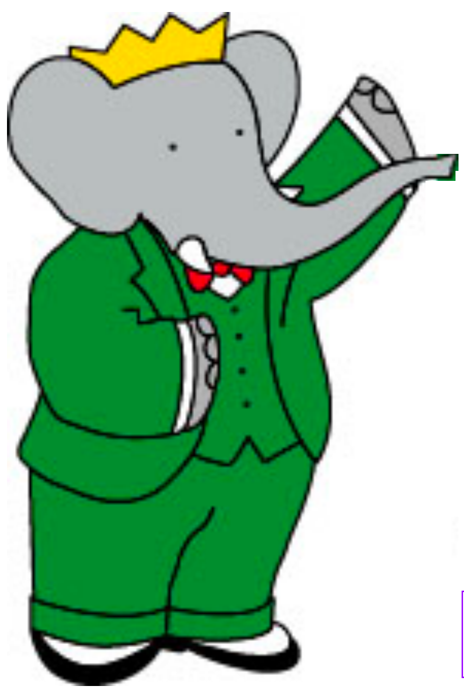
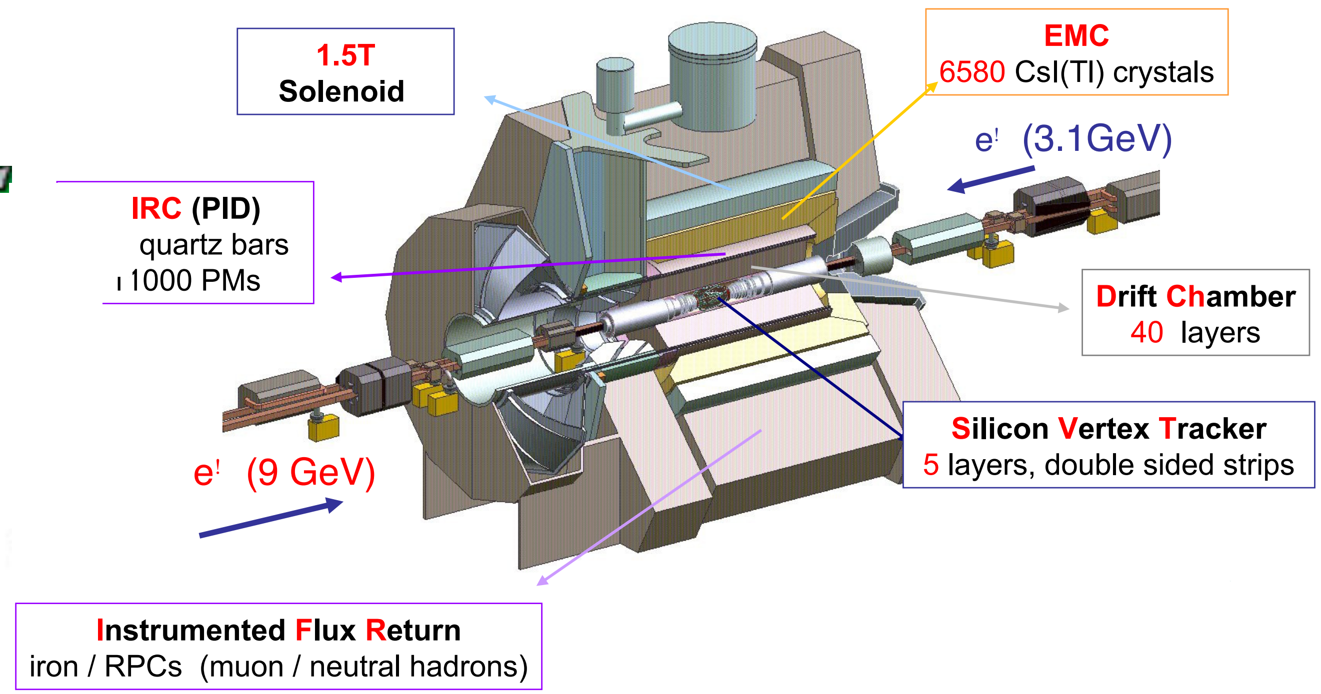
DISPLACED PHOTONS AT BABAR





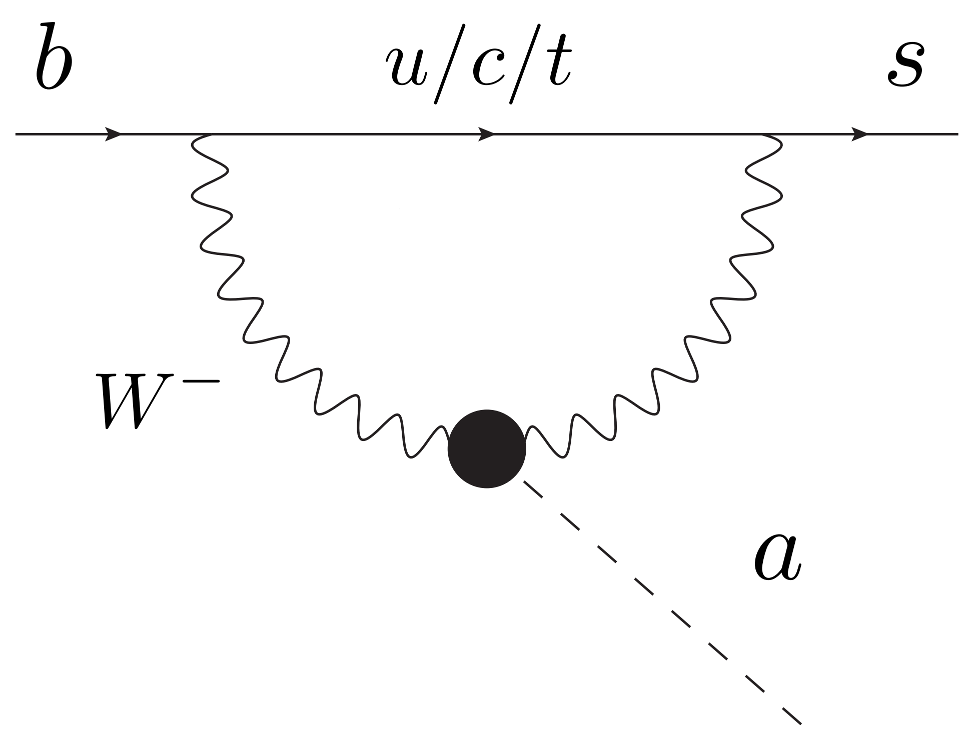
HARVEY MUDD COLLEGE

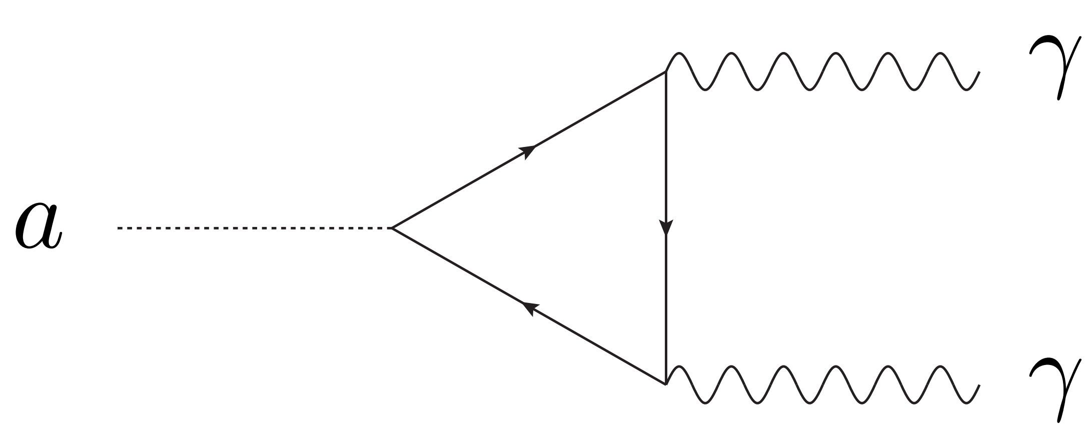
Brian Shuve

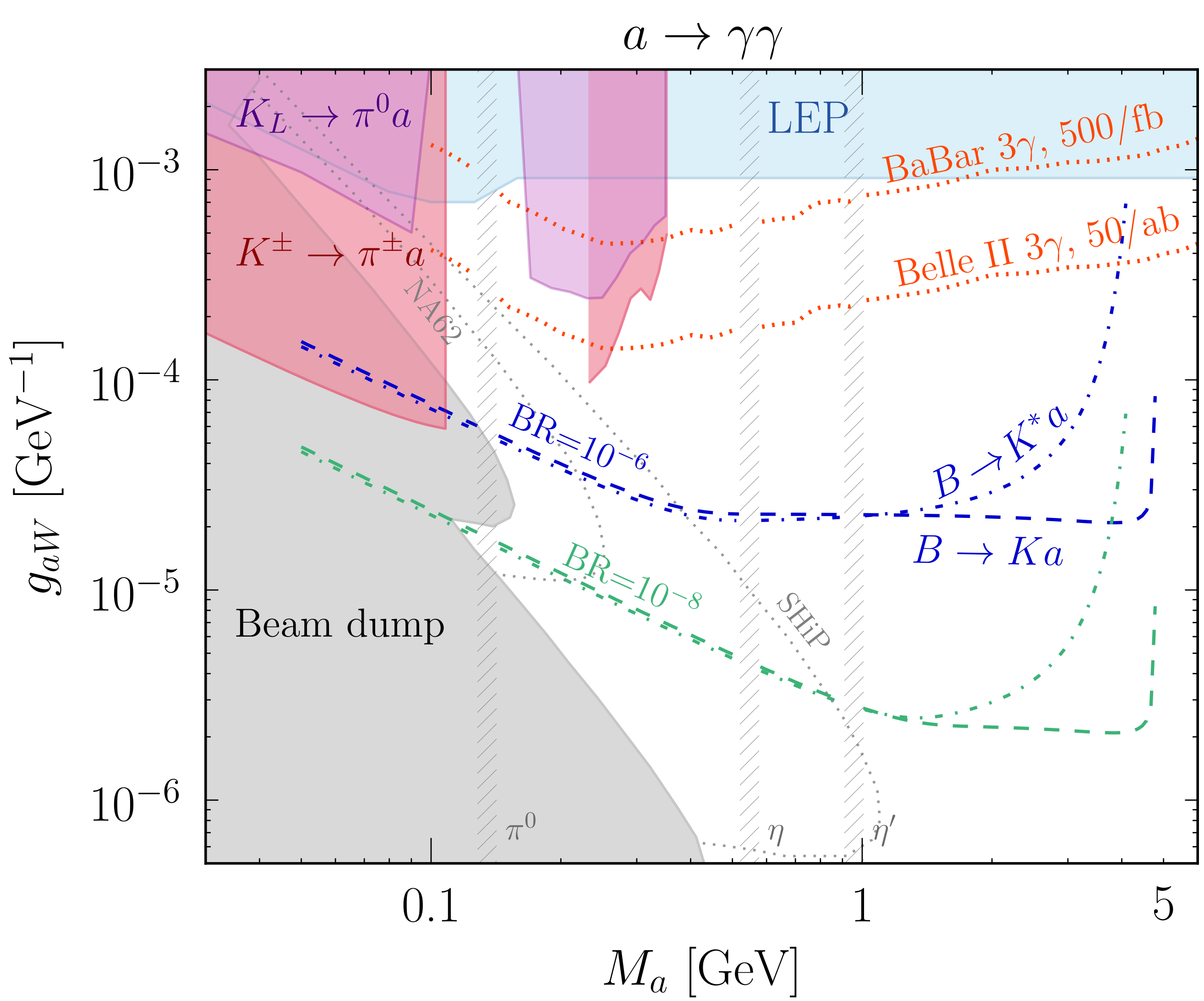
Belle II LLP workshop, Dec. 2020

CONTEXT: ALP SEARCH

- When axion-like particles couple to SU(2) gauge bosons, they can be produced in rare *B* decays

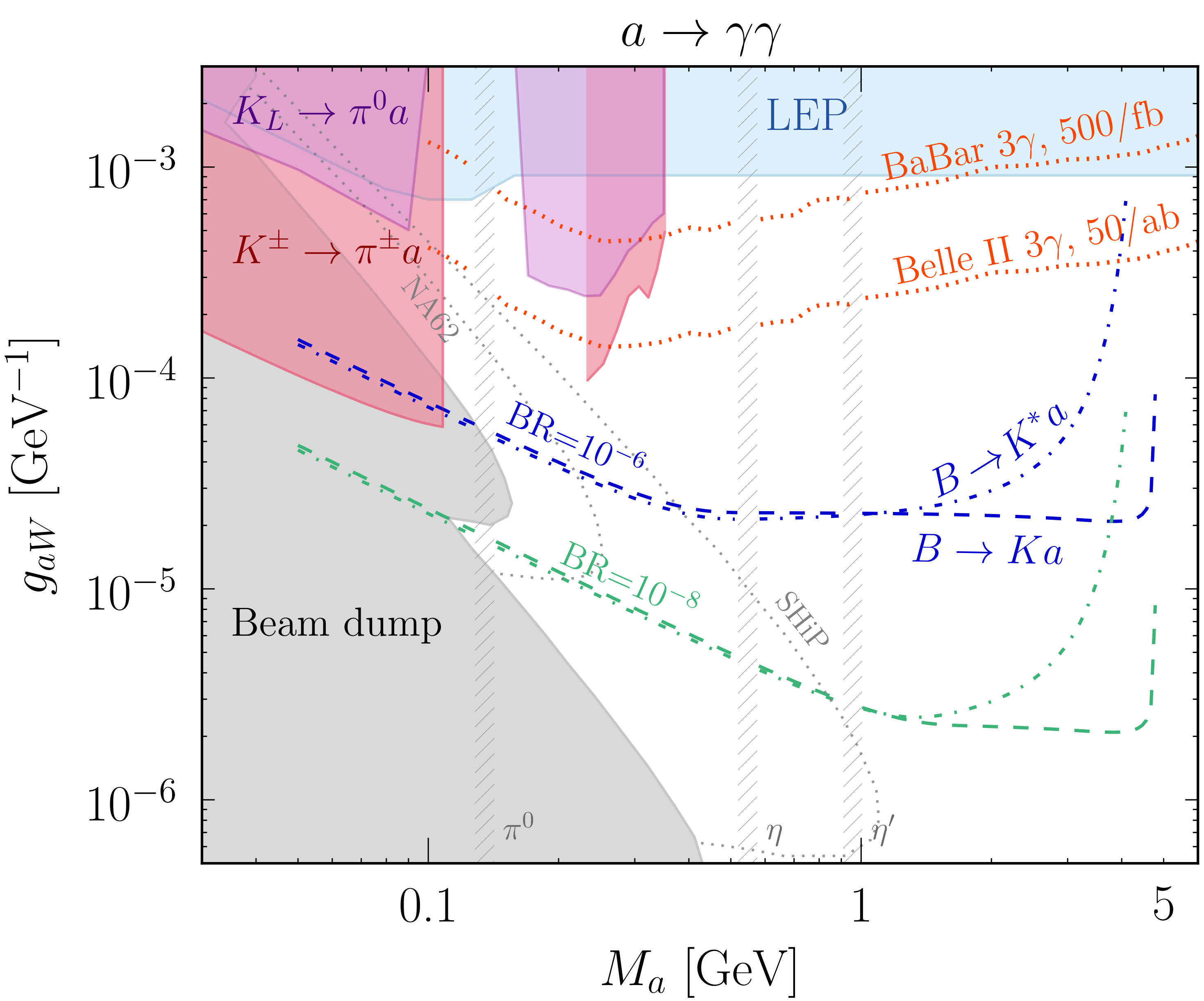






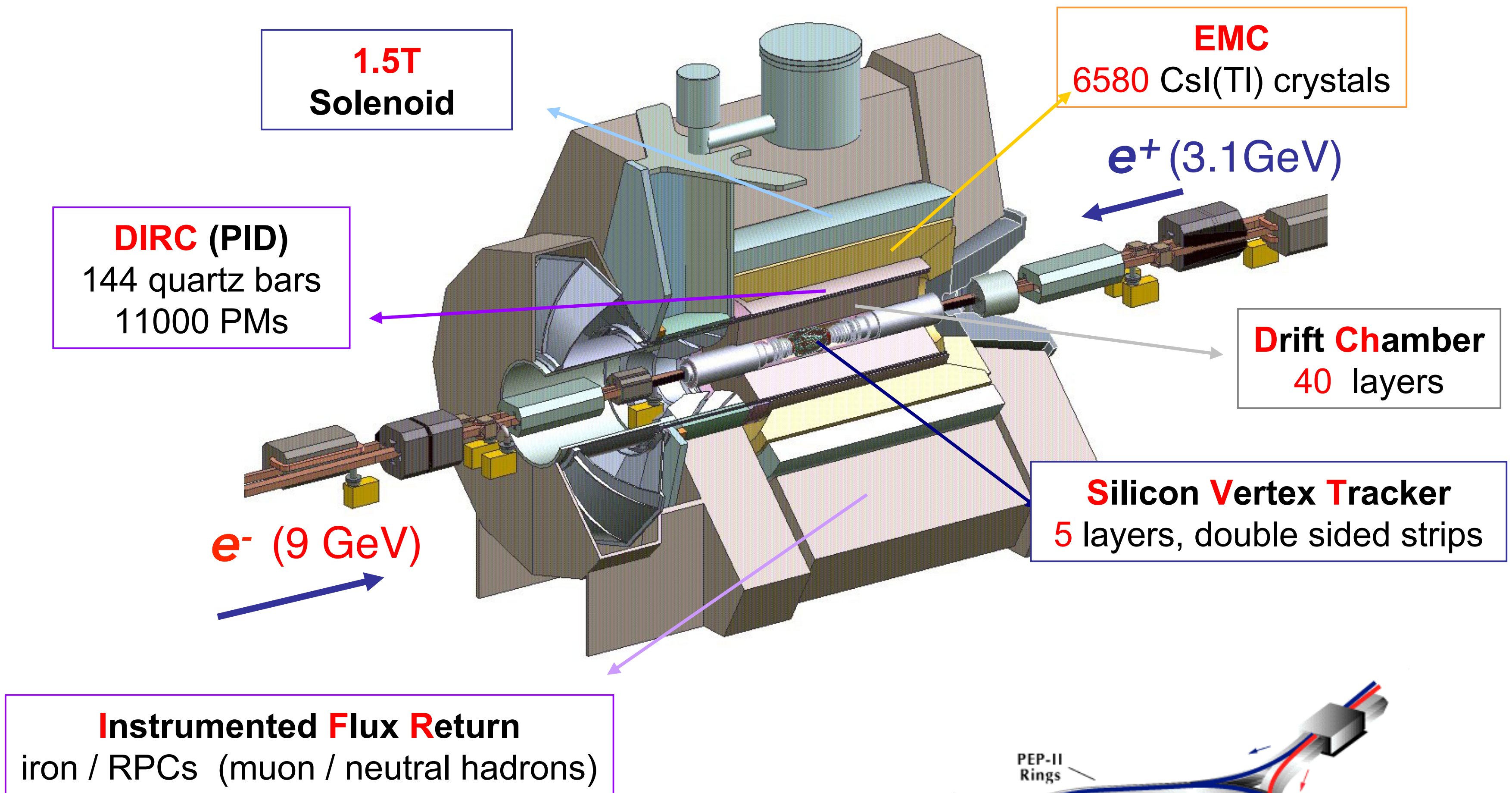
CONTEXT: ALP SEARCH

- We perform the **first search** for ALPs in this process

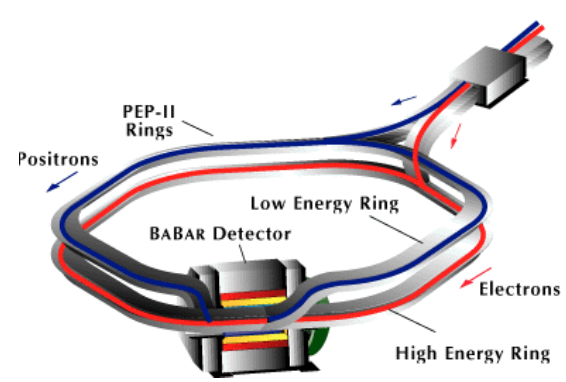


- Most of parameter space: **prompt ALPs**
- For masses < 1 GeV, however, we end up with long-lived ALPs
- We did not design a separate long-lived search, but needed to assess sensitivity to long-lived ALPs

BaBar EXPERIMENT



1999-2008

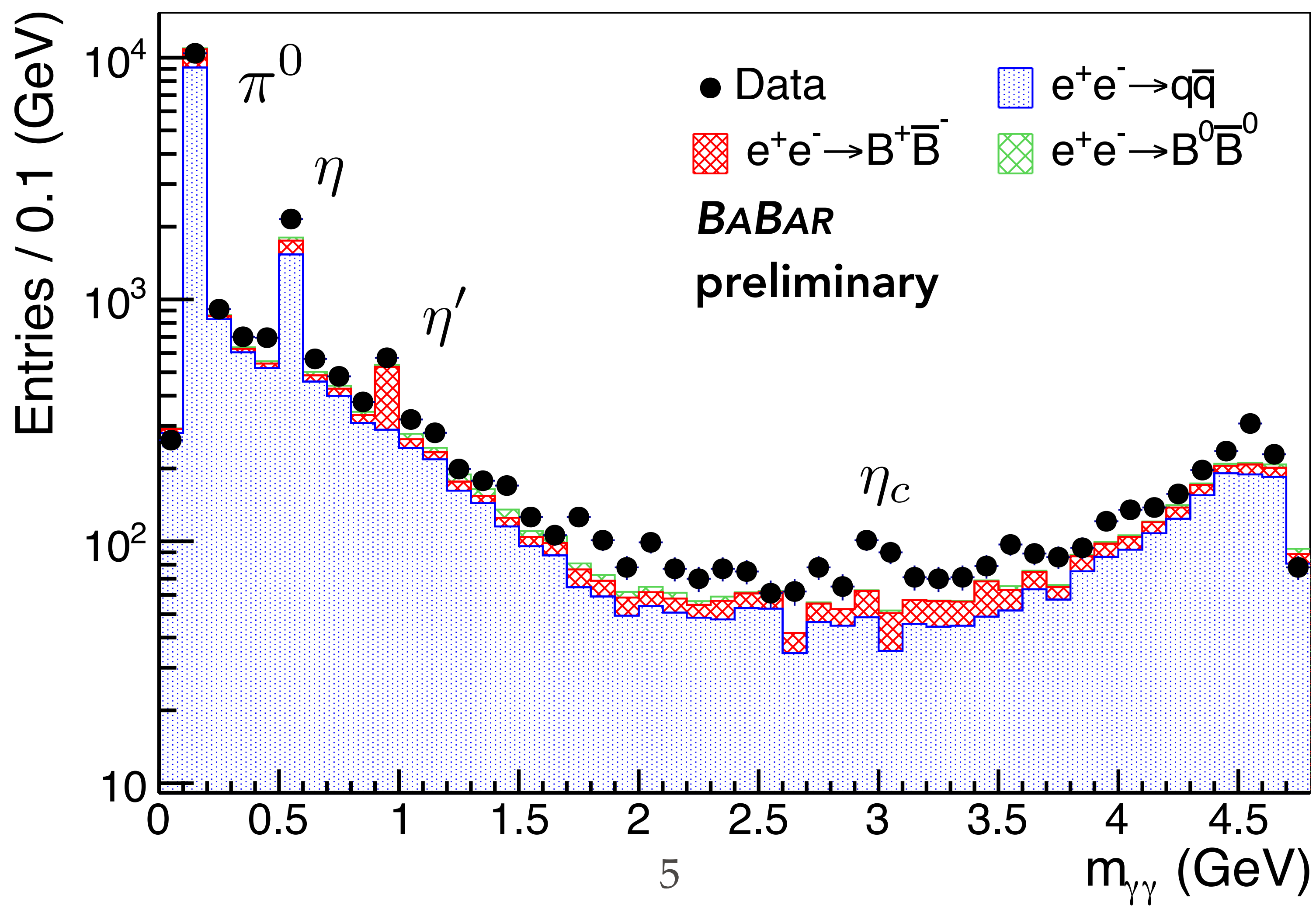


- 432/fb data collected on $\Upsilon(4S)$ peak
- Corresponds to 2.4×10^8 pairs of B^+B^- mesons

- 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
- Train a BDT using signal & background MC events, include shape variables, kinematic information, track/cluster multiplicities, PID,…



SIGNAL EXTRACTION

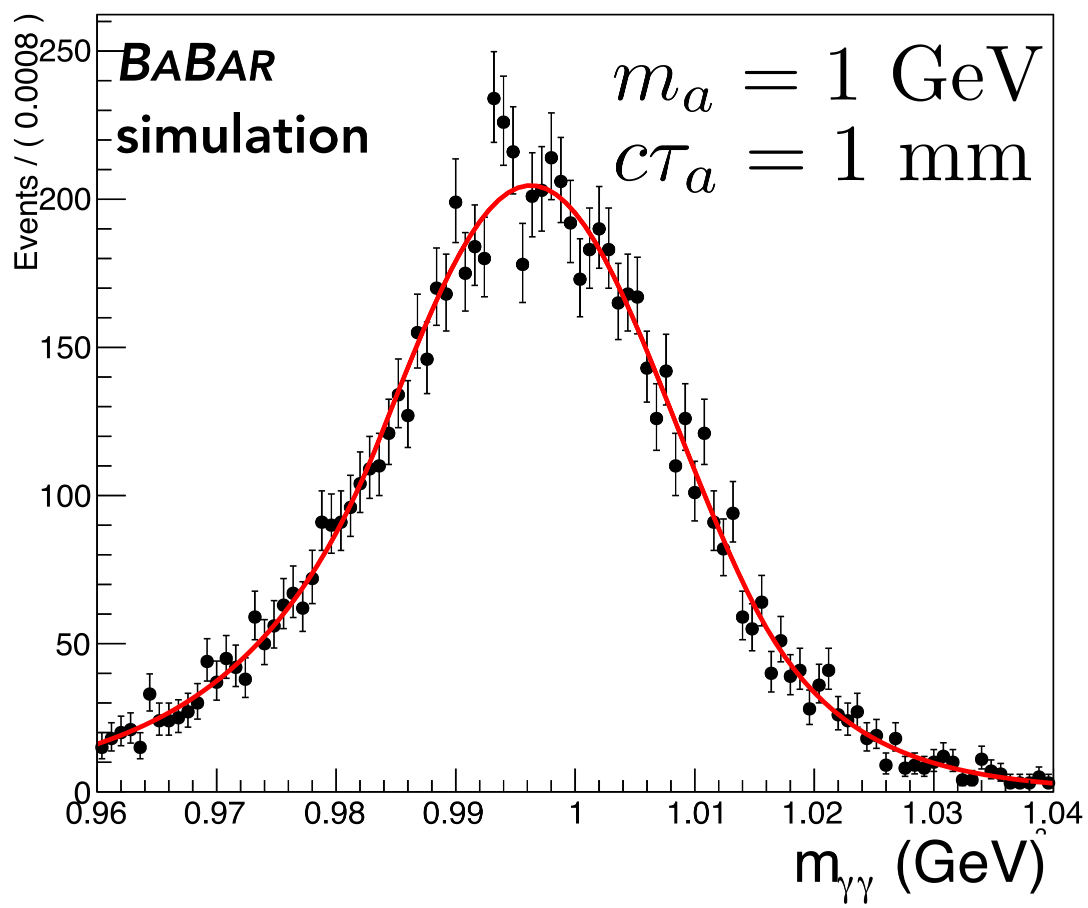
- Use a low-order polynomial to model continuum background, MC for peaking background, signal MC for signal shape

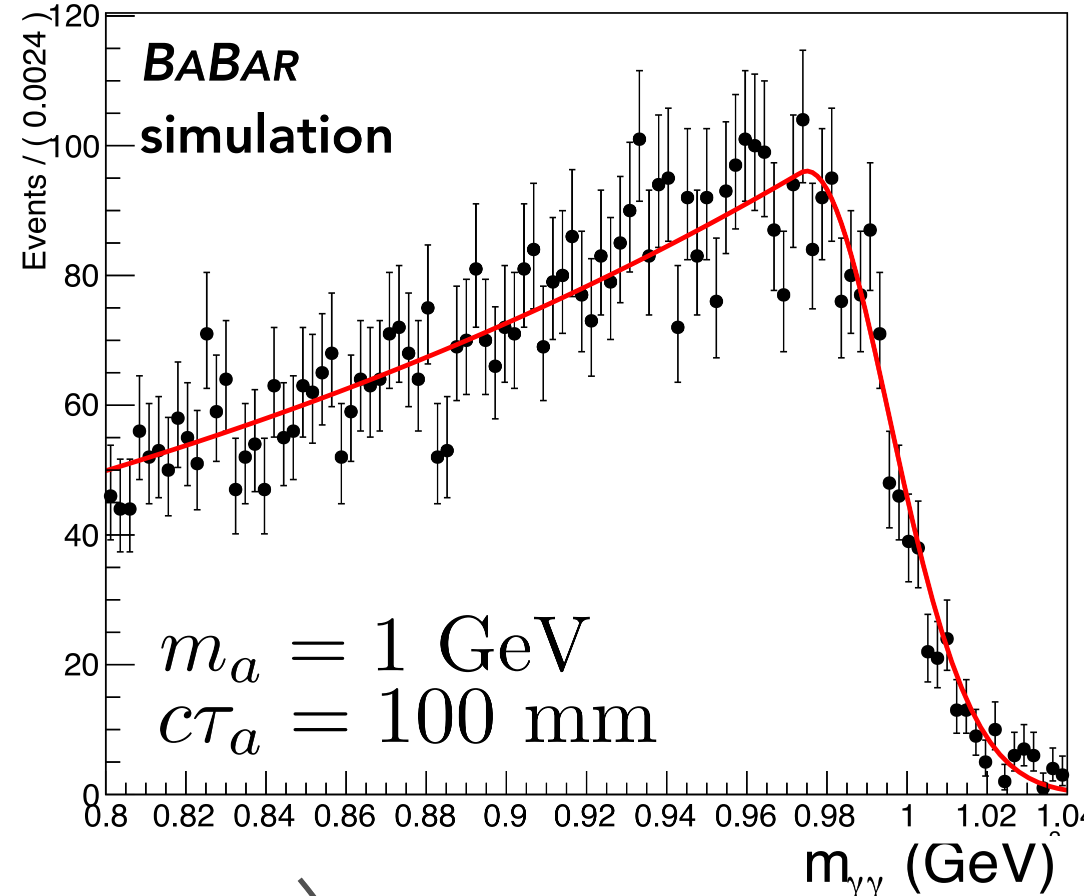
- Perform fits in diphoton mass intervals of width $(30 - 70)\sigma$

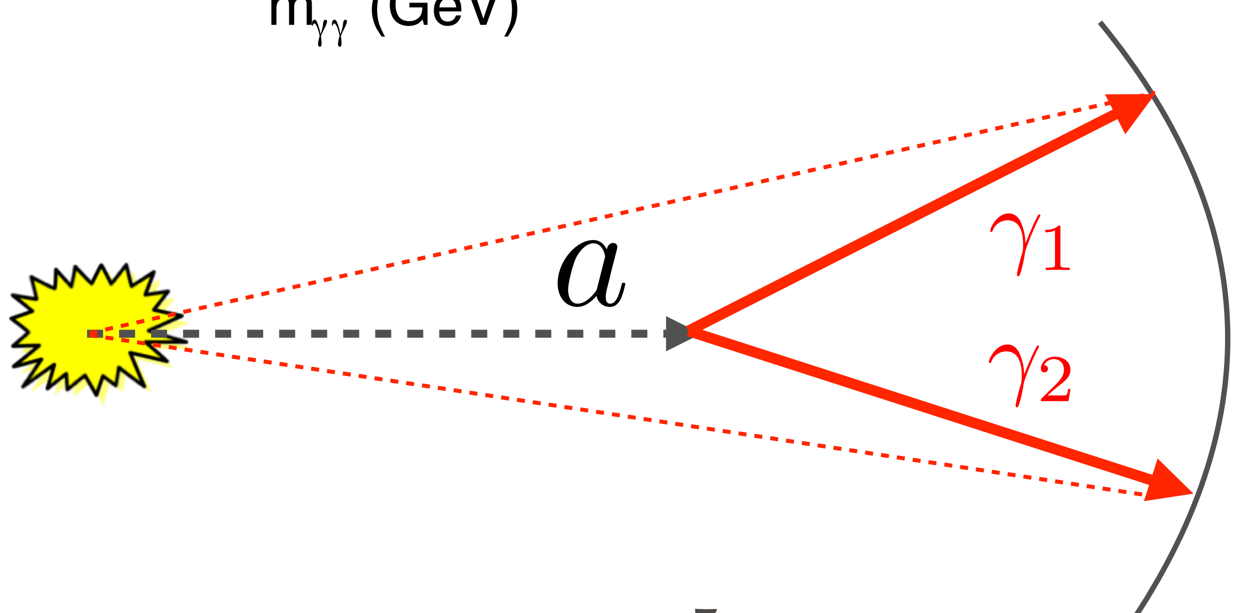
- Signal MC resolution is validated by data/MC comparisons of $B^{\pm} \to K^{\pm}\pi^{0}$ and $B^{\pm} \to K^{\pm}\eta$, found to be consistent within 3%

- Assess systematic uncertainties by varying continuum, peaking background, and signal models

LLP SIGNAL SHAPE

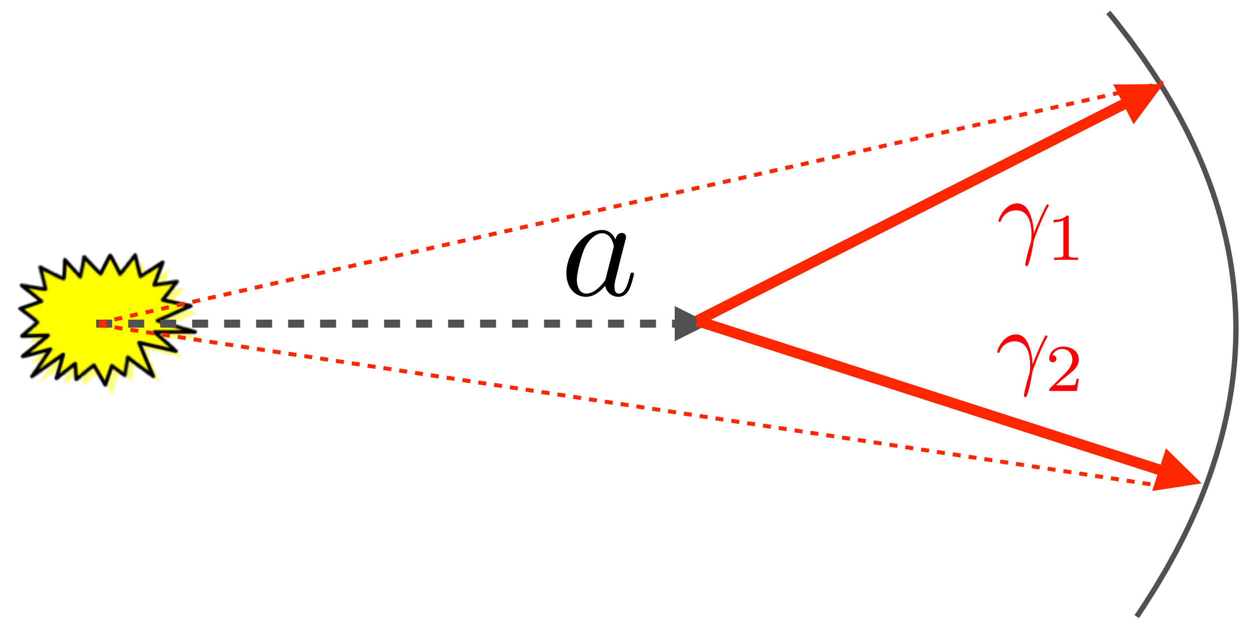






LLP SIGNAL SHAPE

- **Problem:** we don't know where the LLP decays!



- We made some (mostly unsuccessful) attempts to correct the signal shape (for example, in the kinematic fit to the B meson mass of the kaon + 2 photons)
- Used "out-of-the-box" loose photon PID
- For our search, major limiting factor is not generally a drop in photon ID efficiency, but rather the smearing of the signal shape

LLP -> PHOTON IMPROVEMENTS?

- For LLP analysis where the photons are produced in association with charged particles, can constrain photons to originate from DV
- Pointing information from the EMC? Seems difficult
- Timing information (TOP detector): useful if there are other charged particles in the event!
- Dedicated LLP -> photon reconstruction could help improve signal efficiency, as could algorithms that take into account overlapping shower shapes from boosted ALP
- Validation could be done with $K_{\mathrm{L}} \to \pi^+\pi^-\pi^0$?

PRESSING AHEAD...

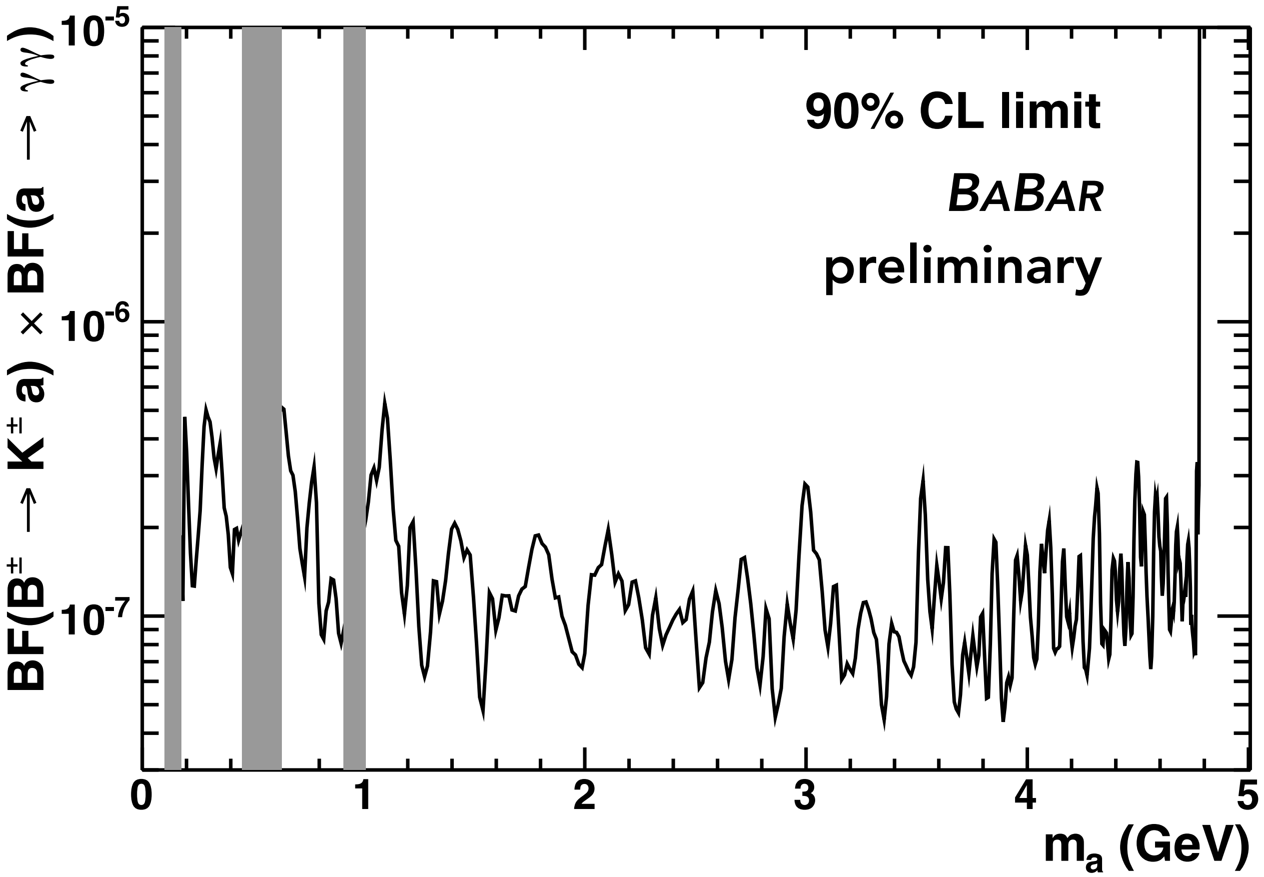
- In the preliminary results presented at ICHEP, we simply ran the same procedure as the prompt analysis, but with the long-lived signal template (and some tweaks to the fit intervals)

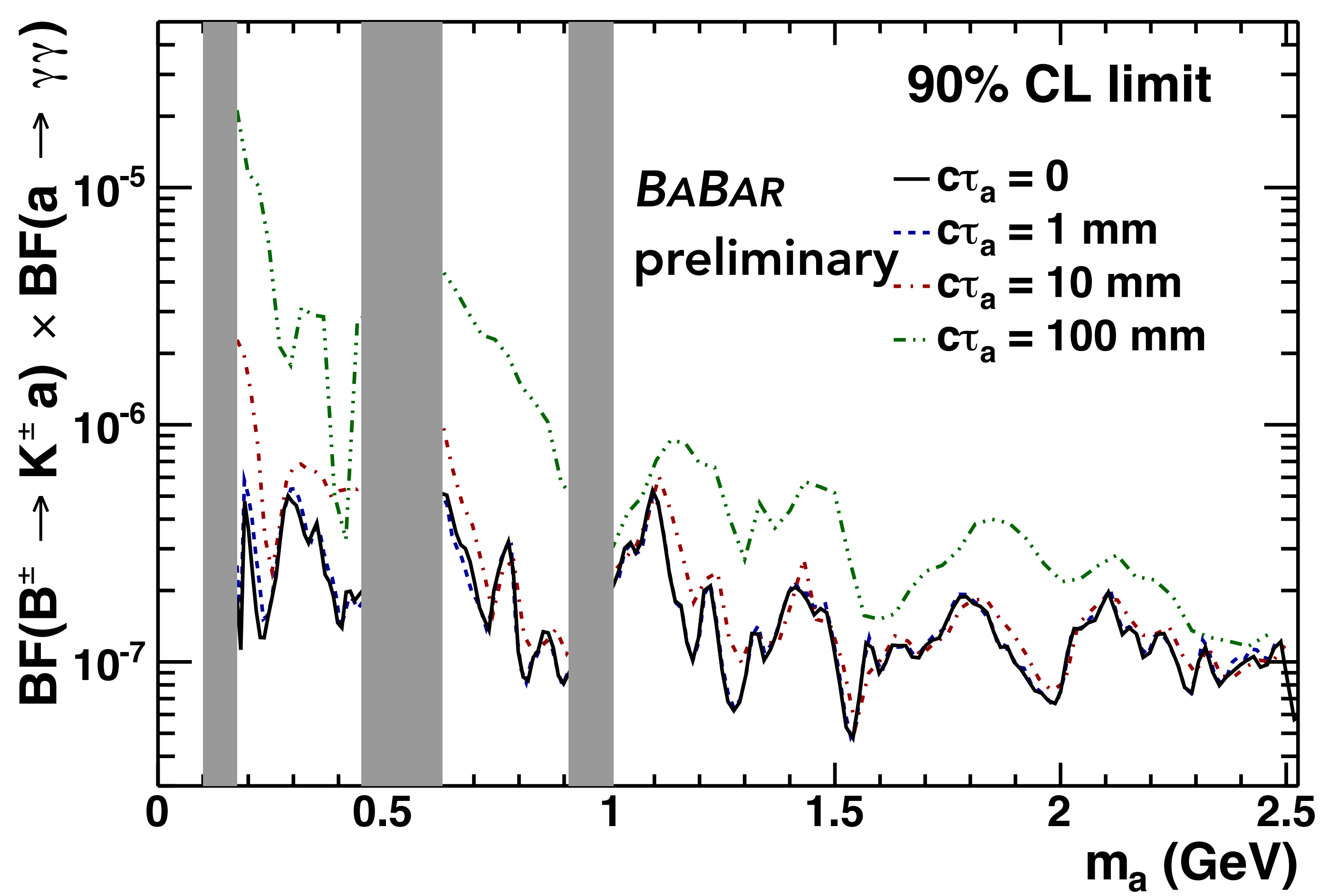
- This conservative approach leads to a sub-optimal determination of the background shape, weaker limits, and larger systematics

- We are currently improving our background modelling, in particularly putting more constraints on the background diphoton mass distribution using MC and control regions

PRESSING AHEAD...

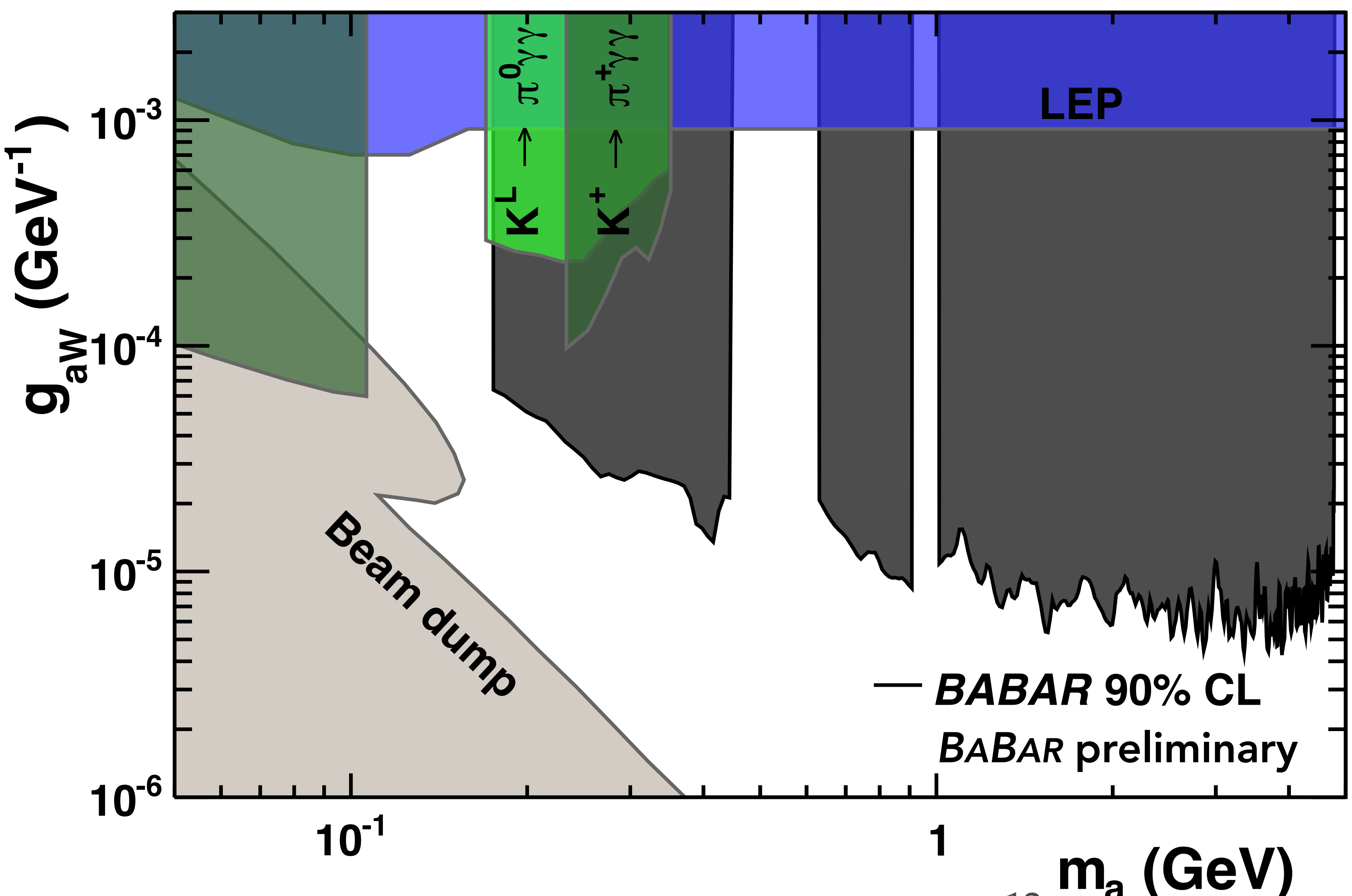
- No significant signal, set Bayesian 90% CL limits assuming a flat prior in the branching fraction





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

- Displaced photons are well motivated by many hidden-sector models

- Time and person-power constraints for the *BaBar* ALP search necessitated an LLP interpretation of a prompt search rather than a dedicated search

- Mis-reconstruction of long-lived ALPs degrades signal resolution, and makes the search more challenging

- A dedicated long-lived ALP search would greatly improve sensitivity *and* the techniques used could potentially be applied to many searches!

BACKUP SLIDES

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:
  - $e^+e^- \to q\bar{q}\ (q = u, d, s, c)$
  - $e^+e^- \to B^+B^-$

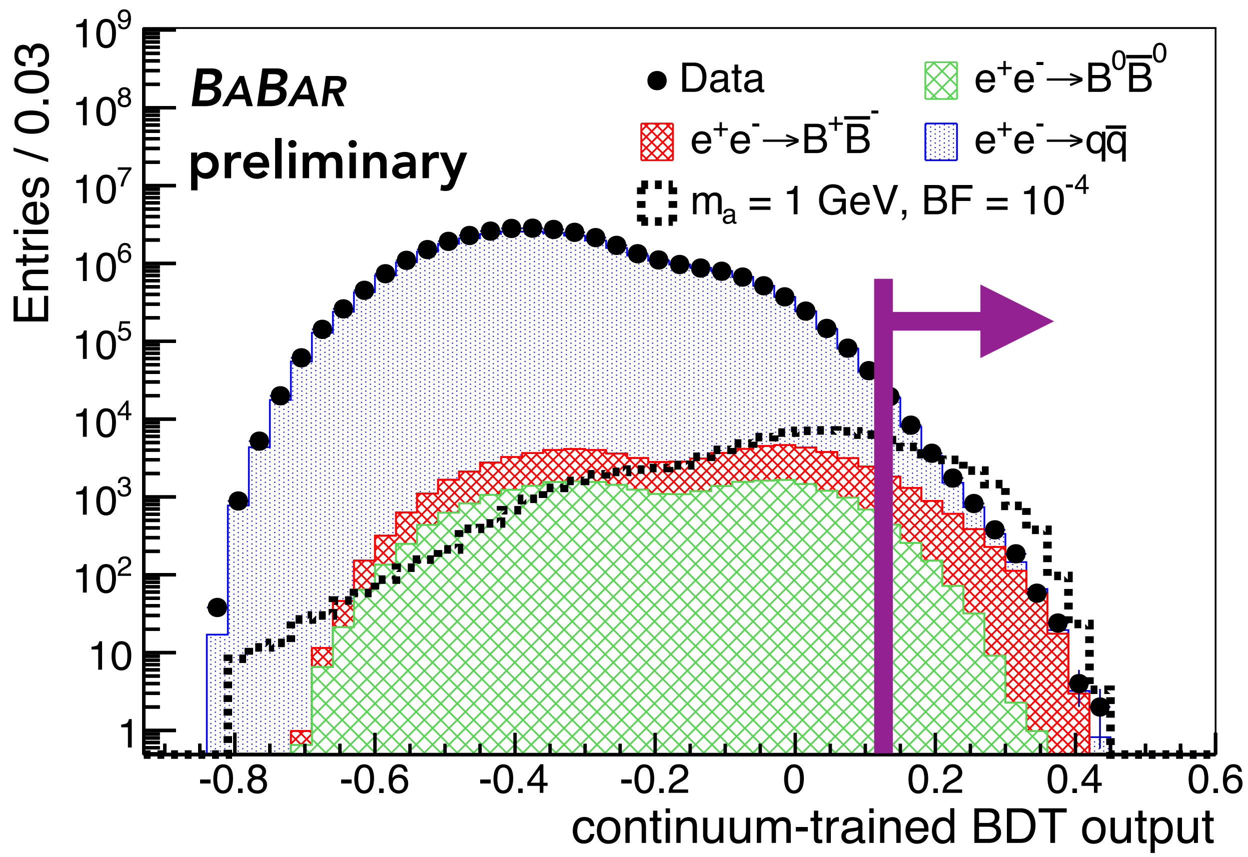
SELECTIONS

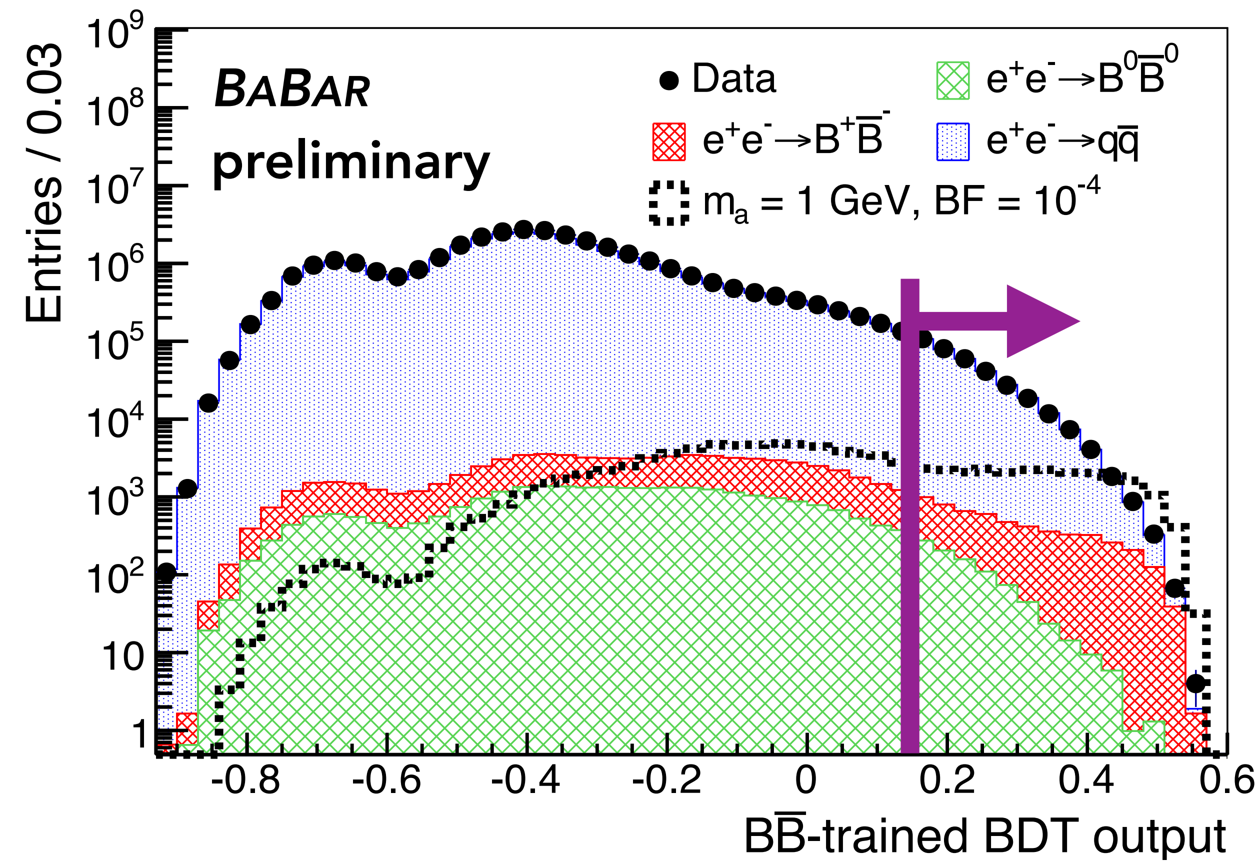
- 13 BDT training observables:
  - m_{ES}
  - ΔE
  - cosine of angle between sphericity axes of $B^{\pm}$ candidate and rest of event (ROE)
  - PID info for kaon candidate
  - 2nd Legendre moment of ROE, calculated relative to $B^{\pm}$ thrust axis
  - helicity angle of most energetic photon, and of 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





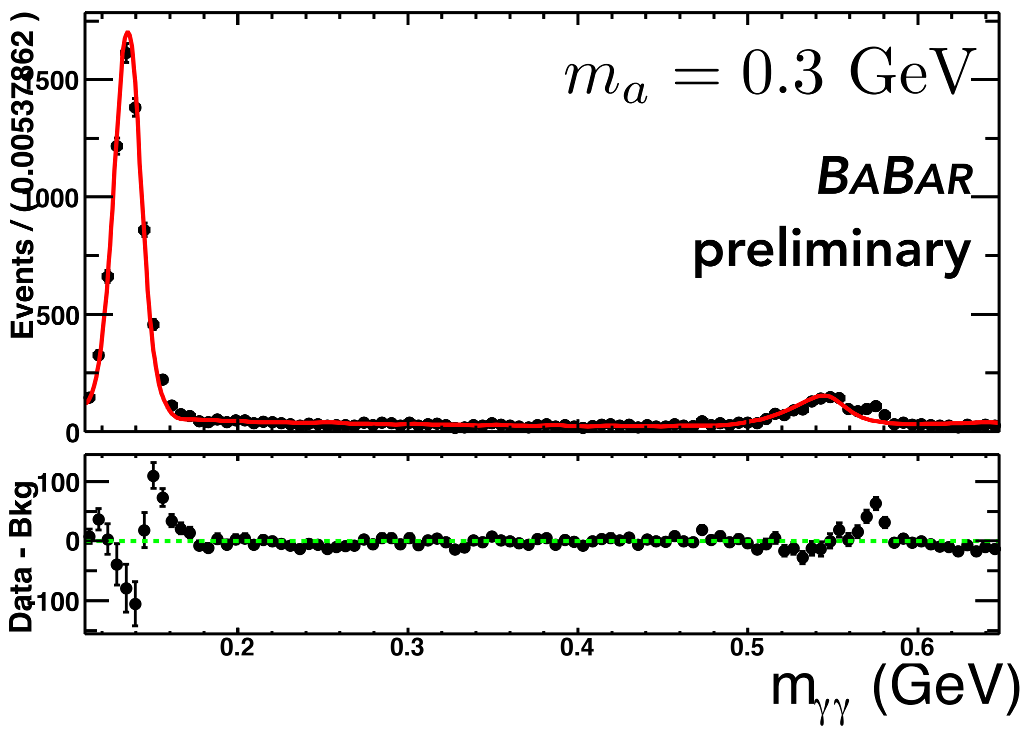
SIGNAL EXTRACTION

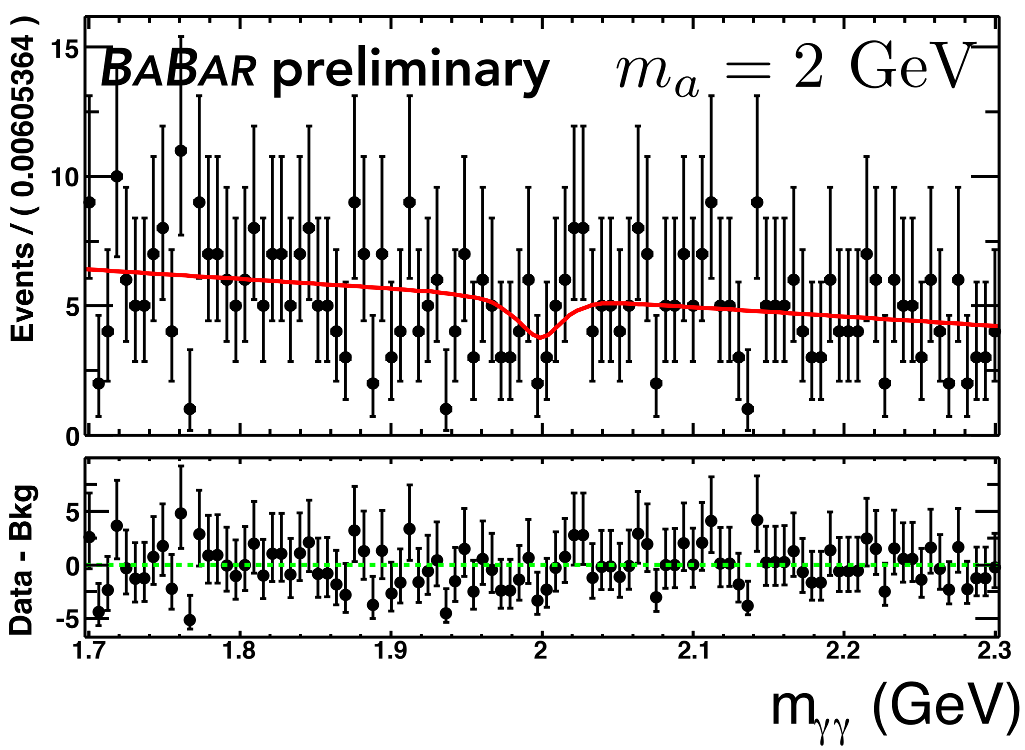
- Perform unbinned maximum likelihood fits for signal peak over smooth background
- 476 mass hypotheses, step size between adjacent mass hypotheses is given by the signal resolution, σ
- σ is determined by fitting a double-sided Crystal Ball function to signal MC at various masses, interpolating for 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

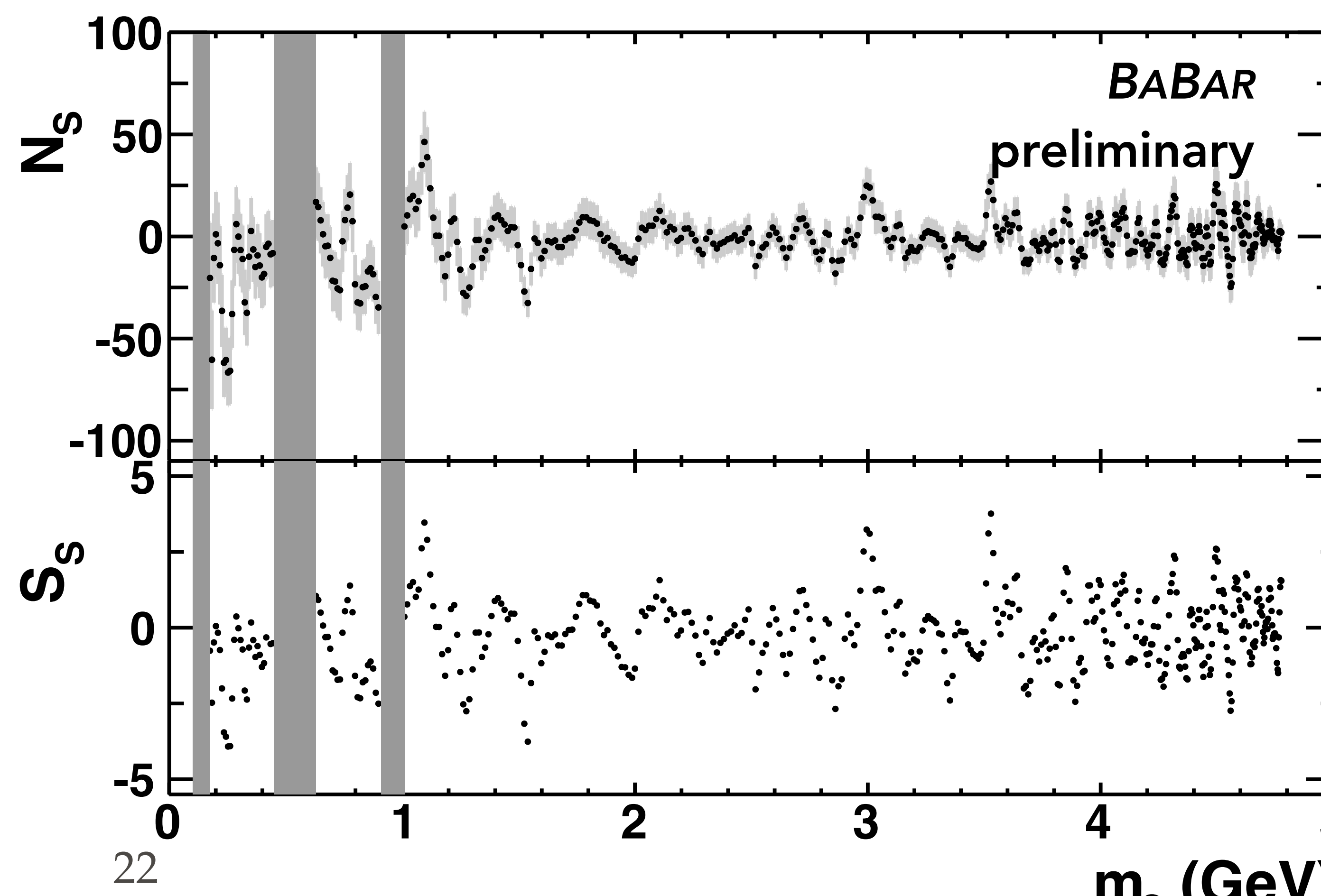
- Fits are performed over intervals of length $(30-70)\sigma$ depending on ALP mass, restricted to the range $0.11\ \mathrm{GeV} < m_a < 4.8\ \mathrm{GeV}$
- Likelihood function includes contributions from signal, continuum background, peaking background
- **Signal PDF:** modeled from signal MC and interpolated 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