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Search for an Axion-Like Particle in $B^\pm \rightarrow K^\pm a$ with $a \rightarrow \gamma\gamma$ at *BABAR*

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on behalf of the *BABAR* Collaboration

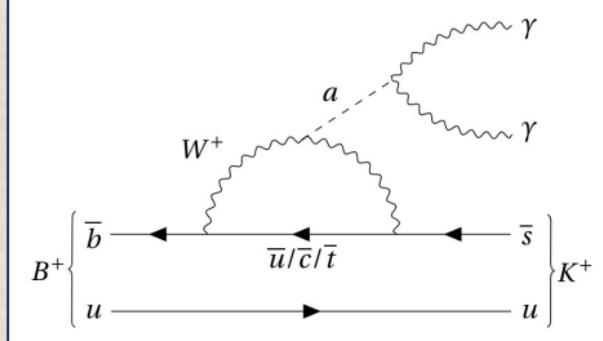
Introduction

- ▶ axion-like particles (ALPs) predicted in many models for New Physics
- ▶ Dark Matter may be coupled to ordinary matter through axion portal
- ▶ valuable to search for ALP varieties with masses and couplings not yet experimentally excluded

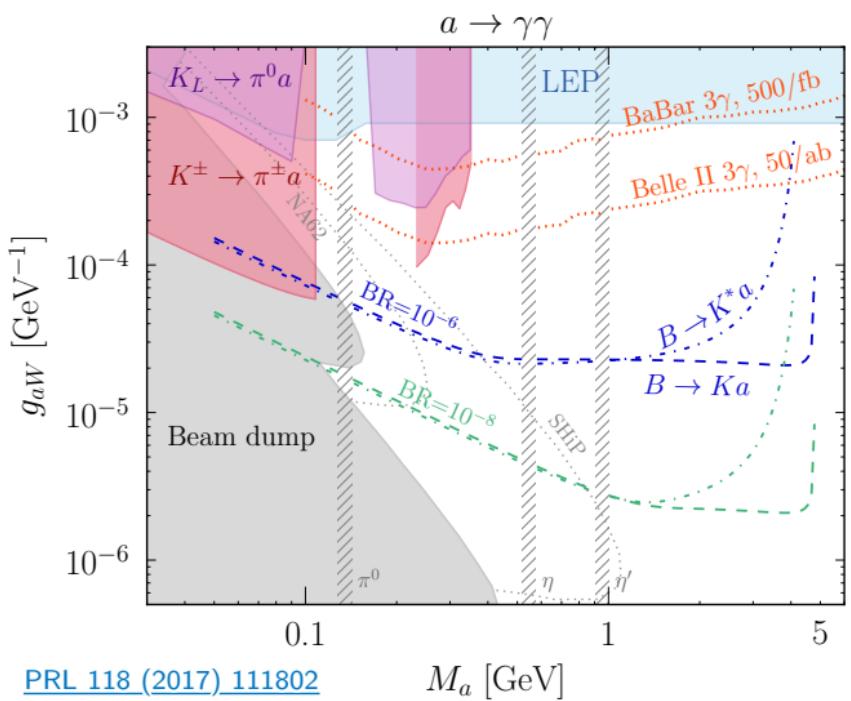
ALP coupled to Standard Model $SU(2)_W$ gauge bosons

- ▶ theory paper by E.Izaguirre, T.Lin, and B.Shuve [[PRL 118 \(2017\) 111802](#)] proposes
- ALP coupled to Standard Model $SU(2)_L$ bosons
- ▶ $\mathcal{L}_{aW} = -\frac{g_{aW}}{4} a W_{\mu\nu}^a \tilde{W}^{a\mu\nu}$
- ▶ after $SU(2)_L - U(1)$ mixing ALP couples to W^\pm, γ
- ▶ branching fraction for ALP production boosted in SM-suppressed FCNC decays like $b \rightarrow sX$

$B^+ \rightarrow K^+ a, \quad a \rightarrow \gamma\gamma$

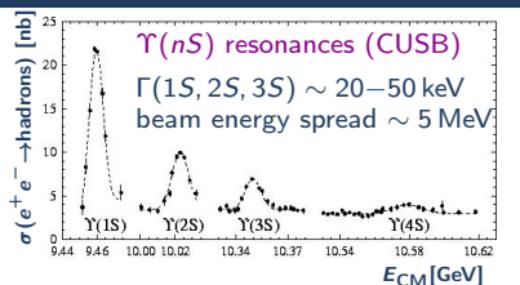


Introduction /2

Expected 90% CL limits for $SU(2)_W$ ALP searches*BABAR* search $B^\pm \rightarrow K^\pm a$ ($a \rightarrow \gamma\gamma$)recently published in
[PRL 128 \(2022\) 13, 131802](#)

BABAR, asymmetric-beam-energies B -factory, 1999-2008

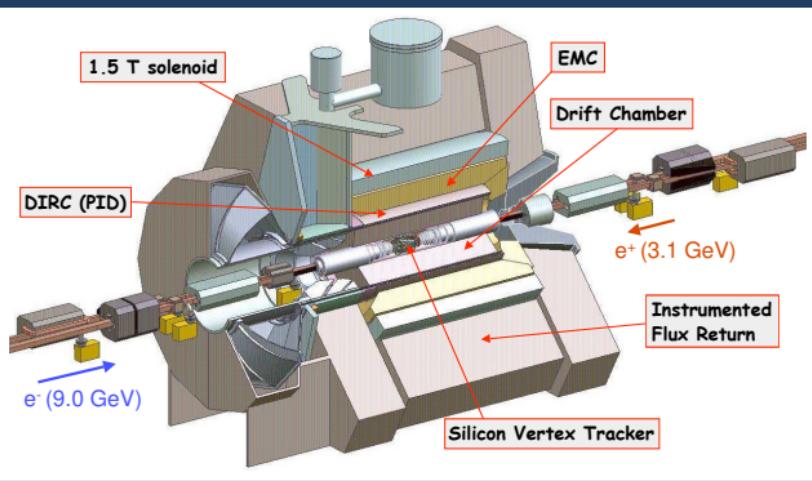
- ▶ primary purpose: measure time-dependent CP violation on coherent B pairs
- ▶ secondarily: general purpose e^+e^- collider & heavy flavour factory with well-defined e^+e^- initial state

center-of-mass energies**integrated \mathcal{L}**

energy	$\mathcal{L}(\text{fb}^{-1})$
$\Upsilon(4s)$	430
$\Upsilon(3s)$	30.2
$\Upsilon(2s)$	14.5
off-peak	54

yields

flavour	events
$B\bar{B}$	$470 \cdot 10^6$
$c\bar{c}$	$690 \cdot 10^6$
$\tau^+\tau^-$	$485 \cdot 10^6$

BABAR general purpose 4π hermetic detector

Monte Carlo simulations

signal Monte Carlo simulations

- ▶ prompt-decay ALP at 24 mass points ($[0.1 - 4.78]$ GeV), 30k events per mass point
- ▶ long-lived ALP for 16 ALP mass points ($[0.1 - 2.5]$ GeV), 30k events per mass point

backgrounds Monte Carlo simulations

- ▶ $e^+ e^- \rightarrow q\bar{q}$, $q = u, d, s, c$ (JETSET)
- ▶ $e^+ e^- \rightarrow B\bar{B}$ (EVTGEN)
- ▶ $e^+ e^- \rightarrow e^+ e^-(\gamma)$ (BHWIDE)
- ▶ $e^+ e^- \rightarrow \mu^+ \mu^-(\gamma)$, $e^+ e^- \rightarrow \tau^+ \tau^-(\gamma)$ (KK + Tauola)

detector response simulation

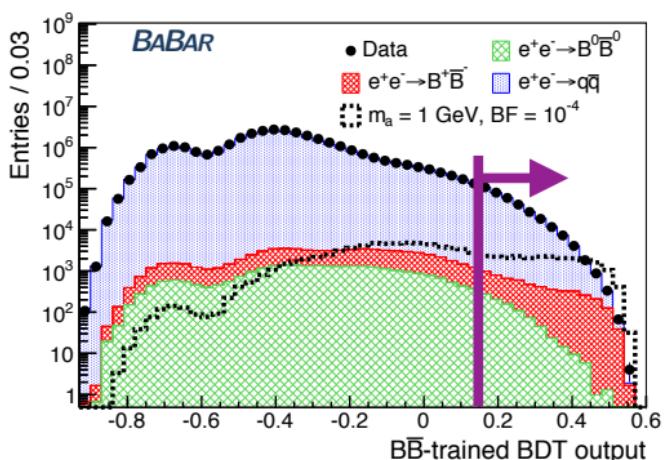
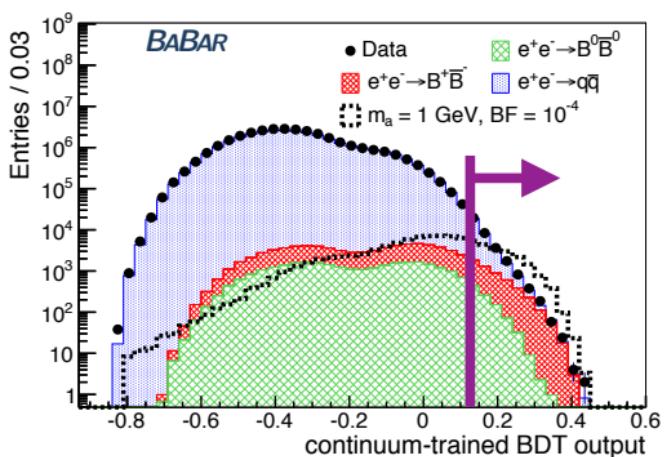
- ▶ GEANT4

Event selection

- ▶ build B^\pm candidate from one identified K^\pm track and two photons
- ▶ $m_{\text{ES}} = \sqrt{(s/2 + \vec{p}_i \cdot \vec{p}_B)^2 / E_i^2 - p_B^2} > 5.0 \text{ GeV}$ (beam-energy-substituted mass)
 - ▶ \sqrt{s} : center-of-mass (CM) energy
 - ▶ \vec{p}_B : B^\pm momentum in lab frame
 - ▶ E_i, \vec{p}_i : energy and momentum of initial state (colliding e^+e^-)
- ▶ $\Delta E = |\sqrt{s}/2 - E_B^*| < 0.3 \text{ GeV}$
 - ▶ E_B^* : B^\pm energy in CM frame

Event selection /2

- ▶ two Boosted Decision Tree (BDT) classifiers
- ▶ first one against continuum (uds) background
- ▶ second one against $B\bar{B}$ background



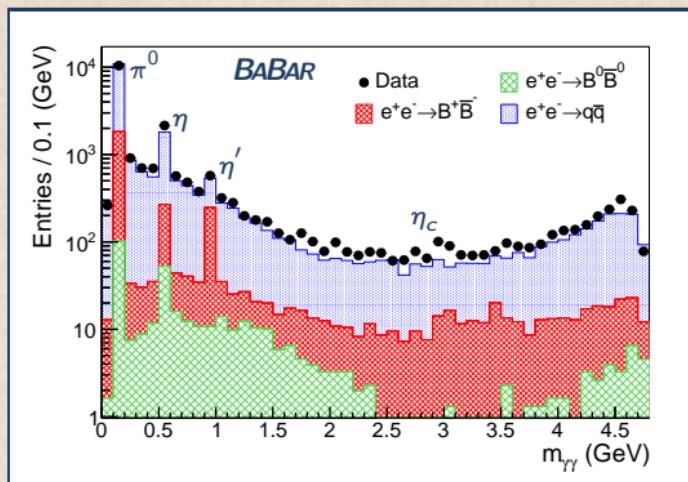
- ▶ overall event selection efficiency $\sim 30\%$ over most of mass range

Kinematic refit

- ▶ photons' momenta determined by calorimeter energy deposits assuming origin in e^+e^- luminous region
- ▶ K^\pm and 2 photons momenta refit under constraints that
 - ▶ m_B matches nominal world-average B^\pm mass
 - ▶ $E_B^* = E_i^*/2$ (B^\pm energy in CM frame matches half the CM event collision energy)

Diphoton mass spectrum

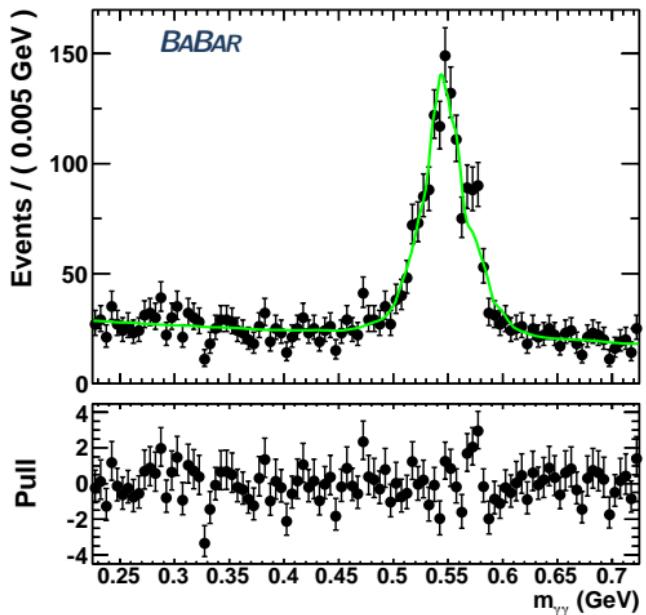
- signal searched by fitting peaks over smooth background on mass windows in diphoton mass spectrum
- simulation mostly predicts less selected event candidates than observed in data
however fits are on data and rely only on background shape, while its normalization is fit on data
- $B^\pm \rightarrow K^\pm \eta_c$ simulation not included in this plot
 - additional dedicated simulation (not shown here) using signal MC broadened according to η_c width



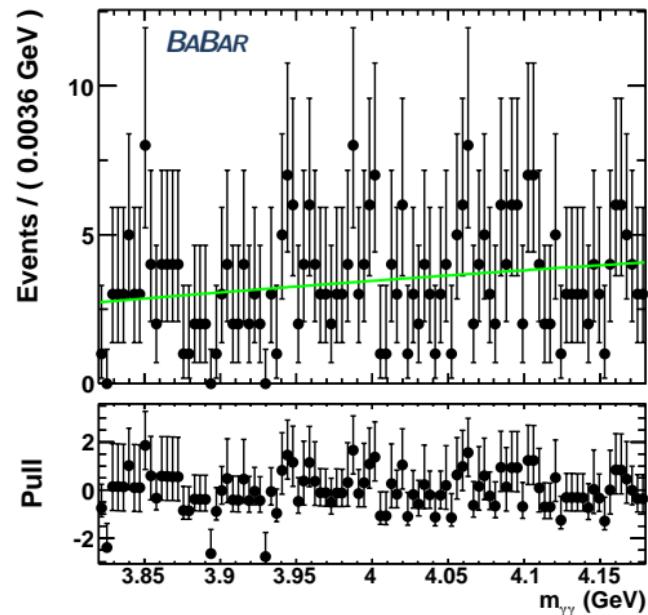
Fit for signal peak on diphoton mass spectrum

- ▶ 461 unbinned maximum likelihood fits of a hypothetical signal peak over a smooth background
- ▶ scan step size equal to diphoton mass resolution
- ▶ signal search fit not performed around resonances π^0 , η , η' but performed on η_c peak
- ▶ signal model from simulation, interpolating the two closest simulated mass points
- ▶ background model
 - ▶ $m_{\gamma\gamma} > 4 \text{ GeV}$: first order polynomial
 - ▶ $m_{\gamma\gamma} < 4 \text{ GeV}$: simulation template plus first order polynomial
 - ▶ π^0 , η , η' modeled by simulation, normalized on data
 - ▶ simulation matches data peak widths to 3% for $B^\pm \rightarrow K^\pm \pi^0$ and $B^\pm \rightarrow K^\pm \eta$
 - ▶ η_c peak modeled by MC using known $\mathcal{B}(B^\pm \rightarrow K^\pm \eta_c) \mathcal{B}(\eta_c \rightarrow \gamma\gamma)$ and η_c peak width in data

Example signal peak fits in two mass windows

mass window on low tail of η resonance

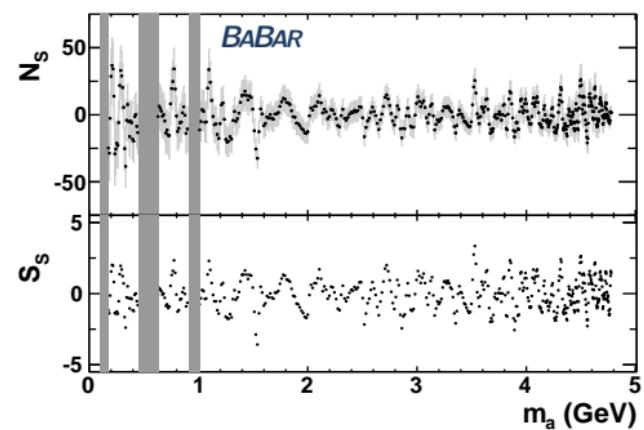
mass window after expected resonances



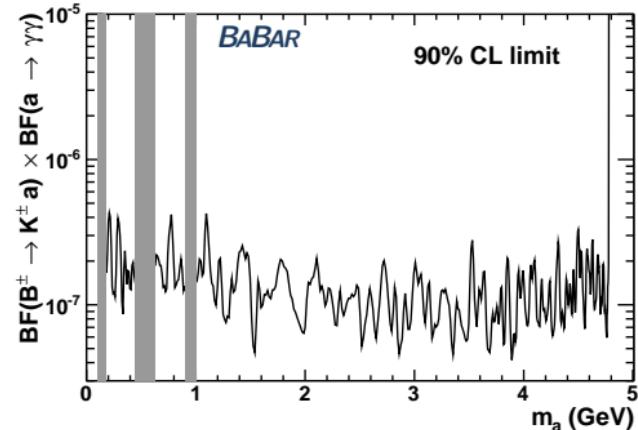
Fit results and upper limits for prompt ALP

- ▶ fits return signed number of events for hypothetical signal peak
- ▶ no signal: global statistical-uncertainties-only significance 1.1σ , accounting for look-elsewhere effect
- ▶ Bayesian 90% CL upper limits computed on $\mathcal{B}(B^\pm \rightarrow Ka) \cdot \mathcal{B}(a \rightarrow \gamma\gamma)$
 - ▶ branching fraction computed with estimated number of B^\pm mesons & MC-estimated signal efficiency
 - ▶ using positive uniform prior (result stable with different priors)

n. of events and significance for prompt ALP



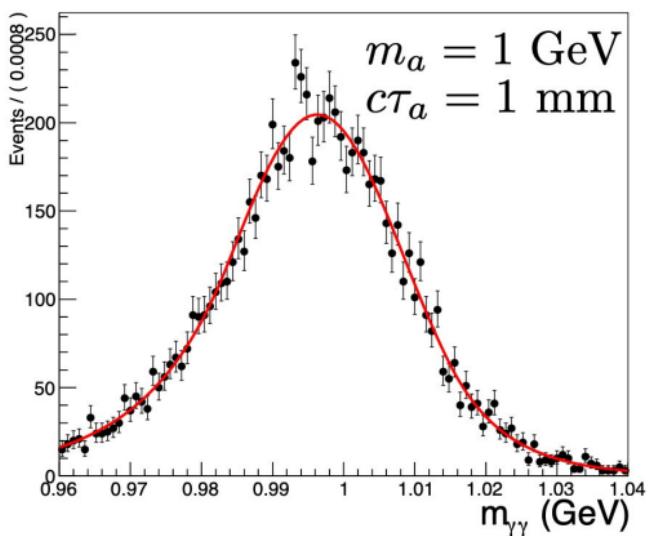
Bayesian 90% CL upper limits for prompt ALP



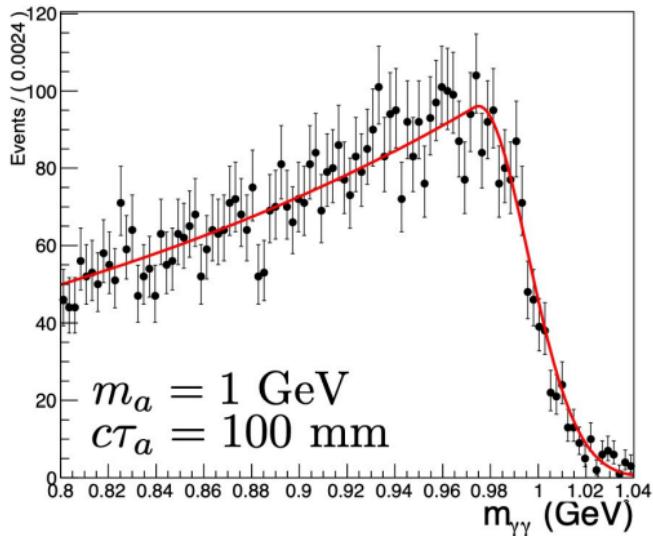
Search for long-lived ALP

- ▶ ALP with $m < 2.5$ GeV can be long-lived \Rightarrow mis-reconstruction of diphoton mass
- ▶ analysis kept unchanged, efficiency loss for long-lived ALPs estimated with MC simulation

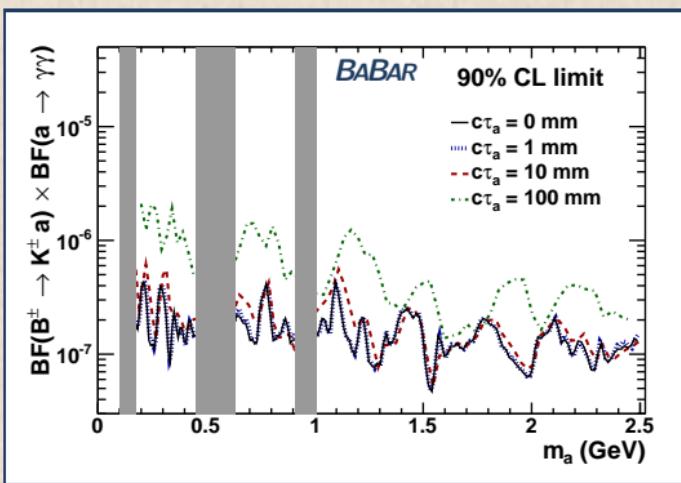
prompt ALP 1 GeV mass reconstruction



long-lived ALP 1 GeV mass reconstruction



Bayesian 90% CL upper limits for prompt and long-lived low-mass ALP



Systematics

main investigated systematics

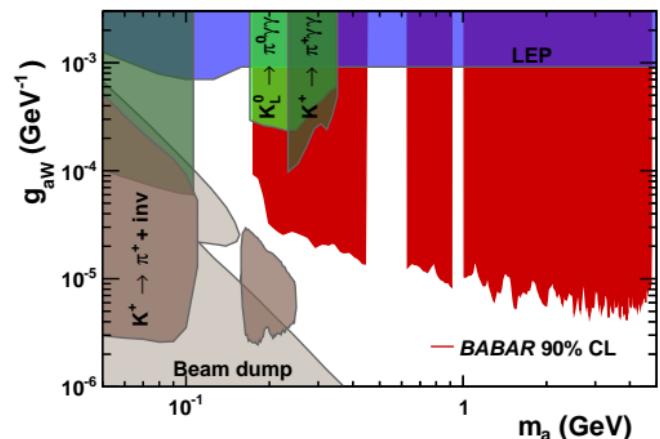
- ▶ signal model
 - ▶ vary parameters (coming from double-sided Crystal Ball function fit on signal simulation)
 - ▶ interpolation of simulated mass peaks of two closest simulated mass points
- ▶ background model
 - ▶ vary relative normalization of non-peaking simulated background components
 - ▶ uncertainties on width of resonances (coming from fits on simulated events)

accounting for systematics

- ▶ convolve unbinned likelihood with Gaussian representing total systematic uncertainty on N_{signal}
- ▶ total systematic uncertainties \ll statistical uncertainties

Excluded ALP parameter space

- ▶ using model-predicted ALP lifetime as function of ALP mass and coupling constant
- ▶ $\sim 100\times$ improvement w.r.t. previous limits
- ▶ [PRL 128 \(2022\) 13, 131802](#)



Conclusions

- ▶ *B*-factories continue to be among best facilities for GeV-scale searches
- ▶ long after end of data-taking, *BABAR* analyses still at the physics reach frontier
- ▶ more light-New-Physics searches on-going on past and present *B*-factories

Backup Slides

BDT variables

- ▶ two Boosted Decision Tree classifiers (BDT)
 - ▶ first one against continuum (uds) background
 - ▶ second one against $B\bar{B}$ background

BDT variables

- ▶ cosine of the angle between two sphericity axes, one computed with the B^\pm constituents and the other with the ROE (rest-of-event, all tracks and neutral clusters not used to make the B^\pm candidate);
- ▶ second Legendre moment of the ROE, calculated relative to the B^\pm thrust axis;
- ▶ m_{ES} and ΔE
- ▶ particle identification information for the K^\pm
- ▶ helicity angle of the K^\pm , which is the angle between the K^\pm and the $\Upsilon(4S)$ as measured in the B^\pm frame
- ▶ helicity angle and energy of the most energetic photon forming the a
- ▶ three invariant masses $m(\gamma_i \gamma_j^P)$, where γ_i is an ALP-daughter photon, γ_j^P is a photon in the ROE, and γ_i and γ_j^P are chosen so that $m(\gamma_i \gamma_j^P)$ is closest to the nominal mass of each of $P = \pi^0, \eta, \eta'$; and
- ▶ multiplicity of neutral candidates in the event.