Results on Recent Analyses from *BABAR*

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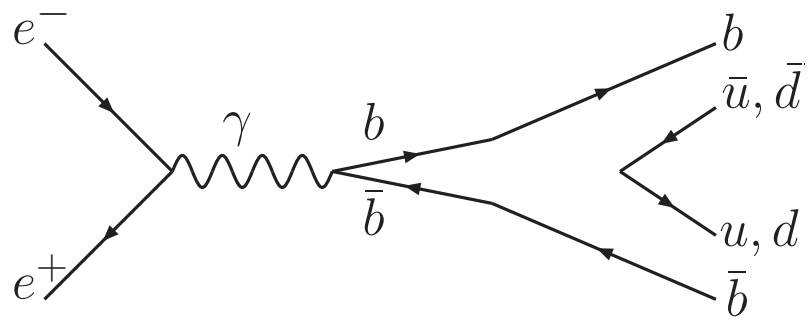
- Search for a dark photon in
  $e^+e^- \to \gamma A', \quad A' \to e^+e^-, \mu^+\mu^-$

- Search for Long-Lived Particles

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

- Search for CP Violation in
  $\overline{B}^0 \to D^{(*)}_{CP} h^0$ decays

BABAR Data Set



$$e^+e^- \to b\bar{b} = \Upsilon(4S) \to B\overline{B}$$

Data taking period: 1999-2008

$\Upsilon(4S)$: 424 fb^{-1}

$\Upsilon(3S)$: 28 fb^{-1}

$\Upsilon(2S)$: 14 fb^{-1}

corresponding to: $471 \times 10^6 B\overline{B}$

between the $b\bar{b}$ resonances: 48 fb^{-1}

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

$$m_{\text{ES}} = \frac{1}{c^2}\sqrt{s/4 - p^{*2}(B) \cdot c^2}$$

Search for a dark photon in

$$e^+e^- \to \gamma A', \quad A' \to e^+e^-, \mu^+\mu^-$$

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: ϵ
  - 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 $e^+e^- \to \gamma e^+e^-$ SM interactions
- Resonant regions in m_{ll} are excluded in the search
  (ω, ϕ, J/ψ, $\psi(2S)$, $\Upsilon(1S)$, and $\Upsilon(2S)$)

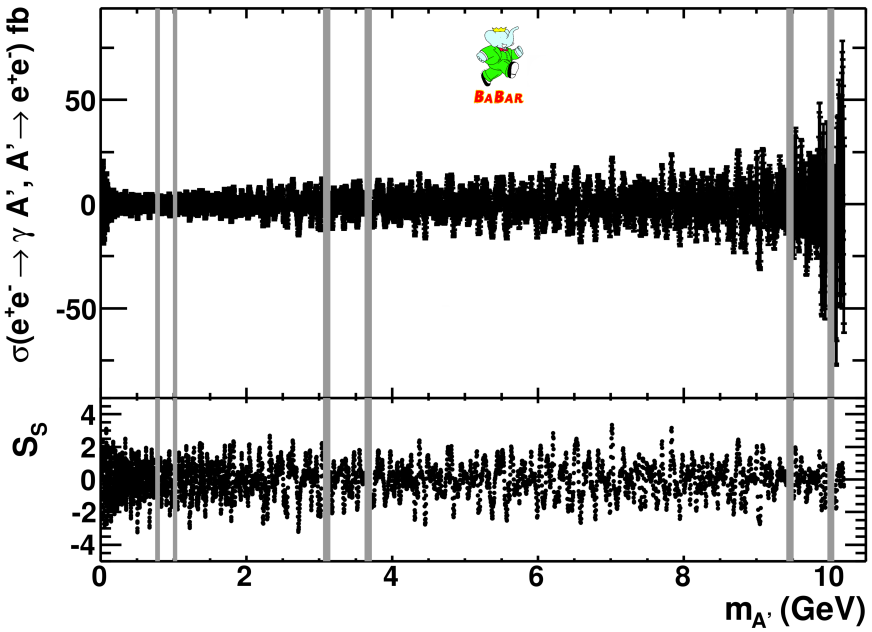
Signal Extraction

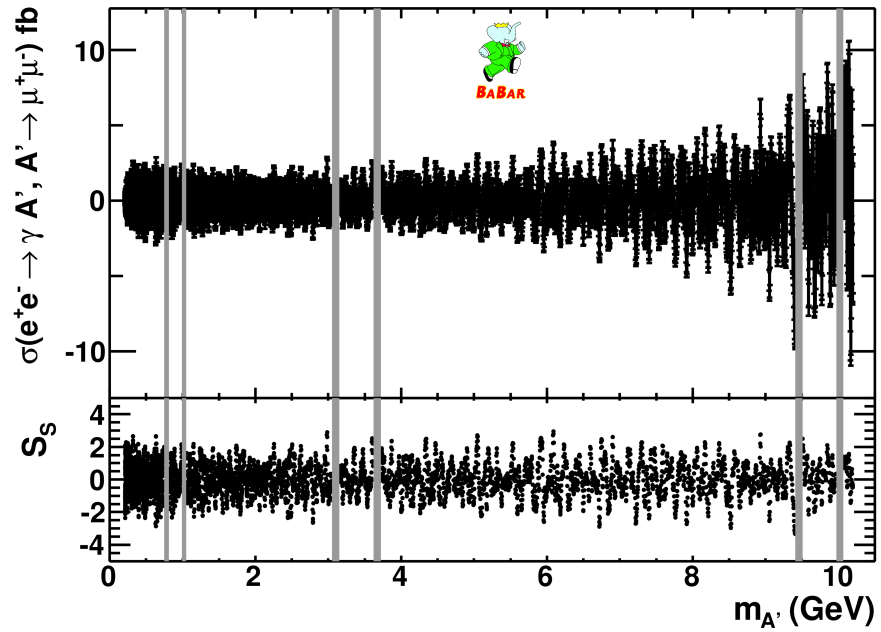
- $m_{e^+e^-}$ and reduced muon mass $m_R = \sqrt{m_{\mu\mu}^2 - 4m_\mu^2}$ are divided in intervals
  - Interval width: 20σ to 30σ of the expected signal resolution in $m(A')$
    signal resolution between 1.5 MeV/c^2 and 8 MeV/c^2
- Fit performed in each interval
- Data taken at different beam energies are fitted separately and results combined
- All of *BABAR* data is used

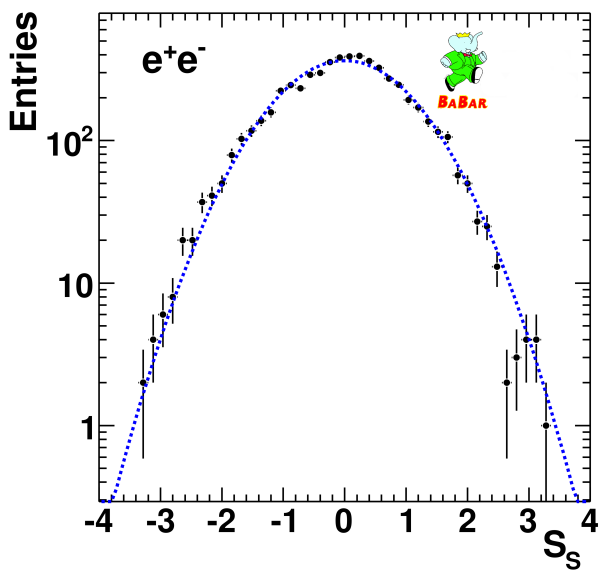
Results

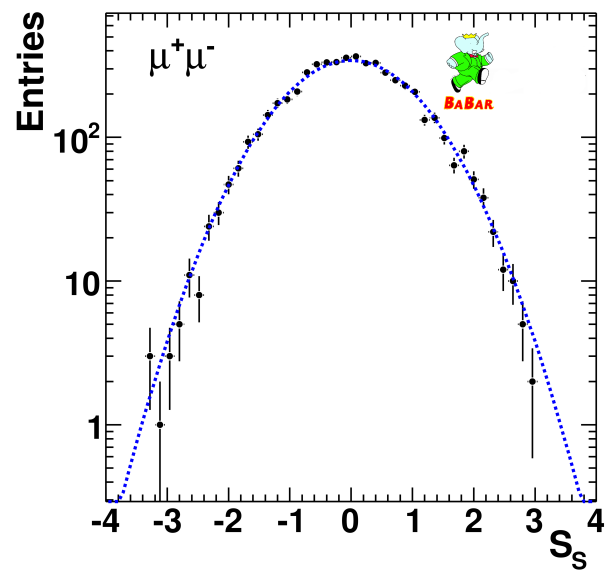
Grey bands show excluded mass regions due to resonances

$$S_S = +/-\sqrt{2log(\mathcal{L}/\mathcal{L}_0)}$$



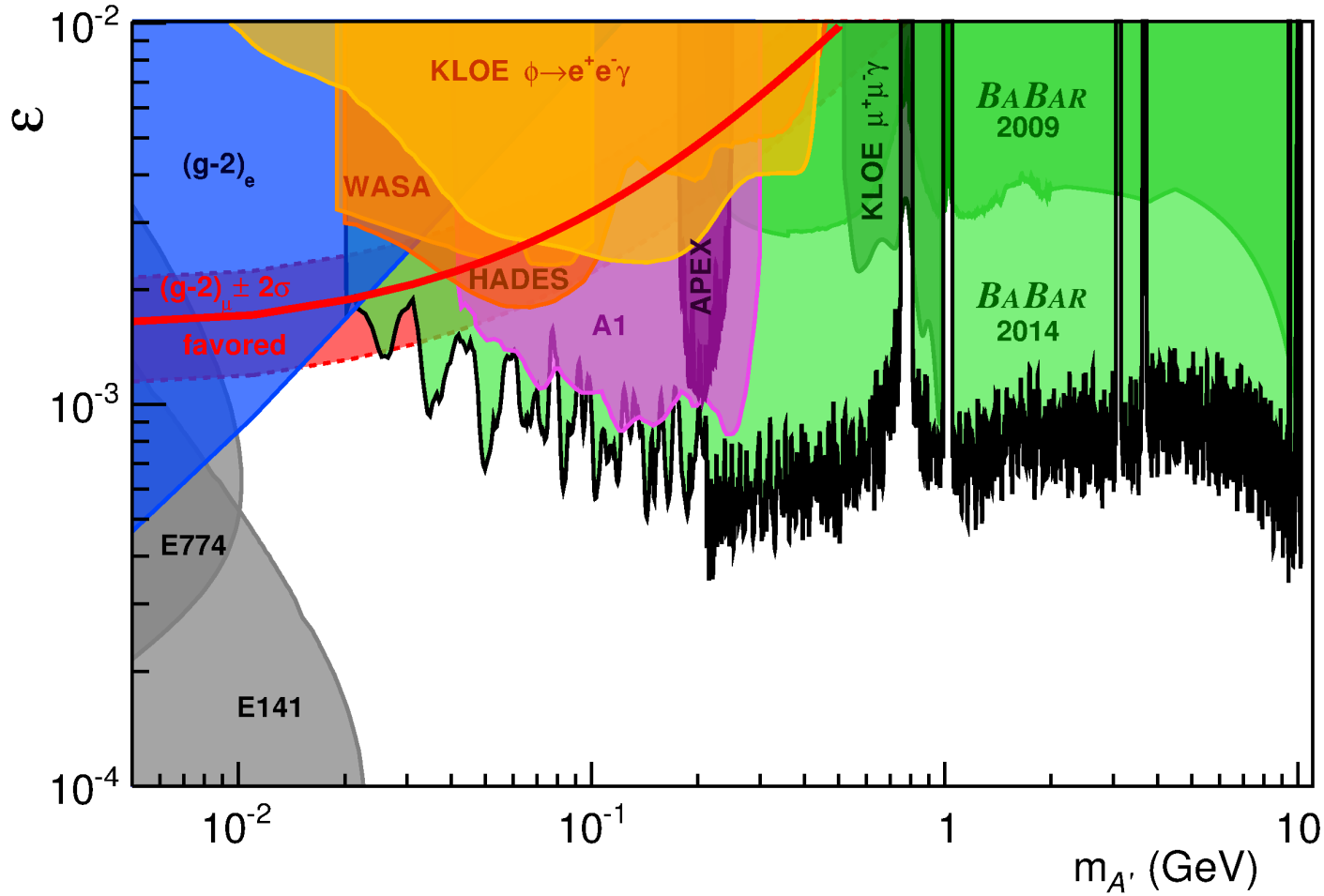






Can be translated to the mixing strength as a function of $m_{A'}$...

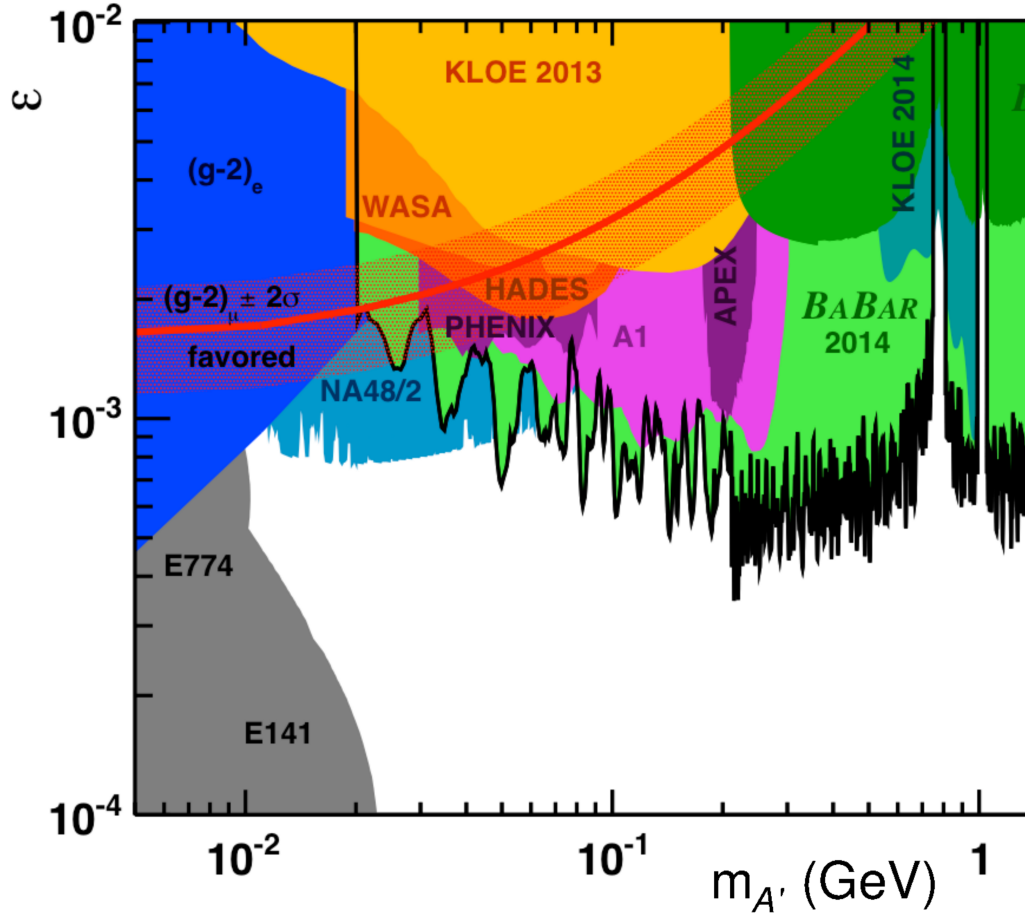
Results



- *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 $15\,\mathrm{MeV}/c^2 \lesssim m_{A'} \lesssim 30\,\mathrm{MeV}/c^2$ remains

Results



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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: $L \to f$, 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 $m(L) \leq 4$ GeV/c^2: $e^+e^- \to B\overline{B}$, $B \to L + N\pi$
  - Simulated process for $m(L) > 4$ GeV/c^2: $\Upsilon(4S) \to L + N\pi$
  - $N = 1, 2$, or 3
  - L is produced uniformly throughout available phase space

- Model dependent approach
  - Simulated process: $B \to X_s L$ 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, Λ, 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 $2\,\mathrm{MeV}/c^2$ steps and the whole mass range is always fitted

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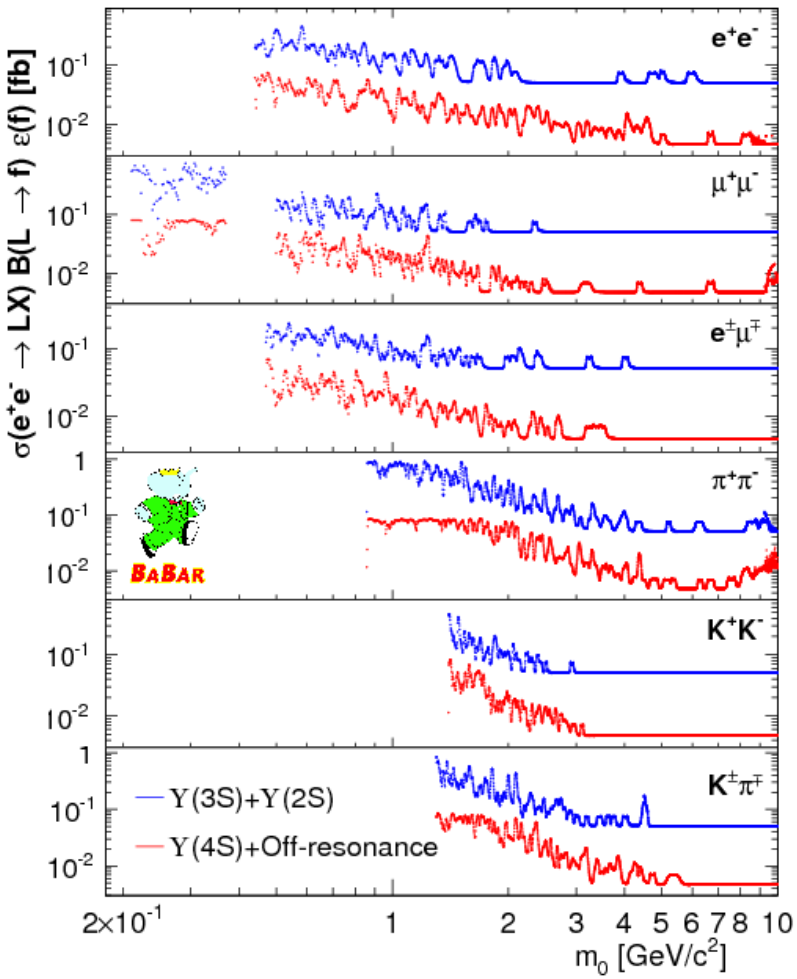
model-independent results



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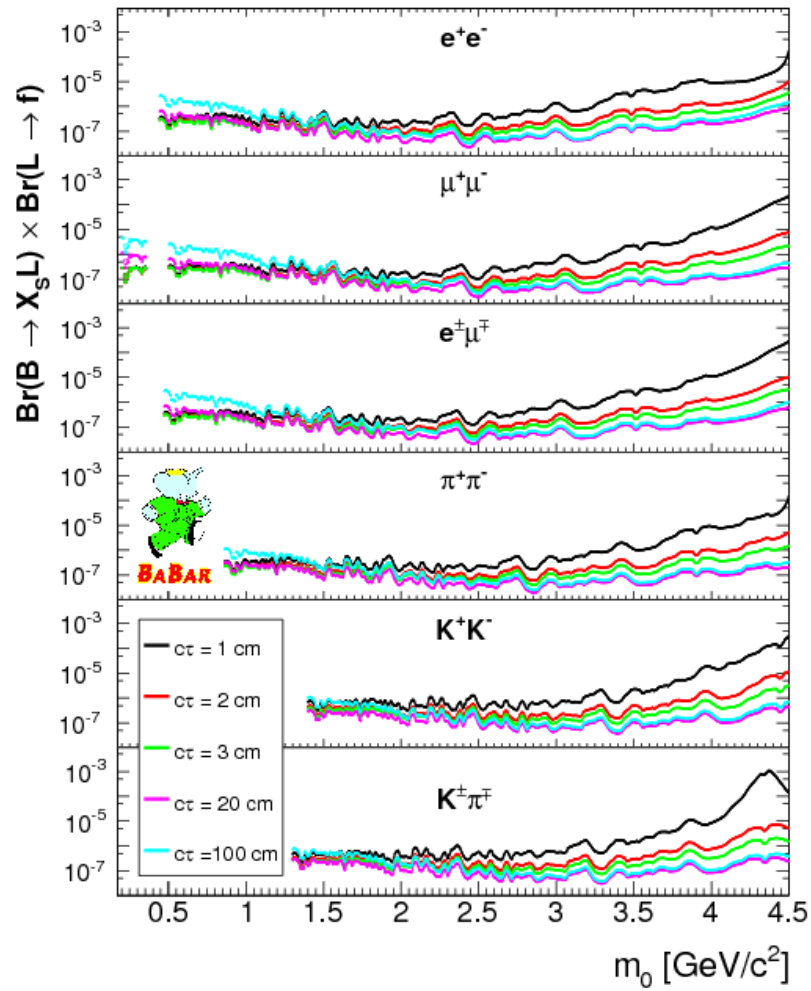

Search for a Light Higgs Resonance in

$$\Upsilon(1S) \to \gamma A^0, \quad A^0 \to c\bar{c}$$

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 Υ decay
- *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 *BABAR* in $A^0 \to \tau^+\tau^-$ searches

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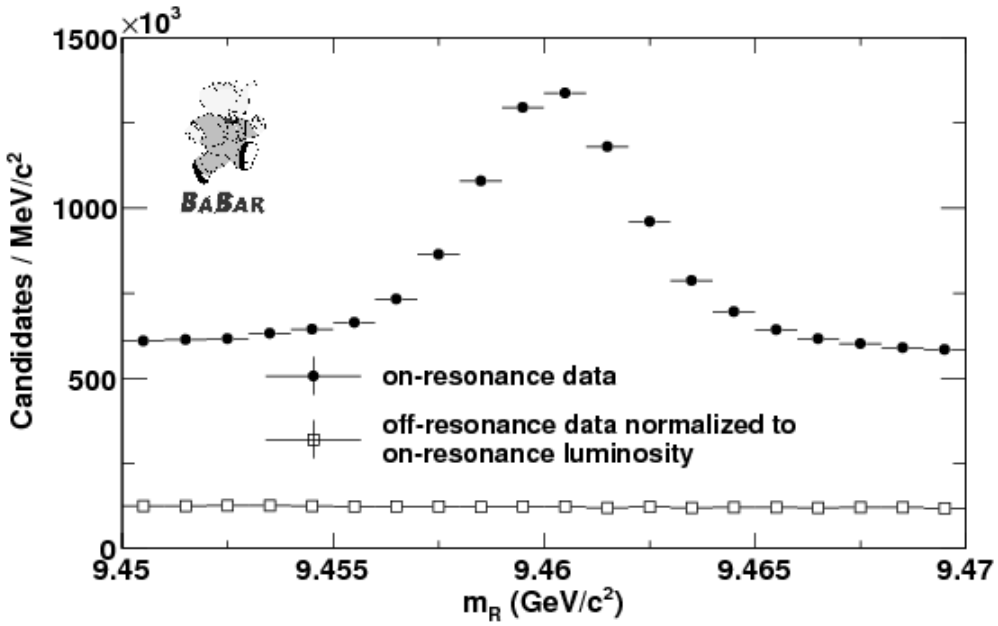
One of the last channels that has not been explored so far: $A^0 \to c\bar{c}$
BABAR can probe A^0 masses between 4.00 GeV/c^2 and 9.25 GeV/c^2

Overview

- $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$, $\Upsilon(1S) \to \gamma A^0$, $A^0 \to c\bar{c}$
  - 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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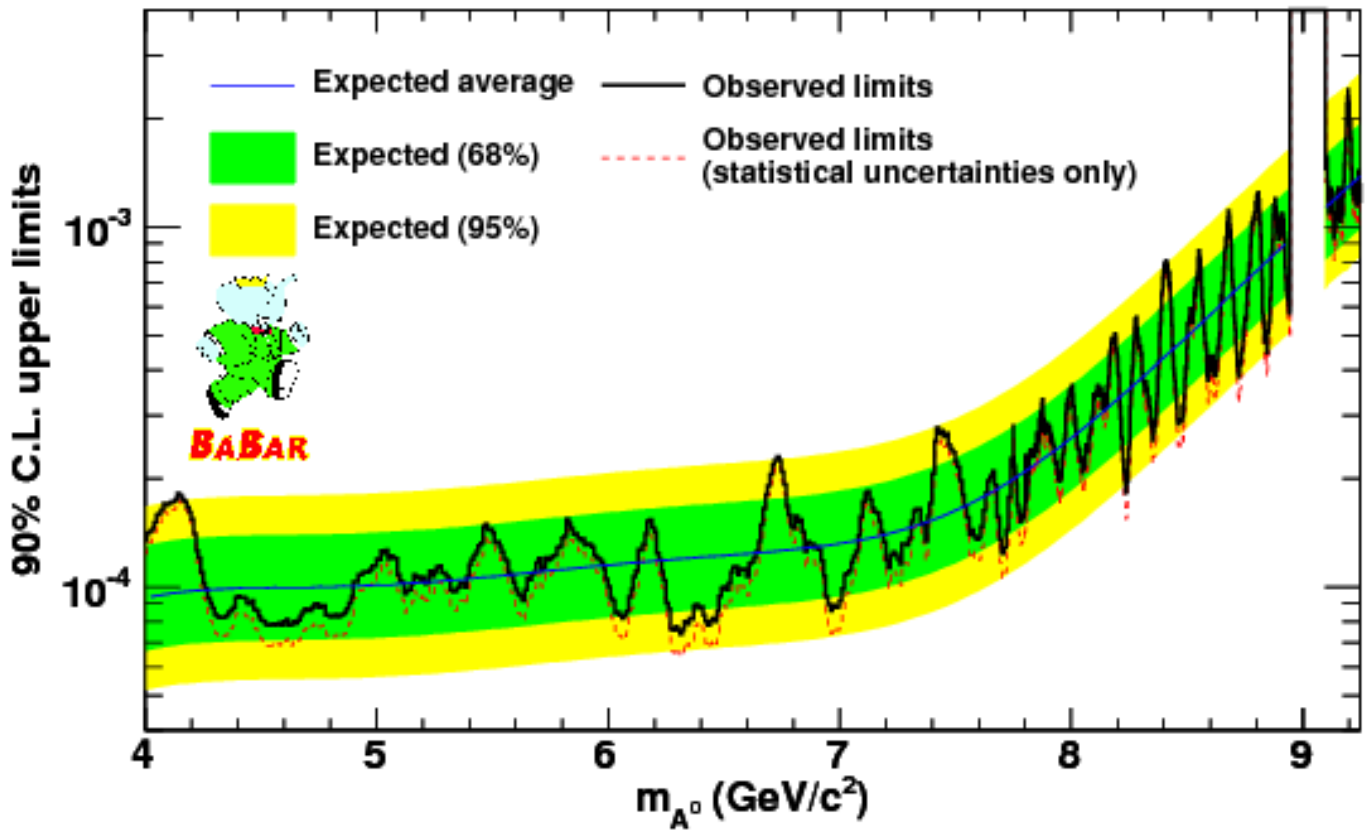

Search for CP Violation in

$$\overline{B}^0 \to D_{CP}^{(*)} h^0$$

by combining the *BABAR* and Belle datasets

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 $h^0 = \pi^0, \eta$, or ω
- Theoretically clean and can be compared with measurement from $b \to c\bar{c}s$
- Branching fractions for B and D_{CP} are low
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New approach: Combine *BABAR* and Belle data!

Overview

- *BABAR* and Belle $\Upsilon(4S)$ data combined: $1.24 \times 10^9 B\overline{B}$!
  (*BABAR*: $(471 \pm 3) \times 10^6 B\overline{B}$, Belle: $(772 \pm 11) \times 10^6 B\overline{B}$)

- 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
  $$P_{\text{sig}}(\Delta t, q) = \frac{1}{4\tau_{B^0}} e^{-\frac{|\Delta t|}{\tau_{B^0}}} [1 + q(\mathcal{S}\sin(\Delta m \Delta t) - \mathcal{C}\cos(\Delta m \Delta t))]$$

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

- Combination is done at the Likelihood level

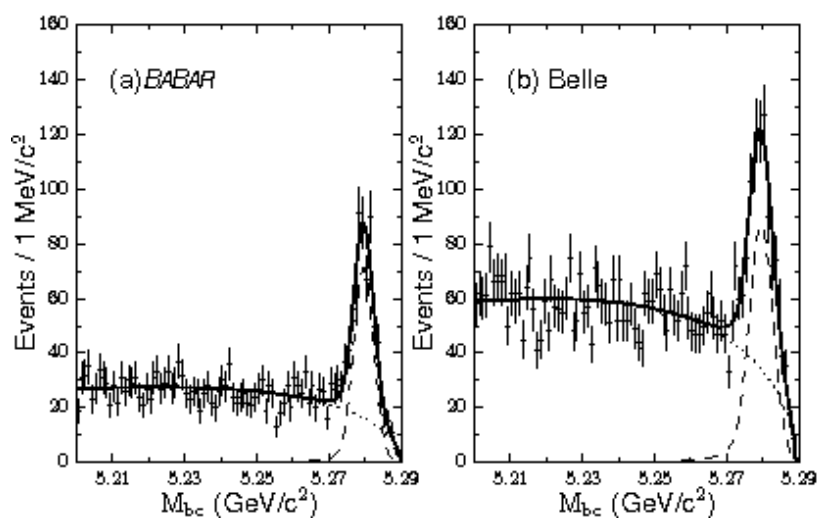
$$\ln \mathcal{L} = \sum_i \mathcal{P}_i^{BABAR} + \sum_i \mathcal{P}_i^{\text{Belle}}$$

Reconstruction and Signal Extraction

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

- Continuum background $e^+e^- \to q\overline{q}$ suppressed by Neural Networks

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



Results

different cross-checks have been performed:

- splitting data by experiment
- splitting data by decay mode
- use $D^0 \to K^+\pi^-$ as null control sample
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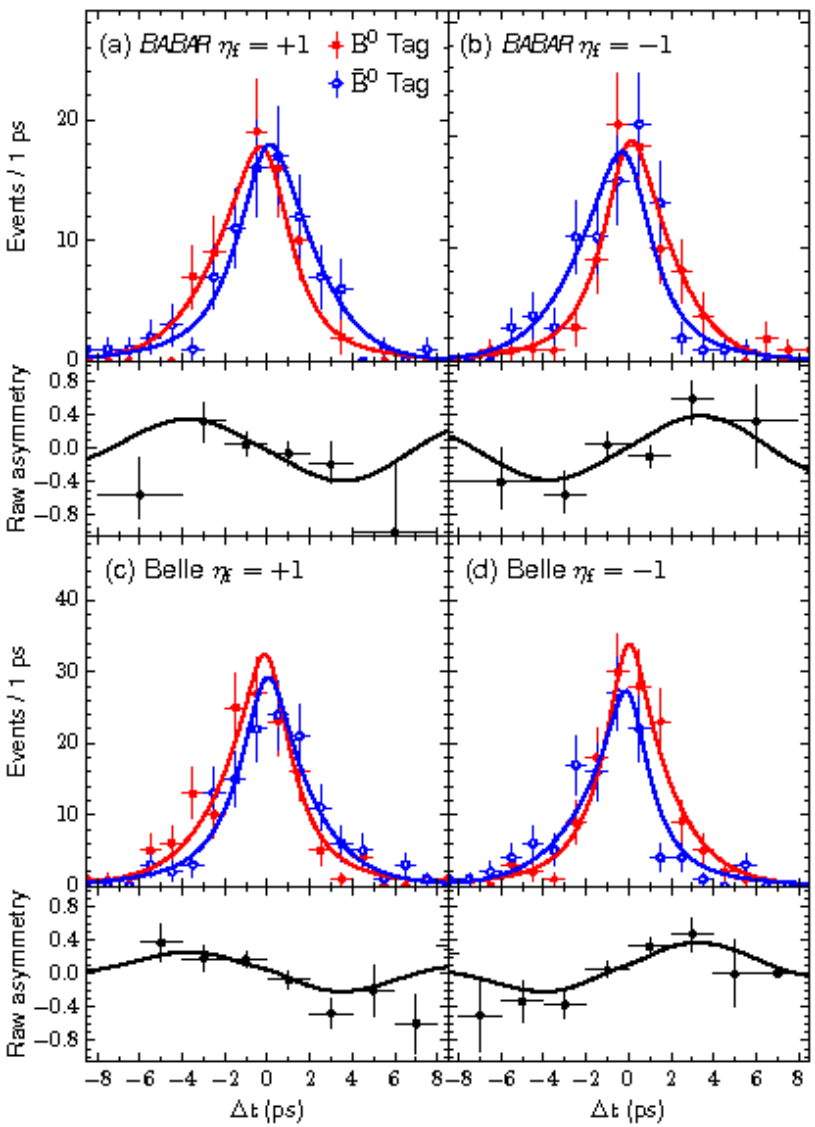

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$-\eta_f \mathcal{S} = 0.66 \pm 0.10 \pm 0.06$

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

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

no evidence for direct CP violation

no mixing-induced CP violation excluded at 5.4σ

First observation of CP violation in $\overline{B}^0 \to D^{(*)}_{CP} h^0$!

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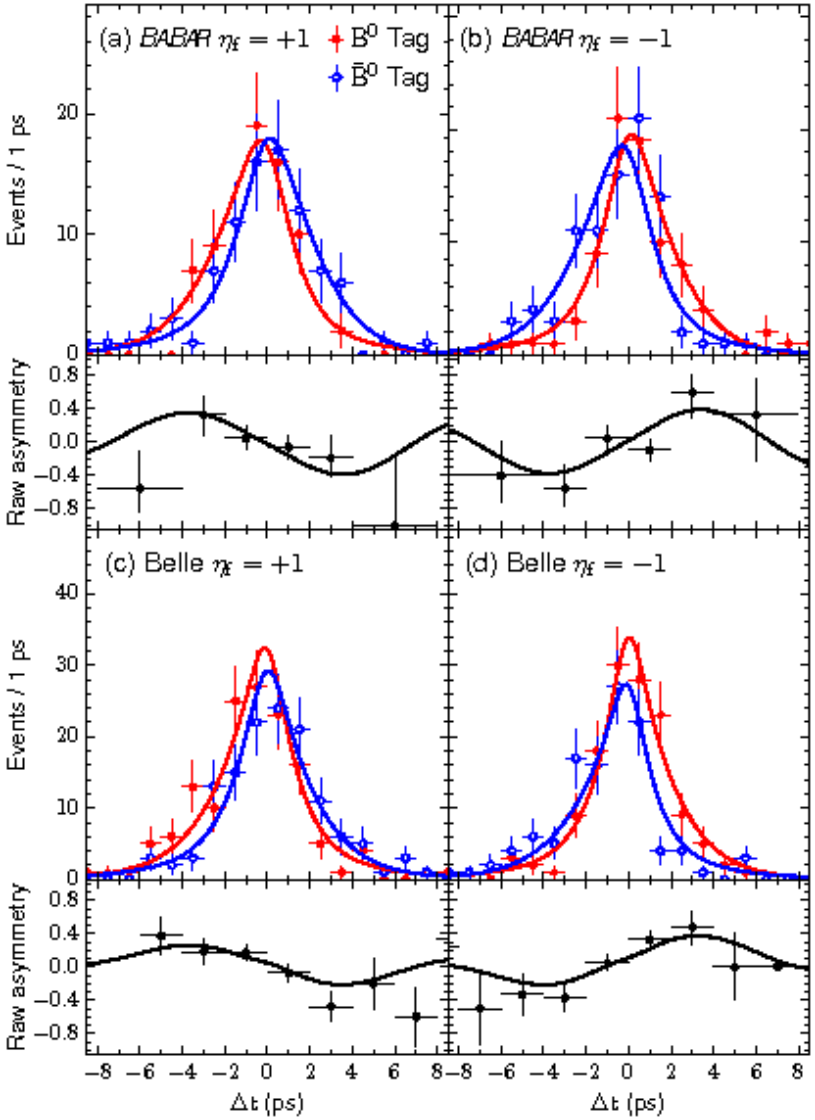

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First measurement performed on more than 1ab^{-1} collected at the $\Upsilon(4S)$!

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- Searches for physics beyond the SM
- Significant limits in dark-forces and light-Higgs searches
- First observation of CP violation in $\overline{B}^0 \to D^{(*)}_{\mathrm{CP}} h^0$

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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.

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  by Isabella Garzia, Monday 2:30pm

- The Time-like Electromagnetic Form Factors of Proton and Charged Kaon at high energies
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