

Searches for Light Scalars, Pseudoscalars, and Gauge Bosons

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In the past few years there has been a great deal of theoretical and experimental activity related to the search for low-mass scalars, pseudoscalars, and vectors in various scenarios of physics beyond the standard model. I review the current status of this topic, focusing on results obtained since FPCP 2014.

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1. Introduction and motivation

A variety of new-physics scenarios allow for new, weakly interacting GeV-scale bosons. A class of scenarios involves a “hidden sector”, a loose term referring to a collection of theoretically related particles, possibly with a rich phenomenology internal to that sector, that are hidden from us due to the lack of a strong interaction with the particles of the standard model (SM). The gravitationally observed dark matter in the universe may be part of such a hidden sector, which is then called the dark sector. This term is often used even when one does not enforce a relation to the observed dark matter, and I will do so here as well. Of particular interest to particle physicists is the possible existence of weak interactions – so-called “portals” – that allow dark-sector particles to be produced in experiments and to decay via detectable signatures.

In what follows, I briefly describe several scenarios in which low-mass scalar, pseudoscalar, and vector bosons arise, and present the results of recent searches for such particles.

2. Searches for a dark photon

A $U(1)$ gauge interaction in the dark sector gives rise to a dark photon A' . The A' may obtain mass via breaking of the symmetry, distinguishing it from the SM photon. A so-called “vector portal” between the SM and the dark sector is provided by a kinetic mixing term in the effective Lagrangian, $\mathcal{L} \supset -\frac{1}{2}\varepsilon F^{\mu\nu}F'_{\mu\nu}$, where $F'_{\mu\nu} = \partial_\mu A'_\nu - \partial_\nu A'_\mu$, $F^{\mu\nu}$ is the corresponding field tensor for the SM $U(1)$ interaction, and ε is the mixing parameter between the two $U(1)$ interactions. The Lagrangian gives rise to processes shown in Fig. 1, in which the dark photon is created on-shell in radiative electron-positron collisions.

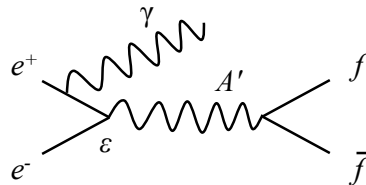


Figure 1: The production of an on-shell dark photon A' in an e^+e^- collision. The cross section is governed by the kinetic-mixing parameter ε . The dark photon subsequently decays into two SM fermions via the same process.

Interest in dark photons was generated a few years ago, when the PAMELA satellite experiment found that the ratio of positron and electron energy spectra in cosmic rays was rising with energy for energies above about 10 GeV [1]. This behavior, which was later confirmed by Fermi [2] and AMS-02 [3], was interpreted as a possible result of GeV-scale dark-photon production from the annihilation of TeV-scale dark-matter fermion pairs [4]. The observed spectrum was also shown to be consistent with the expectation from secondary cosmic-ray production, without requiring any new physics [5]. Nonetheless, this observation raised awareness for the possibility of light hidden-sector photons, prompting a wealth of theoretical and experimental activity.

The latest dark-photon search was performed by the BES-III collaboration, using the processes $e^+e^- \rightarrow \gamma\ell^+\ell^-$, where ℓ is an electron or a muon [6]. In this so-called untagged approach, observation of the initial-state-radiation (ISR) photon was not required, in order to increase the efficiency and accept events in which the photon was too forward to be detected. The dilepton invariant-mass spectrum was fit with a 4th-order polynomial for the background, plus a signal peak whose position was moved throughout the spectrum. This treatment of the signal mass is referred to as a signal “scan”. No significant signal was found, and limits were set on the value of ε as a function of $m_{A'}$.

The BES-III limits are shown in Fig. 2. Also shown are all previous results obtained from different experiments with a variety of methods. These include $e^+e^- \rightarrow \gamma\ell^+\ell^-$ at BABAR [7] and at KLOE [9], $\phi \rightarrow \eta e^+e^-$ at KLOE [8], $\pi^0 \rightarrow \gamma e^+e^-$ at WASA-at-COSY [10] and NA48 [11], $\pi^0 \rightarrow \gamma e^+e^-$ and $\eta \rightarrow \gamma e^+e^-$ at PHENIX [12], and inclusive e^+e^- spectra from proton-target interactions at HADES [13] and from electron-target interactions at A1 [14] and at APEX [15]. Also shown are constraints from measurements of the electron anomalous magnetic moment [16], as well as the region of $\varepsilon, m_{A'}$ parameter space preferred by the discrepancy between the predicted and measured values of the muon anomalous magnetic moment [17]. As shown in the figure, that preferred region is now fully excluded by other measurements. The very low- ε , low- $m_{A'}$ region is excluded by reinterpretations of older beam-dump experiments [18, 19, 20].

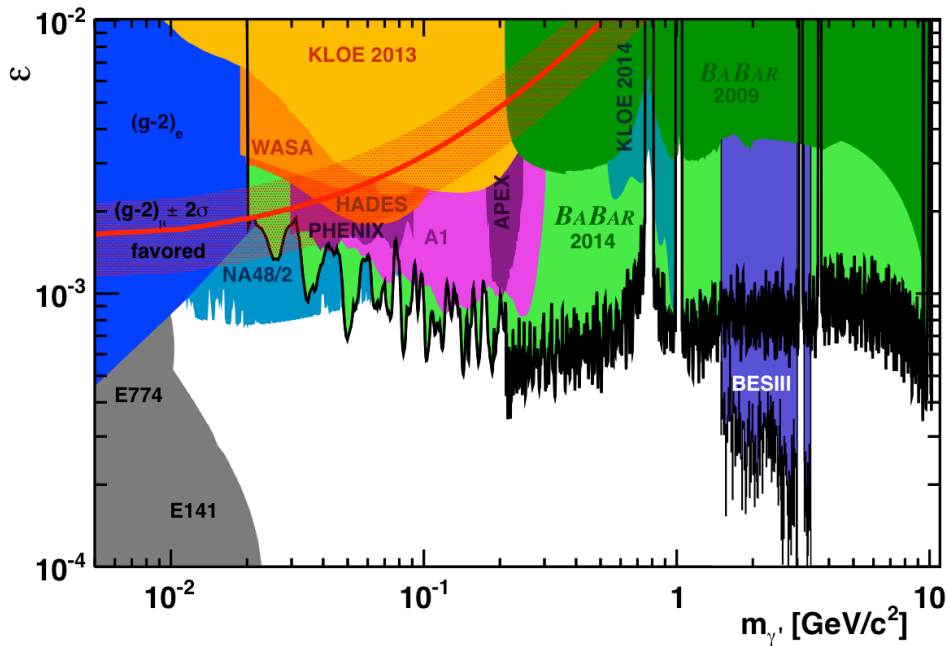


Figure 2: Upper limits on the mixing parameter ε as a function of the dark-photon mass $m_{A'}$ from a variety of experiments. See text for details (Figure: B. Echenard.)

It is worthwhile to consider some improvements to these studies in the near future and beyond. First, I note that the BABAR analysis [7] was “tagged”, i.e., used events in which the ISR photon was observed. By contrast, the untagged approach of the BES-III analysis [6] made it possible to

utilize events in which the ISR photon is emitted at too small a polar angle to be observed. It is likely that BABAR can tighten its current limits for regions of $m_{A'}$ by performing an independent untagged analysis.

Belle can perform the same analysis as BABAR, with double the integrated luminosity L . However, since the analysis is background-dominated, and the signal yield is proportional to ε^2 , the sensitivity to ε is proportional to $L^{-1/4}$. Belle-II will have an integrated luminosity about 100 times that of BABAR, as well as better mass resolution due to the larger drift chamber, and a more efficient e^+e^- trigger. This combination of factors will significantly increase the sensitivity at better than the 4th-root of the ratio of luminosities [21].

Additional dark-photon searches are planned by the Jefferson-Lab experiments LIPSS, Dark-Light, HPS, and APEX [22], as well as VEPP-3 and A1 [21].

3. Searches for a dark photon with dark Higgs

The next step up in model complexity includes also a light Higgs scalar h' . If its mass satisfies $m_{h'} > 2m_{A'}$, the h' can decay into two dark photons. The Belle collaboration has recently searched for this process in the process $e^+e^- \rightarrow A'^*$, with $A'^* \rightarrow A'h'$ and $h' \rightarrow A'A'$ [23]. The three final-state dark photons were searched for in their decays to pairs of leptons or charged pions, or to two lepton pairs and an inclusive final state X whose mass was determined from the missing mass in the event. Background was greatly suppressed by requiring the masses of the three A' candidates to be similar. The number of candidate events observed was consistent with the expected background, and Belle set limits on the product of ε^2 and the dark-sector coupling constant α_D . These limits are shown in Fig. 3.

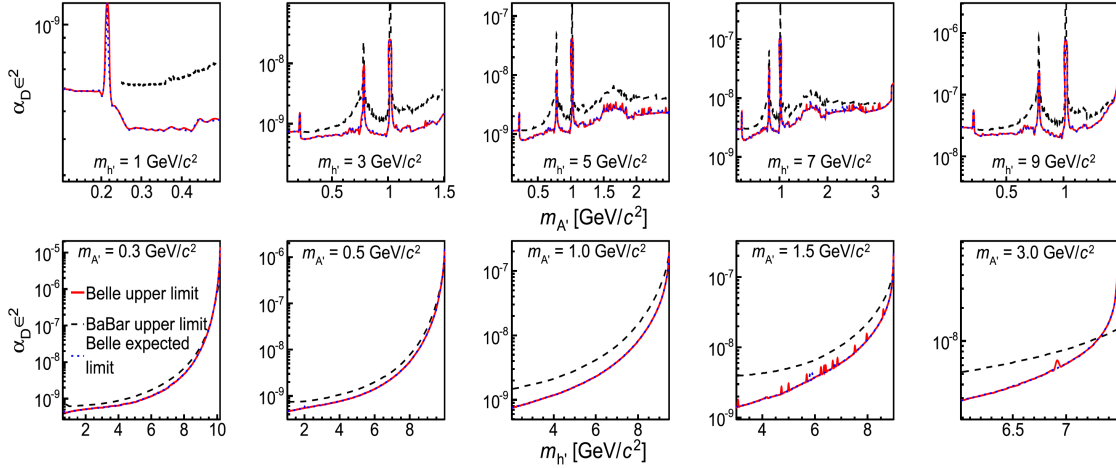


Figure 3: Upper limits on the product $\varepsilon^2 \alpha_D$ from the Belle search for production of three dark photons in e^+e^- collisions [23] (solid red curves). Also shown are earlier results from a similar BABAR analysis [24] (dashed black curves).

4. Searches for a light Higgs

A light Higgs also comes up in scenarios that do not involve a dark photon. One example is the next-to-minimal supersymmetric standard model (NMSSM) [25], which contains a light CP-odd Higgs. Another is a case where a light scalar mixes with the SM Higgs [26, 27], called “Higgs portal” in the case of a dark-sector Higgs. In either case, the light scalar may be produced in decays of a B or Υ meson, as shown in Fig. 4, taking advantage of the large Higgs couplings to the heavy top and bottom quarks.

Depending on the scenario, different symbols are used for the light Higgs. In what follows, I use the generic symbol h .

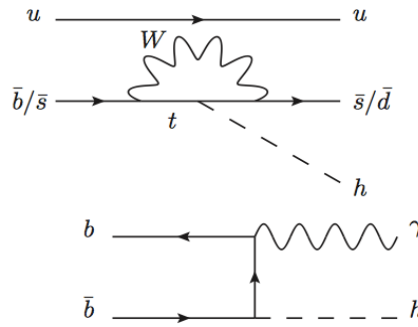


Figure 4: Diagrams for the production of a light scalar h via its large coupling to (top) the top quark in penguin B -meson decays or (bottom) to the bottom quark in radiative Υ decays.

The CLEO collaboration was the first to perform a search for a light Higgs, using radiative decays of the $\Upsilon(1S)$ and the light-Higgs decay channels $h \rightarrow \mu^+\mu^-$ and $h \rightarrow \tau^+\tau^-$ [28]. BABAR has used decays of both the $\Upsilon(3S)$ [29, 30, 31, 32] and the $\Upsilon(1S)$ [33, 34, 35, 36], searching for light-Higgs decays into $\mu^+\mu^-$, $\tau^+\tau^-$, hadrons, and invisible particles. BES-III has done the same with J/ψ decays in the mode $h \rightarrow \mu^+\mu^-$ [37]. CMS has performed both an inclusive search in the $h \rightarrow \mu^+\mu^-$ channel [38] and an exclusive search in decays of the 125-GeV Higgs, $H \rightarrow hh \rightarrow \mu^+\mu^-\mu^+\mu^-$ [39]. In a very recent analysis, ATLAS has searched for $H \rightarrow hh \rightarrow \mu^+\mu^-\tau^+\tau^-$ [41]. Please see Peter Onyisi’s contribution to this conference for details. The combination of all these searches places tight constraints on the NMSSM scenario.

The branching fractions for decays of the h to the different final states depend on its mass and on the parameters of the model. Therefore, it is important to search in all possible channels. Until recently, the only light-Higgs decays that had not yet been explored were decays into heavy quarks. This has now been addressed by BABAR for the $2m_D < m_h < 2m_B$ case, in a new search for $h \rightarrow c\bar{c}$, where the h is produced in the decay $\Upsilon(1S) \rightarrow \gamma h$ [40].

The analysis used a sample of $121 \times 10^6 e^+e^- \rightarrow \Upsilon(2S)$ events, with the decay $\Upsilon(2S) \rightarrow \pi^+\pi^-\Upsilon(1S)$ used to obtain a high-purity sample of $\Upsilon(1S)$ mesons. The square of the mass recoiling against the pions, $(p_{e^+e^-} - p_{\pi^+\pi^-})^2$, where $p_{e^+e^-}$ is the 4-momentum of the incoming beam particles and $p_{\pi^+\pi^-}$ is that of the reconstructed pion pair, was required to be consistent with the

known mass of the $\Upsilon(1S)$. A photon and a charmed meson were then reconstructed, thus tagging the decay $h \rightarrow c\bar{c}$. The mass of the h candidate was calculated from 4-momentum conservation, $m_h^2 = (p_{e^+e^-} - p_{\pi^+\pi^-} - p_\gamma)^2$, where p_γ is the 4-momentum of the photon. The resulting spectrum of h candidates was then fit with a polynomial background, and a signal-peak scan was performed. No significant signal was observed, and limits were set on the product of branching fractions $\mathcal{B}(\Upsilon(1S) \rightarrow \gamma h) \times \mathcal{B}(h \rightarrow c\bar{c})$. These limits are shown in Fig. 5.

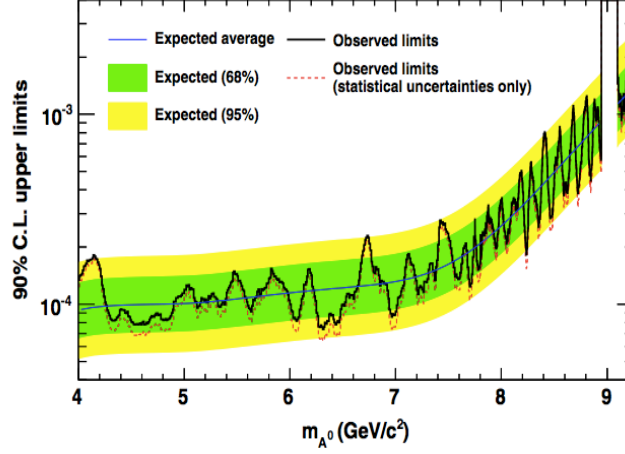


Figure 5: Upper limits at the 90% confidence level on the the product of branching fractions $\mathcal{B}(\Upsilon(1S) \rightarrow \gamma h) \times \mathcal{B}(h \rightarrow c\bar{c})$ from BABAR [40].

5. Long-lived particles

New hidden-sector particles may be weakly interacting enough to be long-lived, so that they can be identified as displaced vertices. In fact, several low- ε , low- $m_{A'}$ limits in the dark-photon parameter space are based on searches for long-lived particles in beam-dump experiments [18, 19, 20].

At colliders, which have inherently lower luminosities than beam-dump experiments, observing such a signature requires that the new particle be produced relatively strongly and only decay very weakly. This is achieved if there exist two different portals with different strengths. Alternatively, the Higgs portal offers such a mechanism, since scalar-fermion couplings are proportional to the fermion mass. Thus, a light Higgs may be produced via a large Yukawa coupling to heavy fermions, as in Fig. 4, yet decay with a small Yukawa coupling if its small mass allows decays only to muons or electrons. An interesting model of this type is that of a GeV-scale inflaton X that mixes with the SM Higgs [42] via the quartic term $\mathcal{L} \supset -\lambda (H^\dagger H - \frac{\alpha}{\lambda} X^2)^2$. Depending on the values of the model parameters, the average inflaton may either decay promptly, form a displaced vector in the detector, or decay outside the detector.

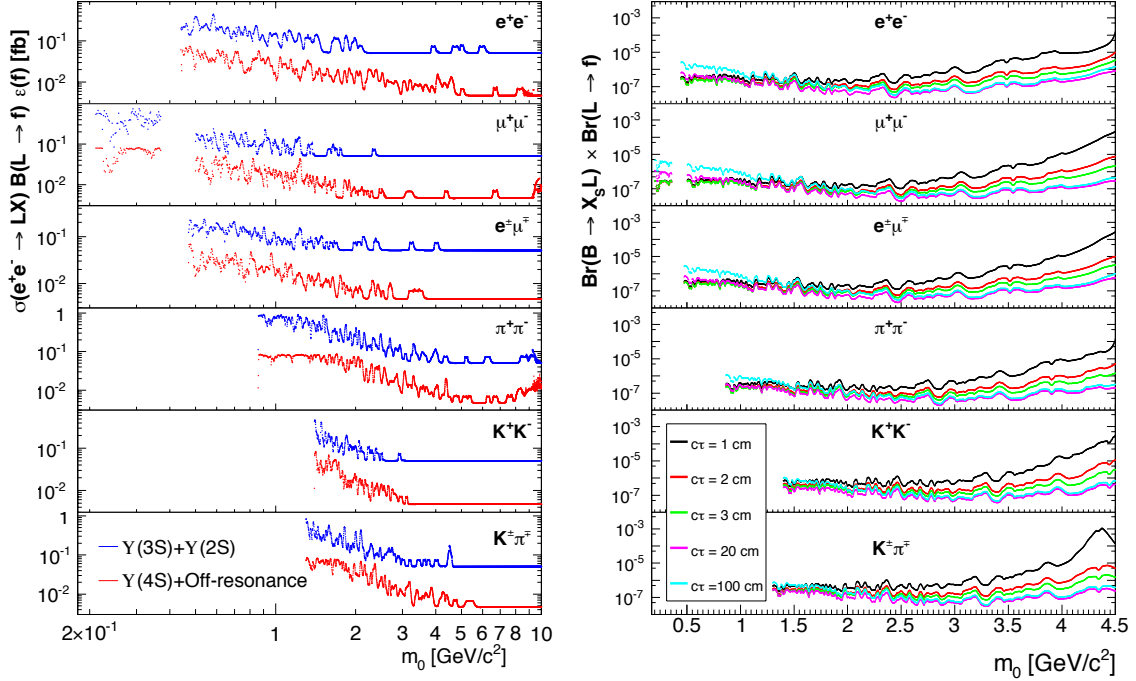


Figure 6: Results of the BABAR search for a long-lived particle L [43]. (Left) “Model-independent” limits on the product of the L production cross section, decay branching fraction into each of the 6 final states shown, and efficiency for reconstruction of that final state. These limits are intended for recasting for specific models, calculating the total efficiency using efficiency tables provided in Ref. [43]. (Right) “Model-dependent” limits in the Higgs-portal scenario of L production in penguin B decays.

BABAR has recently searched for inclusive production of a generic long-lived particle L that decays into two leptons or two charged hadrons, forming a displaced vertex [43]. Under the hypothesis that the L is fully reconstructed, the search consisted in scanning for a peak in the displaced-vertex mass spectrum. No significant signal was found, and the results were reported as two types of limits. In the “model-independent” presentation, upper limits were presented for the product $\sigma(e^+e^- \rightarrow L) \mathcal{B}(L \rightarrow f) \epsilon(f)$ of the L production cross section, the branching fraction for its decay into each final state f under study, and the reconstruction efficiency for f . Efficiency tables in terms of the L mass, its lifetime, and transverse momentum were provided, to enable recasting of the results to any model. In the “model-dependent” presentation, the efficiency was calculated for $B \rightarrow LX_S$ decays, corresponding to the top diagram in Fig. 4, where X_S is a hadronic state with strangeness. Limits on $\mathcal{B}(B \rightarrow LX_S) \mathcal{B}(L \rightarrow f)$ were then presented. The two types of limits are

shown in Fig. 6.

Another possibility for production of long-lived particles is that they are created in decays of heavy, more strongly interacting particles. An example is the model of Ref. [44], where the 125 GeV Higgs decays into two hidden-sector fermions, which decay to the lightest hidden fermion by emitting hidden-sector photons. Being the lightest hidden-sector state, the hidden photon can decay only via kinetic mixing into lepton pairs, and its lifetime is long. The resulting signature is that of displaced lepton jets.

ATLAS has searched for this signature, requiring two lepton jets that are separated by a large azimuthal angle and are well isolated from additional high-transverse-momentum particles in the event [45]. The background estimation was based on sidebands of the angle and the isolation variable. Results of this search are presented in Fig. 7 as an excluded region in the space of ϵ vs. $m_{A'}$, for given hypotheses regarding the other model parameters, such as the masses of the hidden-sector fermions. Also shown are limits from other experiments that appear in Fig. 2, as well as constraints from additional fixed-target experiments (Orsay [46], U70 [20], CHARM [47], LSND [48], E137 [18, 19, 20]) and constraints derived from the supernova cooling rate [49, 50].

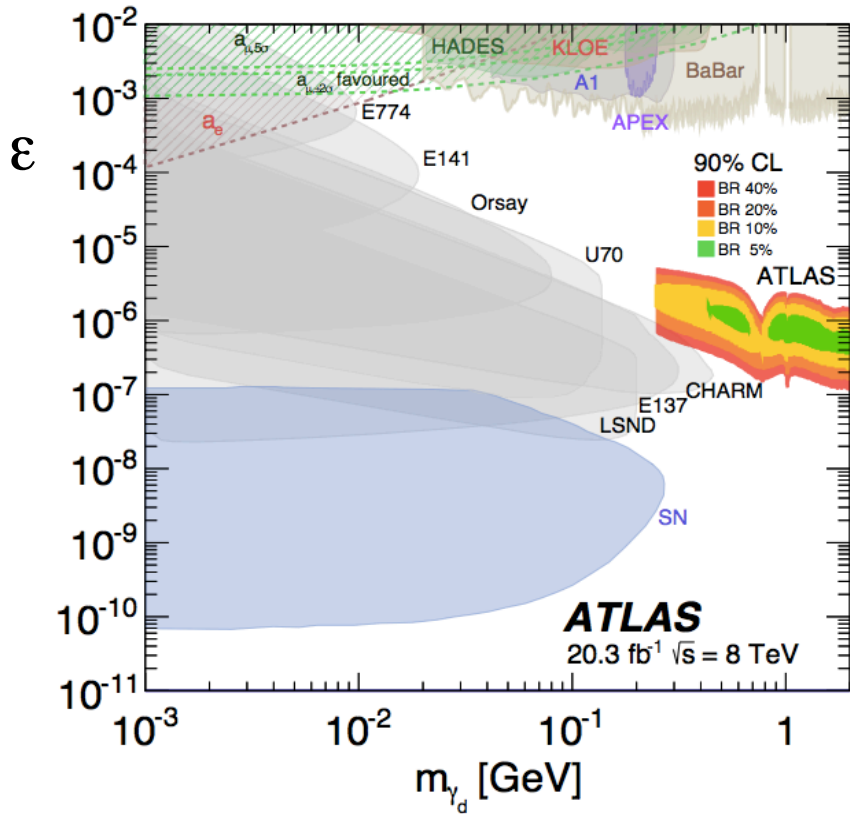


Figure 7: The ϵ vs. $m_{A'}$ parameter region excluded by ATLAS [45] within the context of the model of Ref. [44]. Also seen are constraints from other results. See text for details.

6. Search for a π^0 impostor

In 2009, BABAR found [51] that the $\gamma\gamma^* \rightarrow \pi^0$ transition form factor exceeded the expected high- Q^2 asymptotic value of $185 \text{ MeV}/Q^2$ [53, 52]. Later results from Belle [54] were consistent with both the QCD expectation and the BABAR excess. The possible discrepancy was given a new-physics explanation, in the form of a “ π^0 impostor” ϕ that couples only to τ leptons [55]. Couplings to other heavy fermions are in principle also possible, but are excluded by existing measurements. In order to explain the combined BABAR+Belle deviation from the theoretical expectation, the cross section for $e^+e^- \rightarrow \tau^+\tau^-\phi$ has to be in the 95% confidence level interval [50, 140] pb for a scalar ϕ , [2.5, 5.1] pb for a pseudoscalar, and [0.15, 0.59] pb for a “hard-core pion”, which is a pseudoscalar state that also couples to light quarks and hence mixes with the SM π^0 .

To test such a possibility, BABAR has searched for the process $e^+e^- \rightarrow \tau^+\tau^-\phi$ [56]. The $\tau^+\tau^-$ pair was identified in the final state $\mu^\pm e^\mp$ plus unobserved neutrinos, and the ϕ was reconstructed in the decay $\phi \rightarrow \gamma\gamma$. The $\gamma\gamma$ mass spectrum was fit with a polynomial background, and a signal-peak scan was performed. The results of the fit with the largest signal yield are shown in Fig. 8. The search yielded an upper limits on the cross section of $\sigma < 73 \text{ fb}$ for the pseudoscalar cases case and $\sigma < 370 \text{ fb}$ for a scalar impostor, thus ruling out the models of Ref. [55].

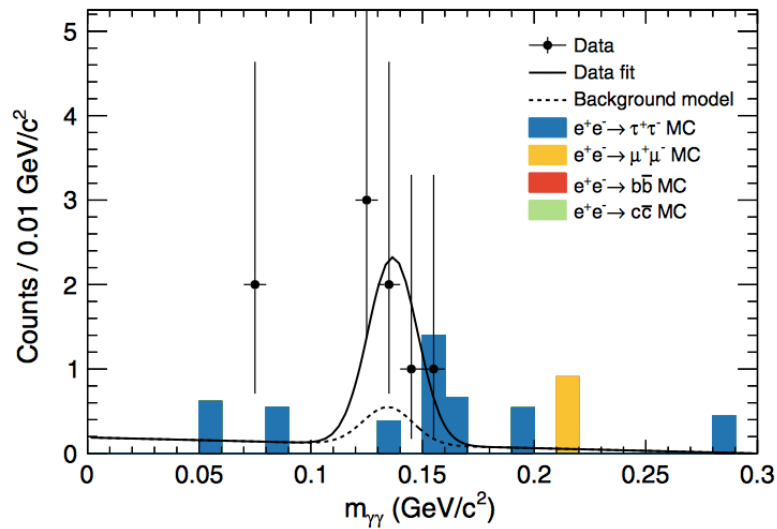


Figure 8: The $\gamma\gamma$ spectrum (data points) seen by BABAR in the search for a π^0 impostor radiated from a τ lepton [56]. The solid curve shows the best fit to signal plus background, with the dashed curve showing the total background.

7. Summary

The results covered in this talk, all published in the past year, are a testament to the interest in the physics of new GeV-scale particles. Searches for such particles take place at a variety of

facilities, including fixed-target experiments, the B factories, and LHC, providing sensitivity to a range of physics scenarios. With LHC continuing to take data and new facilities coming online in the next few years, this will continue to be an active area of research, both theoretically and experimentally.

8. acknowledgments

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