Recent Searches for Dark Sectors and Axion-Like Particle with *BABAR*

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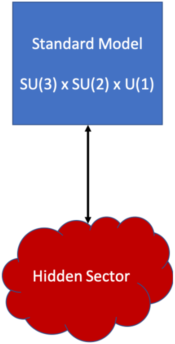
on behalf of the *BABAR* Collaboration

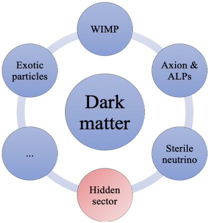
AstroDark 2021

Caltech

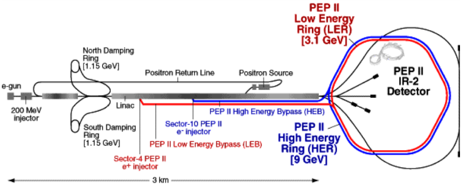
Dark Sectors

- Particle(s) that do NOT interact directly with Standard Model particles.
- Dark sector includes mediator particle(s) coupled to SM via portals: vector, scalar, neutrino, ...
- Dark sector could have rich structure, and dark matter could be part of it.
- Theoretically motivated by many Beyond Standard Model scenarios.





BABAR Experiment



- Asymmetric e^+e^- collider operating at center-of-mass energy of 10.58 GeV.
- Total integrated luminosity of 514 fb^{-1} was collected, mostly at the $\Upsilon(4S)$ resonance, but also at the $\Upsilon(3S)$ and $\Upsilon(2S)$ peaks, as well as off-resonance.

Collaboration is still active more than 10 years after data taking ended!

Content

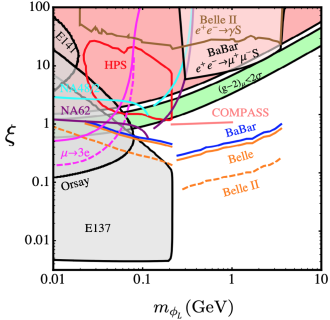
Search for a Dark Leptophilic Scalar in e^+e^- Collisions

Search for Darkonium in e^+e^- Collisions

Search for an Axion-Like Particle in B Meson Decays

Dark Leptophilic Scalar

- The existence of an extended Higgs sector with new light gauge singlets that can mix with the Higgs boson.
- New scalar interacts predominantly with SM leptons rather than quarks[1].



Viable parameter space of the leptonic Higgs model, and projections for the *BABAR* and Belle II experiments in the $e^+e^- \to \tau^+\tau^-\phi_L$ channel.

$$\mathcal{L} = -\xi \sum_{l=e,\mu,\tau} \frac{m_l}{v} \bar{l}\phi_L l$$

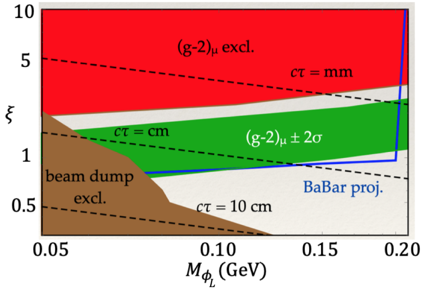
- Motivated by muon $(g-2)$.
- Current best sensitivity comes in part from *BABAR* dark muonic force analysis.
- Coupling to τ larger.

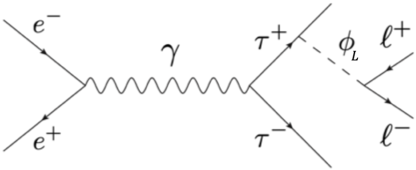
[1]Batell, Brian, et al. "Muon anomalous magnetic moment through the leptonic Higgs portal." Physical Review D 95.7 (2017): 075003.

Leptonic Higgs Portal

Signal: Two leptons (two tracks +

missing momentum/energy), plus a di-lepton resonance.





- Decays preferentially to the most massive lepton-pair kinematically accessible.
- ϕ_L may have displaced vertices decay if ξ is small enough.

Analysis Overview

Search for leptophilic scalar (ϕ_L) radiated off a tau lepton:

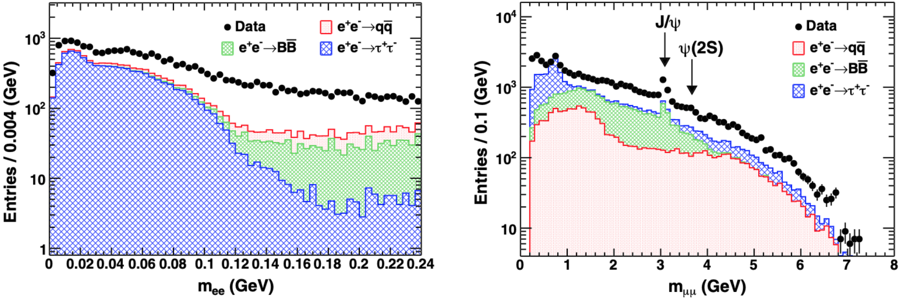
$$e^+e^- \to \tau^+\tau^-\phi_L, \phi_L \to l^+l^- \ (l = e, \mu)$$

- 0.04 GeV $\leq m_{\phi_L} \leq 7$ GeV.
- The cross section for $m_{\phi_L} \leq 2m_\mu$ is measured separately for ϕ_L lifetimes corresponding to $c\tau_{\phi_L}$ values of 0, 1, 10, and 100 mm.

Procedure

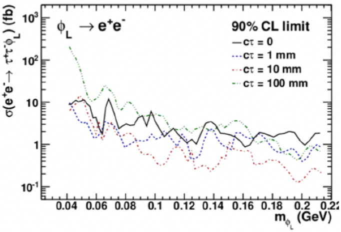
- Consider all 1-prong decays of the tau.
- Select two pairs of oppositely charged tracks.
- Reject events with total visible mass > 9 GeV (Bhabha, photon conversion).
- Train BDT to increase signal purity.
- Optimize analysis for each final state and prompt or long-lived ϕ_L.

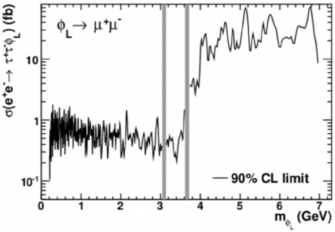
Mass Spectrum



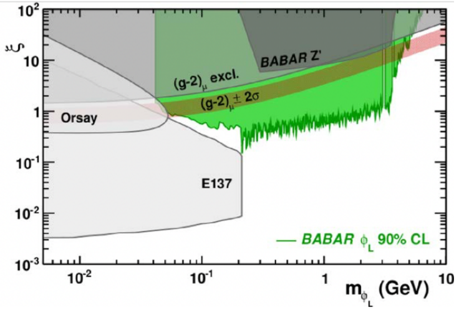
- Data/MC discrepancy is mainly due to processes that are not simulated (ISR production of high-multiplicity QED and hadronic events, two-photon processes).
- Peaking contributions from $J/\psi \to \mu^+\mu^-$ and $\psi(2S) \to \mu^+\mu^-$ decays are also seen, and the corresponding regions are excluded from the signal search.

Dark Leptophilic Scalar Results





P.R.L. 125,181801



- Exclude the possibility of the dark leptophilic scalar accounting for the $g-2$ discrepancy.
- Sharp increase above ditau threshold due to quick decrease of $\phi_L \to \mu^+\mu^-$ branching fraction.

Content

Dark Matter Bound States in Dark Sector

- Vector portal: A new gauge group $U(1)_D$ in dark sector, couple to SM via kinetic mixing:

$$\mathcal{L} = \frac{\varepsilon}{2} F^{\mu\nu} A'_{\mu\nu}$$

  .

- A minimal dark sector model contains a single Dirac fermion (χ) charged under a new $U(1)$ gauge group with a coupling constant g_D.

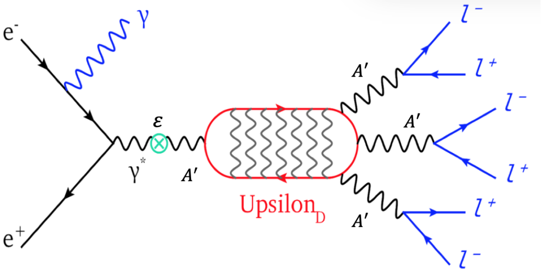
- Sufficiently strong values of g_D could result in the formation of bound states $\chi\bar{\chi}$ (darkonium).

- The existence of stable bound states requires $1.68 m_A \leq \alpha_D m_\chi$[1].

[1] Rogers, F. J., H. C. Graboske Jr, and D. J. Harwood. "Bound eigenstates of the static screened Coulomb potential." Physical Review A 1.6 (1970): 1577.

Dark Photon Physics

- One lowest bound state $\Upsilon_D(J^{PC} = 1^{--})$ predicts the process[2]:



- The dark photon can be massless or massive.
- The dark photon lifetime could be short or long-lived, meaning its decay length could be sufficiently long to produce displaced decay vertices.

$$l_{lab} = \gamma c \tau = \frac{p}{m^2} \cdot \frac{3\hbar c}{\alpha \varepsilon^2}$$

[2] An, Haipeng, et al. "Probing the dark sector with dark matter bound states." Physical review letters 116.15 (2016): 151801.

Darkonium Analysis Strategy

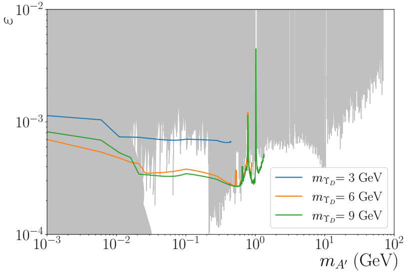
Goal

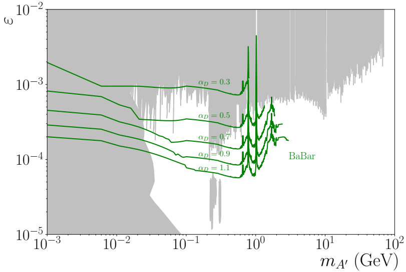
- search for the reaction $e^+e^- \to \gamma \Upsilon_D, \Upsilon_D \to A'A'A'$, A' subsequently decays to $e^+e^-, \mu^+\mu^-$ or $\pi^+\pi^-$
- $0.001 \leq m_{A'} \leq 3.16$ GeV$, 0.05 \leq \Upsilon_D \leq 9.5$ GeV

- Select events with six charged tracks identified as electron, muon or pion by PID algorithm.
- Combine three similar mass A' to form Υ_D candidates.
- Reconstruct same-sign combinations to suppress combinatorial background.
- The ISR photon can be emitted in the EMC acceptance and found or not.
- Train multiple machine learning models to increase signal purity.

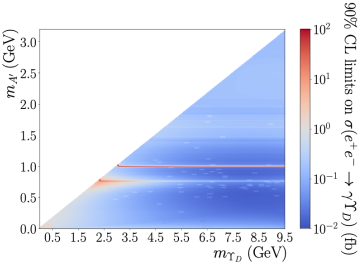
Similar procedure was applied to study the case for displaced dark photon decay.

Darkonium Preliminary Results





The 90% CL upper limits on the kinetic mixing ε for (left) various Υ_D masses assuming $\alpha_D = 0.5$ and (right) various α_D values assuming $m_{\Upsilon_D} = 9$ GeV.



- The 90% C.L. upper limit on the signal cross section is derived.
- The corresponding limits on the $\gamma - A'$ kinetic mixing ε down to $10^{-5} - 10^{-4}$.

arXiv: 2106.08529

Content

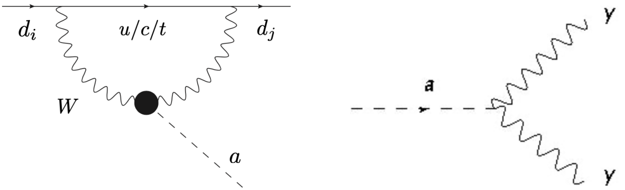
Axion-Like Particle (ALP)

- ALP: Goldstone boson of theory with a Peccei-Quinn symmetry.
- New light pseudoscalar couples predominantly to gauge bosons.

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

where $\tilde{V}^{\mu\nu} = \epsilon^{\mu\nu\rho\sigma} V_{\rho\sigma}/2$, a and V are ALP and gauge boson fields.

- Coupling of ALP to $W^{\pm}$ is difficult to measure as it is suppressed by G_F^2, compared with photon/gluon coupling.
- However, coupling to $W^{\pm}$ bosons can be probed via FCNC process[1].

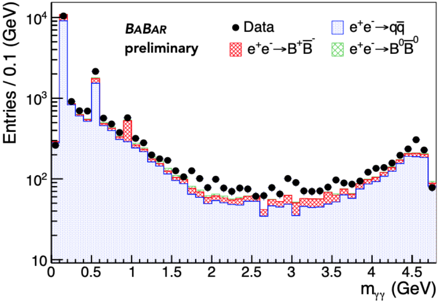


[1] Izaguirre, Eder, Tongyan Lin, and Brian Shuve. "Searching for axionlike particles in flavor-changing neutral current processes." Physical review letters 118.11 (2017): 111802.

ALP Search

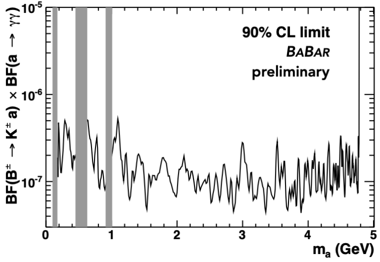
$$B^{\pm} \to K^{\pm} a, a \to \gamma\gamma$$

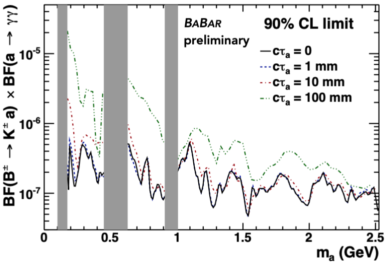
- ALP mass range 0.1 GeV $\leq m_a \leq 4.78$ GeV $(m_{B^+} - m_{K^+})$.
- Exclude π^0, η and η' mass intervals.
- ALP a could be long lived.

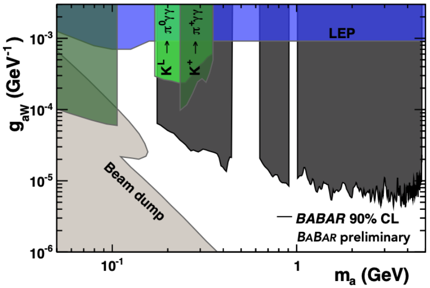


The diphoton mass distribution of ALP candidates together with leading background Monte Carlo.

ALP Preliminary Results







- Improve current constraints by more than two orders of magnitude.
- Sensitivity of FCNC probes of Axion-like Particles production.

Summary

Leptophilic scalar (P.R.L. 125,181801)

- $e^+e^- \to \tau^+\tau^-\phi_L, \phi_L \to l^+l^-$ $(l = e, \mu)$

Darkonium (arXiv: 2106.08529)

- $e^+e^- \to \gamma\Upsilon_D, \Upsilon_D \to A'A'A'$, $A' \to X^+X^-$ $(X = e, \mu, \pi)$

ALP particle in B meson decay (arXiv: 2111.01800)

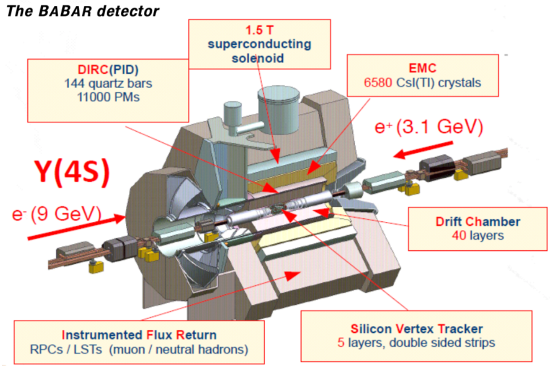
- $B^\pm \to K^\pm a, a \to \gamma\gamma$

No signals are observed.

A few other analyses are still ongoing!

Backup

BABAR Experiments



Dark Leptophilic Scalar - Cross Section

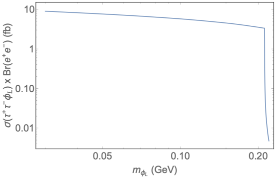


Figure 3: Cross section for $e^+e^- \to \tau^+\tau^-\phi_L$, $\phi_L \to e^+e^-$, with a coupling of $\xi = 1$. The cross section is in the $1-10$ fb range, but drops substantially once the muon decay mode opens up above $m_{\phi_L} = 210$ MeV. The cross section for other values of ξ can be found by multiplying the cross section in this figure by ξ^2.

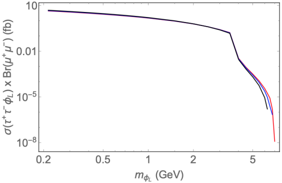


Figure 3: Cross section for $e^+e^- \to \tau^+\tau^-\phi_L$, $\phi_L \to \mu^+\mu^-$, with a coupling of $\xi = 1$. The cross section for other values of ξ can be found by multiplying the cross section in this figure by ξ^2.

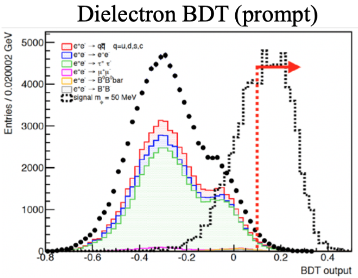
Dark Leptophilic Scalar - MVA

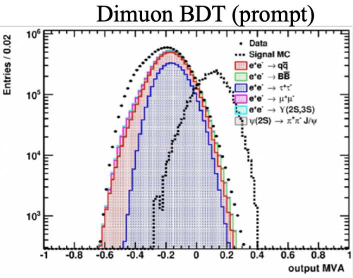
TABLE I: List of variables used as input to the dimuon BDT.

Ratio of second to zeroth Fox-Wolfram moment of all tracks and neutrals.
Invariant mass of the four track system, assuming the pion (muon) mass for the tracks originating from the tau (ϕ_L) decays.
Invariant mass and transverse momentum of all tracks and neutrals.
Invariant mass squared of the system recoiling against all tracks and neutrals.
Transverse momentum of the system recoiling against all tracks and neutrals.
Number of neutral candidates with an energy greater than 50 MeV.
Invariant masses of the three track systems formed by the ϕ_L and the remaining positively or negatively charged tracks.
Momentum of each track from ϕ_L decays.
Angle between the two tracks produced by the tau decay.
Variable indicating if a track has been identified as a muon or an electron by PID algorithm for each track.

TABLE II: List of variables used as input to the dielectron BDT.

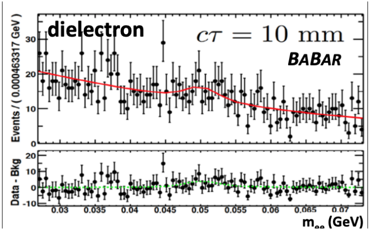
Transverse momentum of the system recoiling against all tracks and neutrals.
Energy of the system recoiling against all tracks and neutrals.
Number of tracks identified as electron candidates by a PID algorithm applied to each track.
Angle between ϕ_L candidate momentum and closest track produced in tau decay.
Angle between ϕ_L candidate momentum and farthest track produced in tau decay.
Angle of ϕ_L candidate relative to the beam in the center-of-mass frame.
Angle between the two tracks produced by the tau decay.
Angle between ϕ_L candidate and nearest neutral candidate with $E > 50$ MeV.
Energy of nearest neutral candidate (with $E > 50$ MeV) to ϕ_L candidate.
Total energy in neutral candidates, each of which has an energy greater than 50 MeV.
Distance between beamspot and ϕ_L candidate vertex.
Uncertainty on distance between beamspot and ϕ_L candidate decay vertex.
ϕ_L candidate vertex significance, defined by the beamspot-vertex distance divided by its uncertainty.
Angle between the ϕ_L candidate momentum, and line from beamspot to ϕ_L decay vertex.
Distance of closest approach to beamspot of e^- in ϕ_L candidate.
Distance of closest approach to beamspot of e^+ in ϕ_L candidate.
Transverse distance between ϕ_L decay vertex and best-fit common origin of τ candidates and ϕ_L candidate.
Vertex χ^2 of kinematic fit to common origin of τ candidates and ϕ_L candidate.
Vertex χ^2 for ϕ_L candidate when re-fit with the constraint that the e^+e^- pair originate from photon conversion in material.
Dielectron mass for ϕ_L candidate when re-fit with the photon conversion constraint.

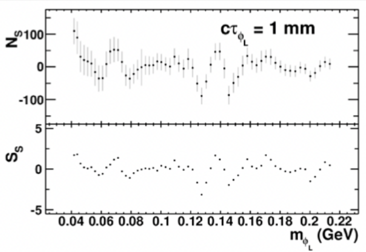


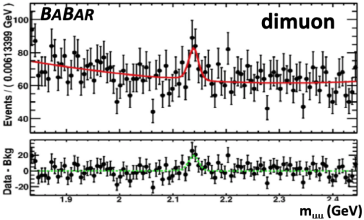


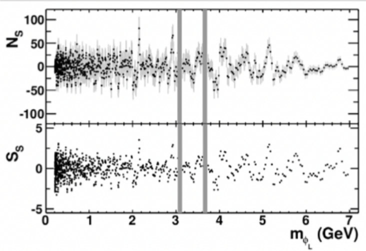
Dark Leptophilic Scalar - Signal Extraction and Fits

We extract signal as a function of dark scalar mass with fits over sliding intervals.



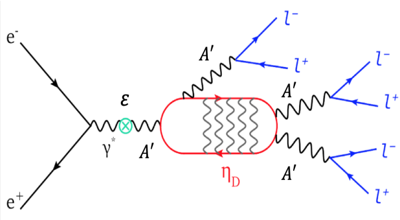


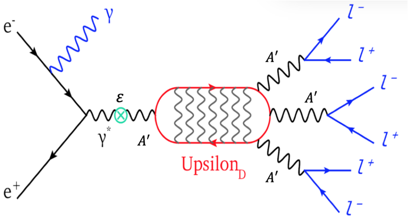




Darkonium - Theoretical Model

$$\mathcal{L} = \mathcal{L}_{SM} + \bar{\chi} i \gamma^{\mu}(\partial_{\mu} - i g_D A'_{\mu})\chi - m_{\chi}\bar{\chi}\chi - \frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} - \frac{\varepsilon}{2}F_{\mu\nu}A'^{\mu\nu} + \frac{1}{2}m^2_{A'}A'_{\mu}A'^{\mu}$$





Darkonium - Analysis Performance

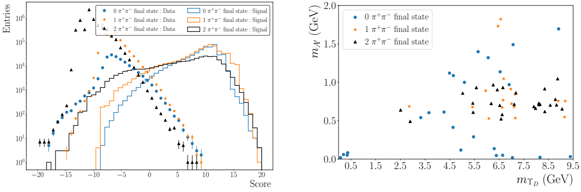


Figure: Analysis performance for prompt dark photon decays. Left: MVA score distribution. Right: mass distribution of observed events passing all selection criteria.

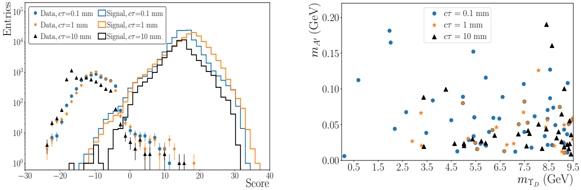


Figure: Analysis performance for displaced dark photon decays. Left: MVA score distribution. Right: mass distribution of observed events passing all selection criteria.

Darkonium - Limits for Displaced A' Decays

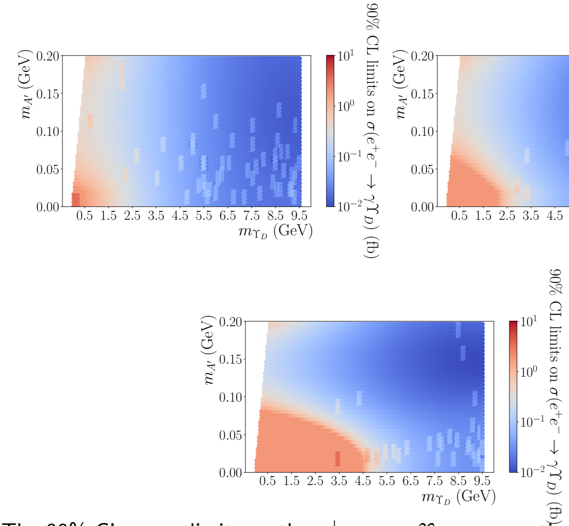
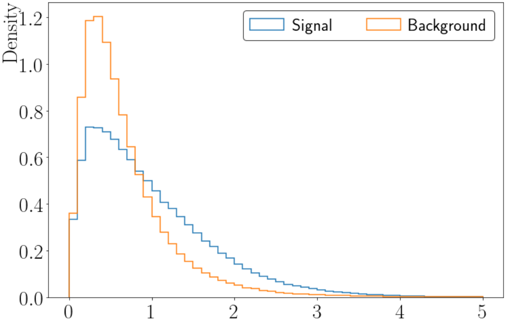


Figure: The 90% CL upper limits on the $e^+e^- \to \gamma\Upsilon_D$ cross-section for (top left) $c\tau_{A'} = 0.1\,\text{mm}$, (top right) $c\tau_{A'} = 1\,\text{mm}$, and (bottom) $c\tau_{A'} = 10\,\text{mm}$.

Darkonium - Same-sign reconstruction



Opposite-sign:
$e^+ e^- \;\; e^+ e^- \;\; \mu^+ \mu^-$
Same-sign:
$e^+ e^+ \;\; e^- e^- \;\; \mu^+ \mu^-$

- Same-sign track combinations are formed by swapping particles with identical flavor between reconstructed dark photon pairs.
- Background: the mass difference distributions between same-sign and opposite-sign pairs tend to be similar.
- Signal: the mass difference distributions between same-sign and opposite-sign pair tend to be larger.

ALP - Observed Events

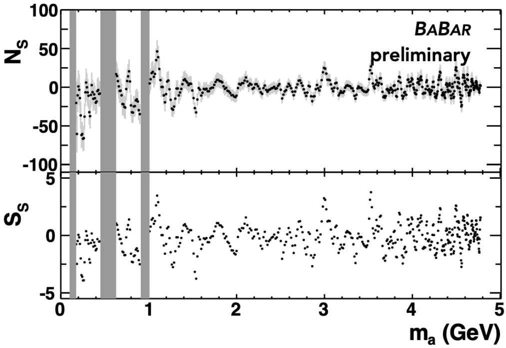


FIG. 2: The distribution of signal events (N_{s}) and local signal significance (S_{s}) from fits as a function of m_a for prompt ALP decays. The step size between adjacent mass hypotheses is equal to the signal resolution, σ. The gray bands indicate the regions excluded from the search in the vicinity of the η and η' masses.

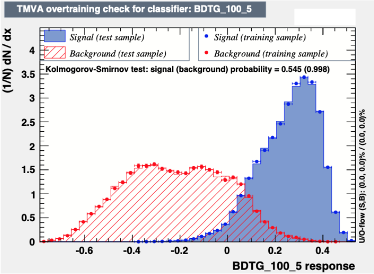
ALP - Event Selection

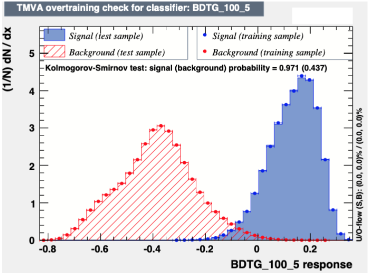
$$B^{\pm} \to K^{\pm}a, a \to \gamma\gamma$$

Pre-Selections:

- Reconstruct a from $\gamma\gamma$ candidate pairs.
- Loose Kaon particle identification.
- $\Delta E = |\sqrt{s}/2 - E_B| < 0.3$ GeV
- $m_{\text{ES}} > 5$ GeV

Multivariate Selections (BDT):





ALP Signal Extraction

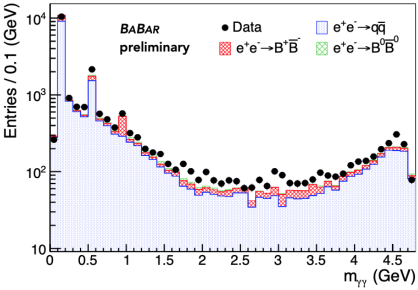


Figure: The diphoton mass distribution of ALP candidates together with leading background Monte Carlo.

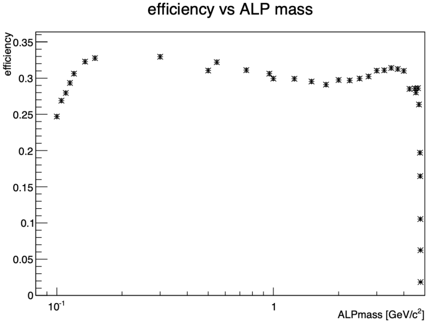


Figure: Signal efficiency as a function of m_a.

- The background is dominated by continuum events.
- The efficiency is relatively flat over most of the mass range.