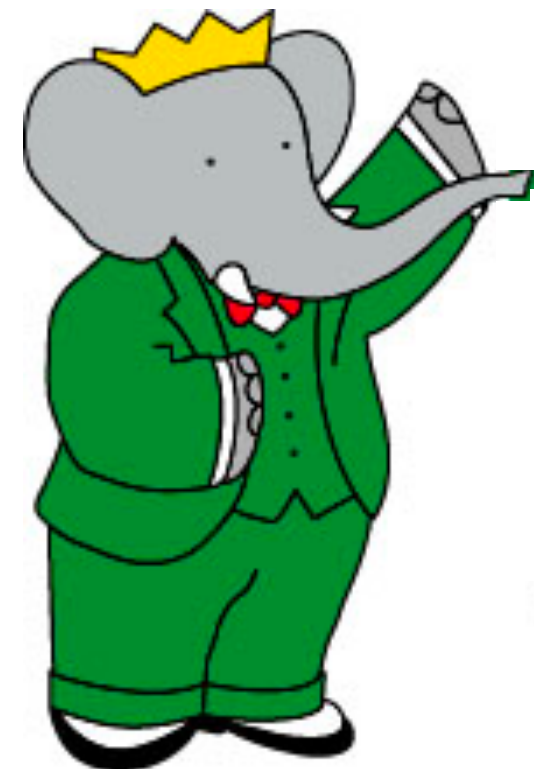# SEARCH FOR AXION-LIKE PARTICLE IN *B* DECAYS AT *BABAR*

Brian Shuve (for Gerald Eigen)
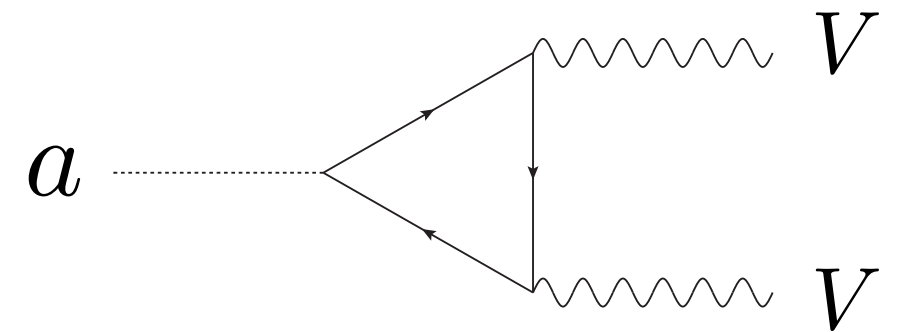on behalf of the *BABAR* Collaboration

June 15, 2021

Patras 2021

AXIONLIKE PARTICLES

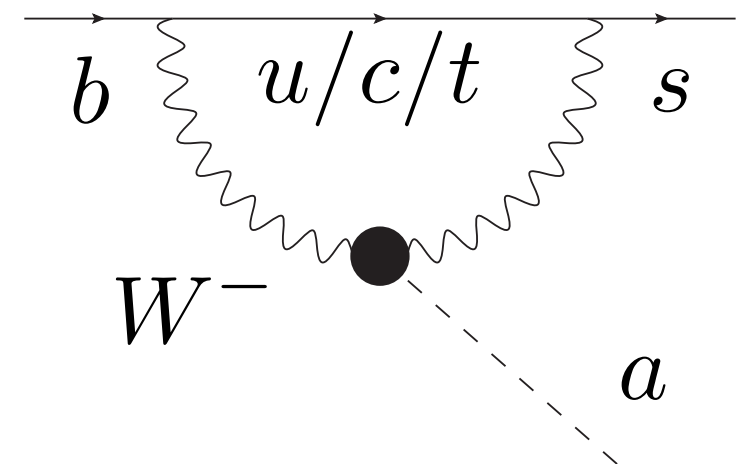- **Axionlike particles (ALPs)** are well-motivated hidden sector particles coupled to pairs of gauge bosons

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

- If ALP couples predominantly to SU(2) gauge bosons, it is produced in rare B meson decays: $B^{\pm} \to K^{\pm} a,\ a \to \gamma\gamma$

- We perform first search for this signature with sample of ~240 million $B^+ B^-$ pairs at BABAR

SELECTIONS

- Form *B* candidate with well identified *K* candidate and 2 photons

- Apply kinematic fit to improve ALP resolution

- Train BDTs to separate signal from $e^+ e^- \to q\bar{q} \; (q = u, d, s, c)$ and $e^+ e^- \to B\bar{B}$ backgrounds

3

SIGNAL EXTRACTION

PHOTON SPECTRUM
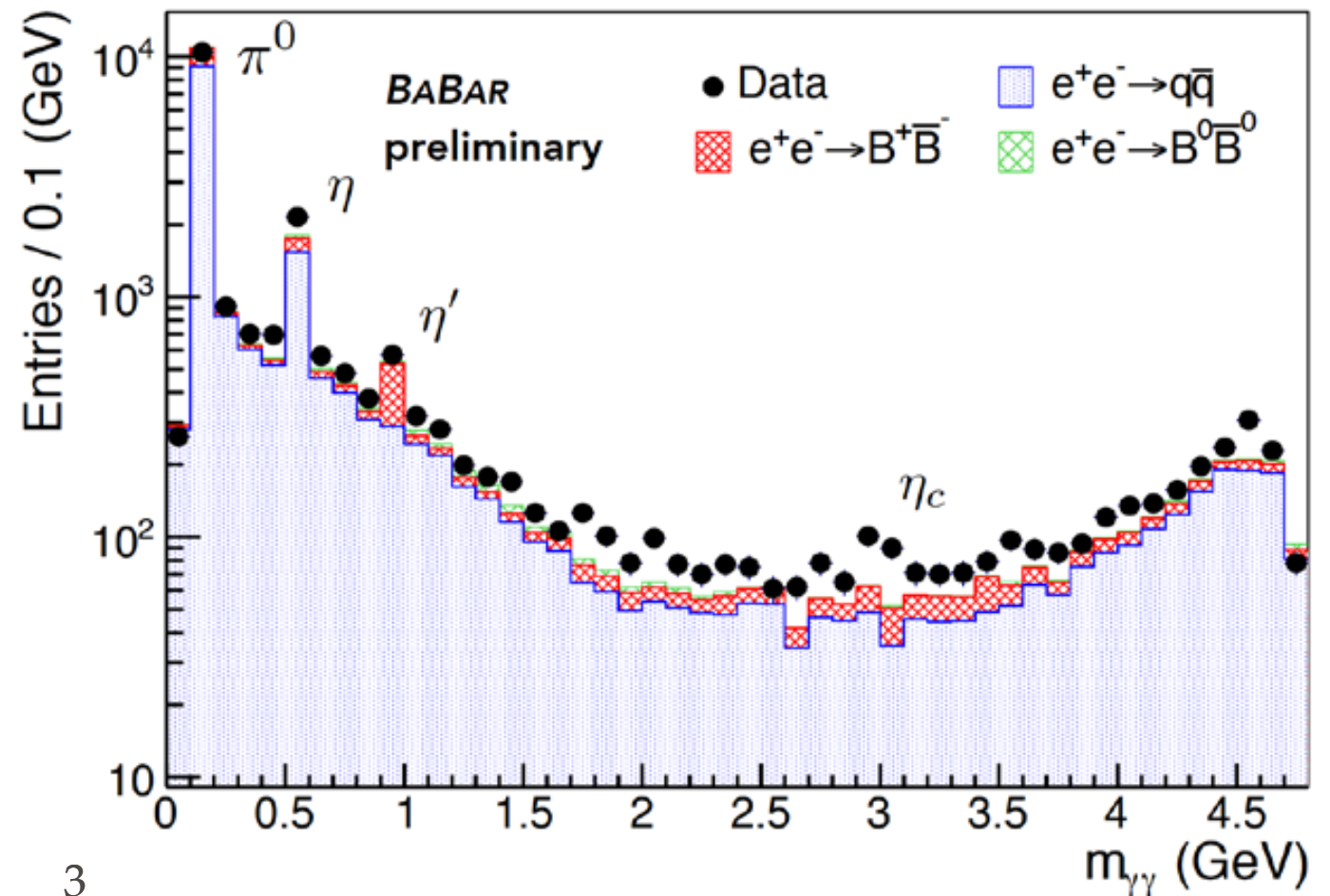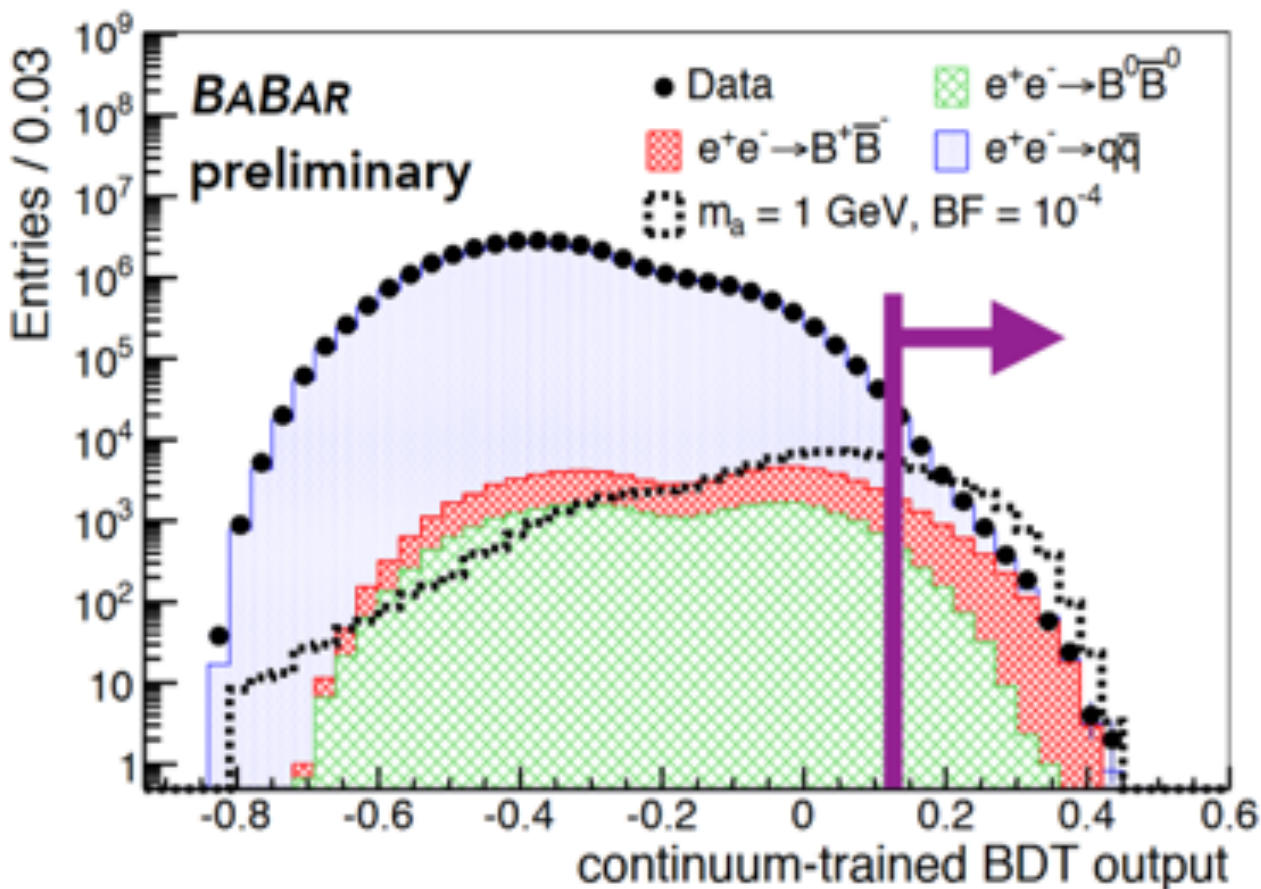
- Extract signal as a function of ALP mass with fits over sliding intervals

- Consider prompt and displaced decays with $c\tau_a = 1, 10, 100$ mm backgrounds observed at $\pi^0/\eta/\eta'$ masses
- No significant signal, results consistent with null hypothesis
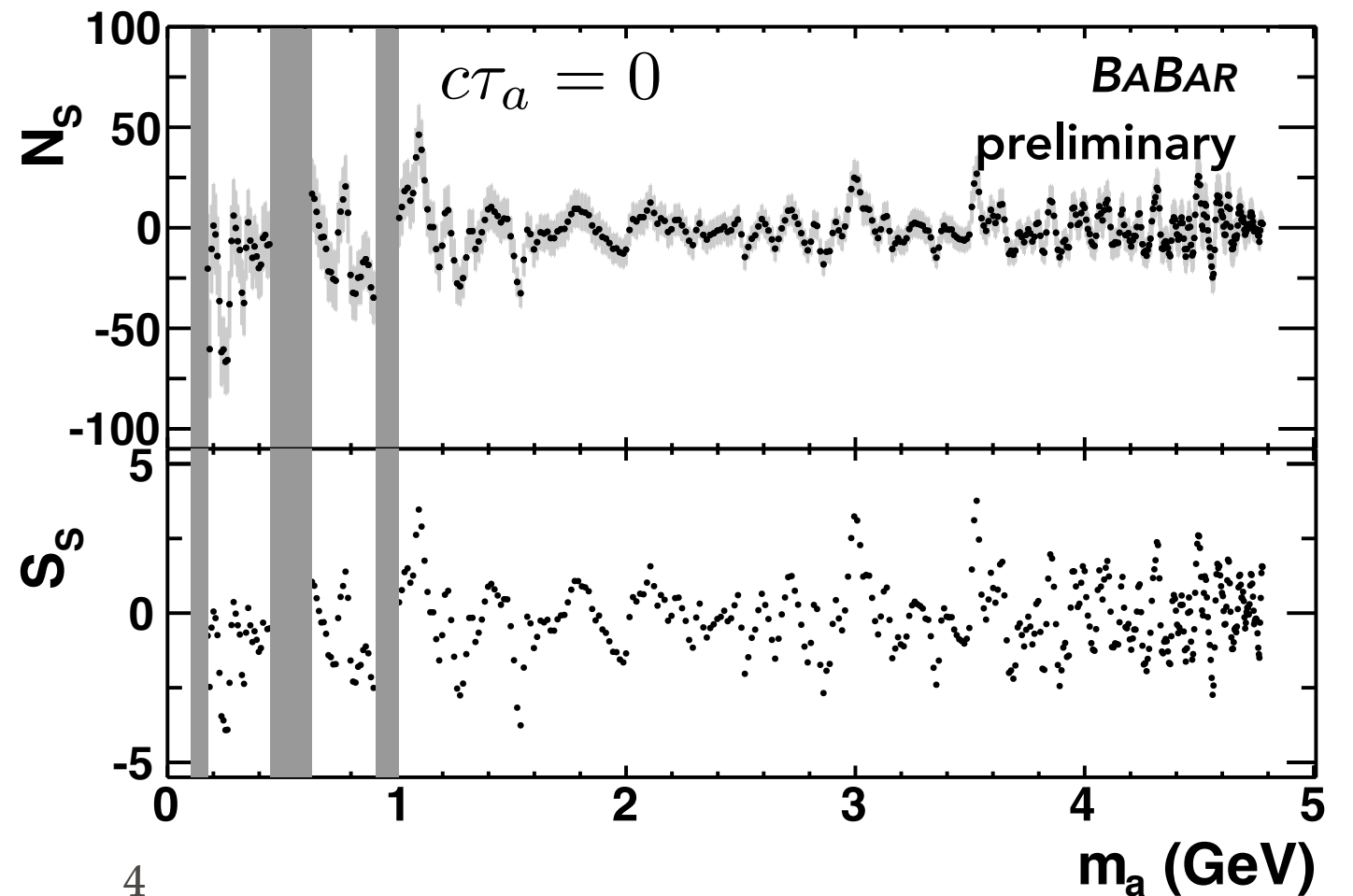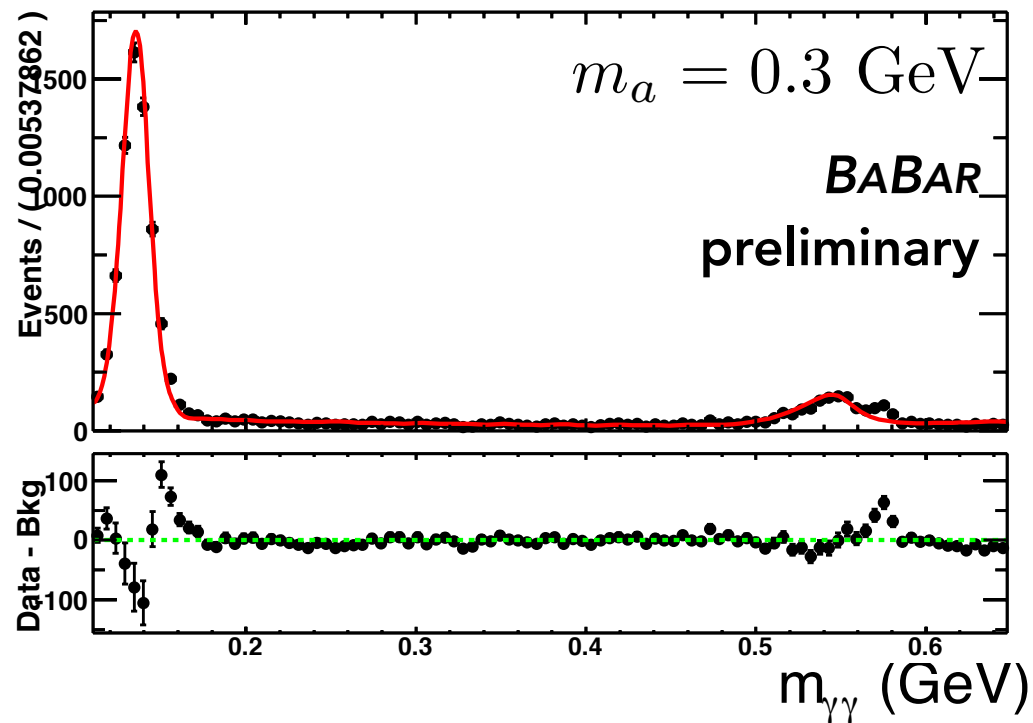
RESULTS

- Extract 90% CL Bayesian limits on the branching fraction (as a function of ALP mass and lifetime) and on the coupling

- Limits up to two orders of magnitude stronger than existing coupling constraints!

- More *BABAR* hidden sector results to be presented 17 June @ 19:20

LIMITS ON ALP COUPLING
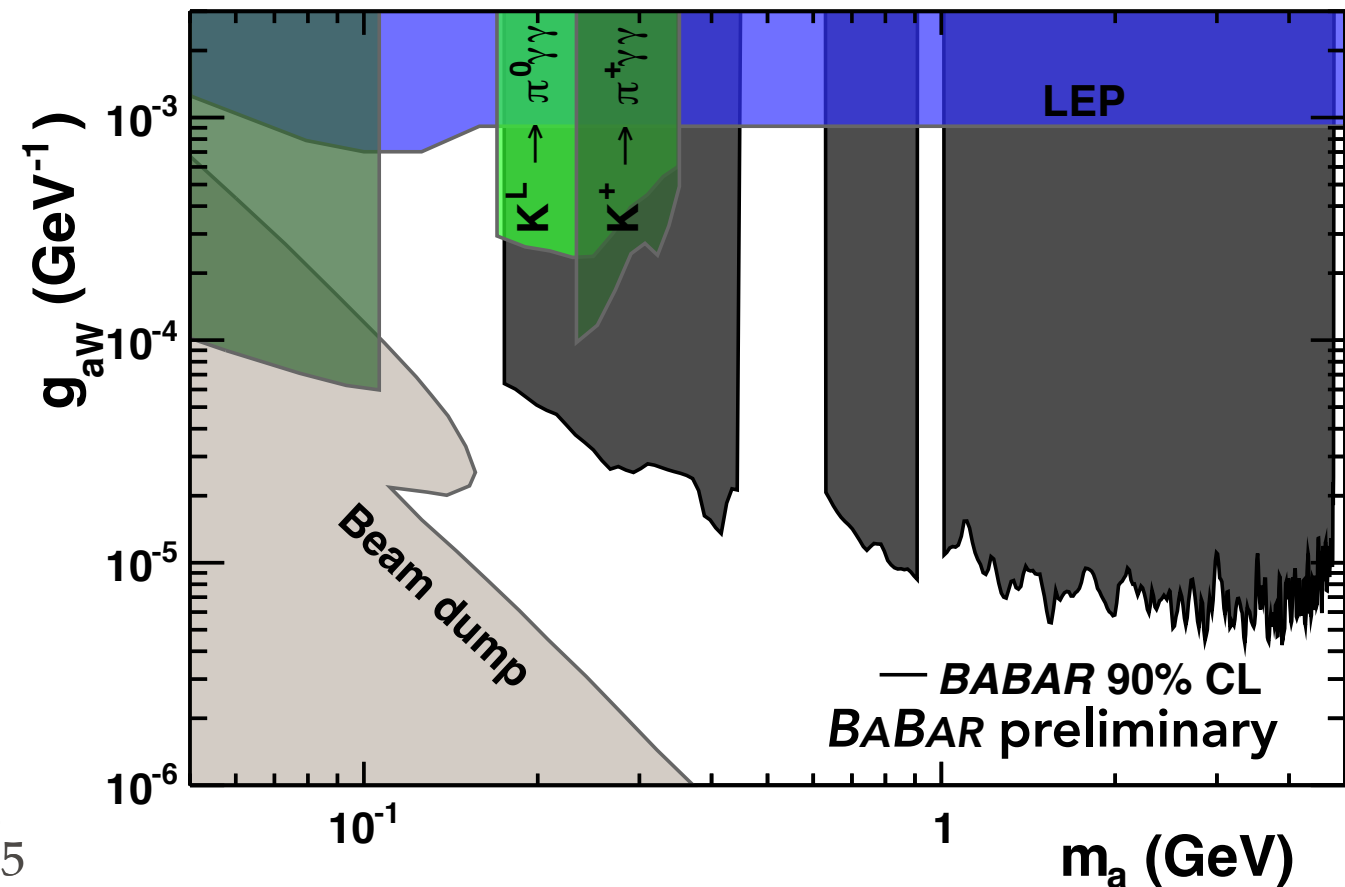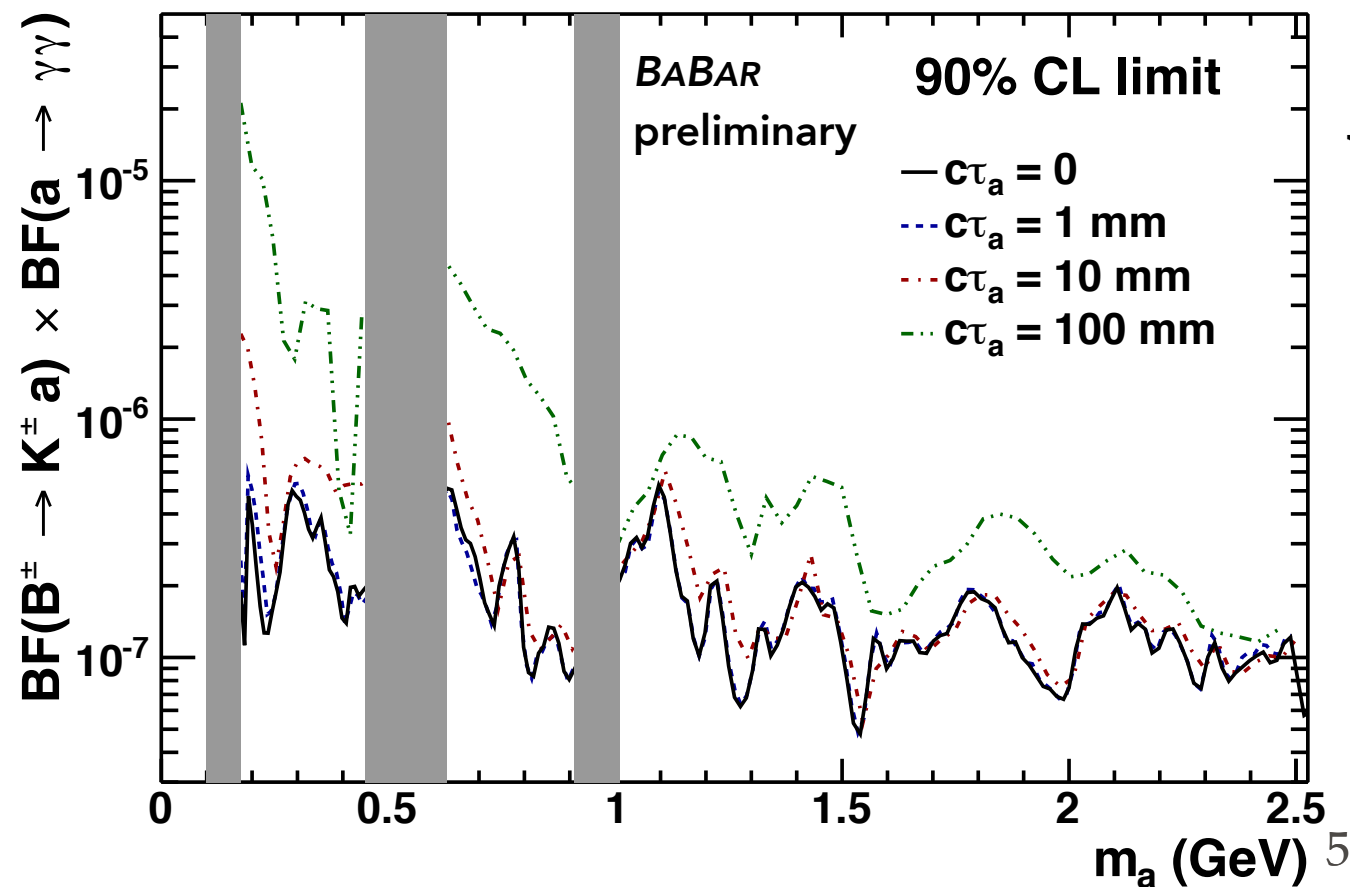
BACKUP SLIDES

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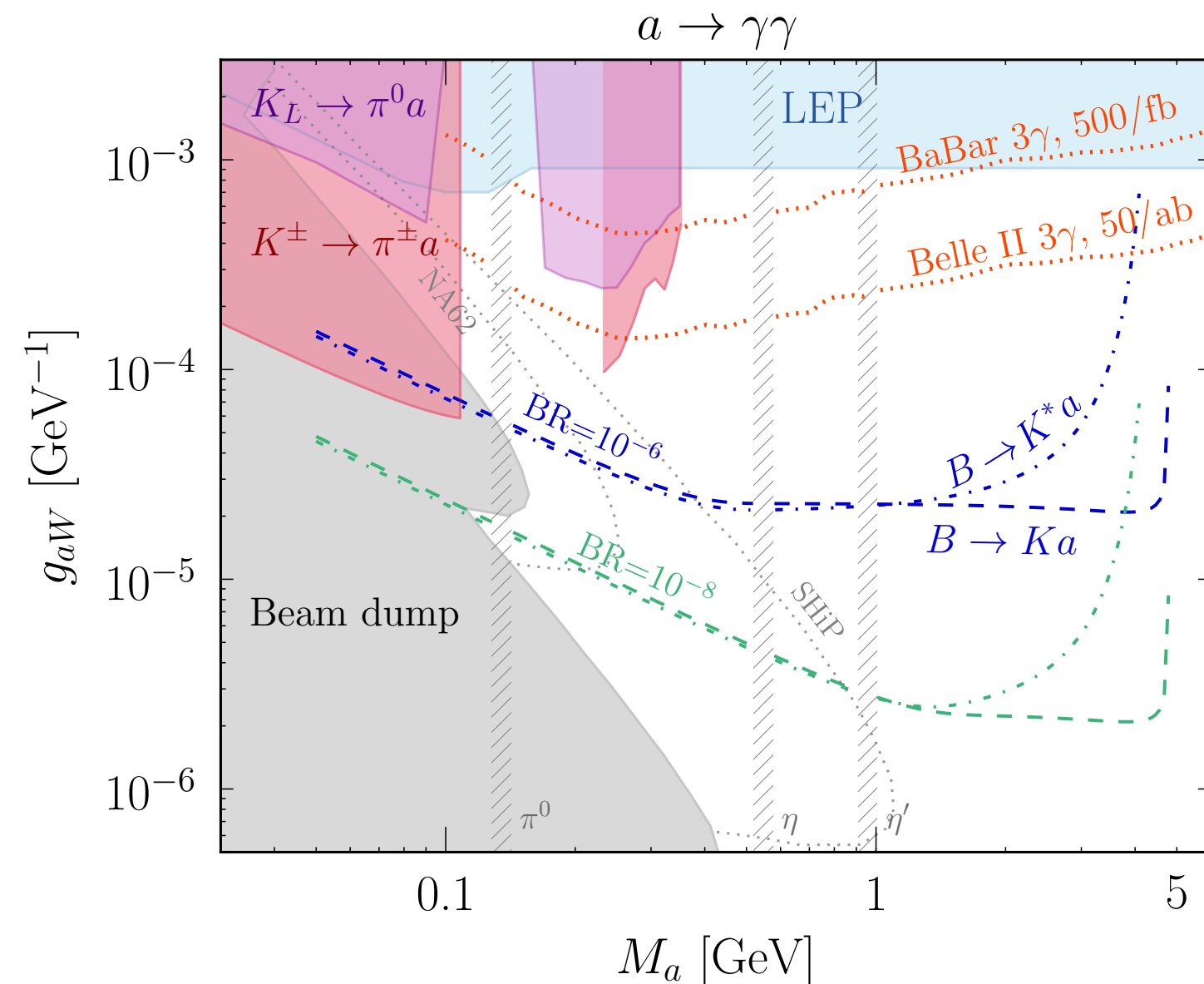
$$\mathcal{L} = -\frac{g_{aV}}{4}\, a\, W^a_{\mu\nu}\tilde{W}^{a\,\mu\nu}$$

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

units : $\hbar = c = 1$

BABAR EXPERIMENT

1.5T Solenoid

EMC
6580 CsI(Tl) crystals

e^+ (3.1GeV)

DIRC (PID)
144 quartz bars
11000 PMs

Drift Chamber
40 layers

Silicon Vertex Tracker
5 layers, double sided strips

e^- (9 GeV)

Instrumented Flux Return
iron / RPCs (muon / neutral hadrons)

1999-2008

PEP-II Rings

Positrons

Low Energy Ring

BaBar Detector

Electrons

High Energy Ring
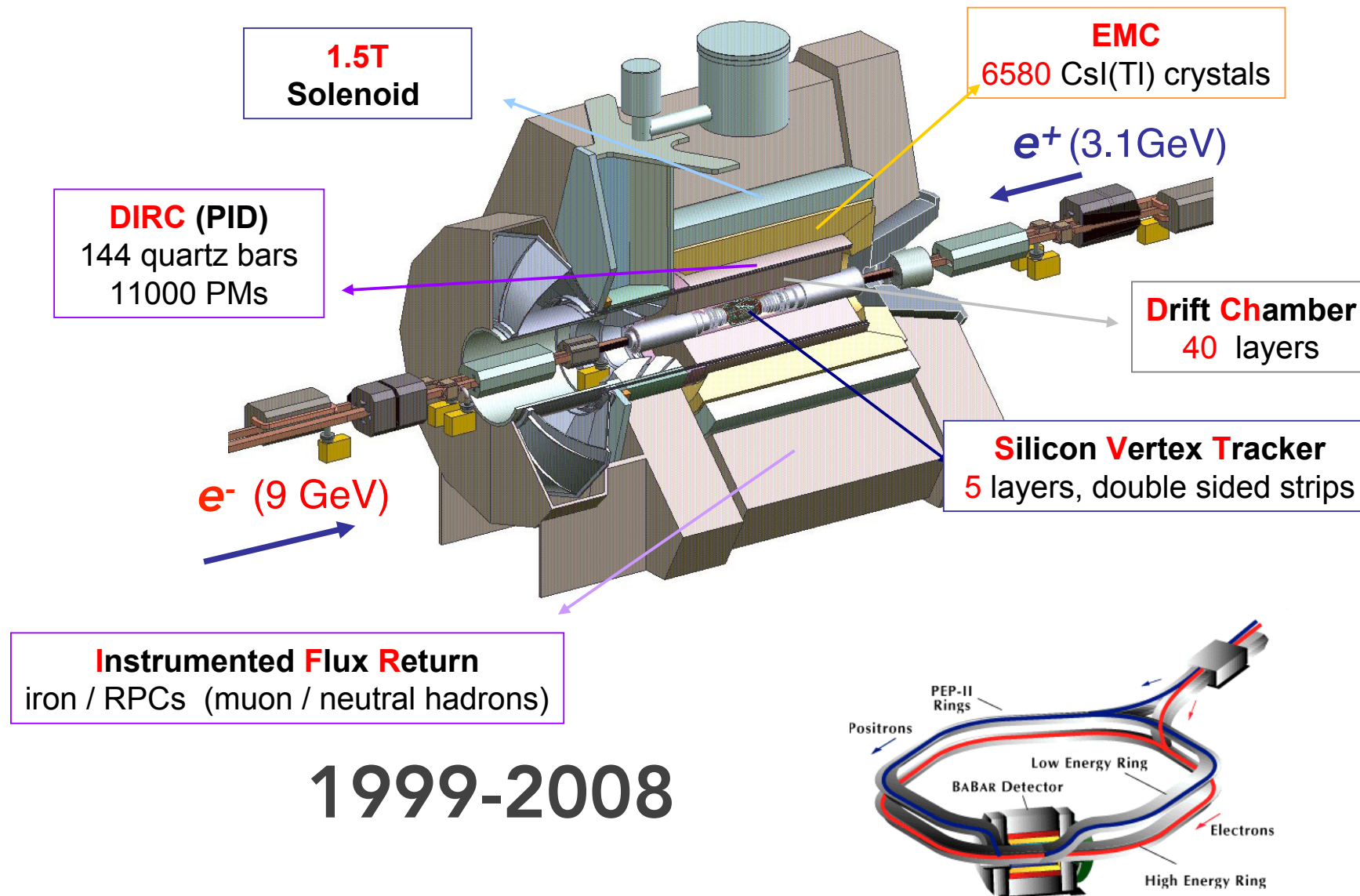
- 432/fb data collected on $\Upsilon(4S)$ peak

- 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 $c\tau_a = 1,\ 10,\ 100\,\mathrm{mm}$

SELECTIONS

- **Preselection:** Reconstruct $B^{\pm}$ candidates from $K^{\pm}$ candidate and two photons

  - Require $$m_{\text{ES}} = \sqrt{\frac{(s/2 + \vec{p}_i \cdot \vec{p}_B)^2}{E_i^2} - p_B^2} > 5.0 \text{ GeV}$$

 $$|\Delta E| = |\sqrt{s}/2 - E_B^{\text{CM}}| < 0.3 \text{ GeV}$$

  - 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'

DIPHOTON SPECTRUM

- Peaking backgrounds observed at $\pi^0/\eta/\eta'$ masses
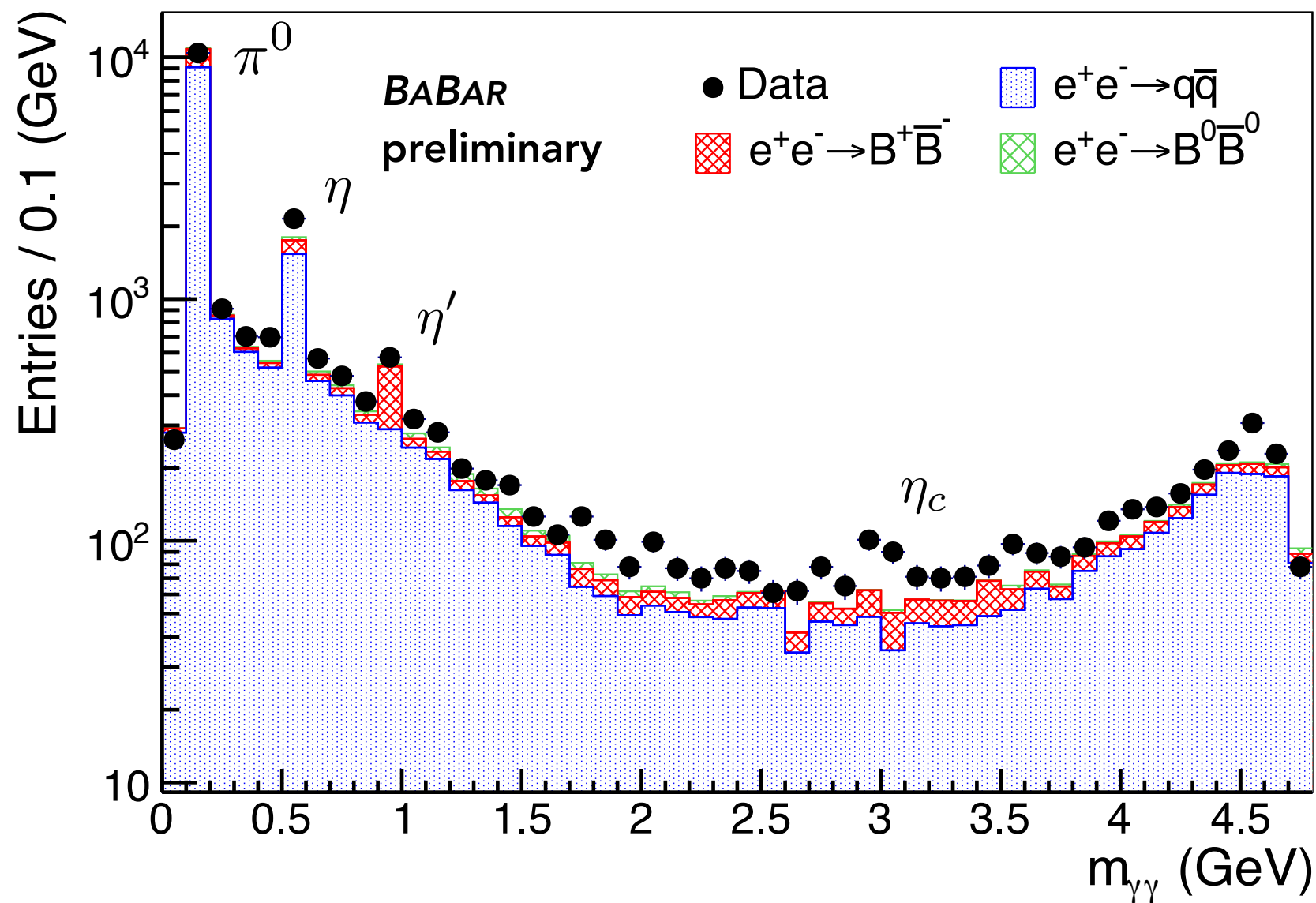
- 2.6σ local excess observed at η_c mass, consistent with world-avg BF $B^\pm \to K^\pm \eta_c$, $\eta_c \to \gamma\gamma$

- Sets 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 $m_a = 0.175 \text{ GeV}$ to 14 MeV at $m_a = 2 \text{ GeV}$, decreasing back to 2 MeV at $m_a = 4.78 \text{ GeV}$ 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 $m_a = 4.78 \text{ GeV}$ to 33% at $m_a = 2 \text{ GeV}$

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

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

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 $c\tau_a = 1, 10, 100$ mm
  - Restricted to $m_a < 2.5$ GeV
  - Bias in reconstruction of signal mass at longer lifetimes