Dark Matter searches at $\textit{BaBar}$

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(on behalf of the $\textit{BaBar}$ collaboration)

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BABAR collected $\sim 533 \text{ fb}^{-1}$ of $e^+e^-$ collisions around the $Y(4S)$ in 1999–2008.
Dark matter model with vector portal (Holdom, Galison & Manohar)

- TeV-scale dark matter $\rightarrow$ Dark Photon pair; Dark Photon $\rightarrow f^+ f^-, \gamma\gamma$, light dark matter (invisible)
  - when $m(A') < 2\,\text{GeV}$ the Dark Photon decays primarily into electrons and muons
- some models include a dark Higgs $h'$ (which gives mass to the Dark Photon)

$$\Delta L = \frac{\epsilon}{2} F_{Y,\mu\nu}^Y F'_{\mu\nu}$$

“Kinetic Mixing”
Astrophysical observations of electron and/or positron excesses may be explained by Dark Matter models including a “dark” gauge boson with mass $\sim$1 GeV, which decays to leptons

- O. Adriani et al. (PAMELA), Observation of an anomalous positron abundance in the cosmic radiation
- J. Chang et al. (ATIC), An excess of cosmic ray electrons at energies of 300-800 GeV
- A.A. Abdo et al. (Fermi LAT), Measurement of the Cosmic Ray e+ plus e- spectrum from 20 GeV to 1 TeV with the Fermi Large Area Telescope
- HESS Collab., Probing the ATIC peak in the cosmic-ray electron spectrum with H.E.S.S
Dark Photons (and dark Higgs bosons) may be detectable at B-factories

- B. Batell, M. Pospelov, A. Ritz, Probing a Secluded U(1) at B-factories, PRD 79 (2009) 115008

\[ e^+e^- \rightarrow \gamma A' \]
\[ e^+e^- \rightarrow A' A' \]
\[ e^+e^- \rightarrow A'h', \quad h' \rightarrow A'A' \]

\[ A' \rightarrow f^+f^- \]
\[ A' \rightarrow \text{invisible} \]
Search for Dark Higgs Boson and Photon in *BaBar* \[ \text{PRL 108 (2012) 2118} \]

**fully reconstructed**
- $e^+e^- \rightarrow A'h', \ h' \rightarrow A'A'$
  - $A' \rightarrow e^+e^-, \mu^+\mu^-, \pi^+\pi^-$
- reconstruct all three Dark Photons
- require at least one Dark Photon to leptons selection
- 6 tracks with $\geq 95\%$ of event energy
- particle identification
- 3 $A'$ candidates with $\Delta M_{ij} < 10 - 240$ MeV depending on final state and $M_{A'}$

**partially reconstructed**
- $e^+e^- \rightarrow A'h', \ h' \rightarrow A'A'$
  - $A'_{1,2} \rightarrow e^+e^-, \mu^+\mu^-, \ A'_3 \rightarrow q\bar{q}$
- reconstruct two Dark Photons
- third photon by subtraction from $e^+e^-$ initial state selection
- 4 or more tracks
- particle identification
- $A'$ masses must match within uncertainties
Search for Dark Higgs Boson in \textit{BABAR}, signal candidates  

- 6 signal candidates in $\sim 500 \text{ fb}^{-1}$ $Y(4S)$ sample
- 3 entries per event 
  (each possible $h' \rightarrow A'A'$ combination)
- consistent with expected background
  - mass sidebands in data
  - same-sign dileptons combinations
- most $A'$ candidates in $\rho, \omega$ mass region

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{signal_candidates.png}
\caption{Signal candidates in \textit{BABAR}}
\end{figure}
Search for Dark Higgs Boson in BABAR, upper limits  

90% CL limits on $\sigma(e^+e^- \rightarrow h'A', \ h' \rightarrow A'A')$ as function of $h'$ and $A'$ masses

- conservative approach, no BKG subtraction
- convert into limits on $\alpha_D \epsilon^2$ (next page)

$(\alpha_D = g_D^2 / 4\pi, \ g_D = \text{the dark sector gauge coupling})$
Search for Dark Higgs Boson in **BABAR**, constraints on NP models

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**BABAR**

**B. Echenard, SLAC, December 2013**

Limit on $\varepsilon^2 = \alpha'/\alpha$ assuming $\alpha_D = \alpha_{em} = 1/137$

![Graph showing limits on $\varepsilon^2 = \alpha'/\alpha$]

Substantial improvement over existing limits for $m(h') < 5–7$ GeV
BABAR light Higgs searches that can be interpreted as Dark Photon searches
Y(3S) → γA^0, A^0 → invisible [A^0 = N-MSSM CP-odd Higgs] arXiv:0808.0017 [hep-ex]

- select events with a photon and nothing else
- photon required to be at large angle to the beam to suppress e^+e^- → γγ with one photon outside acceptance
- other important backgrounds from two-photon and radiative Bhabha events
- two optimizations: for high E(γ) [→ m(A^0) = 6.0–7.8 GeV], and low E(γ) [→ m(A^0) = 0–6 GeV]
- search for peak in missing mass distribution

**simulated A^0 signal**

**recoil mass yield for low E(γ) selection**
$\Upsilon(3S) \rightarrow \gamma A^0, \ A^0 \rightarrow \text{invisible}$  

arXiv:0808.0017 [hep-ex]

90% CL upper limits on 
$B(\Upsilon(3S) \rightarrow \gamma A^0) \times B(A^0 \rightarrow \text{invisible})$ 
$< (0.7 - 31) \times 10^{-6}$ for $m_{A^0} \leq 7.8$ GeV

**Dark Photon constraints by R.Essig et al.**


Hidden Photon $\rightarrow$ invisible ($m_{A'} > 2 m_{\chi}$)
Y(2S) \rightarrow \pi^+\pi^- Y(1S), \quad Y(1S) \rightarrow \gamma A^0, \quad A^0 \rightarrow \text{invisible} \quad \text{PRL 107 021804 (2011)}

90\% \text{ CL upper limits on } B(Y(1S) \rightarrow \gamma A^0) \times B(A^0 \rightarrow \text{invisible})
\leq (1.9 - 4.5) \times 10^{-6} \text{ for } m_{A^0} \leq 8.0 \text{ GeV}
\leq (2.7 - 37) \times 10^{-6} \text{ for } m_{A^0} \leq 9.2 \text{ GeV}
use 99·10^6 Y(2S) and 122·10^6 Y(3S) events
require γ, μ^+μ^- candidates with event energy
search peak in μ^+μ^- invariant mass
no evidence of a peak over exp. background
limits on B(Y(nS) → γA^0) · B(A^0 → μ^+μ^-)
limits on effective coupling f_Y^2 · B(A^0 → μ^+μ^-)

\[
\frac{Y(nS) \rightarrow γA^0}{Y(nS) \rightarrow ℓ^+ℓ^-} = \frac{f_Y^2}{2πα} \left(1 - \frac{m_{A^0}}{m_Y(nS)}\right)
\]
to combine Y(2S) and Y(3S) results

A^0 candidates reduced mass, \( m_R = \sqrt{m_{A^0}^2 - 4m_μ^2} \)
Dark Photon constraints, computed by R. Essig et al., arXiv:1311.0029 [hep-ph]
Search for $e^+e^- \rightarrow Y(2S, 3S) \rightarrow \pi^+\pi^- Y(1S), \ Y(1S) \rightarrow \gamma A^0, \ A^0 \rightarrow \mu^+\mu^-$

2–3 times better than previous 2009 analysis for $m_{A^0} \leq 1.2 \text{ GeV}/c^2$

90% CL upper limits on $f_Y^2 \cdot B(A^0 \rightarrow \mu^+\mu^-)$

Both analyses combined

PRD 87, 031102(R) (2013), arXiv:1210.0287
Other $\textit{BaBar}$ searches that could be re-interpreted as dark photon searches

- $Y(3S) \rightarrow \pi^+\pi^- Y(1S)$, $Y(1S) \rightarrow \text{invisible}$, Phys.Rev.Lett.103:251801,2009, arXiv:0908.2840 [hep-ex]
- $Y(3S) \rightarrow \gamma A^0$, $A^0 \rightarrow \tau^+\tau^-$, Phys.Rev.Lett.103:181801,2009, arXiv:0906.2219 [hep-ex]
- $Y(3S) \rightarrow \pi^+\pi^- Y(1S)$, $Y(1S) \rightarrow \gamma A^0$, $A^0 \rightarrow \tau^+\tau^-$, PRD 88, 071102 (2013), arXiv:1210.5669 [hep-ex]
- $Y(2S,3S) \rightarrow \gamma A^0$, $A^0 \rightarrow \text{hadrons}$, Phys. Rev. Lett. 107, 221803 (2011), arXiv:1108.3549 [hep-ex]
- $Y(2S) \rightarrow \pi^+\pi^- Y(1S)$, $Y(1S) \rightarrow \gamma A^0$, $A^0 \rightarrow s\bar{s}, gg$, PRD 88, 031701(R) (2013), arXiv:1307.5306 [hep-ex]

(presented by E.Guido in Moriond EW 2014)

Other $\textit{BaBar}$ searches in progress

- $A' \rightarrow e^+e^-, \mu^+\mu^-, \gamma\gamma$
- $A^0 \rightarrow c\bar{c}, \gamma\gamma$
Conclusions

♦ *BABAR* searched for light **Dark Higgs** and **Dark photon**, setting constraints on their mass and couplings
♦ searches for light N-MSSM CP-odd Higgs used to constraint light Dark Photon mass and couplings
♦ additional light Higgs *BABAR* searches could be translated into Dark Photon limits
♦ *BABAR* is completing several additional analyses optimized for Dark Photon discovery
♦ low energy $e^+e^-$ colliders are effective in searching for “dark-sector” gauge and Higgs bosons
♦ super flavour factories will be able to further probe the proposed “dark sector” models