Recent Searches for Hidden-Sector Particles and Axion-Like Particle with *BABAR*

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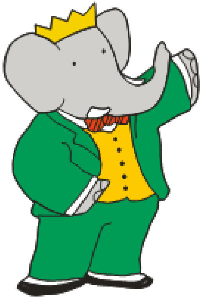
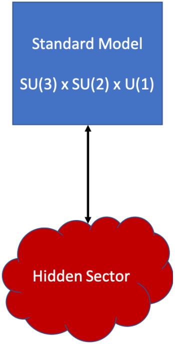
on behalf of the *BABAR* Collaboration

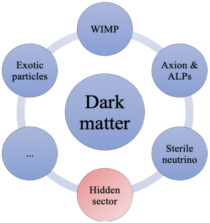
FPCP, 2021



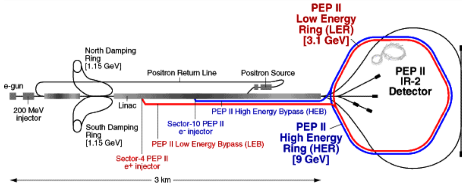
Hidden Sectors

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

Dark Leptophilic Scalar

- New scalar interacts predominantly with SM leptons rather than quarks[1].

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

where ξ is dimensionless coupling strength, ϕ_L is the new leptonic scalar, $v = 246$ GeV is the SM Higgs vacuum expectation value.

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

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

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

Dark Leptophilic Scalar Analysis Strategy

- 4 charged tracks with zero net charge.
- Reject events with total visible mass > 9 GeV (Bhabha, photon conversion).

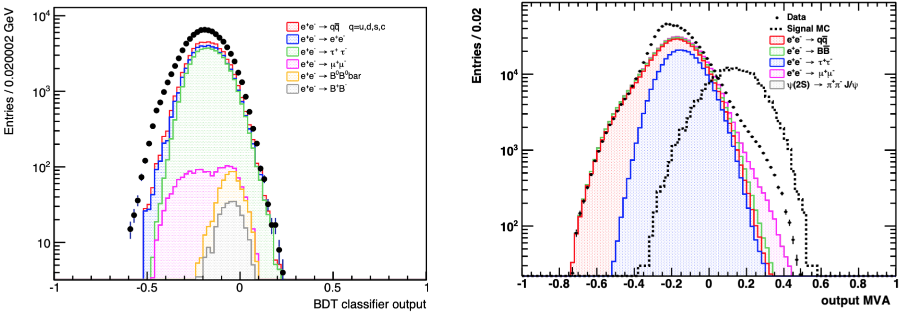
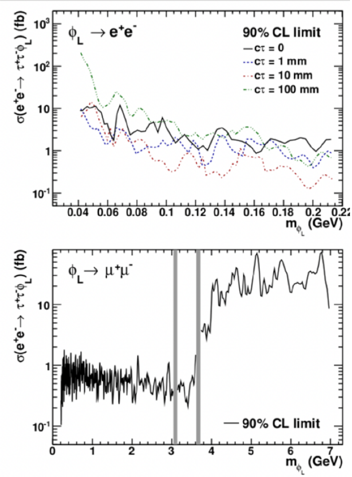


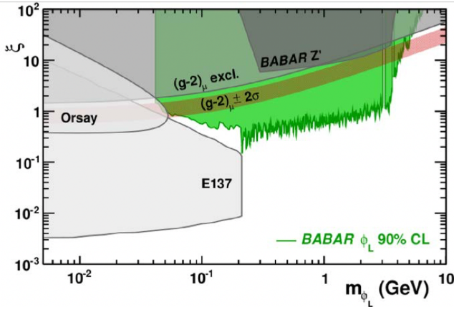
Figure: BDT score distribution for $\phi_L \to e^+e^-$ (left) and $\phi_L \to \mu^+\mu^-$ (right).

- Data / MC discrepancy due to non-modelled MC components (two-photon, ISR, high-multiplicity QED).
- The discrepancy is considered as a source of systematic uncertainties.

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 Hidden Sector

- Vector portal: A new gauge group $U(1)_D$ in hidden 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.

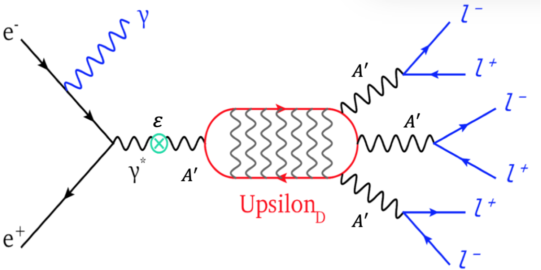
- Sufficiently strong values of g_D could result in the formation of bound states $\chi\bar{\chi}$ (darkonium).

- 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

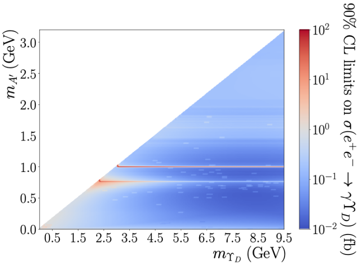
- search for the reaction $e^+e^- \to \gamma\Upsilon_D, \Upsilon_D \to A'A'A'$, A' subsequently decays to $e^+e^-, \mu^+\mu^-$ or $\pi^+\pi^-$
- $0.001 \leq m_{A'} \leq 3.16$ GeV$, 0.05 \leq \Upsilon_D \leq 9.5$ GeV

- 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

- No significant signal is observed.
- 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 $10^{-5} - 10^{-4}$.



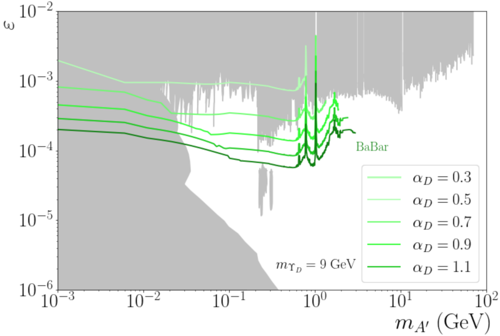


Figure: Left: 90% upper limit of signal cross section for prompt dark photon decays. Right: 90% upper limit of kinetic mixing strength when $m_{\Upsilon_D} = 9$ GeV, for different α_D.

Content

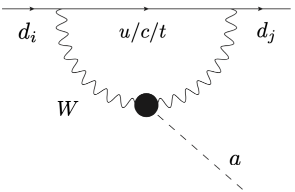
Axion-Like Particle (ALP)

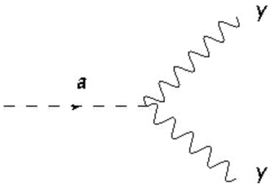
- ALP: Goldstone boson of theory with a Peccei-Quinn symmetry.
- New light pseudoscalar couples predominantly to gauge bosons.

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

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.

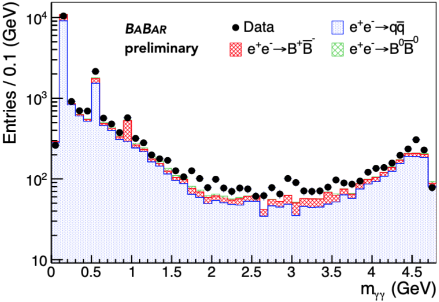
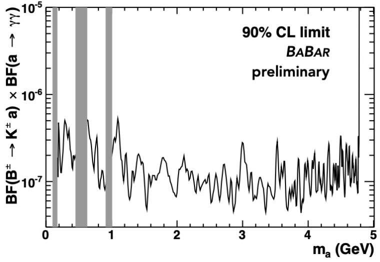
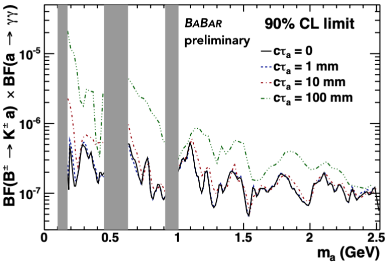
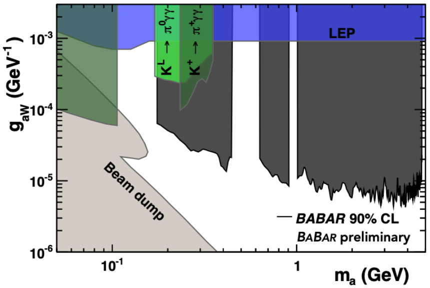


Figure: The diphoton mass distribution of ALP candidates together with leading background Monte Carlo.

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

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

Darkonium

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

ALP particle in B meson decay

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

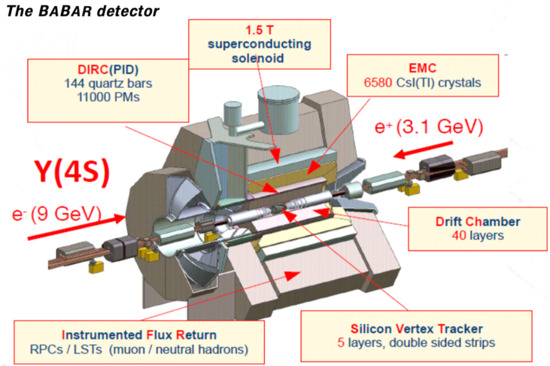
No signals are observed.

A few other analyses are still ongoing!

Backup

Backup

BABAR Experiments



Dark Leptophilic Scalar - Cross Section

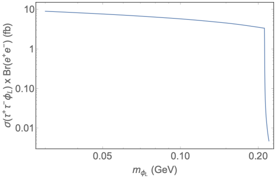


Figure 3: Cross section for $e^+e^- \to \tau^+\tau^-\phi_L$, $\phi_L \to e^+e^-$, with a coupling of $\xi = 1$. The cross section is in the $1 - 10$ fb range, but drops substantially once the muon decay mode opens up above $m_{\phi_L} = 210$ MeV. The cross section for other values of ξ can be found by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

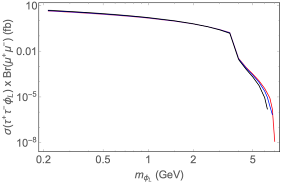


Figure 3: Cross section for $e^+e^- \to \tau^+\tau^-\phi_L$, $\phi_L \to \mu^+\mu^-$, with a coupling of $\xi = 1$. The cross section for other values of ξ can be found by multiplying the cross section in this figure by ξ^2.

Dark Leptophilic Scalar - MVA

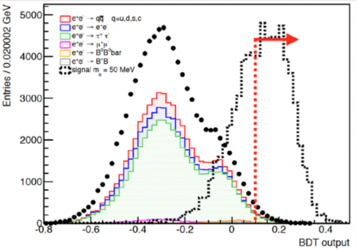
TABLE I: List of variables used as input to the dimuon BDT.

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.

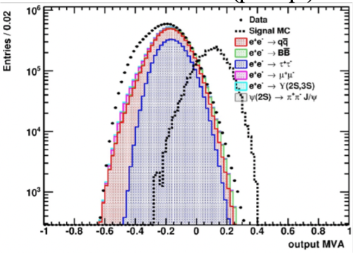
TABLE II: List of variables used as input to the dielectron BDT.

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.

Dielectron BDT (prompt)

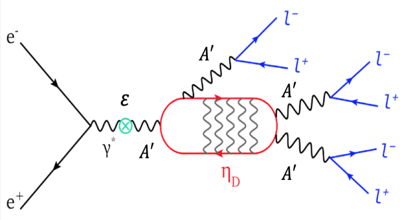


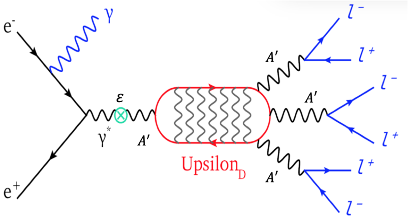
Dimuon BDT (prompt)



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

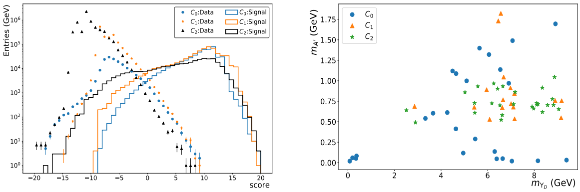


Figure: Analysis performance for prompt dark photon decays. Left: MVA score distribution. Right: mass distribution of observed events passing all selection criteria.

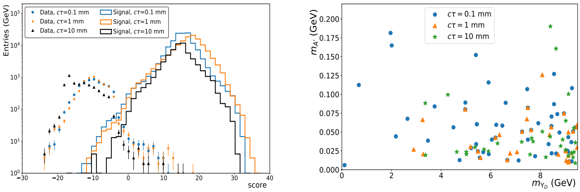


Figure: Analysis performance for displaced dark photon decays. Left: MVA score distribution. Right: mass distribution of observed events passing all selection criteria.

Darkonium - Cross Section Limits for Displaced A' Decays

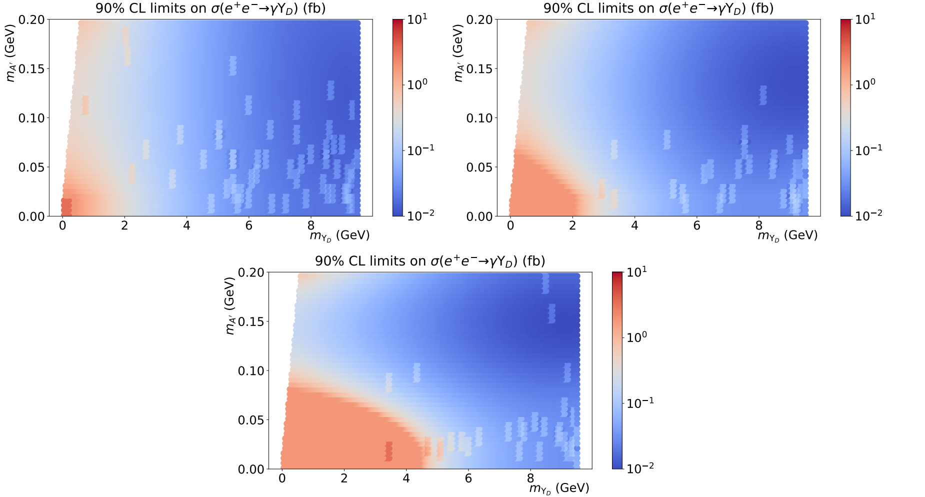


Figure: The 90% CL upper limits on the $e^+e^- \to \gamma\Upsilon_D$ cross-section for dark photon lifetimes corresponding to (top left) $c\tau_{A'} = 0.1\,\mathrm{mm}$, (top right) $c\tau_{A'} = 1\,\mathrm{mm}$, and (bottom) $c\tau_{A'} = 10\,\mathrm{mm}$.

ALP - Observed Events

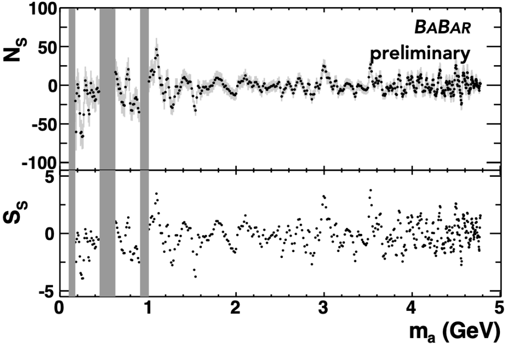


FIG. 2: The distribution of signal events (N_s) and local signal significance (S_s) from fits as a function of m_a for prompt ALP decays. The step size between adjacent mass hypotheses is equal to the signal resolution, σ. The gray bands indicate the regions excluded from the search in the vicinity of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

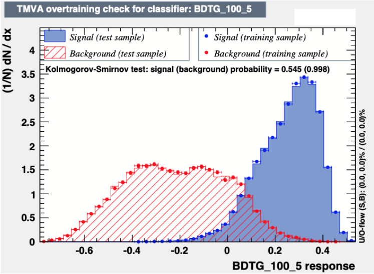
ALP - Event Selection

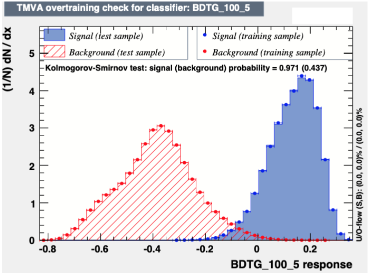
$$B^{\pm} \to K^{\pm}a, a \to \gamma\gamma$$

Pre-Selections:

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

Multivariate Selections (BDT):





ALP Signal Extraction

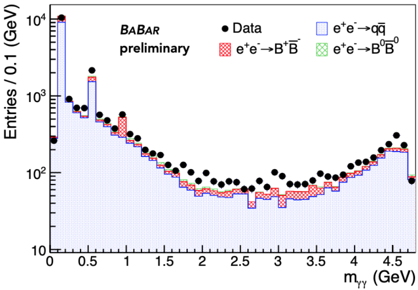


Figure: The diphoton mass distribution of ALP candidates together with leading background Monte Carlo.

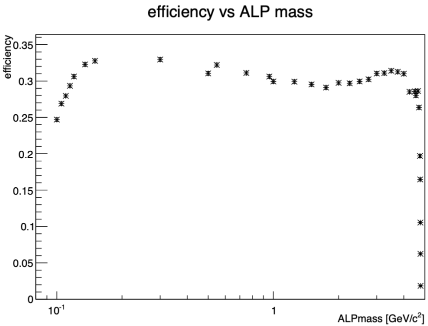


Figure: Signal efficiency as a function of m_a.

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