Search for Light and Dark Higgs at BaBar

On behalf of the BaBar Collaboration

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Search for Light Higgs Boson:

Search for hadronic decays of a light scalar boson in radiative transitions $\gamma \to \gamma A^0$  

Search for di-muon decays of a light CP-odd Higgs boson in radiative $\gamma(1S)$ decays

Search for Light Scalar Higgs Boson Decaying to Tau Pairs in Single-Photon Decays of $\gamma(1S)$

Search for Dark Higgs Boson:

Search for low-mass dark-sector Higgs Bosons


NEW

NEW

Search for Light Higgs Boson

- Minimal Supersymmetric Standard Model introduces 2 Higgs doublets: $h, H$ (CP-even light and heavy), $A$ (CP-odd), $H^\pm$ (charged partners).

- Next-to-Minimal Supersymmetric Standard Model introduces a Higgs singlet to dynamically generate scale of Electroweak symmetry breaking.

- Mixing can produce Light Higgs ($A^0$) = $A_{MSSM} \cos\theta_A + A_{singlet} \sin\theta_A$

- If $BR(H \rightarrow A^0 A^0)$ is large, $m_{A^0} < 2m_b$, coupling of $A^0$ to $Z$ is suppressed: this can evade all LEP limits on $ZH$ production including the ones from model independent searches for Higgs recoiling against $Z \rightarrow \ell^+ \ell^-$. 

- Large branching fraction expected for Light Higgs in $\gamma \rightarrow A^0$ decays.

Search for Light Higgs Boson

Depending on $M(A^0)$, dominant decays are

- $A^0 \rightarrow \text{hadrons}$ (*)
- $A^0 \rightarrow \tau^+ \tau^-$ (*)
- $A^0 \rightarrow \mu^+ \mu^-$ (*)
- $A^0 \rightarrow \text{invisible}$

(* In this talk)

R. Dermisek, J. Gunion

Search for Light Higgs Boson

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(* In this talk)

$A^0 \to gg$
$A^0 \to s\bar{s}$
$A^0 \to c\bar{c}$
$A^0 \to \tau^+ \tau^-$
$A^0 \to \mu^+ \mu^-$

$B(A^0 \to ff) \propto m_f^2 / \tan^2 \beta$ up-type fermions
$B(A^0 \to ff) \propto m_f^2 \tan^2 \beta$ down-type fermions

R. Dermisek, J. Gunion
Where do we stand now?

“Updated constraints from radiative $\Upsilon$ decays on a light CP-odd Higgs”, F. Domingo, JHEP 1104 (2011) 016


Much of the parameter spaces excluded, but not all...
In $\Upsilon(nS)$ rest frame, photon energy measures mass of $A^0$:

Search for monochromatic photon in the recoil mass spectrum

- $A^0 \rightarrow \mu^+\mu^-$, PRL103, 081803 (2009)
- $A^0 \rightarrow \tau^+\tau^-$, PRL103, 181801 (2009)
- $A^0 \rightarrow$ hadrons, PRL107, 221803 (2011) (this talk)

- New searches performed looking for $\Upsilon(nS) \rightarrow \pi^+\pi^-\Upsilon(1S), \Upsilon(1S) \rightarrow \gamma A^0$
- Reduce backgrounds using Missing Mass & Di-pion recoil mass

\[ M_{\text{recoil}}^2 = M_{\Upsilon(2S)}^2 + m_{\pi\pi}^2 - 2M_{\Upsilon(2S)}E_{\pi\pi}^* \]

Missing Mass:
\[ M_X^2 = \left(P_{e^+e^-} - P_{\pi\pi} - P_\gamma\right)^2 \]

- $A^0 \rightarrow \mu^+\mu^-$, NEW! this talk
- $A^0 \rightarrow \tau^+\tau^-$, NEW! this talk
- $A^0 \rightarrow$ invisible (light dark matter), PRL107, 021804 (2011)
Reconstruct everything in the event:
- Photon with 2.5 (2.2) GeV in 3S (2S) data, \( \pi^0 \) veto
- At least 2 charged tracks in \( A^0 \) candidate decay

Reject Bhabha & dimuon with PID

Beam-energy constraint improved \( m_{A^0} \) resolution

Fit \( m_{A^0} \) spectrum to sum of 3 components:
- Continuum
- Nonresonant \( \psi \) decays (spline)
- Resonant \( \psi \) decays (5–16 resonances)

Using 98.3M \( \Upsilon(2S) \) and 121.3M \( \Upsilon(3S) \) decays:
\[ B(\Upsilon(2S, 3S) \rightarrow \gamma A^0) \times B(A^0 \rightarrow \text{hadrons}) < 1 \times 10^{-6} \text{ for } m(A^0) = 0.3 \text{ GeV to } 8 \times 10^{-5} \text{ at 7 GeV} \]

$\Upsilon(1S) \rightarrow \gamma A^0, A^0 \rightarrow \mu^+ \mu^-$

Tag $\Upsilon(1S) \rightarrow \mu \nu \gamma$ using di-pions and search for a bump in reduced mass

Using 92.8 M $\Upsilon(2S)$ and 116.8 M $\Upsilon(3S)$ decays:

$B(\Upsilon(1S) \rightarrow \gamma A^0) \times B(A^0 \rightarrow \mu\mu) < (0.28 - 9.7) \times 10^{-6}$

for $0.212 \leq m_{A^0} \leq 9.20$ GeV which is 2-3 times improvement over previous best limits for $m_{A^0} \leq 1.2$ GeV

$f_Y^2 \times B(A^0 \rightarrow \mu\mu) < (0.29 - 40) \times 10^{-6}$ for $m_{A^0} \leq 9.20$ GeV

Search for Light and Dark Higgs Boson

Swagato Banerjee
Tag $Y(1S) \rightarrow \tau\tau\gamma$ using di-pions; reconstruct tau's decaying to 1-prong states [$ee, \mu\mu, e\mu, e\pi, \mu\pi +$ neutrinos] and search for a bump in spectrum of missing mass [eg. recoiling against the signal photon in $Y(1S)$ frame]

Simulated event $Y(2S) \rightarrow \pi\pi Y(1S)$, $Y(1S) \rightarrow \gamma A^0, A^0 \rightarrow \tau\tau, \tau\tau \rightarrow e+3\nu$

$m_{A^0} = 8.93$ GeV, Local significance = 3.0σ
Global significance = 1.4σ

Probability of 3.0σ or higher fluctuation is < 7.5% in scans at 201 mass points with average correlation of 94.5%
Using 98.3 M $Y(2S)$ decays,
$B(Y(1S) \to \gamma A^0) \times B(A^0 \to \tau\tau) < (0.9 - 13) \times 10^{-5}$ for $3.6 \leq m_{A^0} \leq 9.2$ GeV
$g_b^2 \times B(A^0 \to \tau\tau) < (0.09 - 1.9)$ for $m_{A^0} \leq 9.2$ GeV

Combine results with previous BaBar search, limit $A^0$ couplings over broad range of mass

$B(T(nS) \to \gamma A^0) / B(T(nS) \to l^+l^-) = g_b^2 G_F m_b^2 / \sqrt{2}\pi\alpha F_{QCD} \left(1 - \frac{m_{A^0}^2}{m_{T(nS)}^2}\right)$

Yukawa coupling of $b$-quark to $A^0$
Summary of BaBar Higgs Limits

Generally preferred by NMSSM

In NMSSM: $g_b = \tan \beta \cos \theta_A$

Courtsey: Y. Kolomensky, ICHEP12
Mysteries of the Dark Sector

- Excess of electrons / positrons
- Few / no antiprotons
- Large annihilation cross section

Gauge bosons from the dark sector could be ~ GeV, even though the dark matter particles are ~ TeV

“Dark” Gauge bosons does not decay into proton pairs if its mass is < 2 GeV

Would explain observed high energy positron excess, but no anti-protons.

Kinetic Mixing with the Dark Sector

\[ \Delta \mathcal{L}_{\text{mix}} = \varepsilon F^{\mu\nu} B_{\mu\nu} \]

- Naturalness arguments seems to favor \( \varepsilon \sim 10^{-4} - 10^{-2} \).
- Might be possible to detect at BABAR (sensitivity is around \( 10^{-3} \) or better).
Limit obtained by reinterpreting the $Y(2S,3S) \rightarrow \gamma A^0, A^0 \rightarrow \mu^+\mu^-$ measurements


Coupling of the dark photon to SM fermions is characterized by $\alpha' = \alpha \varepsilon^2$

J.D. Bjorken et al., PRD 80 (2009) 075018
Search for Dark Higgs Boson

- We can look for Higgsstrahlung $e^+e^- \rightarrow A'h' \ (h' \rightarrow A'A')$

Focus on prompt decays

- $m_h > 2m_A$

- Has the advantage of being suppressed only by $\varepsilon^2$.

- Search for $A' \rightarrow e^+e^-, \mu^+\mu^-, \pi^+\pi^-$ combinations.
Search for Dark Higgs Boson

- **Exclusive final states:**
  - 6 tracks with at least one pair of oppositely charged leptons.
  - $3A'$ candidates must contain 95% of CM energy.
  - $A'$ masses must be within 10-240 MeV/c$^2$ of each other (depending on mode and mass)

![Graph showing mass difference and signal MC](image)

Largest mass difference:

- **For $m_{A'} > 1.2$ GeV, also search for inclusive final states:**
  - $4\mu^+X$ or $2\mu 2e+X$
  - Recoil mass of the $X$ similar to di-lepton masses.


521 fb$^{-1}$ of $\Upsilon(4S)$, $\Upsilon(3S)$ and $\Upsilon(2S)$
(10% of data used for optimization)
Search for Dark Higgs Boson

- Veto's are applied to remove $\phi$ and $\omega$ from the search.
- The final event sample contains the following candidates:
  
  \[
  1 \times 4\mu 2\pi \\
  2 \times 2\mu 4\pi \\
  2 \times 2e 4\pi \\
  1 \times 4\mu X
  \]

- Largest systematic (1% – 8%) due to signal-efficiency interpolation between simulated points

90% CL Bayesian upper limit on x-section, computed with a uniform prior:
The dark photon width is proportional to $\alpha_D \epsilon^2$; so we can place limits on this combination of coupling and mixing.

$$\epsilon \quad \text{(dark sector - SM mixing strength)}$$

$$\alpha_D = \frac{g_D}{4\pi} \quad \text{(dark sector gauge coupling)}$$

Assuming $\alpha_D \sim \alpha$, limits on $\epsilon$ are $[10^{-3}, 10^{-4}]$, about 10× better than previous bounds.
Summary

Search for a light Higgs Boson in radiative transitions $\Upsilon \rightarrow \gamma A^0$ has produced limits which rules out much of allowed NMSSM space.

Search for low-mass dark-sector Higgs Bosons has made order of magnitude improvements on the bounds for SM-Dark Sector mixing.