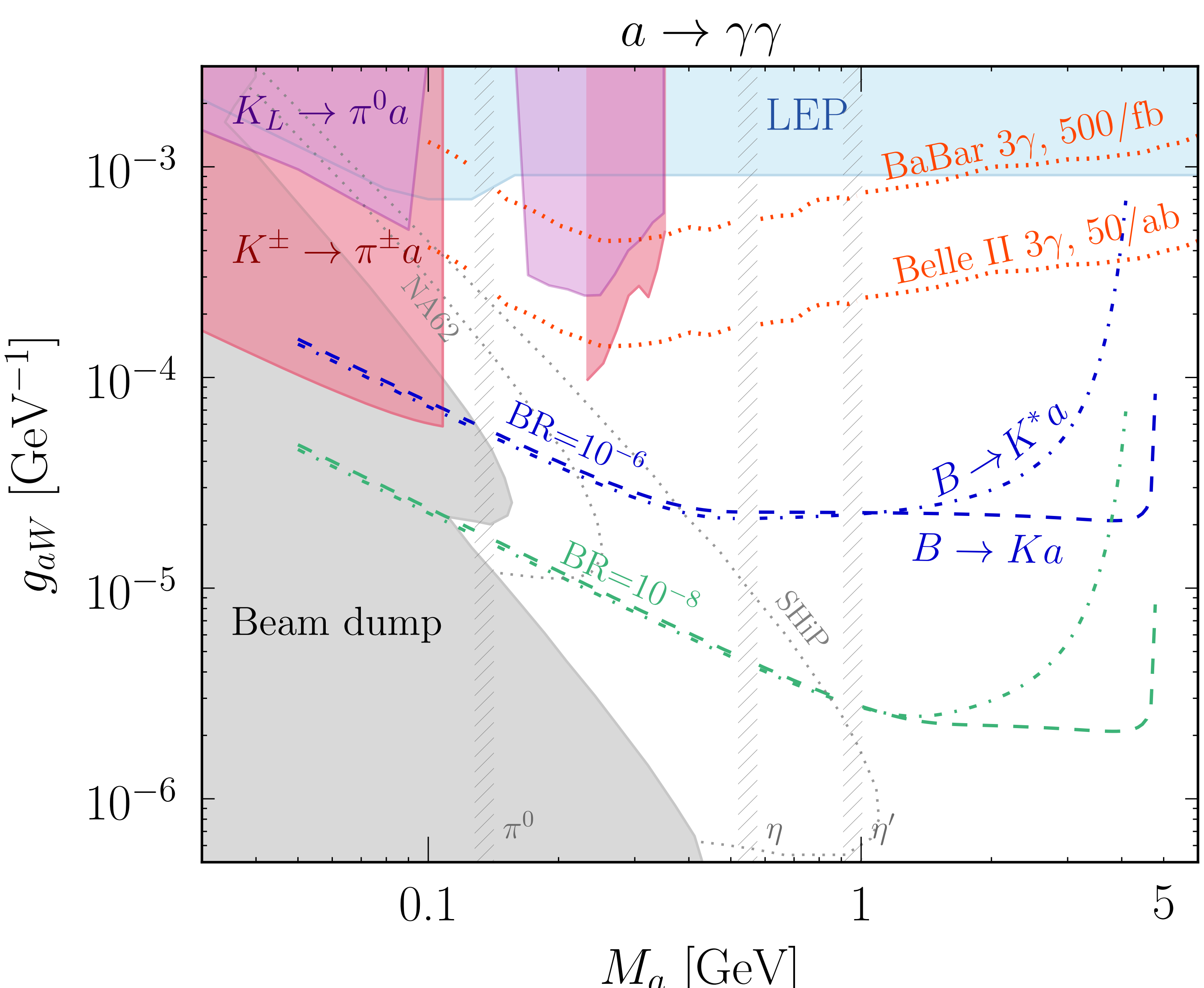
- Most ALP searches target couplings to photons & gluons
- However, ALP-photon coupling actually arises from couplings to hypercharge and SU(2) gauge bosons; generically expect ALP to couple to $W^{\pm}$ bosons as well
- ALP is produced in flavor-changing meson decays





ALPS & MESON DECAYS

- Searches in $B^{\pm} \to K^{\pm} a,\ a \to \gamma\gamma$ very promising for ALPs!
- We perform the **first search** for ALPs in this process

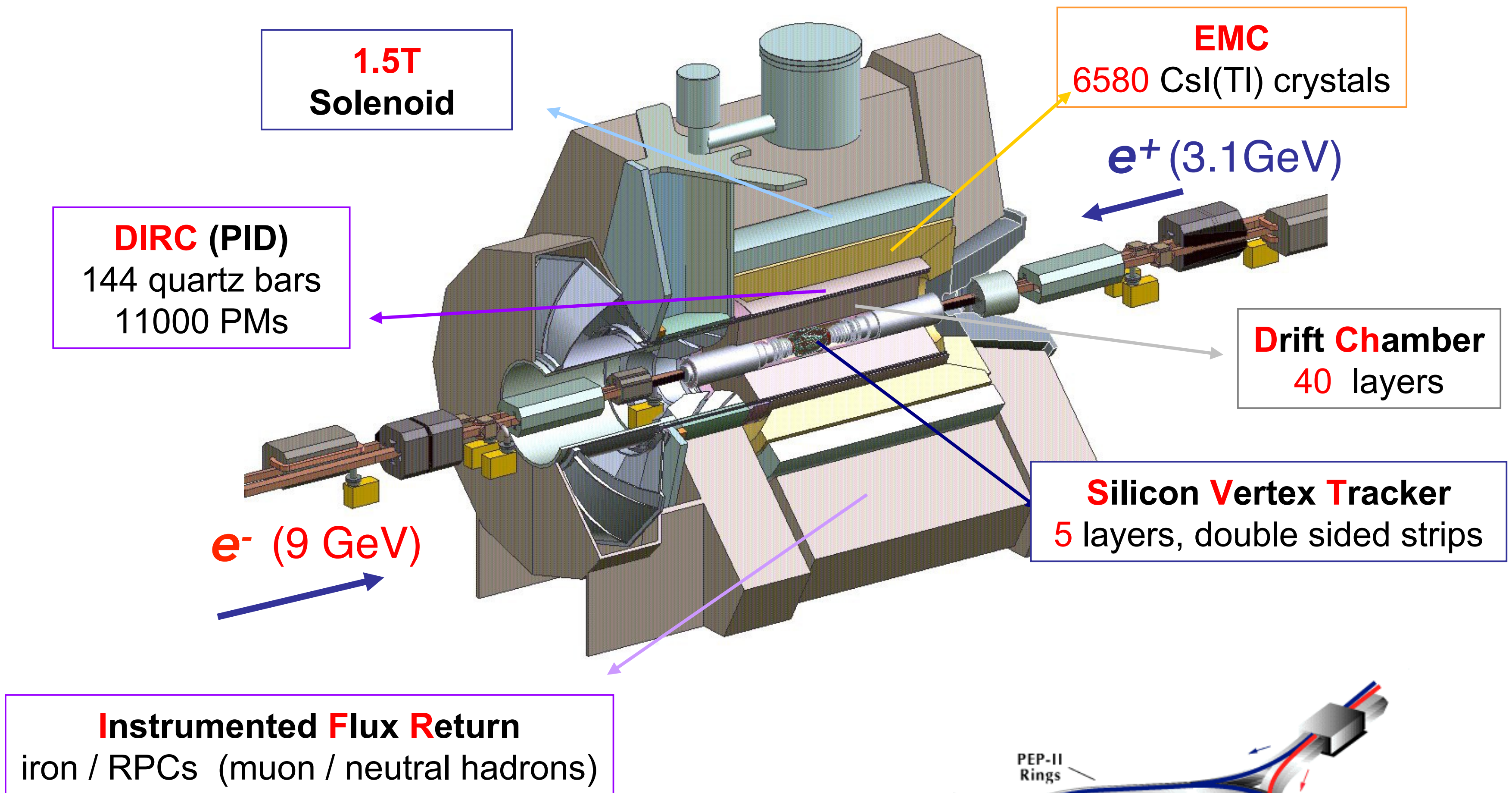


$$\mathcal{L} = -\frac{g_{aV}}{4}\, a\, W^{a}_{\mu\nu} \tilde{W}^{a\,\mu\nu}$$

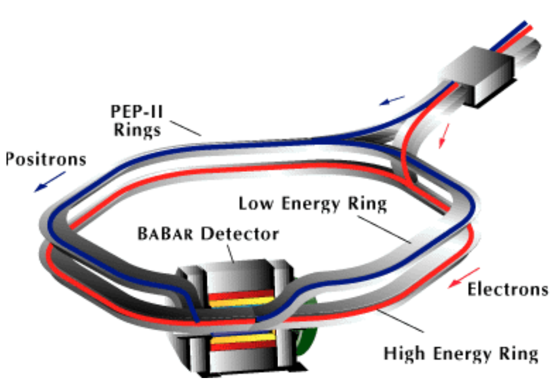
$$BF(a \to \gamma\gamma) = 100\%$$

$\text{units}: \ \hbar = c = 1$

BABAR EXPERIMENT



1999-2008



- 432/fb data collected on $\Upsilon(4S)$ peak
- Corresponds to 2.4×10^8 pairs of B^+B^- mesons

- Blind analysis strategy: use 8% of total dataset as optimization sample used to determine analysis method, discard for final results

ANALYSIS STRATEGY

- Reconstruct $B^{\pm} \to K^{\pm}a,\ a \to \gamma\gamma$ candidates, look for narrow peak in diphoton invariant mass spectrum
- Measure $B^{\pm} \to K^{\pm}a,\ a \to \gamma\gamma$ branching fraction for $0.1\,\mathrm{GeV} < m_a < 4.78\,\mathrm{GeV}$
- Exclude mass intervals in vicinity of peaking $\pi^0/\eta/\eta'$ backgrounds: 0.1-0.175 GeV, 0.45-0.63 GeV, 0.91-1.01 GeV
- For $m_a < 2.5\ \mathrm{GeV}$, ALPs can be long lived, and we additionally determine signal BFs for $c\tau_a = 1,\ 10,\ 100\ \mathrm{mm}$

MONTE CARLO SIMULATIONS

- **Signal:** simulated with EvtGen, promptly decaying samples for 24 ALP mass points (0.1-4.78 GeV), long-lived samples for 16 ALP mass points (0.1-2.5 GeV)

- **Background:** samples generated & weighted to data luminosity
  - $e^+e^- \to q\bar{q}\ (q = u, d, s, c)$ (JETSET)
  - $e^+e^- \to B\bar{B}$ (EvtGen)
  - $e^+e^- \to e^+e^-(\gamma)$ (BHWIDE)
  - $e^+e^- \to \mu^+\mu^-(\gamma),\ \tau^+\tau^-(\gamma)$ (KK with TAUOLA)

- Detector effects fully simulated with GEANT4

SELECTIONS

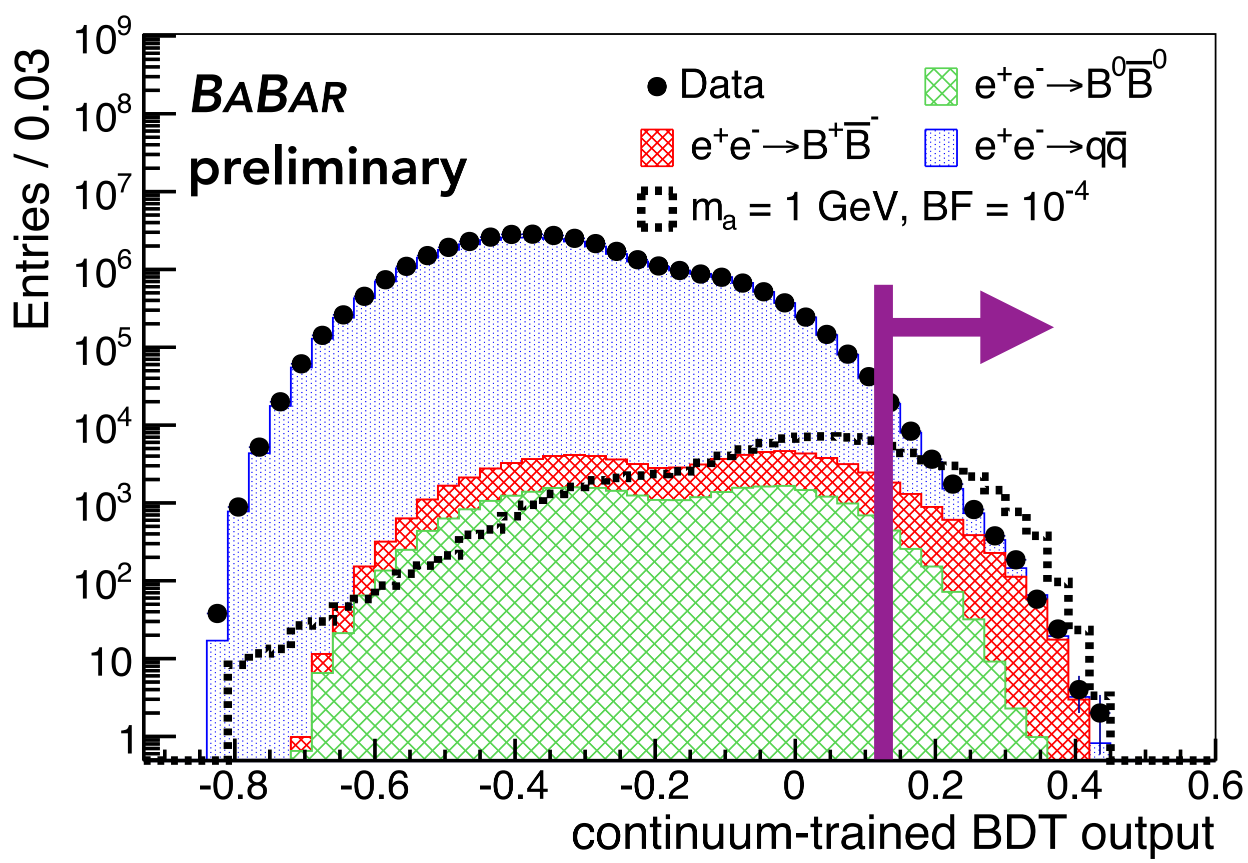
- **Preselection:** Reconstruct $B^{\pm}$ candidates from $K^{\pm}$ candidate and two photons
  - Require $$m_{\mathrm{ES}} = \sqrt{\frac{(s/2 + \vec{p}_i \cdot \vec{p}_B)^2}{E_i^2} - p_B^2} > 5.0\ \mathrm{GeV}$$ $$|\Delta E| = |\sqrt{s}/2 - E_B^{\mathrm{CM}}| < 0.3\ \mathrm{GeV}$$
  - Perform kinematic fit requiring photon and kaon to originate from beamspot, constrain mass to $m_{B^{\pm}}$ and energy to beam energy
- **Train 2 Boosted Decision Trees:** each is trained on MC for one of the two predominant backgrounds:
  - $e^+e^- \to q\bar{q}\ (q = u, d, s, c)$
  - $e^+e^- \to B^+B^-$

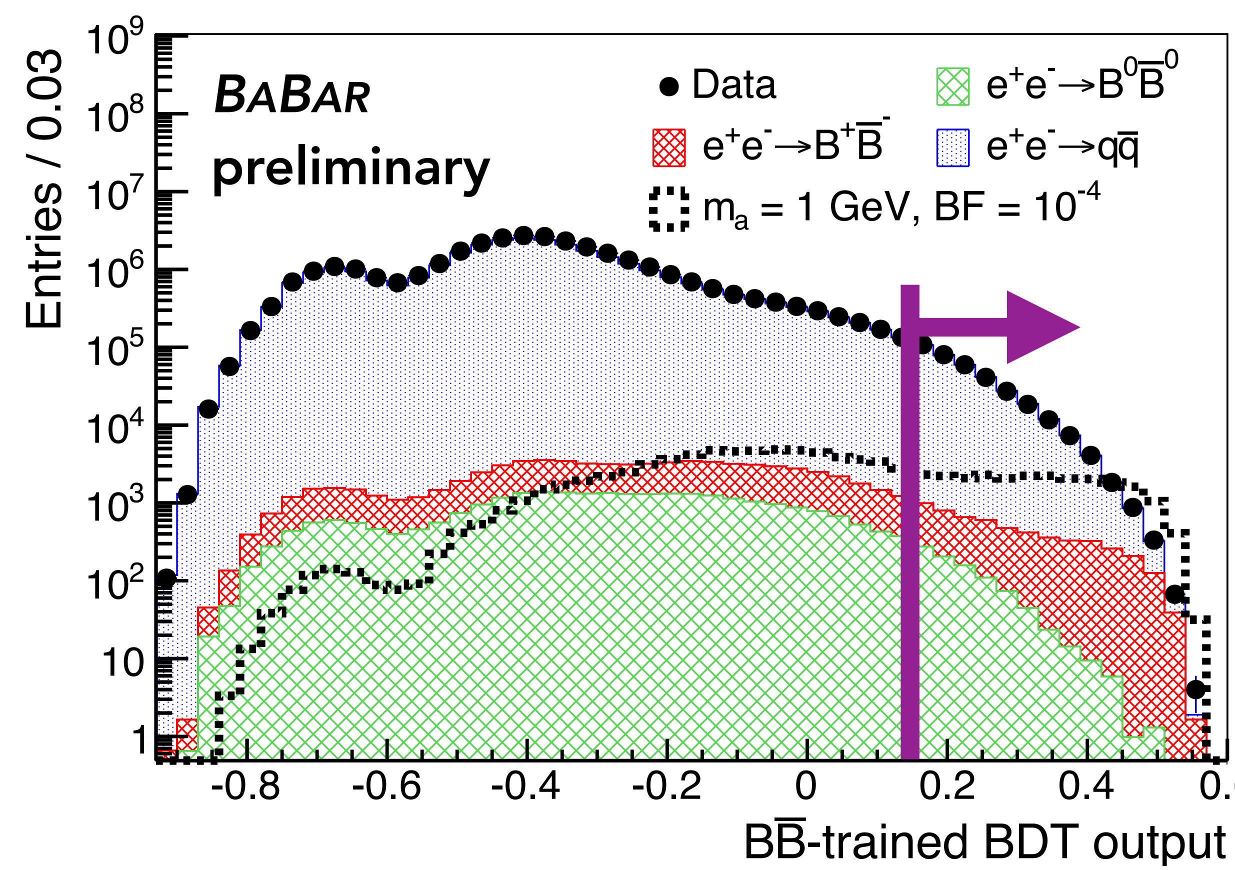
SELECTIONS

- 13 BDT training observables:
  - m_{ES}
  - ΔE
  - cosine of angle between sphericity axes of $B^{\pm}$ candidate and rest of event (ROE)
  - PID info for kaon candidate
  - 2nd Legendre moment of ROE, calculated relative to $B^{\pm}$ thrust axis
  - helicity angle of most energetic photon, and of kaon
  - energy of most energetic photon in a candidate
  - invariant mass of ROE
  - multiplicity of neutral clusters
  - invariant mass of diphoton pair, with 1 photon in $B^{\pm}$ candidate and 1 photon in ROE, closest to each of π^0, η, η'

FINAL SELECTIONS

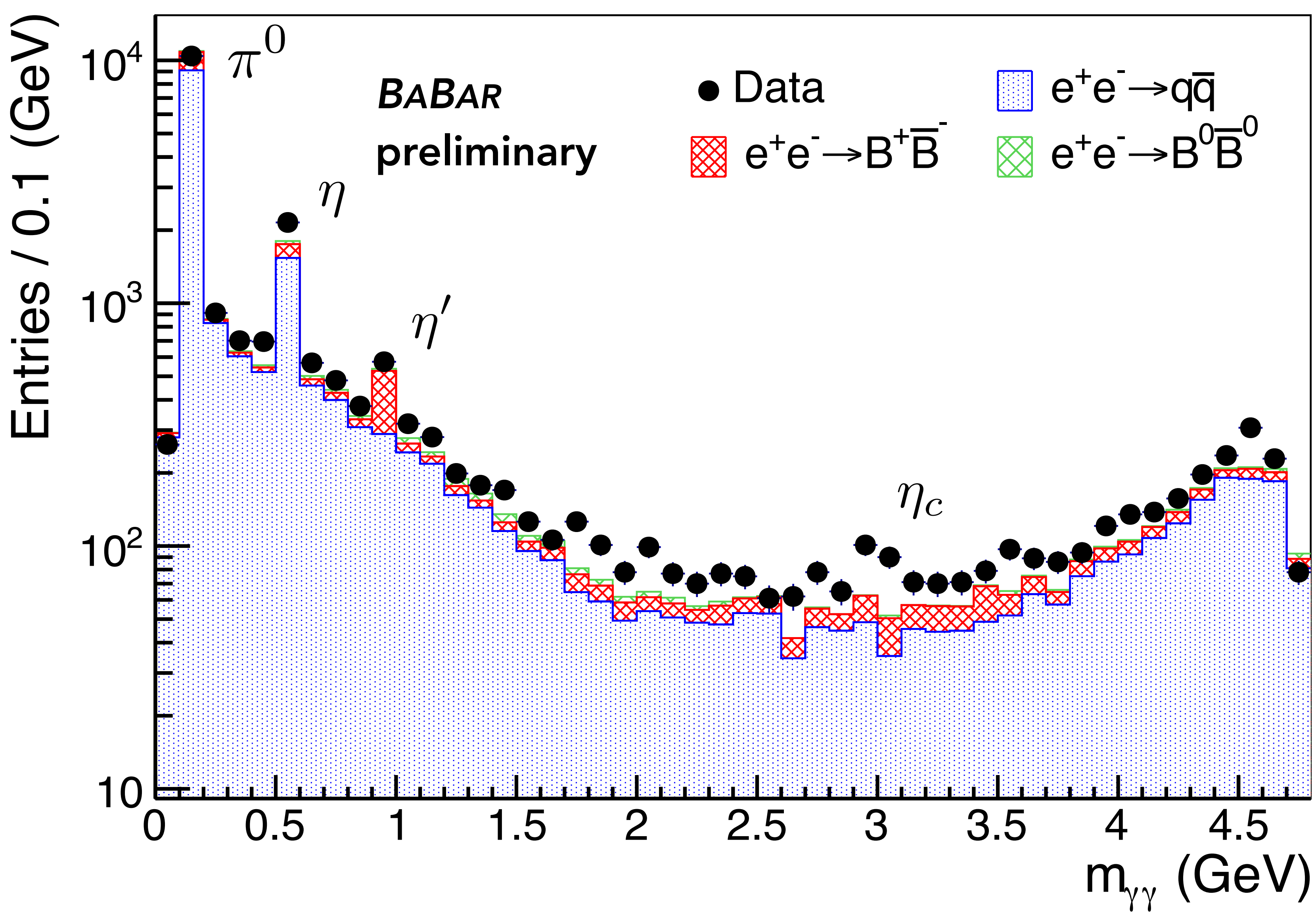
- Cut of > 0.13 on continuum-trained BDT output, > 0.15 on B^+B^--trained BDT output
- Adopted same BDT cuts for all signal masses





DIPHOTON SPECTRUM

- Peaking backgrounds observed at $\pi^0/\eta/\eta'$ masses



- 2.6σ local excess observed at η_c mass, consistent with world-avg BF $B^{\pm} \to K^{\pm}\eta_c,\, \eta_c \to \gamma\gamma$
- Set conservative limits on ALP at η_c mass by assuming all events are signal

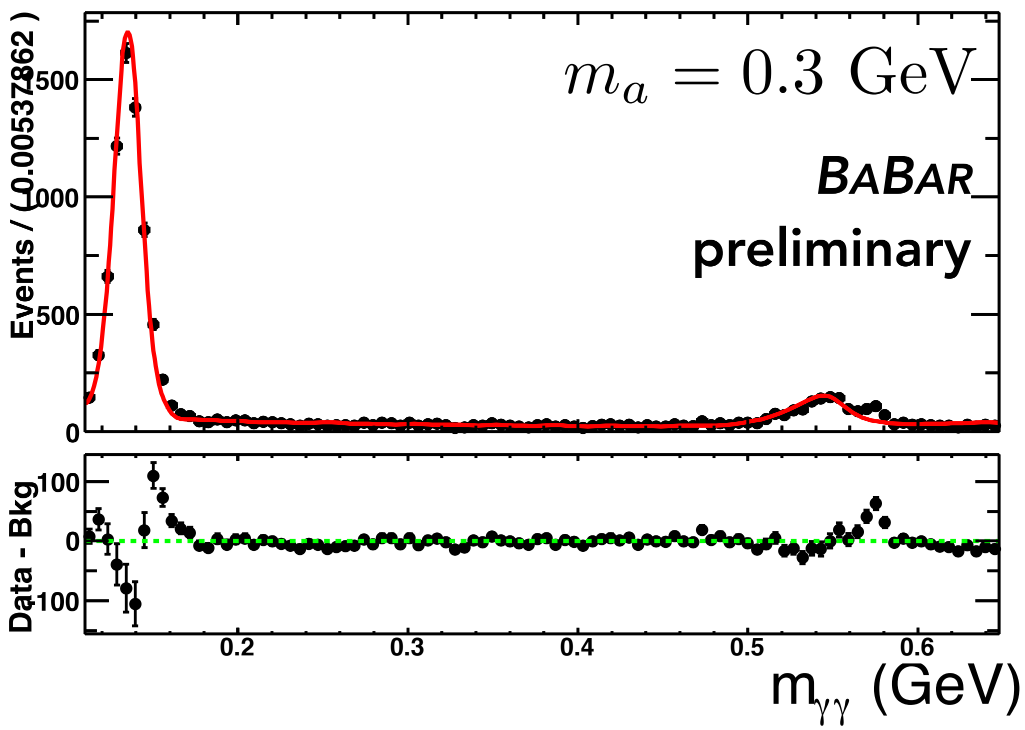
SIGNAL EXTRACTION

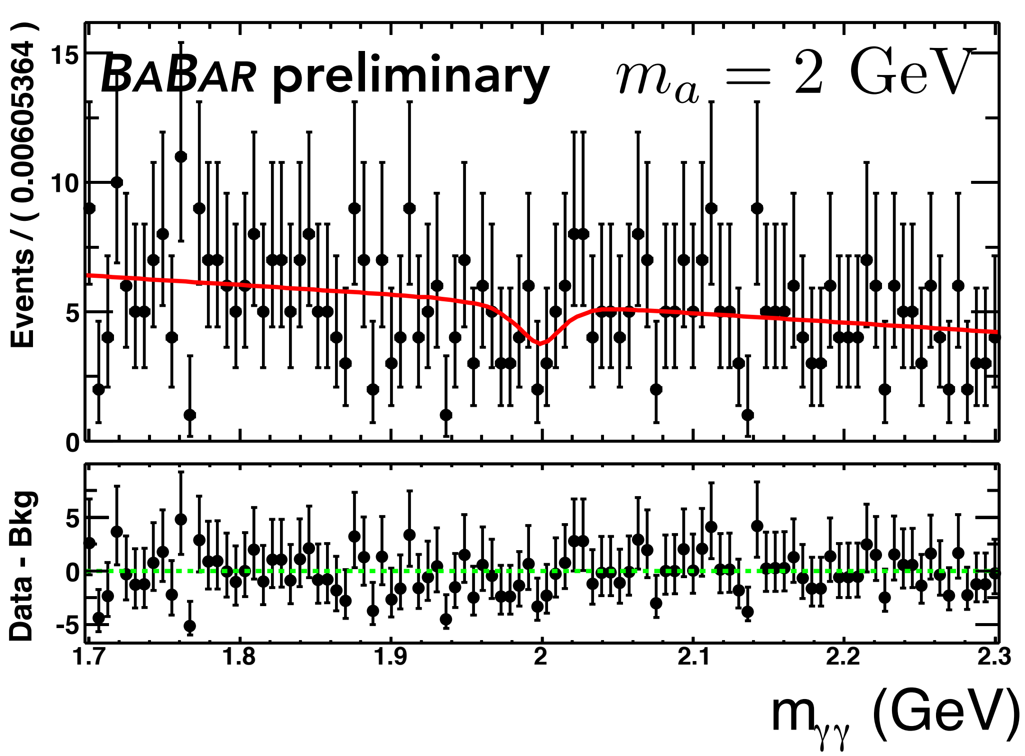
- Perform unbinned maximum likelihood fits for signal peak over smooth background
- 476 mass hypotheses, step size between adjacent mass hypotheses is given by the signal resolution, σ
- σ is determined by fitting a double-sided Crystal Ball function to signal MC at various masses, interpolating for intermediate values
- Resolution ranges from 8 MeV at $m_a = 0.175\ \mathrm{GeV}$ to 14 MeV at $m_a = 2\ \mathrm{GeV}$, decreasing back to 2 MeV at $m_a = 4.78\ \mathrm{GeV}$ as a result of the kinematic fit
- Signal MC resolution is validated by data/MC comparisons of $B^\pm \to K^\pm \pi^0$ and $B^\pm \to K^\pm \eta$, found to be consistent within 3%
- Signal efficiency derived from MC, ranges from 2% at $m_a = 4.78\ \mathrm{GeV}$ to 33% at $m_a = 2\ \mathrm{GeV}$

FIT PROPERTIES

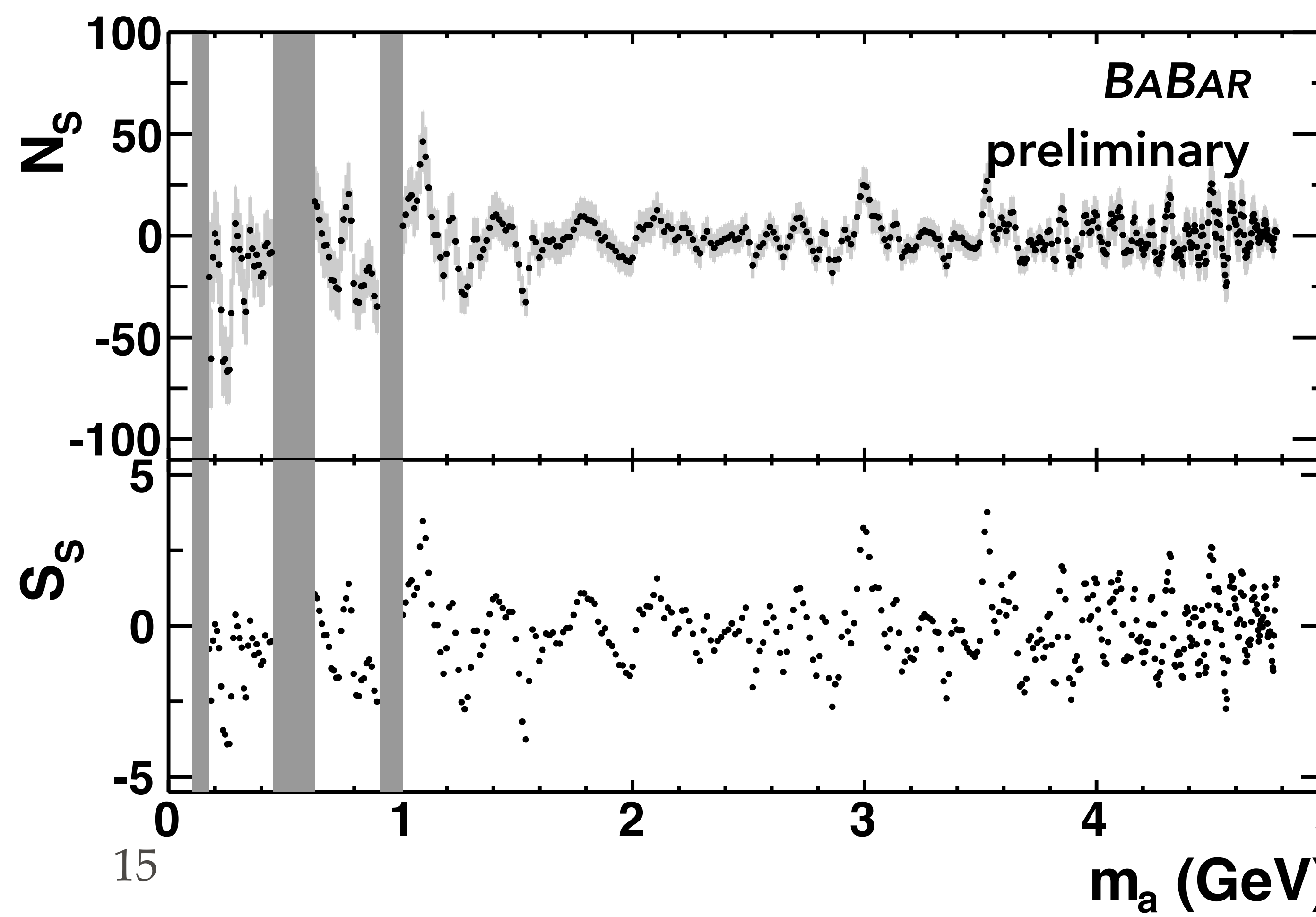
- Fits are performed over intervals of length $(30-70)\sigma$ depending on ALP mass, restricted to the range $0.11\ \mathrm{GeV} < m_a < 4.8\ \mathrm{GeV}$
- Likelihood function includes contributions from signal, continuum background, peaking background
- **Signal PDF:** modeled from signal MC and interpolated between simulated mass points
- **Continuum background PDF:** second-order polynomial for $m_a < 1.35\ \mathrm{GeV}$, first-order polynomial at higher masses
- **Peaking background PDF:** each SM diphoton resonance 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 $\pi^0/\eta/\eta'$ that is broadened because of kinematic fit

SIGNAL YIELD





- (left) sample fits
- (right below) signal yield and local significance
- most significant excess $< 1\sigma$ after including trial factors

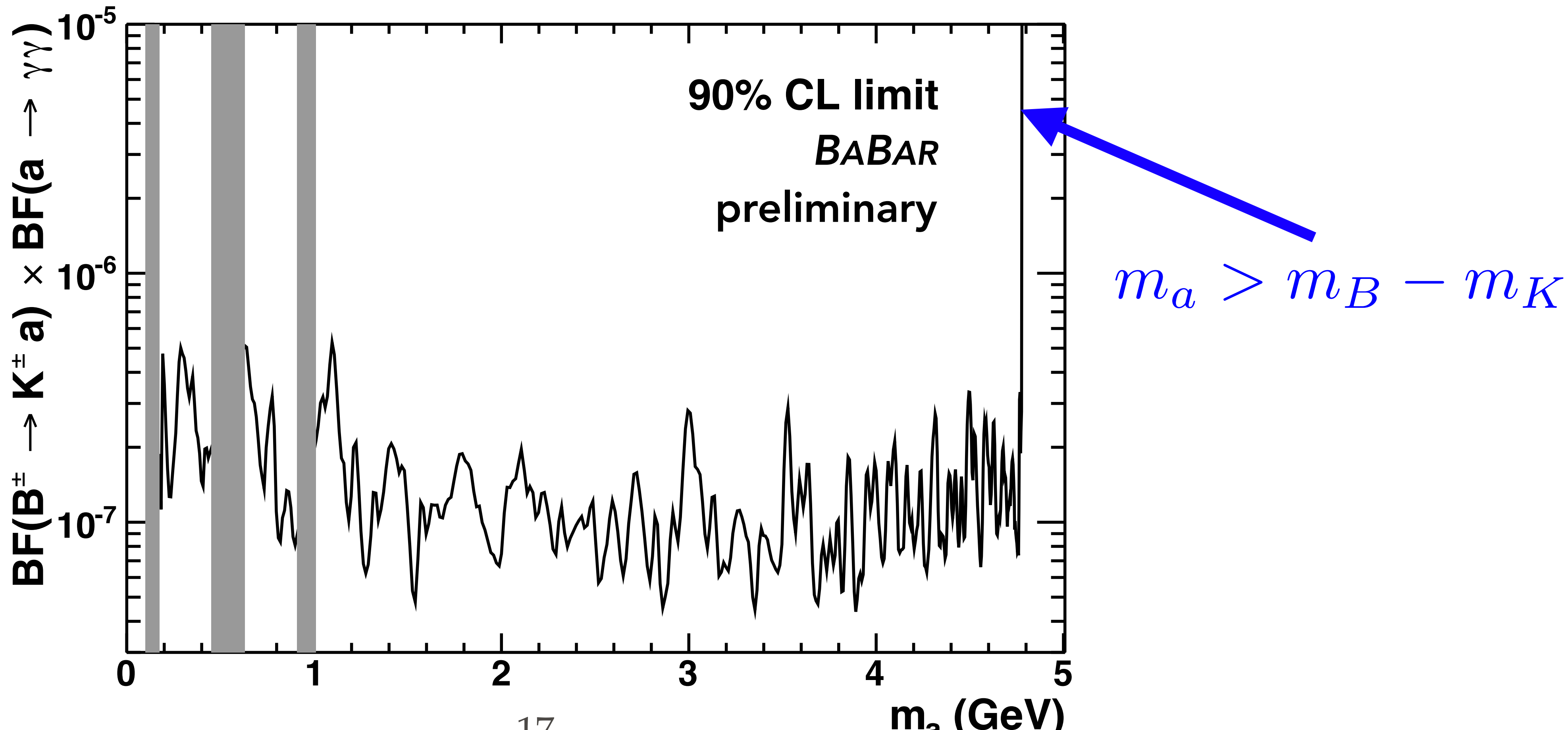


SYSTEMATIC UNCERTAINTIES

- Assess uncertainty on signal yield from fit by varying order of polynomial for continuum background (3rd-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
    - Dominates total uncertainty for some masses in vicinity of π^0/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 negligible by comparison, including on limited signal MC statistics, luminosity

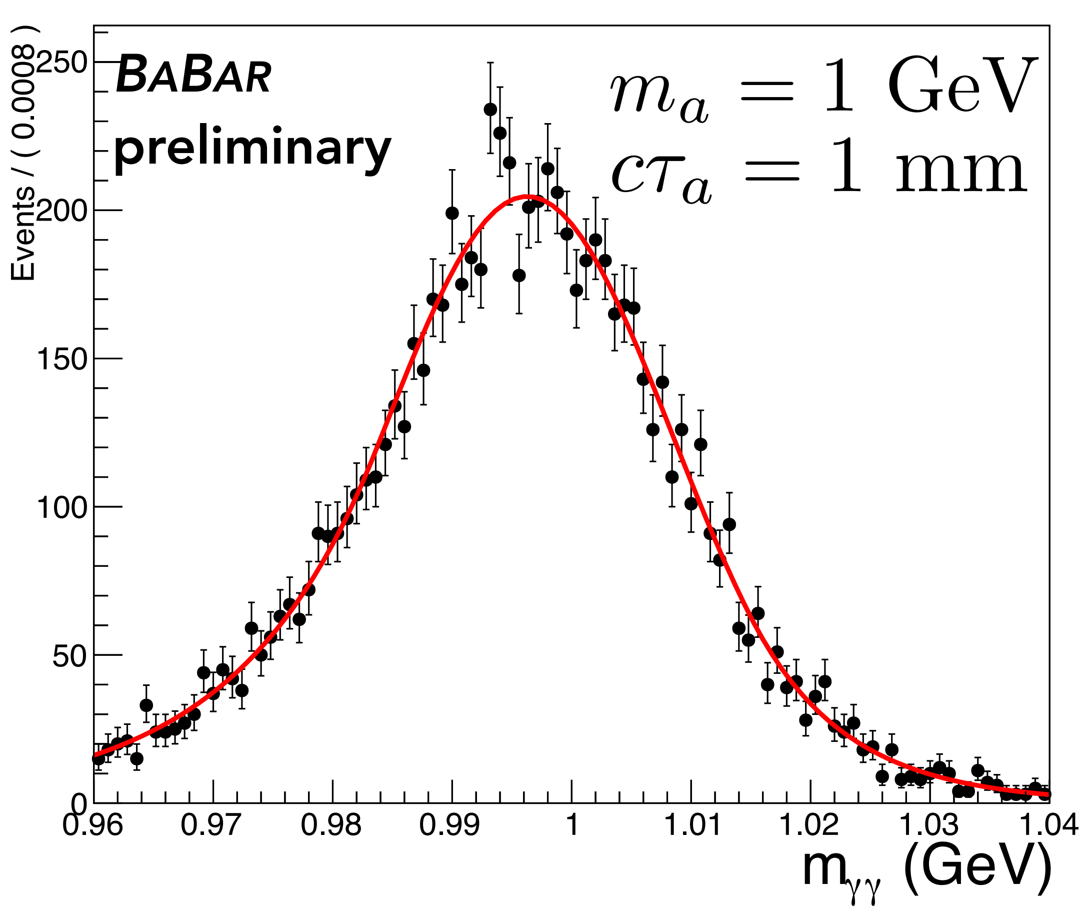
BRANCHING FRACTION LIMITS

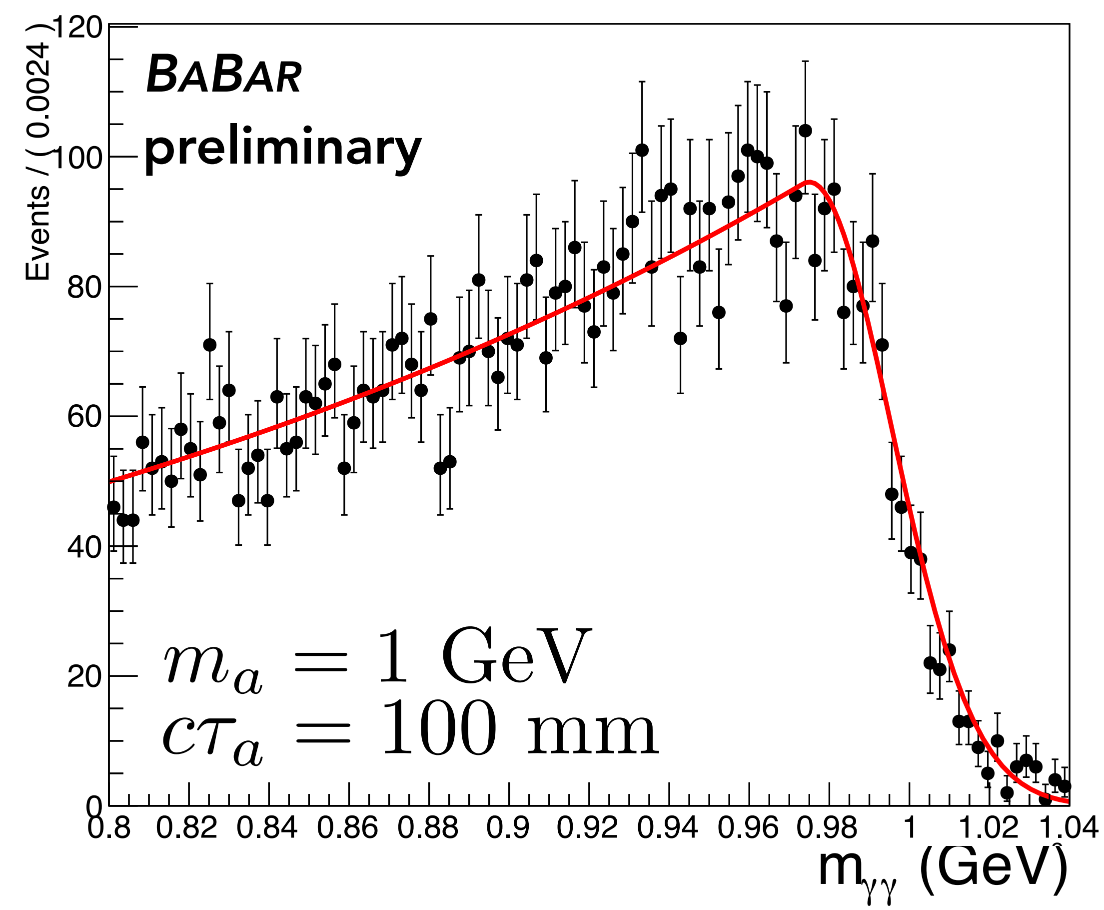
- In the absence of significant signal, Bayesian 90% CL upper limits are derived on $BF(B^{\pm} \to K^{\pm}a,\, a \to \gamma\gamma)$
  - Take uniform prior for positive values of BF
  - Systematic effects included by convolving likelihood with a Gaussian distribution whose std. dev. is equal to total systematic uncertainty



LONG-LIVED ALPS

- Search optimized for prompt ALPs, performed search on long-lived ALPs without dedicated optimization to assess search sensitivity
- Apply same selections, fit procedures for $c\tau_a = 1,\ 10,\ 100\ \mathrm{mm}$
    - Restricted to $m_a < 2.5\ \mathrm{GeV}$
    - Bias in reconstruction of signal mass at longer lifetimes



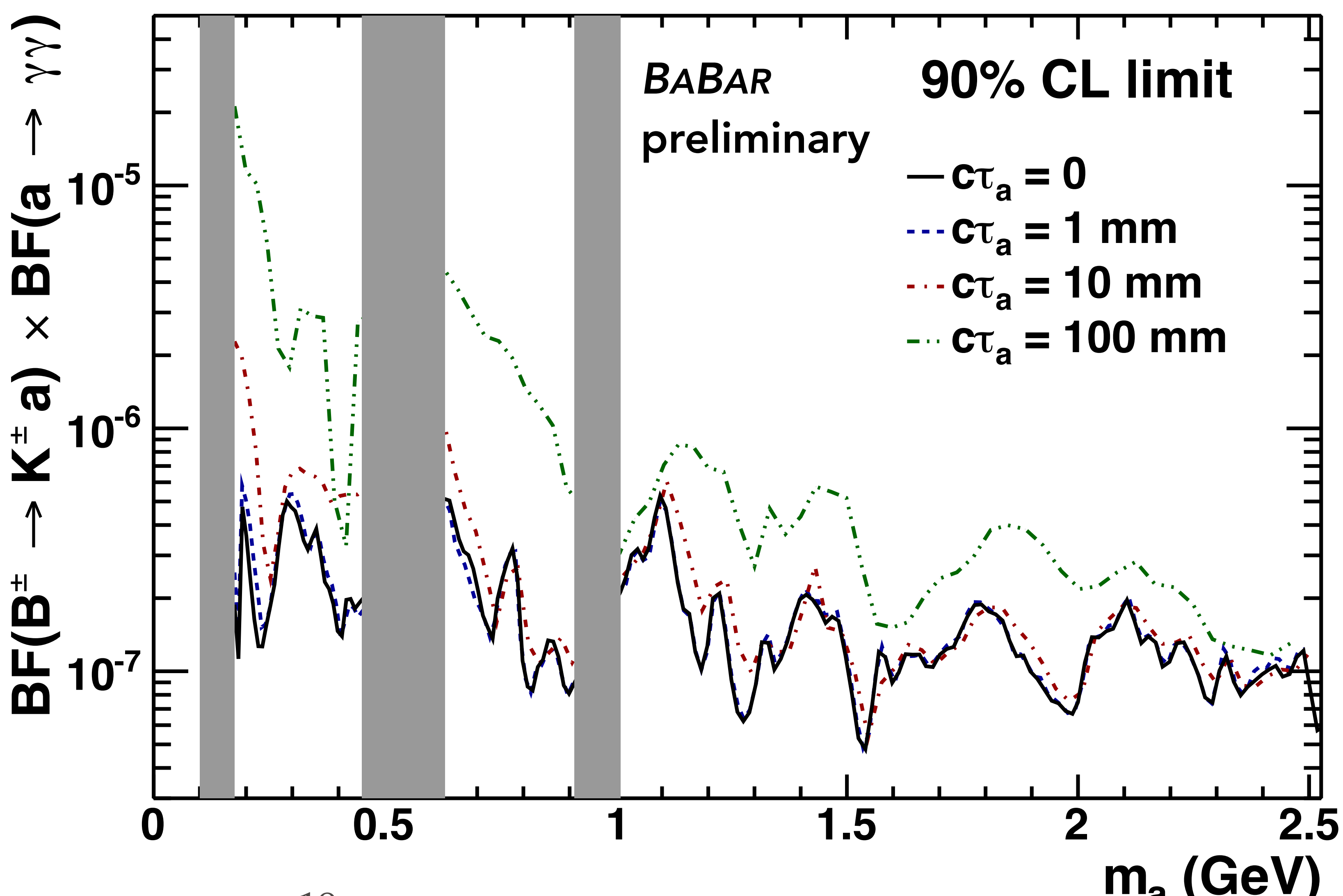


LONG-LIVED ALPS

- Fit has trouble disentangling lower signal tail & continuum background, giving larger systematic uncertainties on signal yield from background description

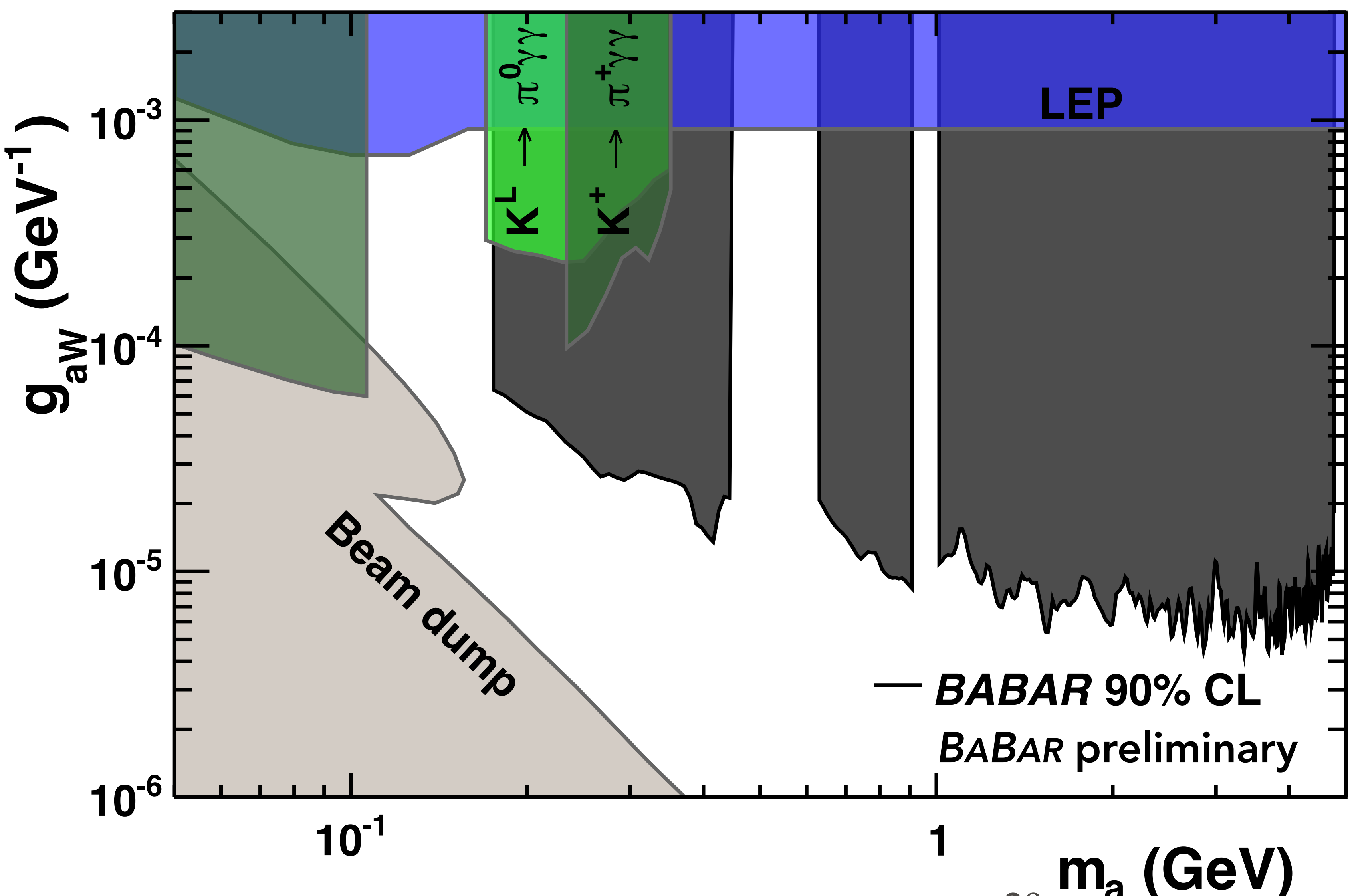
- No significant signal, set 90% CL limits for each lifetime

- Otherwise, systematics comparable to before



LIMITS ON ALP COUPLING

- The coupling g_{aW} predicts both ALP BF and lifetime
- Use limit on BF as function of lifetime to set limit on g_{aW}



- Improve limit on coupling by over 2 orders of magnitude for many masses!

SUMMARY

- **First search** for axion-like particles in the reaction $B^{\pm} \to K^{\pm} a,\, a \to \gamma\gamma$
- Set 90% CL limits that are up to **4 orders of magnitude stronger in signal rate than existing constraints**, except in the vicinity of peaking SM backgrounds $(\pi^0,\, \eta,\, \eta')$
- Flavor-changing meson decays are excellent probes of ALPs coupled to electroweak gauge bosons, complementing other searches
- *BaBar* continues to add to its extensive hidden-sector search program, with more results to come!

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