Results on Recent Analyses from \textit{BaBar}

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- Search for a dark photon in  
  \[ e^+e^- \rightarrow \gamma A', \quad A' \rightarrow e^+e^-, \mu^+\mu^- \]

- Search for Long-Lived Particles

- Search for a light Higgs resonance  
  \[ \Upsilon(1S) \rightarrow \gamma A^0, \quad A^0 \rightarrow c\bar{c} \]

- Search for CP Violation in  
  \[ \bar{B}^0 \rightarrow D_{CP}^{(*)}h^0 \] decays
Data taking period: 1999-2008

\( \Upsilon(4S) : 424 \text{ fb}^{-1} \)
\( \Upsilon(3S) : 28 \text{ fb}^{-1} \)
\( \Upsilon(2S) : 14 \text{ fb}^{-1} \)

corresponding to: \( 471 \times 10^6 B\bar{B} \)

between the \( b\bar{b} \) resonances: \( 48 \text{ fb}^{-1} \)

\[ E(e^+e^-) = \sqrt{s} \sim 10.58 \text{ GeV} = m(\Upsilon(4S)) \sim 2 \cdot m(B) \]

\[ m_{ES} = \frac{1}{c^2} \sqrt{s/4 - p^2(B) \cdot c^2} \]
Search for a dark photon in

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Phys. Rev. Lett. 113, 201801 (06/2014)
Motivation

• Dark matter particles don’t interact much with Standard Model (SM) particles

• Possibility: new $U(1)'$ with corresponding dark photon $A'$
  
  – Could couple to the SM hypercharge via kinetic mixing
  
  – Mixing strength: $\epsilon$
  
  – Effective interaction between dark photon and electromagnetic current: $\epsilon e A'_\mu J^{\mu}_{EM}$
  
  – These dark photons would mediate annihilation of dark matter particles into SM fermions

• If such $A'$ is the reason for observed anomalies in cosmic rays, the mass of $A'$ should be in the range of MeV/$c^2$ to about 2 GeV/$c^2$
  
  (Positron excess and lack of antiprotons)

  We can probe $0.02 \text{ GeV}/c^2 < m_{A'} < 10 \text{ GeV}/c^2$
Selection Criteria

- Events with 2 oppositely charged tracks and a single photon are selected
- Particle ID requirements for the charged tracks
- Fitted with a beam-energy constraint and charged tracks coming from a common vertex
- Neural network used to suppress $e^+ e^- \rightarrow \gamma e^+ e^-$ SM interactions
- Resonant regions in $m_{ll}$ are excluded in the search
  $(\omega, \phi, J/\psi, \psi(2S), \Upsilon(1S), \text{and } \Upsilon(2S))$
Signal Extraction

- $m_{e^+e^-}$ and reduced muon mass $m_R = \sqrt{m_{\mu\mu}^2 - 4m_{\mu}^2}$ are divided in intervals
  - Interval width: $20\sigma$ to $30\sigma$ of the expected signal resolution in $m(A')$
    - signal resolution between 1.5 MeV/$c^2$ and 8 MeV/$c^2$

- Fit performed in each interval

- Data taken at different beam energies are fitted separately and results combined

- All of BABAR data is used
Results

Grey bands show excluded mass regions due to resonances

\[ S_S = +/ - \sqrt{2 \log(L/L_0)} \]

Can be translated to the mixing strength as a function of \( m_{A'} \)...
Results

- BABAR 2009 based on search for light CP-odd Higgs boson using only a subsample of data used in this analysis

- Range of the parameter space motivated by interpretation of the discrepancy between measured and calculated \((g - 2)_\mu\) mostly excluded

- Only 15 MeV/c^2 \(\lesssim m_{A'} \lesssim 30\) MeV/c^2 remains
• *BABAR* 2009 based on search for light CP-odd Higgs boson using only a subsample of data used in this analysis

• Range of the parameter space motivated by interpretation of the discrepancy between measured and calculated $(g - 2)_{\mu}$ completely excluded
Search for Long-Lived Particles

Phys. Rev. Lett. 114, 171801 (02/2015)
Motivation

• Same astrophysical anomalous observations that inspired dark photon search generated general interest in GeV-scale hidden-sector

• Searches for Long-Lived particles have been performed in the sub-GeV and multi-GeV mass range by other experiments

• Dedicated experiments to search for Long-Lived particles have been proposed or under construction

• $O(1 \text{ GeV}/c^2)$ mass range remains mostly unexplored
  – Belle search for a heavy neutralino is only $B$-factory result on such searches
  – But $B$-factories are ideal laboratory to probe the $O(1 \text{ GeV}/c^2)$ mass range

• BABAR search: $L \rightarrow f$, with $f = e^+e^-, \mu^+\mu^-, e^\pm\mu^\mp, \pi^+\pi^-, K^+K^-$, or $K^\pm\pi^\mp$
  – Model independent search: $0.5 \text{ GeV}/c^2 \leq m(L) \leq 9.5 \text{ GeV}/c^2$
  – Model dependent search: $0.5 \text{ GeV}/c^2 \leq m(L) \leq 4.5 \text{ GeV}/c^2$
  – All available BABAR data is used
Overview

• Model independent approach
  – Signal MC is produced at 11 different masses $m(L)$
  – Simulated process for $m(L) \leq 4 \text{ GeV}/c^2$: $e^+e^- \to B\bar{B}$, $B \to L + N\pi$
  – Simulated process for $m(L) > 4 \text{ GeV}/c^2$: $\Upsilon(4S) \to L + N\pi$
  – $N = 1, 2, \text{ or } 3$
  – $L$ is produced uniformly throughout available phase space

• Model dependent approach
  – Simulated process: $B \to X_sL$ with $X_s = K, K^*(892)$, or $K^*(1680)$

• PID for charged tracks used and have to form common vertex

• Candidates rejected if vertex is within beam pipe material, support tube, or DCH wall

• Criteria on distance to $e^+e^-$ interaction point

• Mass regions excluded to account for false signal from $K_S^0$, $\Lambda$, and low mass regions where the mass distribution of background MC events is not smooth
Signal Extraction

Signal yield extracted for each final state as function of $m(L)$ using unbinned maximum likelihood fits where $m(L)$ is varied in 2 MeV/$c^2$ steps and the whole mass range is always fitted
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Search for a Light Higgs Resonance in

\( \Upsilon(1S) \rightarrow \gamma A^0, \ A^0 \rightarrow c\bar{c} \)

Phys. Rev. D 91, 071102 (02/2015)
Motivation

- New Physics models predict a rich Higgs sector

- Higgs boson discovered at CERN consistent with SM Higgs, but could also one of the heavier Higgs bosons in such theories

- The lightest Higgs boson in such models ($A^0$) could be produced in an $\Upsilon$ decay

- $\textit{BABAR}$ already ruled out much of the parameter space for $A^0$ masses below the $c\bar{c}$ threshold

- Above the $c\bar{c}$ threshold some part of the parameter space has been ruled out by $\textit{BABAR}$ in $A^0 \rightarrow \tau^+\tau^-$ searches
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One of the last channels that has not been explored so far: $A^0 \rightarrow c\bar{c}$

$BABAR$ can probe $A^0$ masses between 4.00 GeV/$c^2$ and 9.25 GeV/$c^2$
Overview

- $\Upsilon(2S) \rightarrow \pi^+ \pi^- \Upsilon(1S), \quad \Upsilon(1S) \rightarrow \gamma A^0, \quad A^0 \rightarrow c\bar{c}$
  - Select events with a dipion candidate and a photon
  - Mass of the system recoiling against the dipion, $m_R$, must be consistent with a $\Upsilon(1S)$
  - Event must contain at least one $D(^*)$ candidate
  - $A^0$ candidate mass is determined from the mass of the system recoiling against the dipion and photon, $m_x$

- BDT used to separate signal from background candidates
  - 10 different BDT classifiers
  - 24 variables as BDT input
Signal Extraction

- $A^0$ should be visible as a peak in the $m_x$ distribution
- Fits on $m_x$ spectrum performed for different $m(A^0)$ hypothesis
  - $m(A^0)$ changed in 10 MeV/$c^2$ or 2 MeV/$c^2$ steps depending on the mass region
  - This is at least 3 times smaller than the width of the signal PDF
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Search for CP Violation in

\[ \mathcal{B}^0 \rightarrow D^{(*)}_{CP} h^0 \]

by combining the \textit{BABAR} and Belle datasets

\textit{arXiv:1505.04147}
(accepted for publication in PRL, 07/2015)
Motivation

• Only tree-level amplitudes contribute to $\overline{B}^0 \to D_{CP}^{(*)} h^0$ with $h^0 = \pi^0, \eta, \omega$

• Theoretically clean and can be compared with measurement from $b \to c\bar{c}s$

• Branching fractions for $B$ and $D_{CP}$ are low

• Reconstruction efficiencies are low, too
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New approach: Combine $\textit{BABAR}$ and Belle data!
Overview

- BABAR and Belle $\Upsilon(4S)$ data combined: $1.24 \times 10^9 B\bar{B}$!

$\left(\text{BABAR: } (471 \pm 3) \times 10^6 B\bar{B}, \; \text{Belle: } (772 \pm 11) \times 10^6 B\bar{B}\right)$

- Data is analyzed together with almost the same selection criteria applied

- One $B$ flavor needs to be tagged for the time dependent analysis

- BABAR and Belle specific flavor tagging algorithms and resolution models are used

- Common signal model is used

$$P_{\text{sig}}(\Delta t, q) = \frac{1}{4\tau_{B0}} e^{-|\Delta t|/\tau_{B0}} \left[ 1 + q(S \sin(\Delta m \Delta t) - C \cos(\Delta m \Delta t)) \right]$$

- SM predictions: $C = 0, -\eta_f S = \sin(2\beta)$

- Combination is done at the Likelihood level

$$\ln L = \sum_i P_i^{\text{BABAR}} + \sum_i P_i^{\text{Belle}}$$
Reconstruction and Signal Extraction

- $\bar{B}^0 \rightarrow D^{(*)}_{CP} h^0$ with $h^0 = \pi^0, \eta, \text{ or } \omega$, reconstructed in 12 final states (7 CP-even, 5 CP-odd final states)
  - $D^* \rightarrow D_{CP} \pi^0$
  - $D_{CP} \rightarrow K^+ K^-, K_S^0 \pi^0, K_S^0 \omega$
  - $\pi^0 \rightarrow \gamma \gamma, \eta \rightarrow \gamma \gamma, \pi^+ \pi^- \pi^0, \omega \rightarrow \pi^+ \pi^- \pi^0$

- Continuum background $e^+ e^- \rightarrow q\bar{q}$ suppressed by Neural Networks

- Signal extracted from $m_{ES} = M_{bc} = \sqrt{(\sqrt{s}/2)^2 - (p_B^*)^2}$ by unbinned maximum Likelihood fits

\[\begin{align*}
  \text{(a) BABAR} & \\
  \text{(b) Belle} & 
\end{align*}\]
Results

different cross-checks have been performed:

- splitting data by experiment
- splitting data by decay mode
- use $D^0 \rightarrow K^+\pi^-$ as null control sample
- measure $\tau_{B^0}$
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$C = -0.02 \pm 0.07 \pm 0.03$

$-\eta_f S = 0.66 \pm 0.10 \pm 0.06$

good agreement with $\sin(2\beta)$ from $b \rightarrow c\bar{c} s$

$(\sin(2\beta) = 0.69 \pm 0.02)$

no evidence for direct CP violation

no mixing-induced CP violation excluded at 5.4σ

First observation of CP violation in $\bar{B}^0 \rightarrow D_{CP}^{(*)}h^0!$
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First observation of CP violation

in $\bar{B}^0 \rightarrow D_{CP}^{(*)}h^0$!

First measurement performed on more than $1 \text{ab}^{-1}$ collected at the $\Upsilon(4S)$!
Summary

- Searches for physics beyond the SM
- Significant limits in dark-forces and light-Higgs searches
- First observation of CP violation in $B^0 \rightarrow D_{CP}^{(*)} h^0$
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  – Only possible by combining B\(\)ABAR and Belle data
  
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Many years after data-taking, $BABAR$ still has a rich physics program producing first-class results.

(≈220 papers published since data taking stopped, 12 papers in 2015 so far published/submitted)
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Many more analyses are in the pipeline, some also in collaboration with Belle.
Other \textbf{BABAR} Presentations

• Studies of Charmonium Production in e+e- Annihilation and B decays at \textbf{BABAR} 
  by Isabella Garzia, Monday 2:30pm

• The Time-like Electromagnetic Form Factors of Proton and Charged Kaon at high energies 
  by Fabio Anulli, Monday 4:35pm

• XYZ States: Experimental Overview, by Valentina Santoro, Tuesday 8:30am

• Low Energy Hadronic Cross Section Measurements at \textbf{BABAR} and Implications for the g-2 of 
  the Muon, by Evgeny Solodov, Tuesday 4:15pm

• Charmonium decays in \textbf{BABAR}, by Antimo Palano, Thursday 8:30am

• Measurement of the Collins Asymmetries with the \textbf{BABAR} Detector 
  by David Norvil Brown, Thursday 11:05am
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Thank you for your attention!