Searches for low-mass Higgs states @ BaBar

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Outline

- **Search for a Dark Sector Higgs Boson**

BABAR preliminary

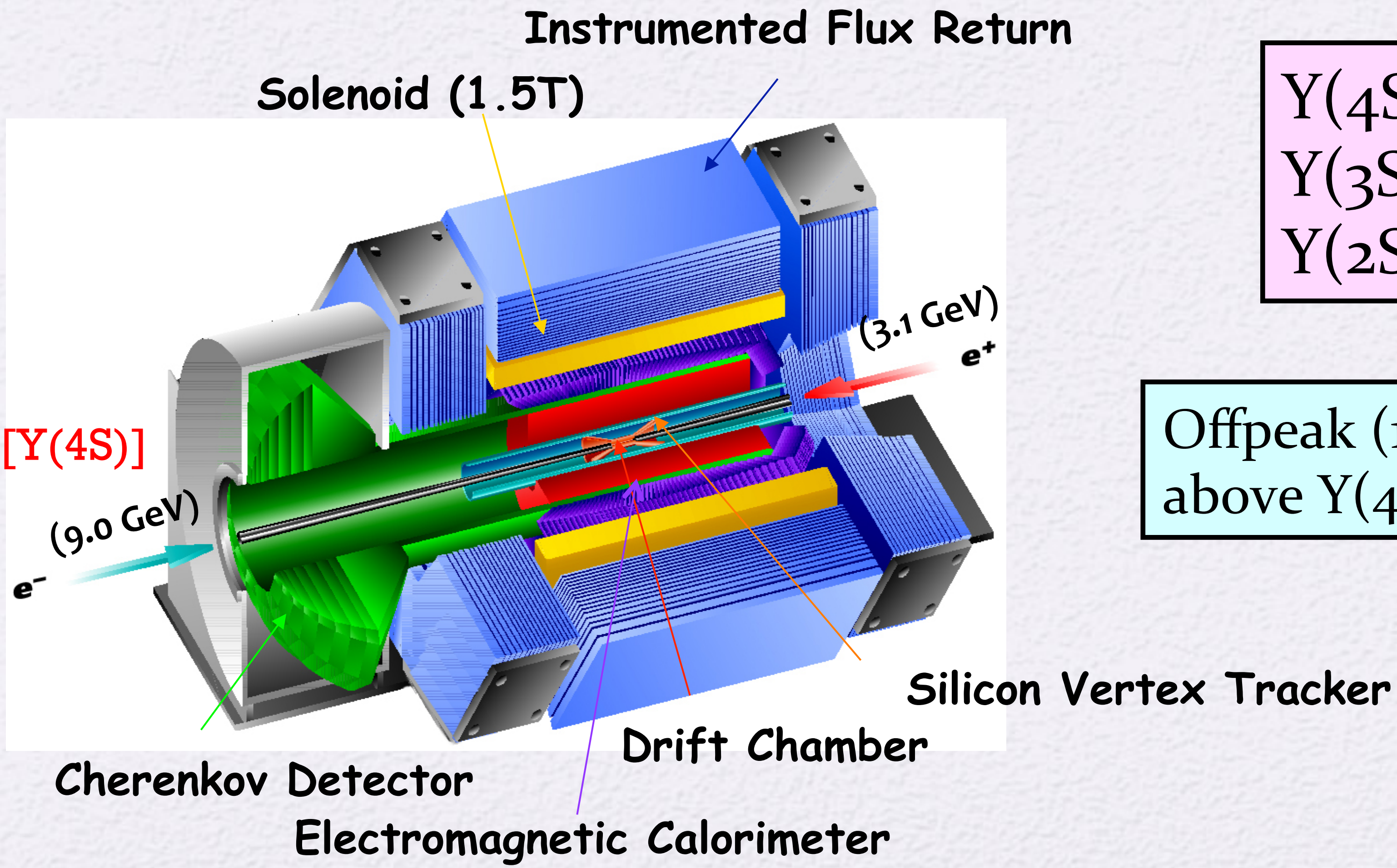
arXiv:1202.1313

- **Search for a Low Mass Higgs Boson**

PRL 103,081803 (2009)
PRL 103, 181801 (2009)
PRL 107, 221803 (2011)
PRL 107, 021804 (2011)
PRL 103, 251801 (2009)

The BaBar detector and data sample

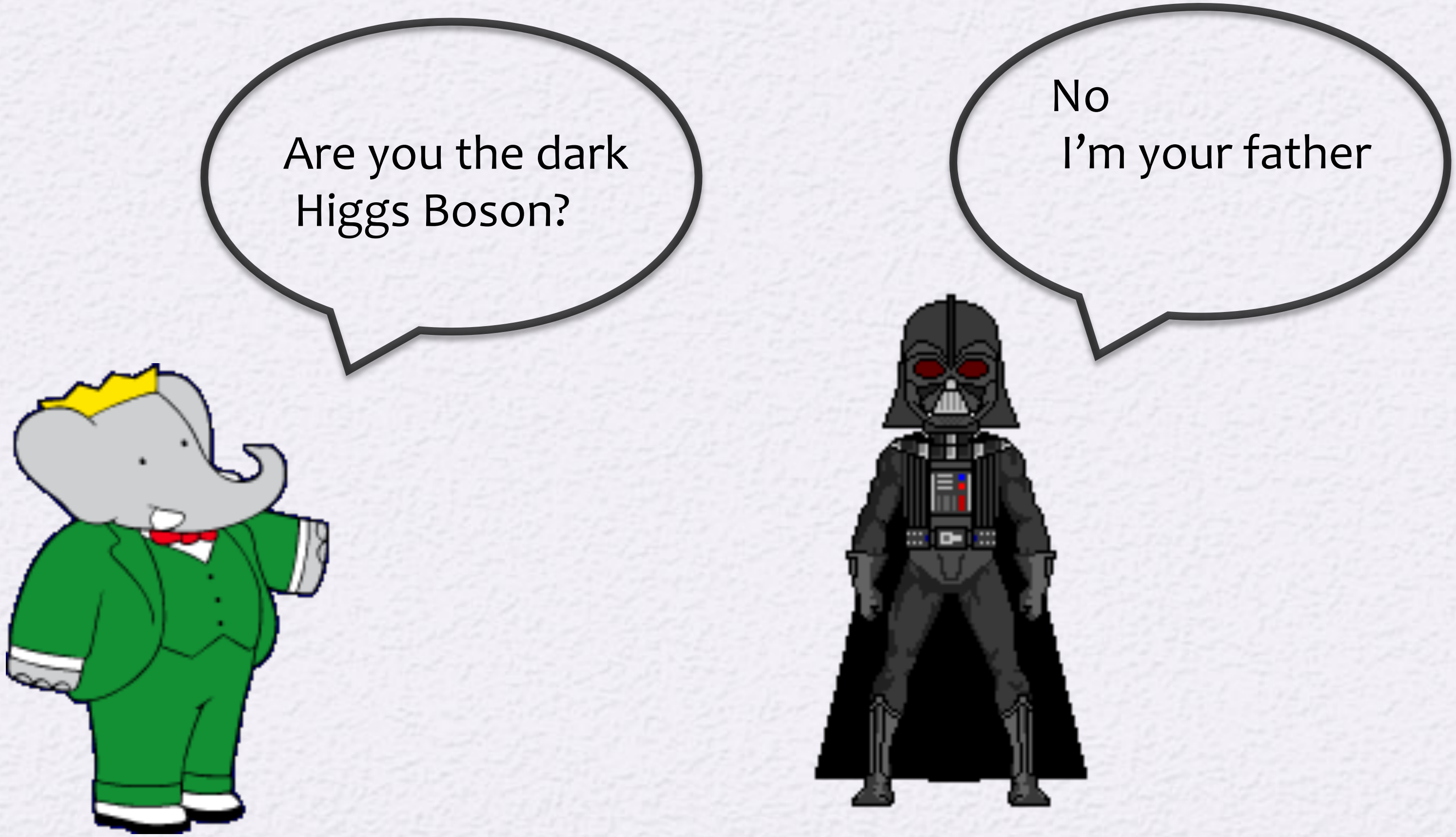
BaBar PEP-II is a powerful *b* factory: 467 million $B\bar{B}$ pairs in the total data sample



Y(4S): 432 fb^{-1}
Y(3S): 30.2 fb^{-1}
Y(2S): 14.5 fb^{-1}

Offpeak (10.54GeV) + Scan above Y(4S): 53.9 fb^{-1}

Search for Dark Higgs Boson @ BaBar



BABAR preliminary

Dark forces (theoretical framework)

Overwhelming astrophysical evidence of dark matter

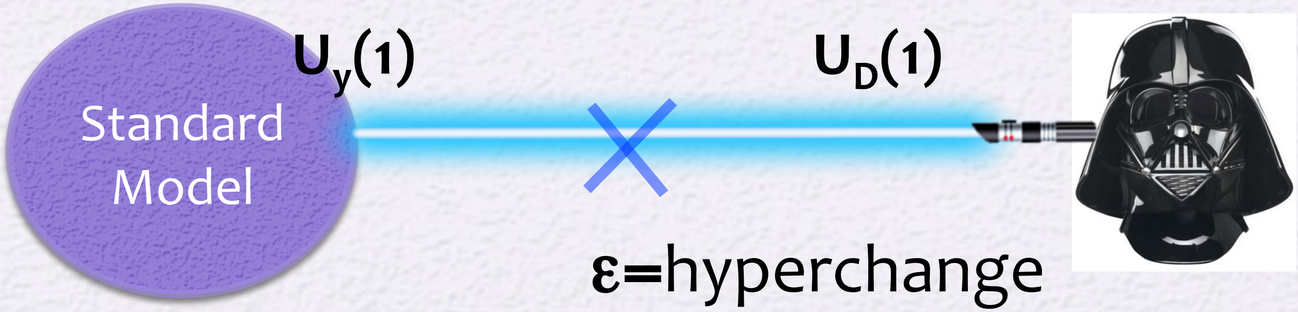
Models introducing a new 'dark' force mediated by a new gauge boson with a mass around a GeV have been proposed to explain the observations of PAMELA, FERMI, DAMA/LIBRA, CREST,...

PRD 79, 015014 (2009)

Wimp-like dark matter particles can annihilate into pairs of dark bosons, which subsequently annihilate to lepton pairs (protons are kinematically forbidden).

PRD 79. 115008(2009)

New dark sector has been introduced that couples to the SM with a dark boson (i.e. the dark photon A') through a small kinetic mixing term



ε=hyperchange mixing strength

BABAR preliminary

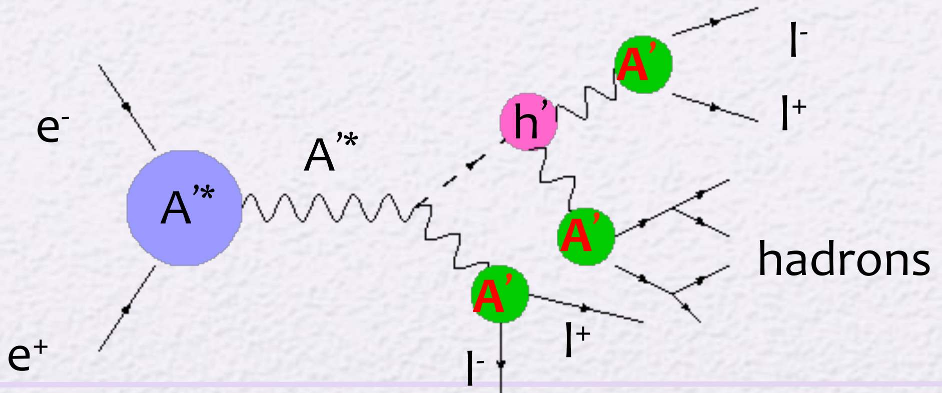
Dark forces search @ BaBar

arXiv:1202.1313

- A consequence of this dark sector scenario is the possibility to probe its existence at low-energy e^+e^- collider

B. Batelli et al. PRD 79, 115008 (2009)
R.Essig et al. PRD 80. 015003 (2009)

- Dark boson mass is generated via the Higgs mechanism, adding a dark Higgs boson (h') to the theory
- The dark photon and Higgs bosons could have a comparable mass (GeV-scale)
- A very minimal scenario has a single dark photon and a single dark Higgs boson
- We will use the Higgs's-strahlung process **$e^+e^- \rightarrow A'^* \rightarrow A'h', h' \rightarrow A'A'$**



Dark forces search @ BaBar: event selection

arXiv:1202.1313

BABAR preliminary

Event Selection (Two ways):

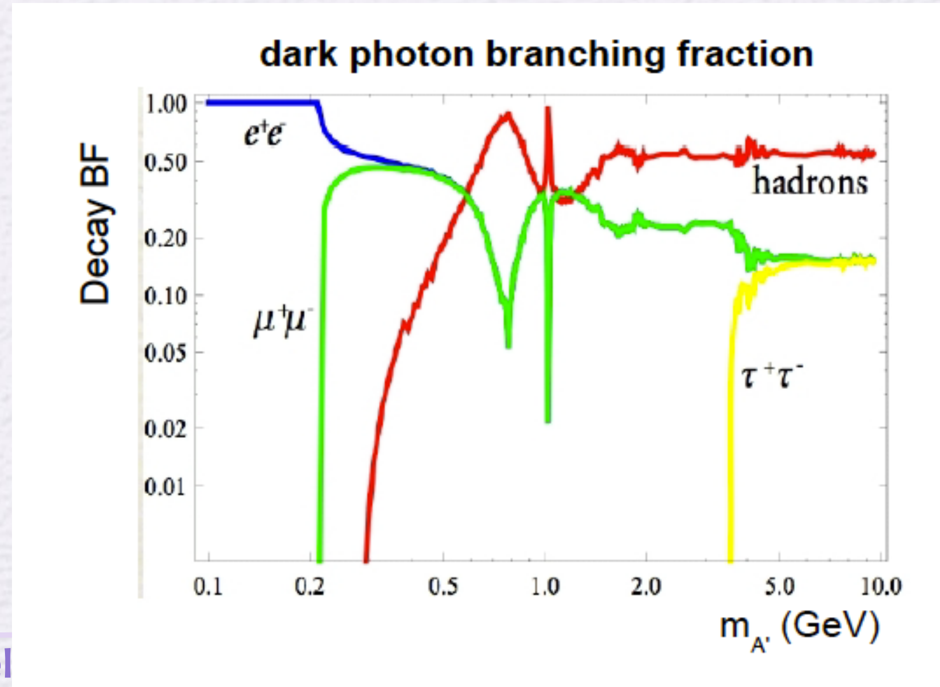
- Fully reconstructed all 3 dark photons: $A' \rightarrow e^+e^-, \mu^+\mu^-, \pi^+\pi^-$
  - 6 tracks with an invariant mass $m_{tot} > 0.95 \sqrt{s}$

- Partial reconstruction: 2 A' decaying to leptons and 1 A' to $q\bar{q}$:
  - $A1' \rightarrow e^+e^-, \mu^+\mu^-$, $A2' \rightarrow \mu^+\mu^-$, $A3' \rightarrow X$ ($X \neq l^+l^-$ or $\pi^+\pi^-$)
  - 4 or more tracks
  - Reconstruct four-momentum $p_3 = p_{ee} - p_1 - p_2$

PID for $A' \rightarrow l^+l^-, \pi^+\pi^-$

cos of helicity angle of $A' \rightarrow e^+e^- < 0.9$

3 A' candidates have similar masses



BABAR preliminary

Dark forces search @ BaBar: results (1)

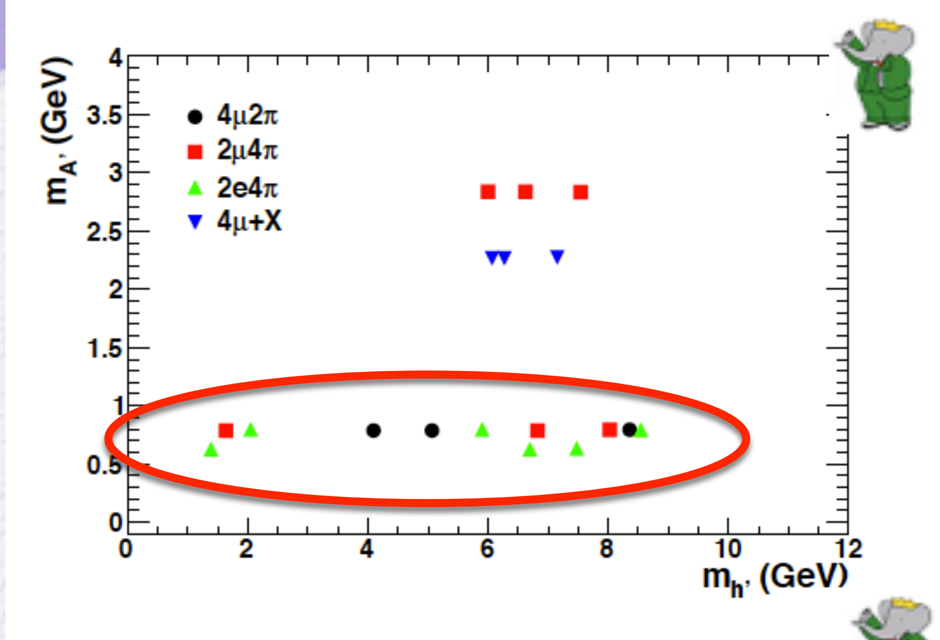
$e^+e^- \to A'^* \to A'h', h' \to A'A'$

arXiv:1202.1313

After all the selection criteria have been applied we have six events selected: (No signal observed in 6 lepton search)

3 entries are plotted for each events corresponding to the possible assignment of the decay $h' \to A'A'$

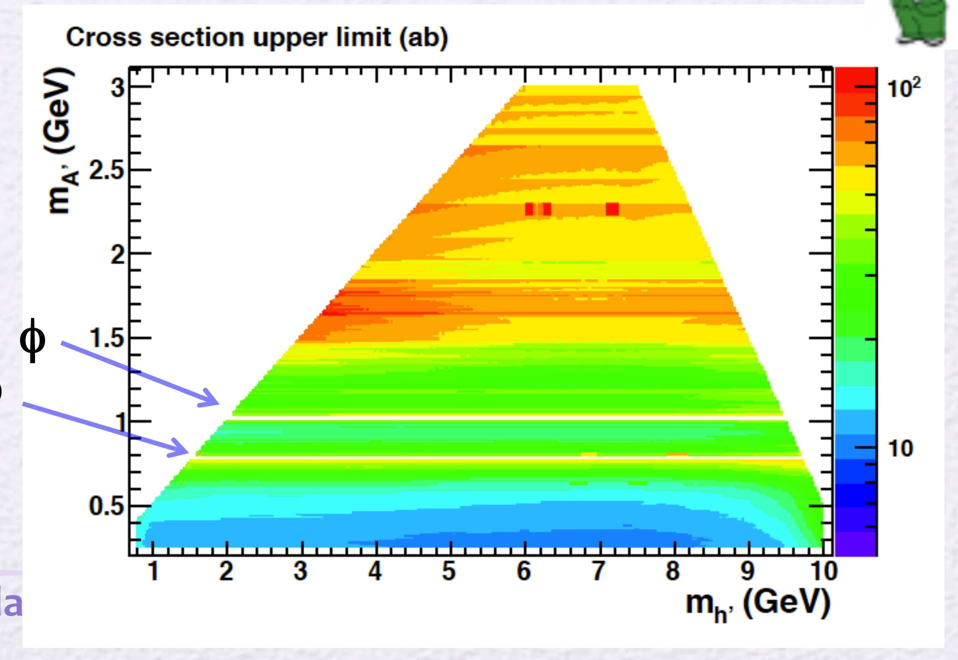
Most likely from $e+e^- \to e^+e^-\rho\rho$, $e+e^- \to e^+e^-\omega\omega$ or 6 π final states



Consistent with the pure background hypothesis from control sample

Upper limit (90% CL) on $(e^+e^- \to A'^* \to A'h', h' \to A'A') <$ 10-100 ab

The limits in the ω- and ϕ mesons regions are order of magnitude largert hen the average limits and are masked to avoid overflow



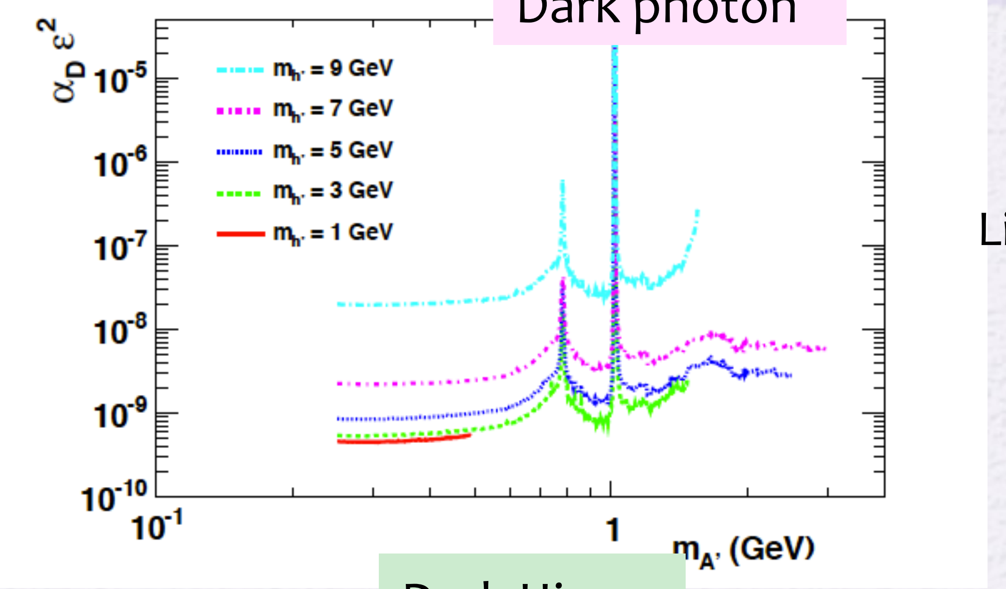
Dark forces search @ BaBar: results (2)

arXiv:1202.1313

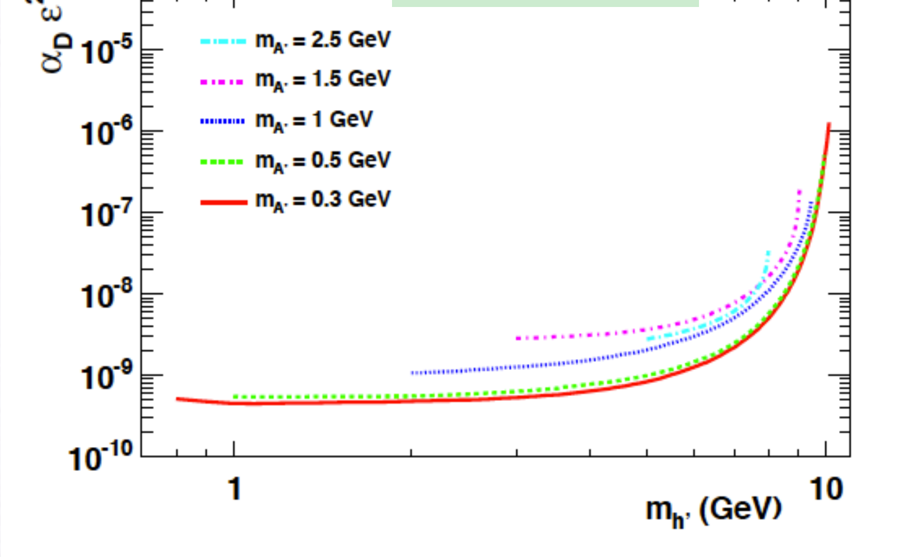
The limits on the cross section are translated into 90% upper limit on the product $\alpha_D\varepsilon^2$, where $\alpha_D = g_D 2/4\pi$, g_D is the dark sector gauge coupling, ε is the mixing strength

BABAR preliminary

Dark photon

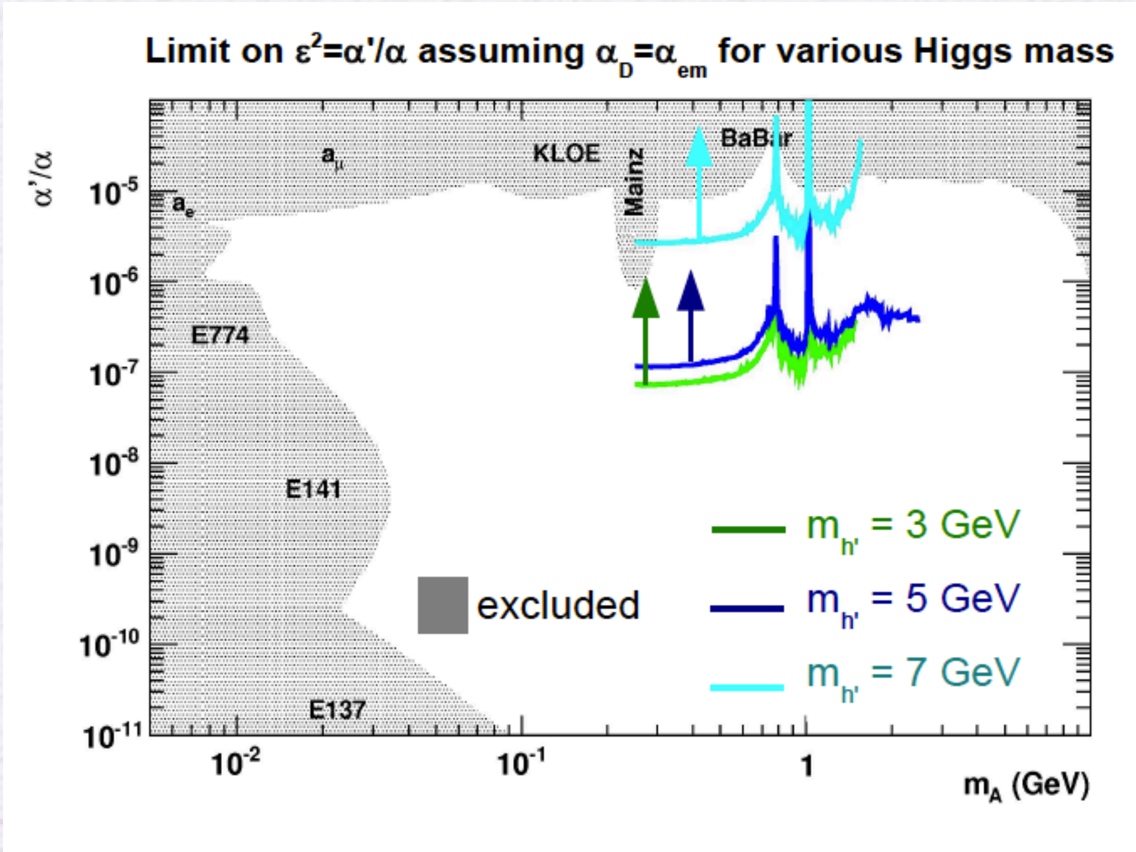


Dark Higgs



$\alpha_D\varepsilon^2$ <few x10^{-10} at 90% CL

Limit on $\varepsilon^2=\alpha'/\alpha$ for $\alpha_D=\alpha_e$ (solid) and $\alpha_D=1$ (dashed)



Search for Light Higgs Boson @ BaBar

Search for light Higgs @ BaBar (motivation)

- Light Higgs arise in several beyond SM scenarios:
  - in the next-to-minimal supersymmetric standard model (NMSSM), an additional Higgs singlet field is introduced to solve the hierarchy problem
- Results in an additional CP-odd Higgs state, **A^0**, whose mass need not be larger than $2m_b$
- Also add a light neutralino

Phys. Rev. D 77, 015013(2008)

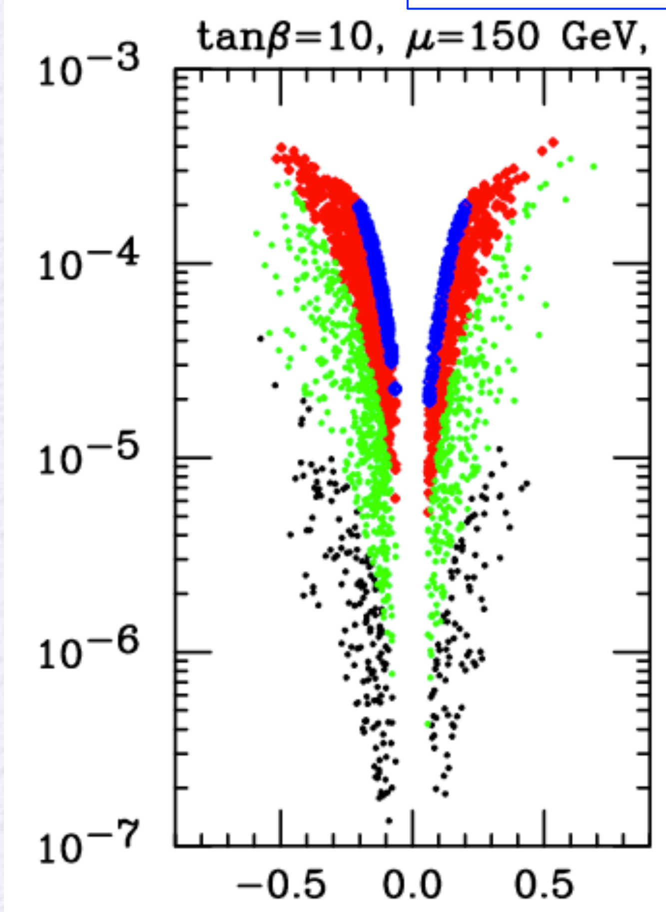
- Since $m_{A0}<2m_b$, model can evade LEP constraints while predicting large BF
- Light CP–odd Higgs can be directly produced in transition $\Upsilon(nS) \rightarrow \gamma A^0$, where $A^0 \rightarrow$ SM particles
- Low mass Dark Matter Candidate (χ) can be directly produced in transition
  - $\Upsilon(nS) \rightarrow \chi\chi$
  - $\Upsilon(nS) \rightarrow \gamma\chi\chi$

Gunion, et. Al, PRD 73, 015011 (2006)

Phys. Rev. D 76, 051105 (2007)

$m_{A0}<2m_\tau$
$2m_\tau<m_{A0}<7.5$ GeV
7.5 GeV$<m_{A0}<8.8$ GeV
8.8 GeV$<m_{A0}<9.2$GeV

M1,2,3(gaugino masses) =100, 200, 300 GeV



$\cos\theta_A$

$A^0=\cos\theta_A a_{MSSM}+\sin\theta_A\ a_{singlet}$

Search for light Higgs @ BaBar (Analysis techniques)

To search for light Higgs in BaBar we have used two main analysis techniques

- 2-body radiative decay of Υ states Υ(nS) →γA⁰ (n=1,2,3)
  - Key experimental signature: monochromatic photon in the CM frame

$$E^*_\gamma = \frac{m_\Upsilon - m^2_{A^0}}{2m_\Upsilon}$$

$\Upsilon(2,3S) \rightarrow \gamma A^0$, $A^0 \rightarrow \mu^+\mu^-$	**PRL 103, 081803 (2009)**
$\Upsilon(2,3S) \rightarrow \gamma A^0$, $A^0 \rightarrow \tau^+\tau^-$	**PRL 103, 181801 (2009)**
$\Upsilon(2,3S) \rightarrow \gamma A^0$, $A^0 \rightarrow$ hadrons	**PRL 107, 221803 (2011)**

- $\Upsilon(nS) \rightarrow \pi\pi\Upsilon(1S)$, $\Upsilon(1S) \rightarrow$ invisible (+γ)
  - Key experimental signatures:
    - Exactly 2 tracks forming a vertex identified as pions
    - ππ Recoiling mass

$$\sqrt{s + M^2_{\pi\pi} - 2\sqrt{sE^*_{\pi\pi}}} \approx M_{\Upsilon(1S)}$$

$\Upsilon(1S) \rightarrow$ invisible+γ	**PRL 107, 021804 (2011)**
$\Upsilon(1S) \rightarrow$ invisible	**PRL 103, 251801 (2009)**

$\Upsilon(2S,3S) \rightarrow \gamma A^0$, $A^0 \rightarrow \mu^+\mu^-, \tau^+\tau^-$

$\Upsilon(2S,3S) \rightarrow \gamma A^0$, $A^0 \rightarrow \mu^+\mu^-$ PRL 103, 081803 (2009)

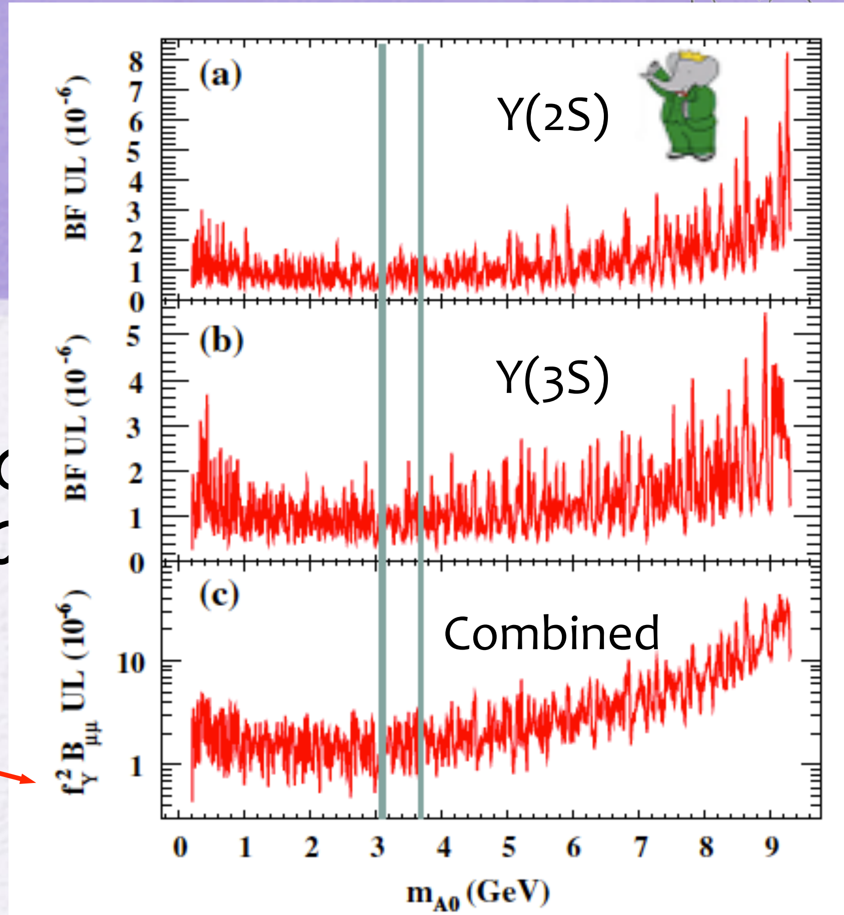
- 2 tracks, forming vertex & muon PID
- 1 photon with E_γ>200 MeV

Fit and scan of the $\mu^+\mu^-$ invariant mass

$B(\Upsilon(2S) \rightarrow \gamma A^0, A^0 \rightarrow \mu^+\mu^-) < (0.26\text{–}8.3)\times10^{-6}$ 90%C

$B(\Upsilon(2S) \rightarrow \gamma A^0, A^0 \rightarrow \mu^+\mu^-) < (0.27\text{–}5.5)\times10^{-6}$ 90%C

NO SIGNIFICANT SIGNAL OBSERVED



f_Υ is the effective Yukawa coupling of bound b-quark to A^0

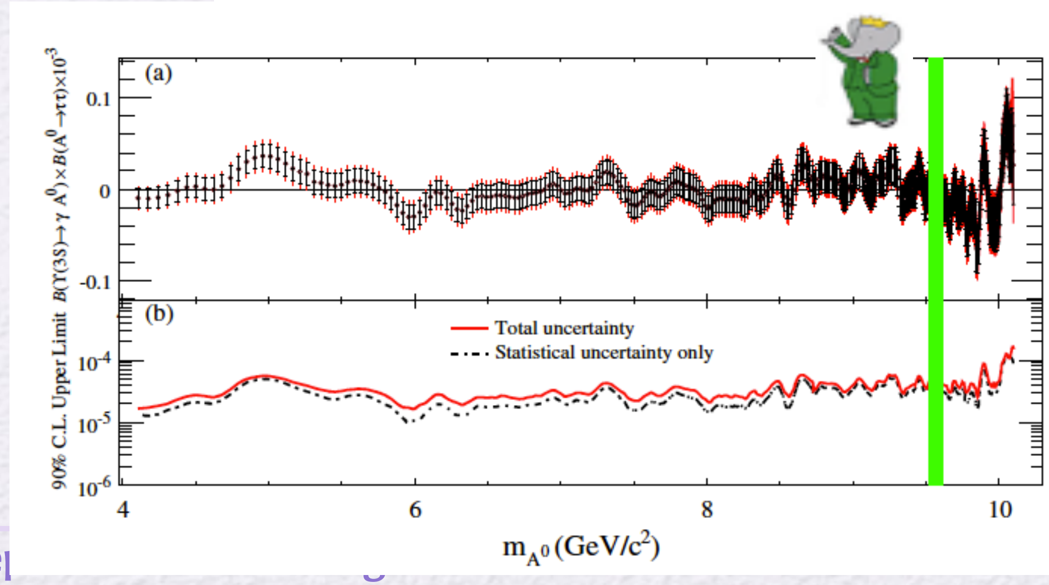
$\Upsilon(2S,3S) \rightarrow \gamma A^0$, $A^0 \rightarrow \tau^+\tau^-$ PRL 103, 181801 (2009)

- Consider both $\tau^+ \rightarrow e^+\nu\bar{\nu}$ and $\tau^+ \rightarrow \mu^+\nu\bar{\nu}$
- E_γ>100 MeV and 2 tracks Identified as leptons
- Fit and Scan E_γ

$$E_\gamma^* = \frac{m_\Upsilon^2 - m_{A^0}^2}{2m_\Upsilon}$$

$B(\Upsilon(2S,3S) \rightarrow \gamma A^0, A^0 \rightarrow \tau^+\tau^-) < (1.5\text{–}16)\times10^{-5}$ 90%CL

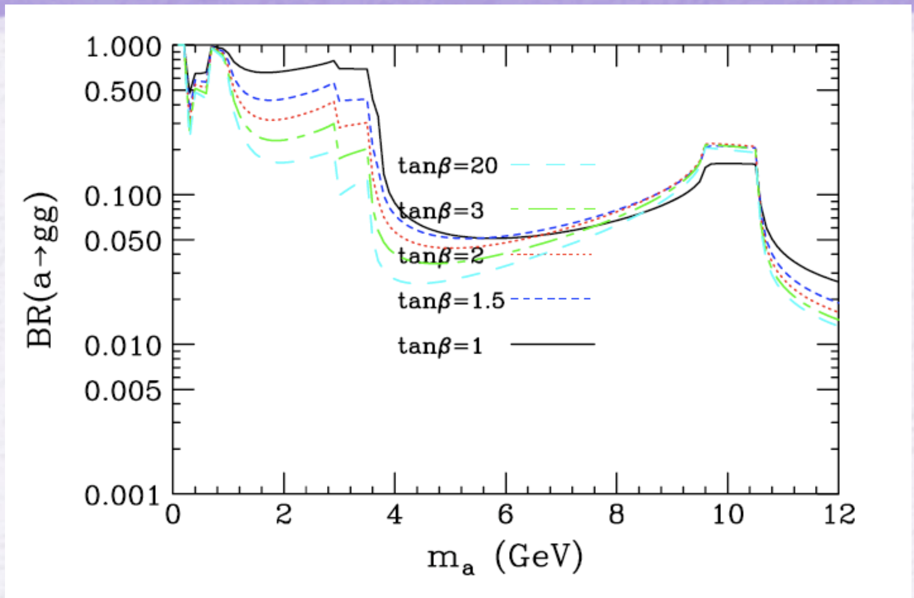
NO SIGNIFICANT SIGNAL OBSERVED

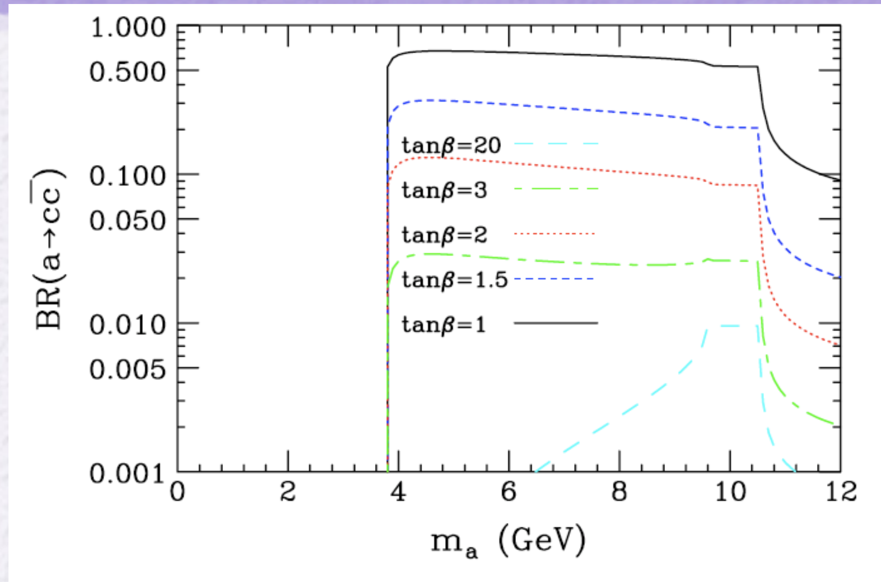


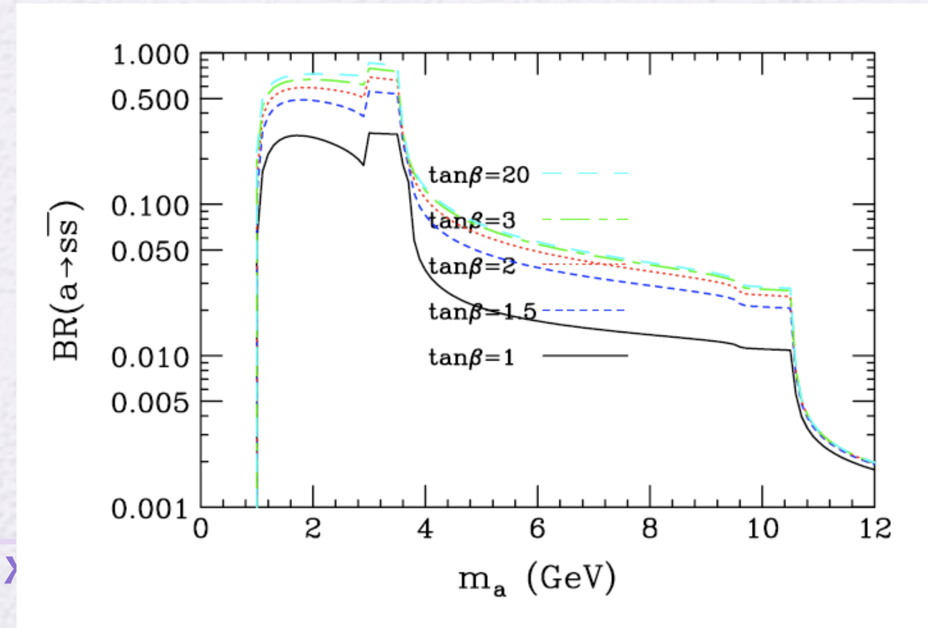
Search for hadronic decays of the A^0 (motivation)

PRL 107, 221803 (2011)

Hadronic decays of A^0 can be dominant depending on its mass and tanβ





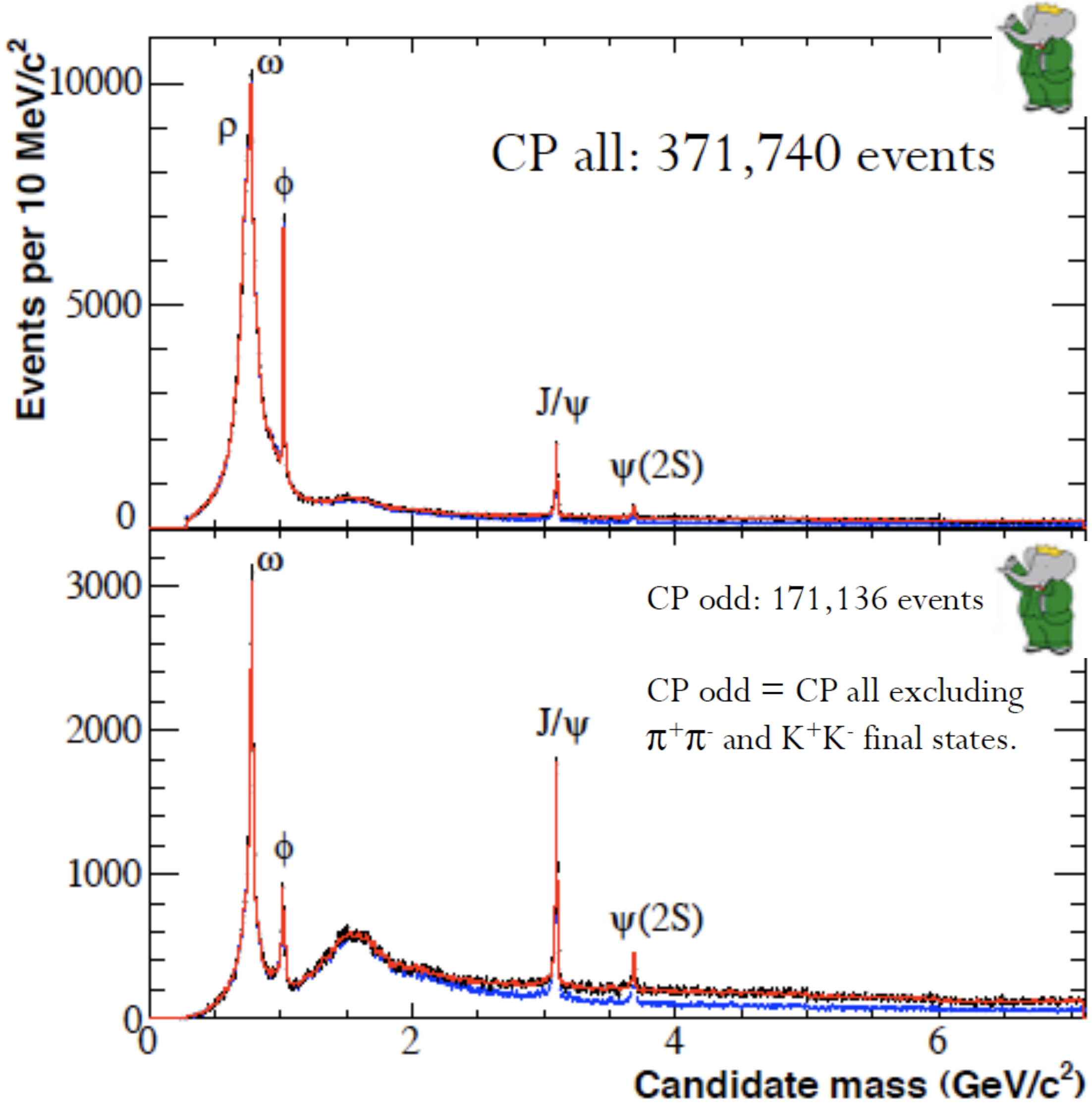


R. Dermisek and J.F. Gunion, Phys. Rev.D 81, 075003 (2010)

Search for hadronic decays of the A^0 (event selection)

PRL 107, 221803 (2011)

Look for a narrow resonance in A^0 mass spectrum for fully reconstructed $\Upsilon(2S,3S) \to \gamma A^0$ event, assuming that A^0 is CP odd, or no assumption ("CP all")



After applying all the selection criteria the remaining backgrounds are:

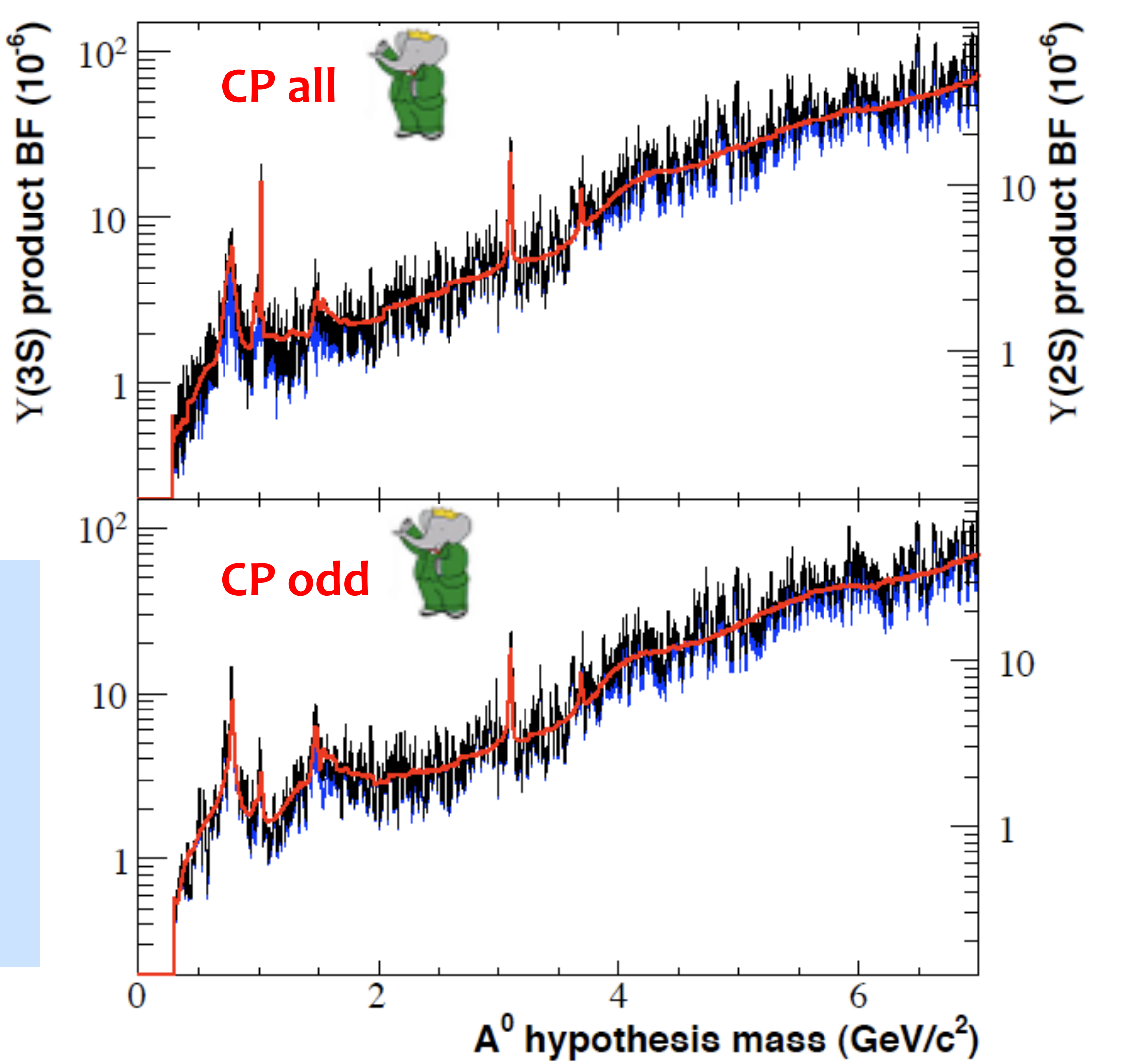
- ✓"Continuum": ISR production of resonances ($e^+e^- \to \gamma M$) or non-resonant ($e^+e^- \to \gamma X$)
- ✓Υ radiative decay, resonant ($\Upsilon \to \gamma M$) and non-resonant ($\Upsilon \to \gamma X$)
- ✓At high A^0 mass, π^0 decay can fake radiative photon

Search for hadronic decays of the A° (results)

PRL 107, 221803 (2011)

Most significant signals:
CP all: 2.9 σ at 3.107 GeV/c² (stats+systematics)
CP odd: 3.1 σ at 4.727 GeV/c² (stats+systematics)

Upper limit vs. hypothesis mass



Upper limits are calculate at 90% CL on **B[Y(3S) →A⁰γ]×B(A⁰→hadrons)** and **B[Y(2S) →A⁰γ]×B(A⁰→hadrons)**
Assuming that the same matrix element describes both 2S and 3S decays

The Y(2S) and Y(3S) data collected By BaBar has produced searches for Light Higgs production in several modes **but unfortunately no observation**

Υ(1S) →invisible

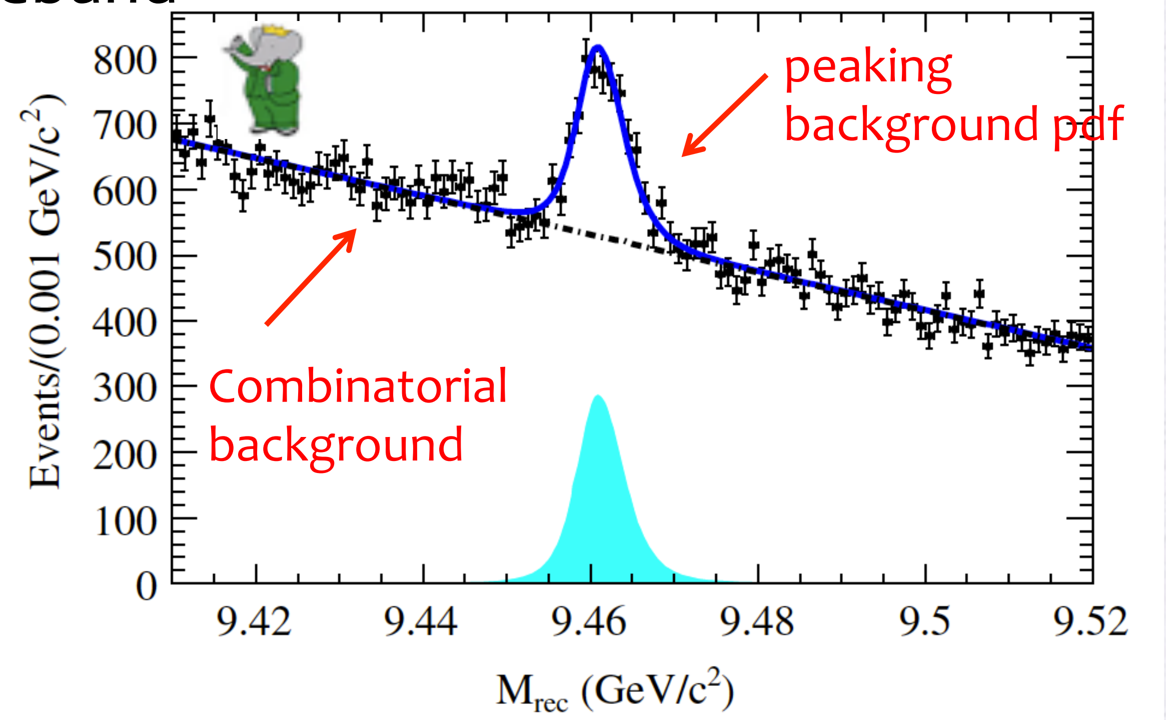
PRL 103, 251801 (2009)

Υ(3S) →$\pi^+\pi^-$Υ(1S), Υ(1S)→invisible

- Exactly 2 tracks forming a vertex and identified as pions
- Require no extra activity in event

Fit to ππ Recoil Mass $$M^2_{REC} = s + M^2_{\pi\pi} - 2\sqrt{s}E^*_{\pi\pi}$$

- Peaking bkg (from Υ(1S) →undetected) estimated from MC
- Continuum background from sideband



No evidence of dark matter contribution

NO SIGNIFICANT SIGNAL OBSERVED

B(Υ(1S) →invisible) <(3.0)x10^{-4} @90% CL

Υ(1S) →invisible (+γ)

PRL 107, 021804 (2011)

Υ(2S) →$\pi^+\pi^-$Υ(1S), Υ(1S,)→invisible+γ

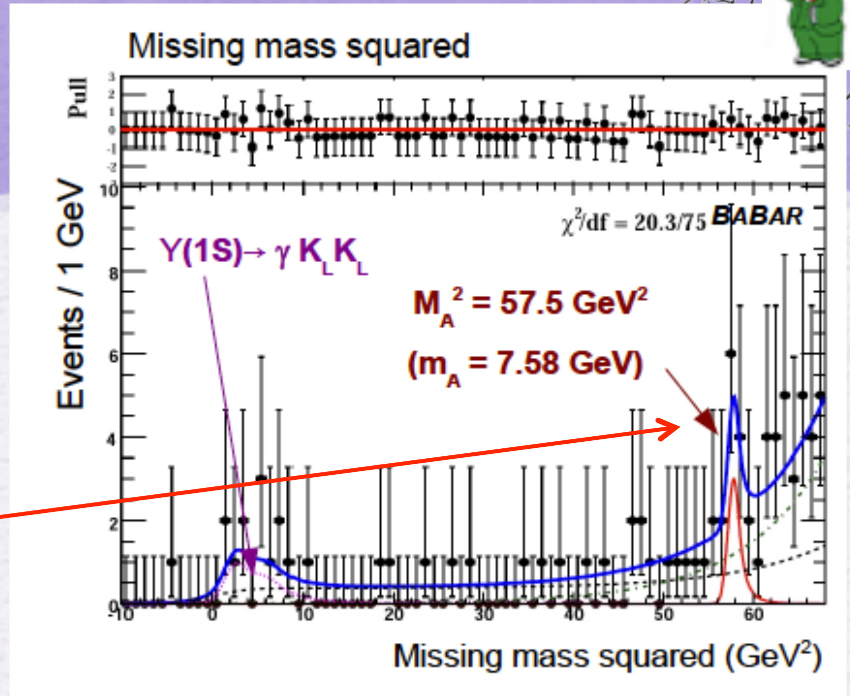
1 photon with E_γ>0.15 GeV

2D fit to ππ Recoiling Mass & Missing Mass²

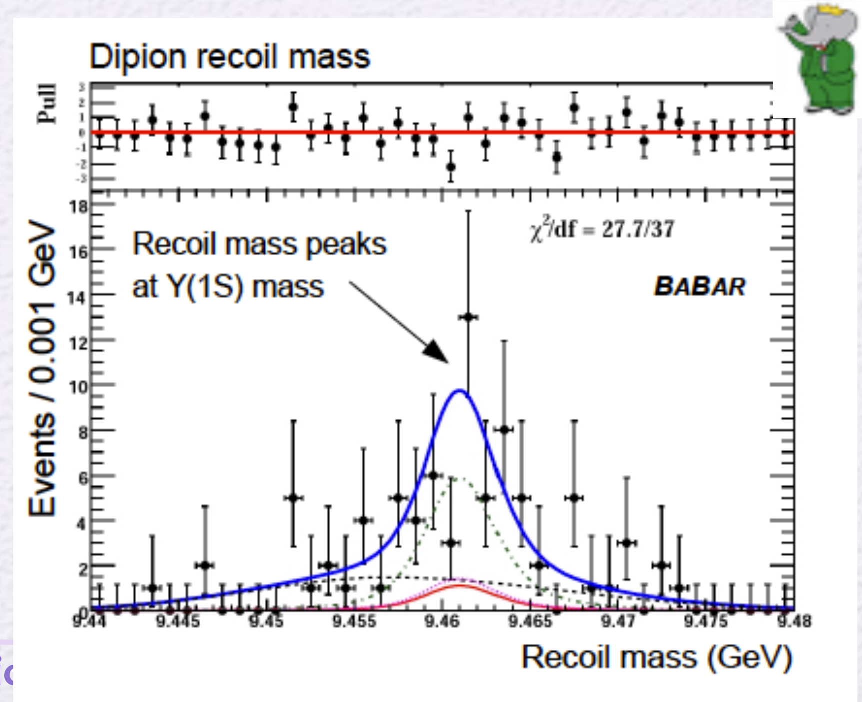
$$M_X^2 = (P_{e^+e^-} - P_{\pi\pi} - P_\gamma)$$

Most significant peak at m_A = 7.58 GeV (M_x^2 = 57.5 GeV²) with significance 2.0σ.

Probability >30% to observe a peak of this significance anywhere



NO SIGNIFICANT SIGNAL OBSERVED



B(Υ(1S)→γA^0, A^0→invisible)<(1.9-37)x10^{-6}

B(Υ(1S) →γχχ)<(0.5-24)x10^{-5} @90% CL

Conclusions

- We have searched for evidence of dark sector candidates and evidence of CP–odd light Higgs in the $\Upsilon(2S)$ and $\Upsilon(3S)$ data
- No significant signal observed
- More stringent limits set on space parameters of NP model
- Many analyses are still ongoing
- New results are expected in the near future

BACK-UP SLIDES

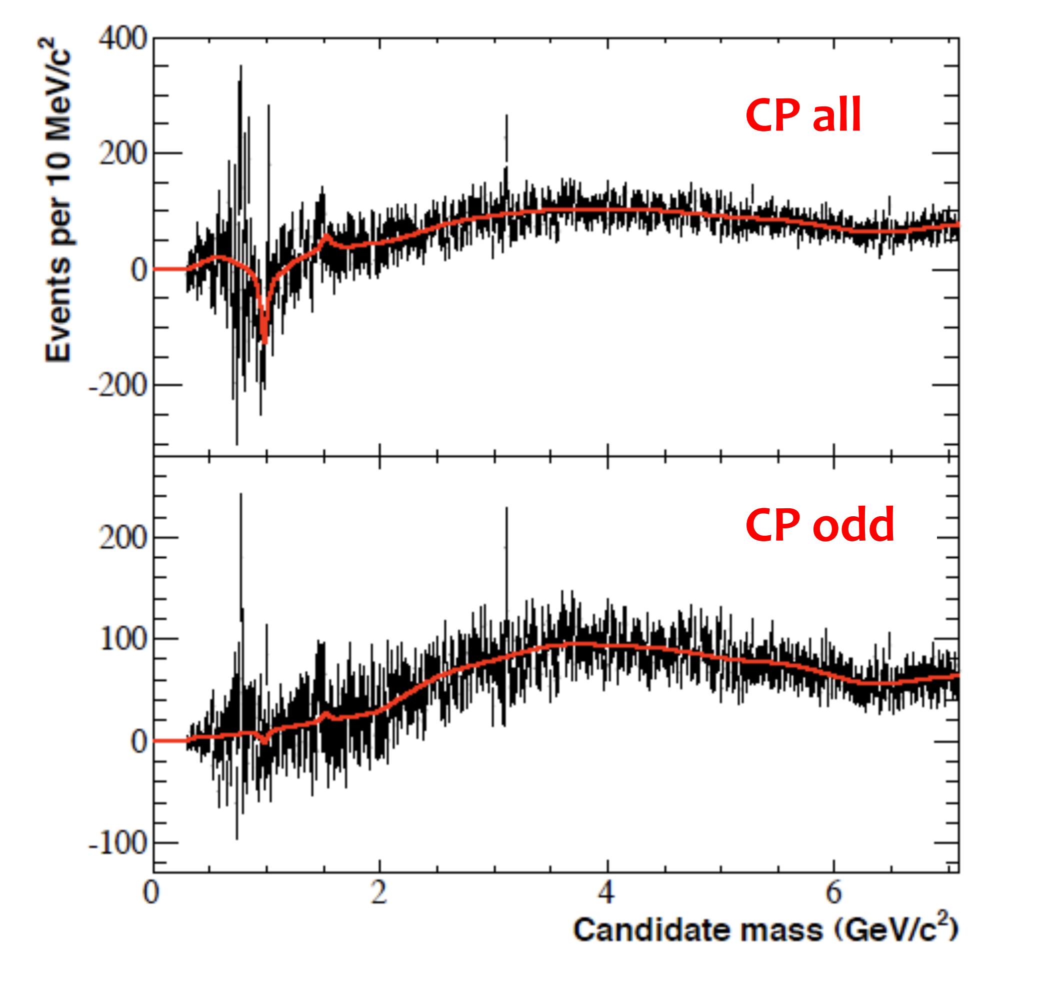
Search for hadronic decays of the A^0 (fit)

PRL 107, 221803 (2011)

The Higgs signal at a particular mass hypothesis is the number of events in a mass window centered on m_i minus the estimated background events in that window

The number of background event is obtained from a fit to the candidate mass distribution.

Mass spectrum after continuum subtraction



Statistical significance vs. hypothesis mass