Searches for a Low-Mass Higgs in Upsilon Decays in \textbf{\textit{Babar}}

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\begin{figure}
\centering
\includegraphics[width=\textwidth]{graph.png}
\end{figure}
Motivation

- NMSSM models with light CP-odd Higgs
  - Solve fine-tuning problems in MSSM
  - CP-odd Higgs, $A^0$, below $2m_b$ is not constrained by LEP
    - Large BR for $\Upsilon\gamma A^0$ possible

- Dark matter axion portal
  - Nomura, Thaler, arXiv:0810.5397
    - Predict $\text{BR}(\Upsilon\gamma A) \sim 10^{-6} - 10^{-5}$ with $m_A \sim 400-800$ MeV

- Also interesting to look in $\eta_b$ region
  - Leptonic BR is expected to be small if $\eta_b$ is a meson

J.Gunion et al

Non-singlet fraction ($\cos\theta_A$)

$\text{BR}(\Upsilon\gamma A^0)$

$\begin{align*}
m_{A^0} &< 2m_\tau \\
2m_\tau &< m_{A^0} < 7.5 \text{ GeV} \\
7.5 \text{ GeV} &< m_{A^0} < 8.8 \text{ GeV} \\
8.8 \text{ GeV} &< m_{A^0} < 9.2 \text{ GeV}
\end{align*}$

PRD76, 051105 (2007)
Experimental Constraints

HyperCP anomaly

Resonance-like structure in $\Sigma \rightarrow p\mu^+\mu^-$ near threshold ($m_{\mu\mu} = 214$ MeV)
Small width ($\Gamma < 1$ MeV)
If light CP-odd Higgs, could be produced in $Y \rightarrow \gamma X(214)$.

CLEO limits on $Y(1S) \rightarrow \gamma A^0$

H. Park et al., PRL 94, 021801 (2005)

W. Love et al., PRL 101, 151802 (2008)
BaBar 2008 Dataset


Dedicated run on Y(3S) and Y(2S), cross section scan above Y(4S)

122M Y(3S) decays

99M Y(2S) decays
Searches for a Light Higgs in BaBar

Well-understood initial state (narrow $\Upsilon(2S)$ or $\Upsilon(3S)$ resonance)
Fully or partially reconstructed final state, depending on the decay pattern of $A^0$

This talk:
- $A^0 \rightarrow \mu^+\mu^-$
- $A^0 \rightarrow \tau^+\tau^-$
- $A^0 \rightarrow$ invisible (light dark matter)

Key experimental signature:
monochromatic photon in CMS
Y(2S,3S)→γA^0, A^0→μ^+μ^−

- Fully-reconstructed final state: 2 charged tracks, 1 photon
  - 1 or 2 muons identified
  - E^*γ > 0.2 GeV
  - Loose kinematic selection requires consistency with CMS energy and momentum

Backgrounds dominated by (irreducible) e^+e^−→γμ^+μ^− and two-body decays of ISR-produced of φ(1020), ρ(770), J/ψ, Y(1S)
Identify A^0 decays by a narrow peak in μ^+μ^− invariant mass (resolution 2-10 MeV)
Strategy for $A^0 \rightarrow \mu^+ \mu^-$

- Signal extraction: ML fit in slices of invariant mass
  - 1955 distinct slices from $0.212 \leq m_{A^0} \leq 9.3$ GeV, in 2-5 MeV steps
  - Fit to “reduced mass” $m_R = \sqrt{m^2_{A^0} - 4m^2_{\mu}} = 2|p^A_{\mu}|$
  - Smooth threshold behavior, slightly shifted from $m_{A^0}$

Signal PDF

Background PDF
Results: $Y(2S,3S)\rightarrow \gamma A^0, A^0 \rightarrow \mu^+\mu^-$

Expect standard normal distribution for 1955 scan points under null hypothesis
Observe no significant outliers.
**Upper Limits:** $Y(2S,3S) \rightarrow \gamma A^0, A^0 \rightarrow \mu^+ \mu^-$

Significant constraints on theoretical models
Rule out Higgs interpretation of HyperCP events
Also limit
$$\mathcal{B}(\eta_b \rightarrow \mu^+ \mu^-) < 0.9\%$$
at 90% C.L.

Combined results for effective Yukawa coupling $f_Y$

$$\frac{\mathcal{B}(Y(nS) \rightarrow \gamma A^0)}{\mathcal{B}(Y(nS) \rightarrow l^+ l^-)} = \frac{f_Y^2}{2\pi\alpha} \left(1 - \frac{m_{A^0}^2}{m_Y(nS)}\right)$$

For $m_{A^0} < 1$ GeV, this corresponds to $f_Y < 0.12 f_{SM}$

arXiv:0905.4539
Results at Low Mass: $A^0 \rightarrow \mu^+ \mu^-$

Range predicted by Axion model (Nomura, Thaler)

J/ψ region excluded
Y(3S) \rightarrow \gamma A^{0}, \ A^{0} \rightarrow \tau^{+}\tau^{-}

• Expect tau decays of $A^{0}$ to be dominant above the tau threshold

• Strategy:
  - Reconstruct leptonic decays $\tau \rightarrow (e, \mu)\nu\nu$
  - 3 final states: $ee$, $\mu\mu$, $e\mu$
  - Select events with exactly 2 identified leptons, 1 energetic photon, and large missing energy and mass consistent with tau decays
  - 10-26% efficiency depending on $E_\gamma$ and final state
  - Look for $A^{0}$ decays as a narrow peak in the photon energy spectrum above $E^*_\gamma > 0.2$ GeV
\[ Y(3S) \rightarrow \gamma A^0, \ A^0 \rightarrow \tau^+\tau^- \] Spectrum

Selection optimized in five large energy regions.

Background dominated by irreducible \( e^+e^- \rightarrow \tau^+\tau^- \)

Describe background by a smooth distribution, include peaking contributions for \( \chi_b(2P) \rightarrow \gamma Y(1S,2S) \)

Signal distribution: Crystal Ball PDF with low-energy tail, resolution 10-55 MeV grows with \( E_\gamma \)
Y(3S) → γA⁰, A⁰ → τ⁺τ⁻ Background

Two (of five) representative fits
Y(3S) → γA⁰, A⁰ → τ⁺τ⁻ Results

- No significant peaks
- Significant constraints on NMSSM parameter space
- Also set a limit
  - \( \mathcal{B}(\eta_b \rightarrow \tau^+\tau^-) < 8\% \)
  - at 90% C.L.

\[ \chi_b \text{ region excluded} \]
Invisible Decays of $A^0$

Search for events with single energetic photon above $E_\gamma > 2.2$ GeV and large missing energy

Search for $A^0$ signal as a peak in $E_\gamma$ spectrum

No significant signal; limits on BR constrain NMSSM parameter space

arXiv:0808.0017
Conclusions

• No signal of a light scalar particle (e.g. CP-odd Higgs) in radiative decays of Y(2S) and Y(3S) in $\mu^+\mu^-$, $\tau^+\tau^-$, or invisible final states

  - Set upper limits that rule out much of available parameter space; most stringent constraints to date
    ✅ Rule out CP-odd Higgs interpretation of HyperCP anomaly
  - Also set a limit on dimuon and $\tau^+\tau^-$ BF of $\eta_b$
    \[
    \begin{align*}
    \mathcal{B}(\eta_b \rightarrow \mu^+\mu^-) &< 0.9\% \\
    \mathcal{B}(\eta_b \rightarrow \tau^+\tau^-) &< 8\%
    \end{align*}
    \]  @ 90 C.L.
    ✅ Consistent with mesonic interpretation
    ✅ First ever measurements of the exclusive $\eta_b$ decays

• Publications

  ✅ arXiv:0905.4539 ($A^0 \rightarrow \mu^+\mu^-$), submitted to PRL
  ✅ Preliminary ($A^0 \rightarrow \tau^+\tau^-$), to be submitted to PRL
  ✅ arXiv:0808.0017 ($A^0 \rightarrow \text{invisible}$), preliminary
NMSSM Predictions for $Y \rightarrow \gamma A^0$
vs BaBar Limits

$A^0 \rightarrow \mu^+\mu^-$

$A^0 \rightarrow \tau^+\tau^-$

$A^0 \rightarrow \text{invisible}$

$\text{m}_{A^0} < 2m_\tau$

$2m_\tau < m_{A^0} < 7.5 \text{ GeV}$

$7.5 \text{ GeV} < m_{A^0} < 8.8 \text{ GeV}$

$8.8 \text{ GeV} < m_{A^0} < 9.2 \text{ GeV}$
Backup
$A^0 \rightarrow \mu^+ \mu^-$ Mass Spectrum

Entries / 10 MeV

One muon identified
Both muons identified

Y(3S) data

$m_R$ (GeV)
$A^0 \rightarrow \mu^+ \mu^-$: Yukawa Coupling

$0.212 \leq m(A^0) < 1.05$ GeV

$1.05 \leq m(A^0) < 4$ GeV

$4 \leq m(A^0) \leq 9.3$ GeV

90% CL UL on Yukawa coupling $f_Y^2 \times B_{\mu \mu}$
$\eta_b \to \mu^+ \mu^-$ Results

$\chi^2$/df = 25.3/25

$\chi^2$/df = 50.7/35

$\mathcal{B}(\Upsilon(2S) \to \gamma \eta_b) \times \mathcal{B}(\eta_b \to \mu^+ \mu^-) = (-0.4 \pm 3.9 \pm 1.4) \times 10^{-6}$

$\mathcal{B}(\Upsilon(3S) \to \gamma \eta_b) \times \mathcal{B}(\eta_b \to \mu^+ \mu^-) = (-1.5 \pm 2.9 \pm 1.6) \times 10^{-6}$

$\mathcal{B}(\eta_b \to \mu^+ \mu^-) = (-0.10 \pm 0.93 \pm 0.33)\% \ (\Upsilon(2S) \text{ dataset})$

$\mathcal{B}(\eta_b \to \mu^+ \mu^-) = (-0.31 \pm 0.61 \pm 0.32)\% \ (\Upsilon(3S) \text{ dataset})$

$\mathcal{B}(\eta_b \to \mu^+ \mu^-) = (-0.25 \pm 0.51 \pm 0.33)\% \ (\text{average})$

90% CL Upper Limit: $\mathcal{B}(\eta_b \to \mu^+ \mu^-) < 0.9\%$
$A^0 \rightarrow \mu^+\mu^-$ HyperCP Point

No significant peak at $m(A^0) = 0.214$ GeV
Set a stringent upper limit:

$$f_T^2(m_{A^0} = 0.214 \text{ GeV}) < 1.6 \times 10^{-6} \text{ at 90\% C.L}$$
Significance Calculation

• Need to take into account the “number of samples”
  
  Generally, \( P_{N_{\text{sample}}} (\chi^2) \approx N_{\text{sample}} P_1 (\chi^2) \)

• Need to determine the number of independent samples
  
  Look at correlation between adjacent scan points

\[ \chi^2 / \text{ndf} = 21.32 / 6 \]
\[ \mu_0 = 0.8785 \pm 0.01094 \]
Generate $10^8$ toy experiments with 1966 bins:
normal distribution for each bin, adjacent bins correlated by 88%
Typical trial factor $\sim 1500$
Event Selection for $A^0 \rightarrow \text{invisible}$

- Require a single photon with $E^*_\gamma > 2.2$ GeV
- No charged tracks
- No additional energy in EMC above 100 MeV
- Missing momentum points to EMC
- No activity in IFR aligning with missing momentum
- Selection efficiency: 10-11% ($E^*_\gamma > 3$ GeV), ~20% ($E^*_\gamma < 3$ GeV)

 Dominant background from $e^+e^- \rightarrow \gamma\gamma$, with one of the photons missing the EM calorimeter. Veto such events by detecting activity in the muon detector (IFR).