Search for dark-sector Higgs and gauge bosons at *BABAR*

Alberto Lusiani
INFN and Scuola Normale Superiore di Pisa
(on behalf of the *BABAR* collaboration)

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Astrophysical observations of electron and/or positron excesses may be explained by Dark Matter models including a "dark" gauge boson with mass arount 1 GeV, which decays to leptons

- O. Adriani et al. (**PAMELA**), Observation of an anomalous positron abundance in the cosmic radiation
  - Nature 458:607-609,2009, arXiv:0810.4995
- J. Chang et al. (**ATIC**), An excess of cosmic ray electrons at energies of 300-800 GeV
  - Nature 456, 362 (2008)
- 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
  - Phys.Rev.Lett.102:181101,2009, arXiv:0905.0025.
- **HESS** Collab., Probing the ATIC peak in the cosmic-ray electron spectrum with H.E.S.S
  - Astron.Astrophys.508:561, 2009, arXiv:0905.0105

Dark-sector New Physics models, main features

- new dark sector with a $U(1)_{DARK}$ gauge group, with a **O(GeV) mass gauge photon (A', $B_{\mu\nu}$)**
- interaction with Standard Model fields thru **kinetic mixing** term $\epsilon F^{\mu\nu} B_{\mu\nu}$
- dark photon coupling to SM fermions: $\alpha' = \epsilon^2 \alpha$
- **TeV-scale dark matter ➞ dark photon pair ➞ leptons**
  - ► if $m(A') < 2$ GeV then dark photon decays to electrons and muons
- poorly constrained and worth exploring
- some models include a dark Higgs (which gives mass to the dark photon)

Dark photons and dark Higgs bosons may be produced at B-factories

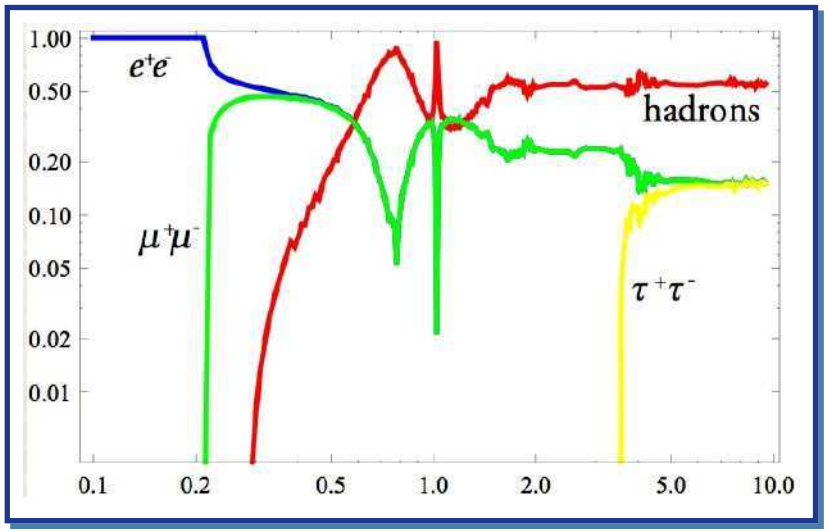
- $e^+e^- \to \gamma A', \quad A' \to f^+f^-$
- $e^+e^- \to A'A', \quad A' \to f^+f^-$
- $e^+e^- \to A'h', \quad h' \to A'A', \quad A' \to f^+f^-$
  - h' = dark-sector Higgs boson

- B.McElrath, Invisible Quarkonium Decays as a Sensitive Probe of Dark Matter, PRD 72 (2005) 103508
- Y.Nomura, J.Thaler, Dark Matter through the Axion Portal, PRD 79 (2009) 075008
- B.Batell, M.Pospelov, A.Ritz, Probing a Secluded U(1) at B-factories, PRD 79 (2009) 115008
- N.Arkani-Hamed *et al.*, A Theory of Dark Matter, PRD 79 (2009) 015014

Dark-photon branching fractions and constraints

dark photon branching fractions

B.Batell, M.Pospelov, A.Ritz, PRD 79 (2009) 115008



red line: parameters required to explain $(g-2)_\mu$ anomaly

M. Pospelov, PRD 80 (2009) 095002

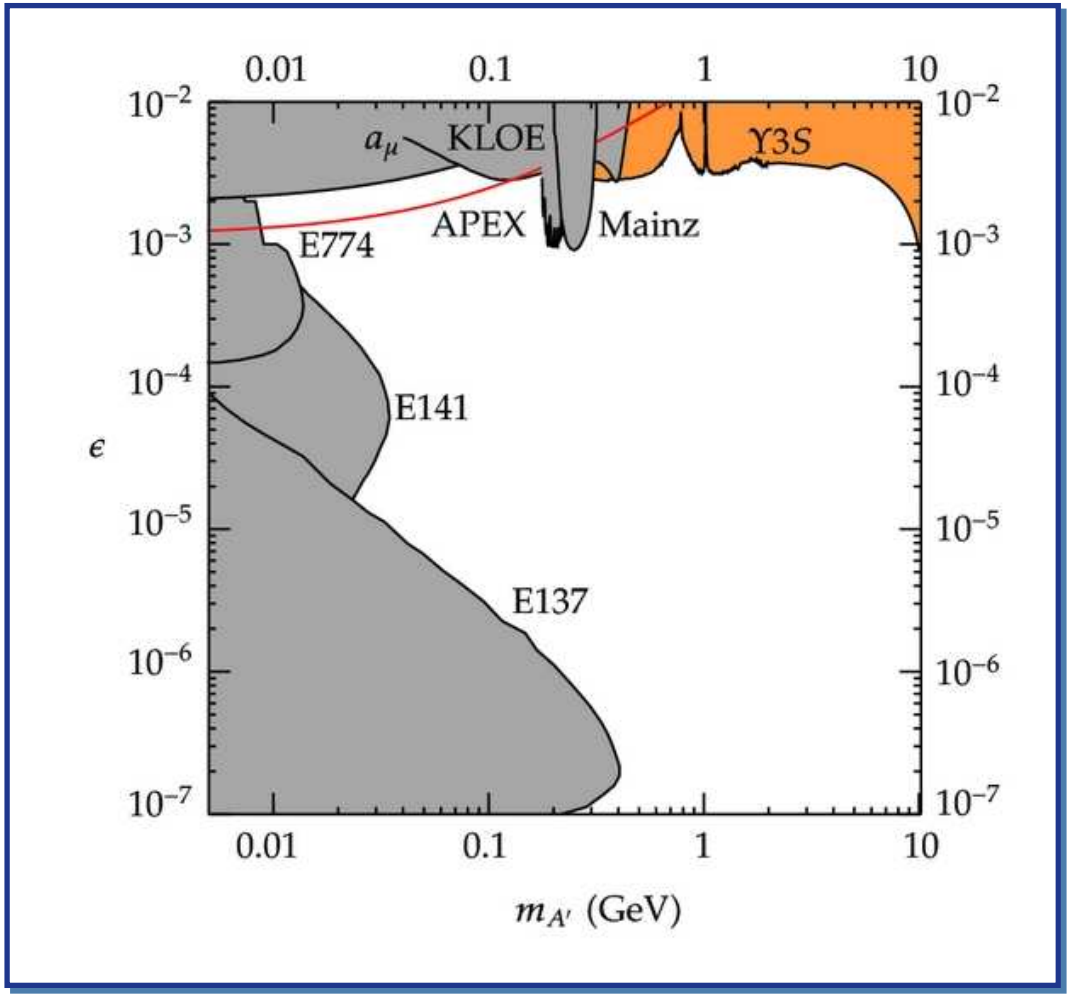
Y(3*S*): re-intepretation of Aspen 2009 *BABAR* prelim. light Higgs search

$\Upsilon(3S) \to A'\gamma, \quad A' \to \mu^+\mu^-$

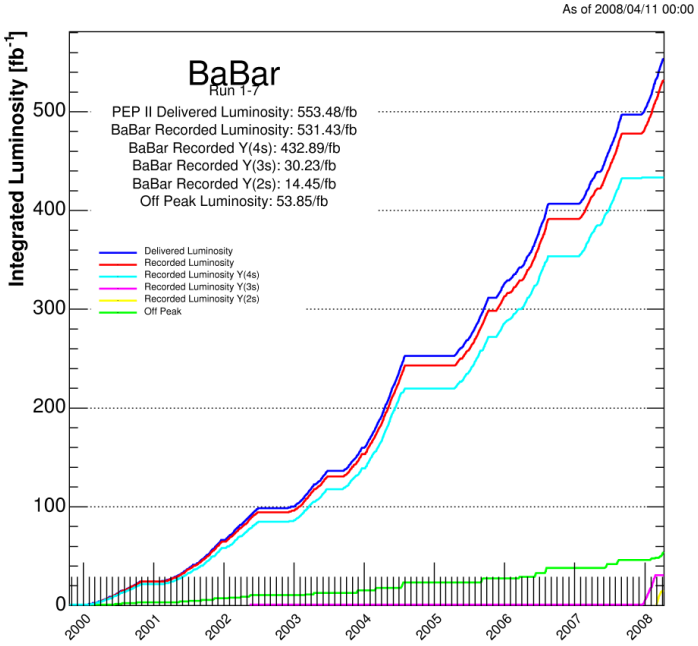
J.D. Bjorken et al., PRD 80 (2009) 075018

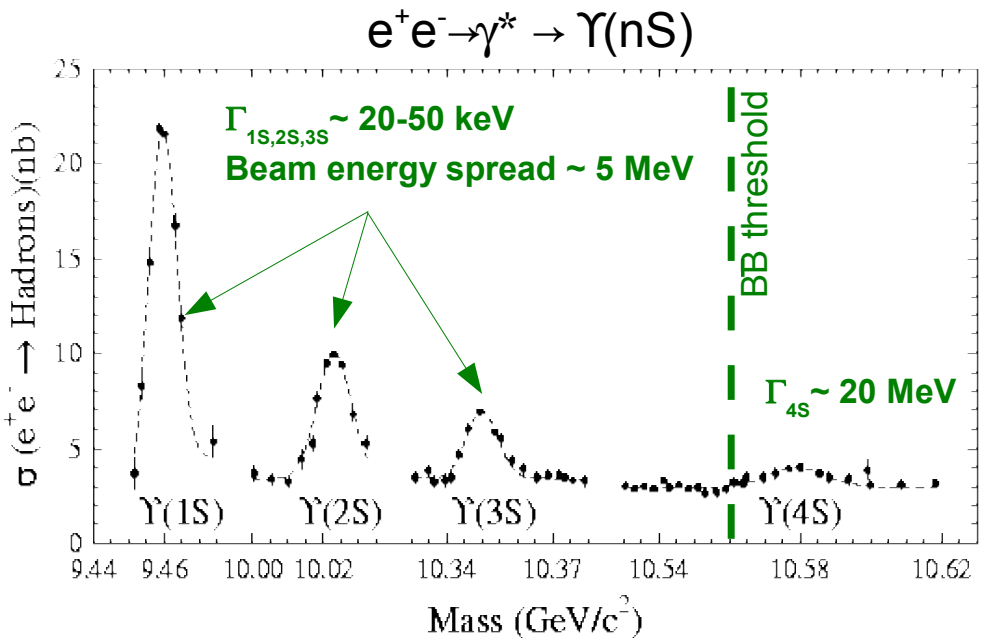
Constraints in $\epsilon = \sqrt{\alpha'/\alpha}$ – $m(A')$ plane

B.Echenard, Adv. in HEP, art.id 514014 (2012)



BABAR collected ~ 533 fb^{-1} of e^+e^- collisions around the Y(4*S*) in 1999–2008



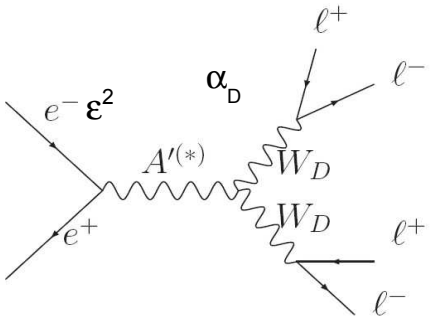


***BABAR* data sample contains**

~470 x 10^6 Υ(4S)
~120 x 10^6 Υ(3S) (10x Belle, 25x CLEO)
~100 x 10^6 Υ(2S) (10x CLEO)
~ 18 x 10^6 Υ(1S) from $\Upsilon(2S) \to \pi^+\pi^- \Upsilon(1S)$

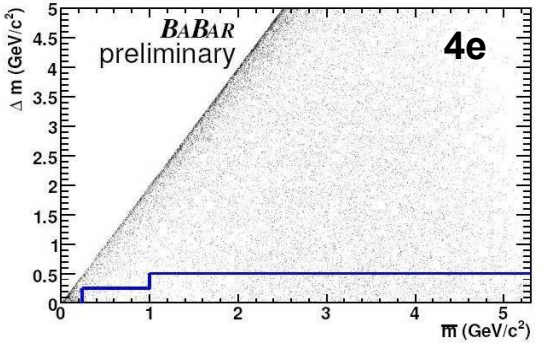
Search for Dark gauge Boson in *BABAR* arXiv:0908.2821

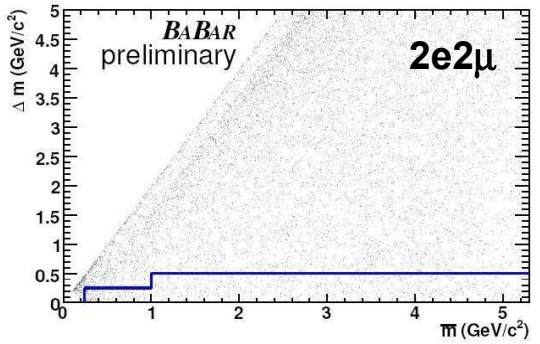
$e^+e^- \to A'^* \to W W'$, $W^{(')} \to e^+e^-, \mu^+\mu^-$

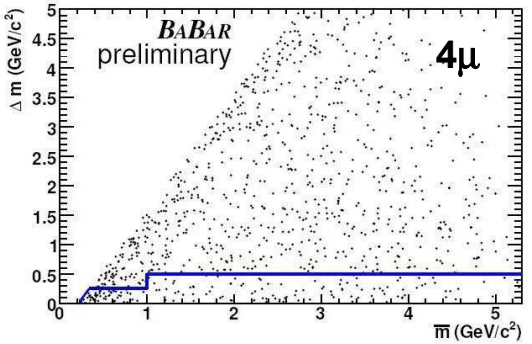


$\alpha_D = g_D^{\,2} / 4\pi$

g_D dark sector gauge coupling







$\bar{m} = (m_{min} + m_{max}) / 2$

$\Delta m = (m_{\_\_} - m_{\_\_})/2$

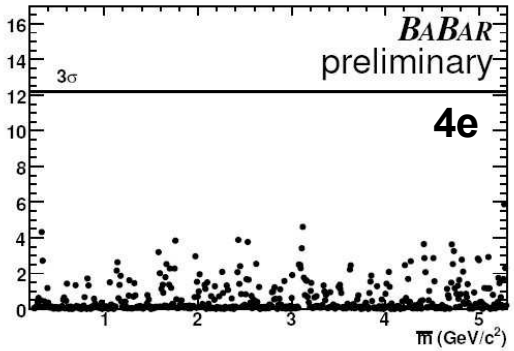
- The simplest extension to a non-Abelian case is SU(2)xU(1), which has **4 bosons: A', W, W' and W''**
- Can produce a pair of dark bosons though an off-shell A'. Process suppressed only by $\alpha_D \varepsilon^2$
- Search for **two dileptonic resonances with similar mass**

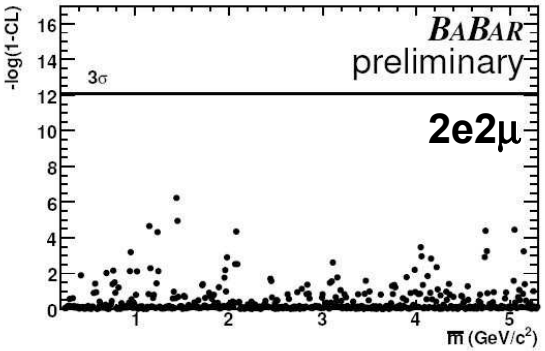
Search for Dark gauge Boson in *BABAR* arXiv:0908.2821

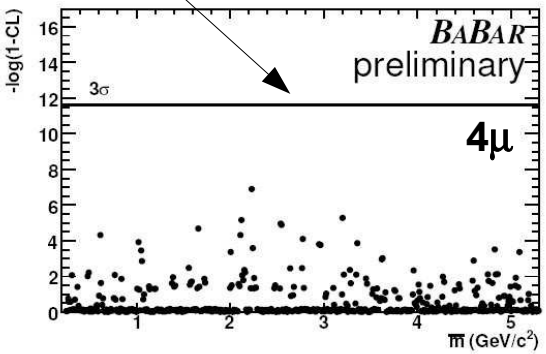
Scan mass spectrum for signal (507 points)

CL distribution

3σ limit, including trial factors

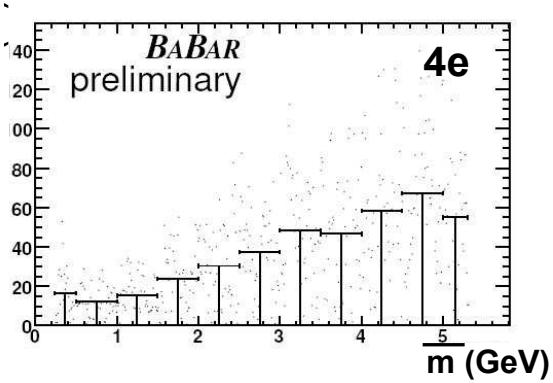


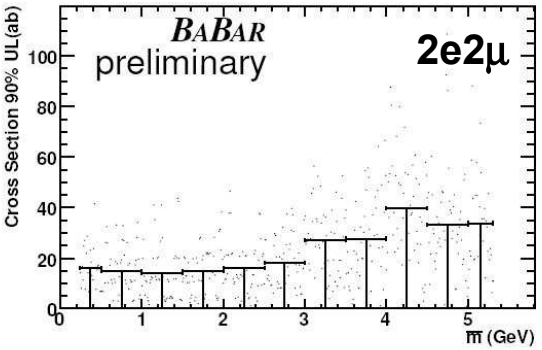


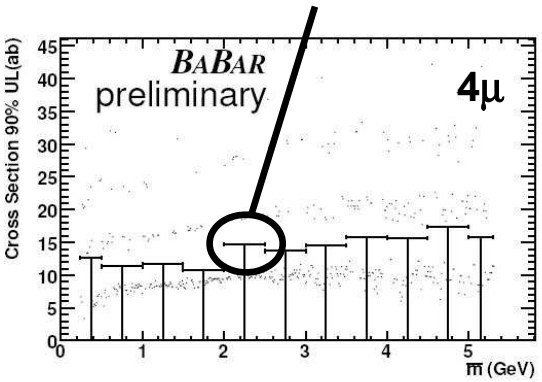


e^+e^- $^{23}_{11}$ $W_D W'_D$ $^{23}_{11}$ 4l cross-section upper limits

Average limit over many bins

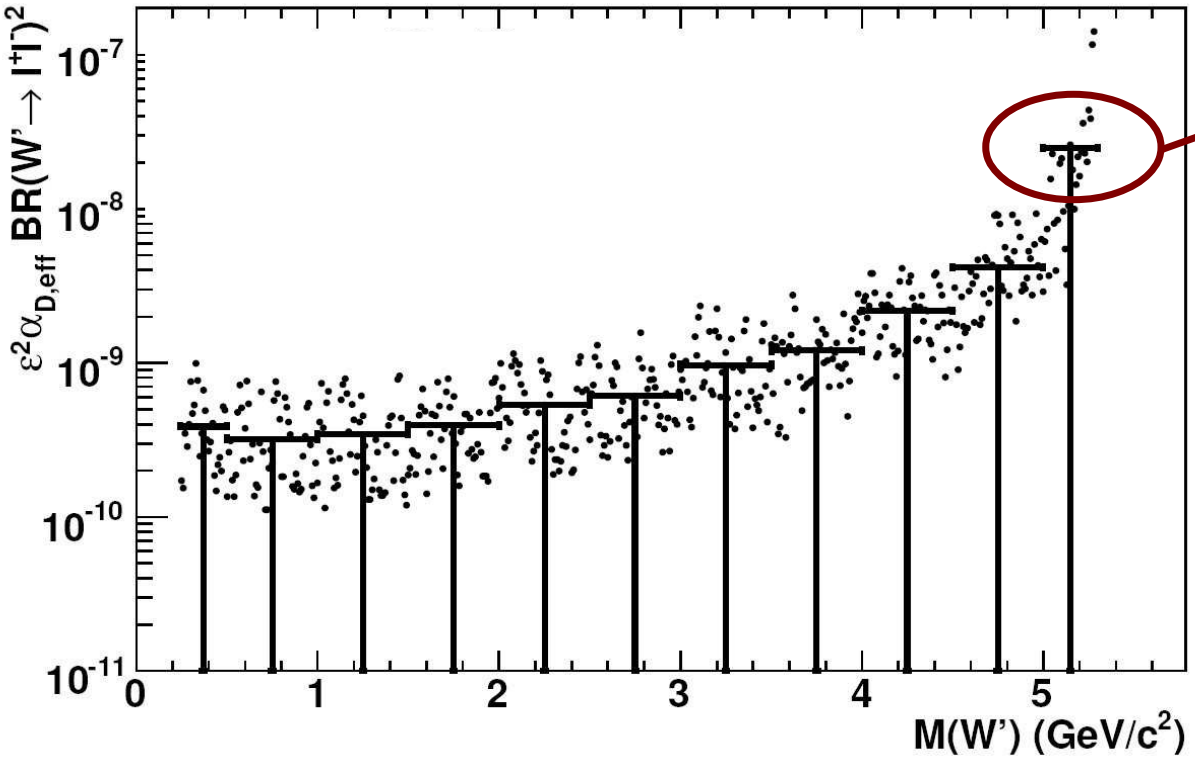






Search for Dark gauge Boson in *BABAR* arXiv:0908.2821

Upper limits on $\alpha_D \varepsilon^2$ x BF$(W \to l^+l^-)^2$ for $m_W = m_{W'}$



Average limit over many bins

Limits on $\varepsilon^2 < 10^{-7} - 10^{-3}$ assuming $\alpha_D = \alpha_{em}$

Expect limits at roughly the same order of magnitude for $m_W - m_{W'} >> 0$

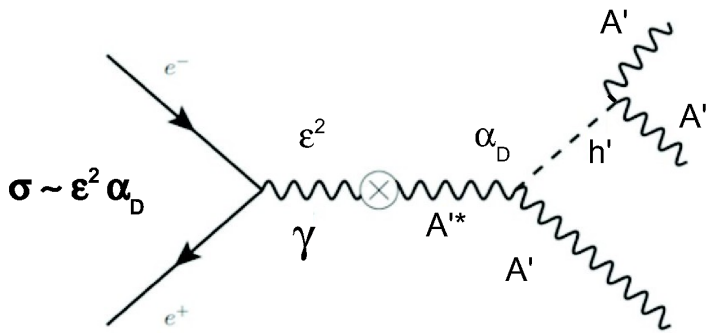
Search for Dark Higgs Boson in *BABAR*

B. Batell et al., PRD 79 (2009) 1150
R. Essig et al., PRD 80 (2009) 0150

- Dark photon mass is generated via the Higgs mechanism, **adding a dark Higgs boson (h') to the theory.**
- **A minimal scenario** has a **single dark photon and a single dark Higgs boson**.
- The **dark Higgs mass** could be at **the GeV scale**
- The **Higgs-strahlung process**

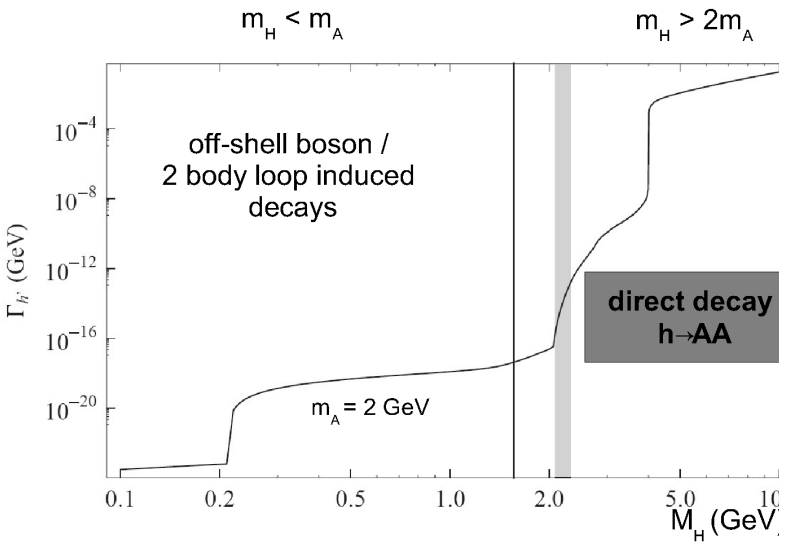
  $e^+e^- \to A'^* \to h'\,A'$, $h' \to A'\,A'$

  is very interesting, as it is **only suppressed by ε^2** and is expected to have a **very small background.**



$\alpha_D = g_D^2 / 4\pi$
g_D is the dark sector gauge coupling

Higgs decay topology



Focus on prompt decays
$m_h > 2m_A$

Search for Dark Higgs Boson in *BABAR* PRL 108 (2012) 2118

Fully reconstructed

$e^+e^- \to h' A', h' \to A' A'$
with $A' \to e^+e^-, \mu^+\mu^-, \pi^+\pi^-$

Partially reconstructed

$e^+e^- \to h' A_1', h' \to A_2' A_3'$
$A'_{1,2} \to e^+e^-, \mu^+\mu^-, A'_3 \to X$ + perm.

Fully reconstructed signal

- Three dark photons fully reconstructed

Modes included

- $e^+e^- \to (l^+l^-)\ (l^+l^-)\ (l^+l^-)$ l=e,μ
- $e^+e^- \to (l^+l^-)\ (l^+l^-)\ (\pi^+\pi^-)$
- $e^+e^- \to (l^+l^-)\ (\pi^+\pi^-)\ (\pi^+\pi^-)$

Selection

- 6 tracks with an invariant mass $m_{tot} > 0.95\ \sqrt{s}$
- apply particle identification
- cosine helicity angle of $A' \to e^+e^-$ candidates < 0.9
- three dark photon candidates have similar mass

Partially reconstructed signal

- In the high mass region ($m_A > 1.2$ GeV), the decay of the dark photon is dominated by $A' \to q\bar{q}$
- Measure 2 A' decaying to leptons and 1 $A' \to q\bar{q}$
- Assign recoiling system to A_3, $P_3 = P_{ee} - P_1 - P_2$

Modes included

- $e^+e^- \to (l^+l^-)\ (\mu^+\mu^-) + X$ where X is not l^+l^- / $\pi^+\pi^-$

Selection

- 4 or more tracks
- apply particle identification for $A' \to l^+l^-$ decays
- cosine helicity angle of $A' \to e^+e^-$ candidates < 0.9
- three dark photon candidates have similar mass

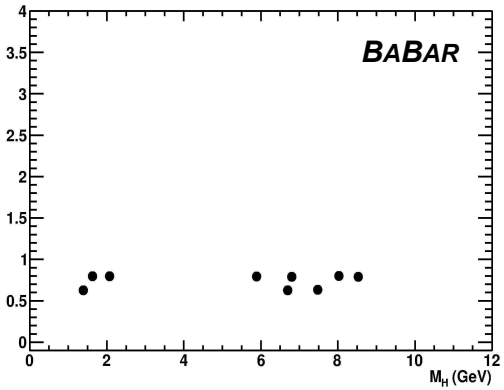
Search for Dark Higgs Boson in *BABAR* PRL 108 (2012) 2118

- Six events are selected from the full *BABAR* dataset (~500 fb^{-1})
- Three entries for each event, corresponding to the three possible assignments of the h' → A'A' decay
- Estimate background from
  - wrong-sign combinations, e.g.

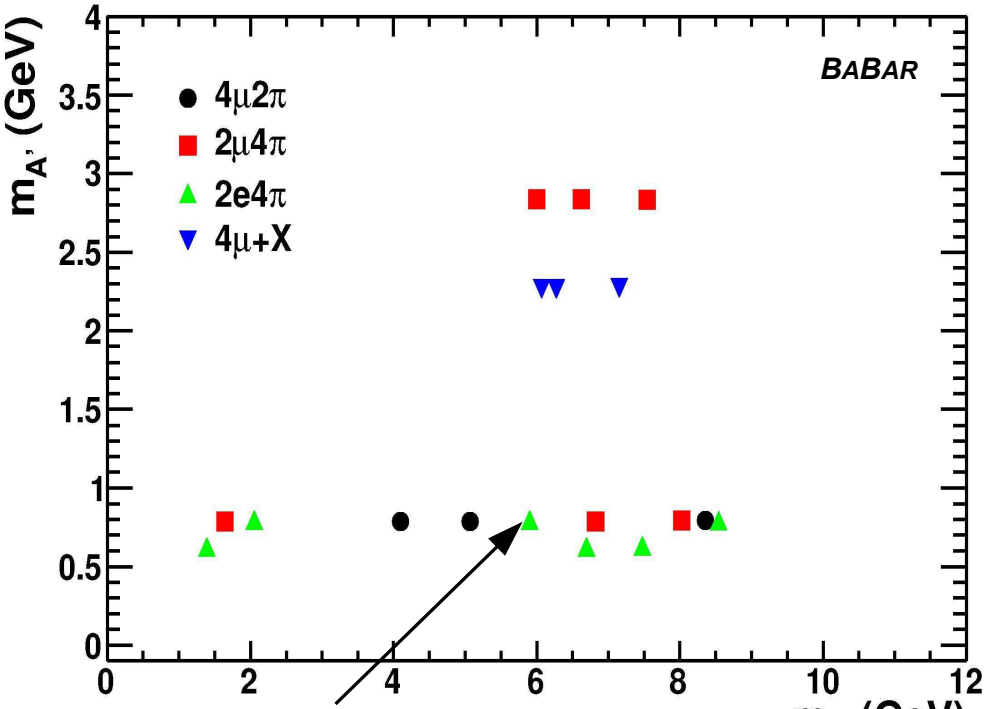
    $e^+e^- \to (e^+e^+)\,(e^-e^-)\,(\mu^+\mu^-)$

  - sidebands from final sample
  - rate for 6 leptons ~ 100x rate for 4π+2l above 1.5 GeV

Wrong-sign combinations



Signal candidates



Likely $e^+e^- \to e^+e^-\,\rho\rho,\omega\omega$
or $e^+e^- \to 6\pi^{\pm}$

No events with 6 leptons, consistent with the pure background hypothesis

Search for Dark Higgs Boson in *BABAR* PRL 108 (2012) 2118

Limit on the cross section $e^+e^- \to h'\,A'$, $h' \to A'\,A'$ in the regime $m_H > 2\,m_A$

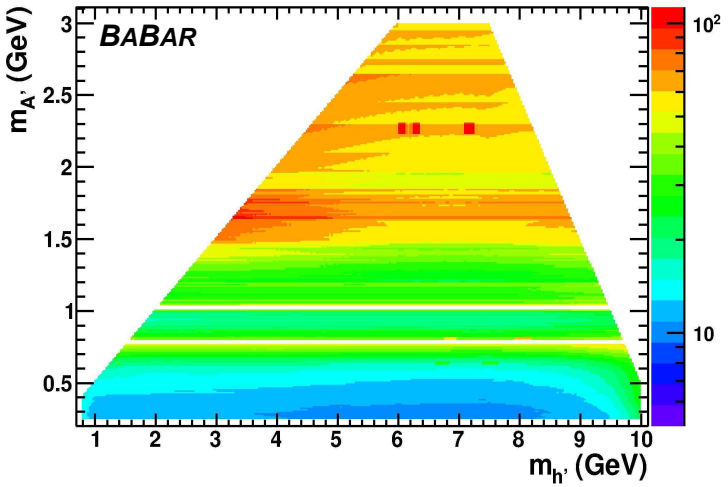
- Scan the m_h vs m_A plane, Bayesian limit with uniform prior in cross-section
- Conservative approach, treat every event as signal candidate (hot spots in bi-dimensional plot)
- **Limits from 10 to ~100 ab**

Extract limits[1] on the product $\alpha_D\varepsilon^2$

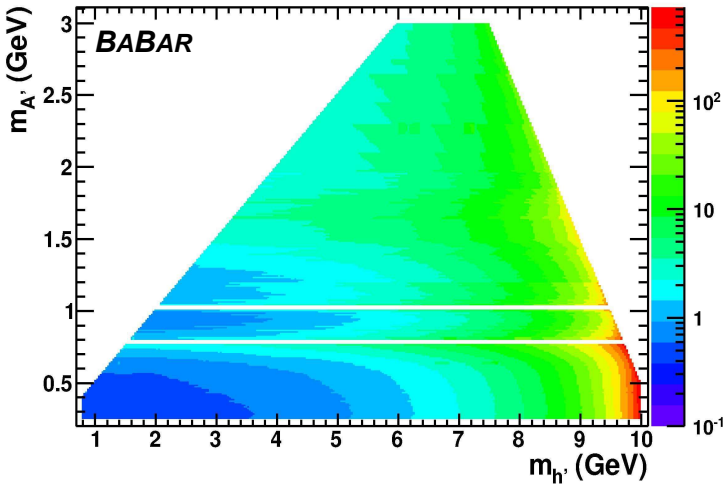
$$\sigma_{e^+e^-\to Vh'} = \frac{\pi\alpha\alpha'\kappa^2}{3s}\left(1-\frac{m_V^2}{s}\right)^{-2}\sqrt{\lambda\left(1,\frac{m_{h'}^2}{s},\frac{m_V^2}{s}\right)}\left[\lambda\left(1,\frac{m_{h'}^2}{s},\frac{m_V^2}{s}\right)+\frac{12m_V^2}{s}\right]$$

- **Limits down to a few x 10^{-10}**

90% CL upper limit on cross section (ab)



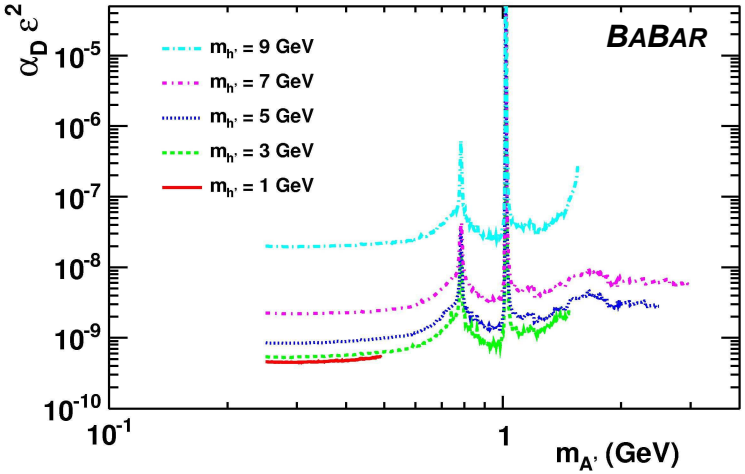
90% CL upper limit on $\alpha_D\varepsilon^2$ (x 10^{-9})



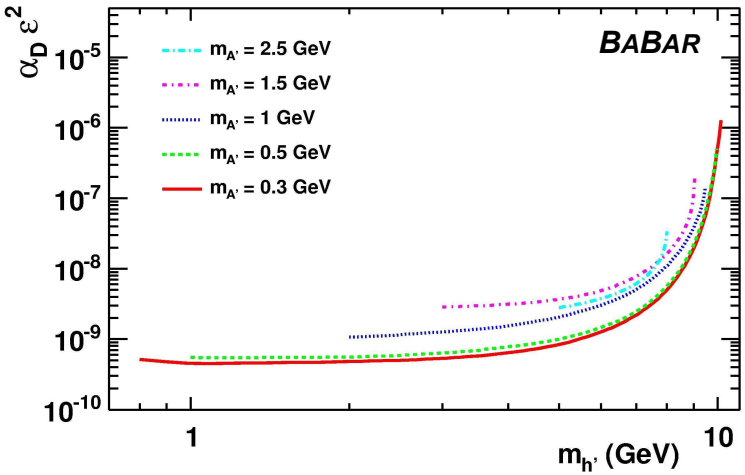
3. *Batell, M. Pospelov and A. Ritz, Phys.Rev.D79:115008,2009.*

Search for Dark Higgs Boson in *BABAR* PRL 108 (2012) 2118

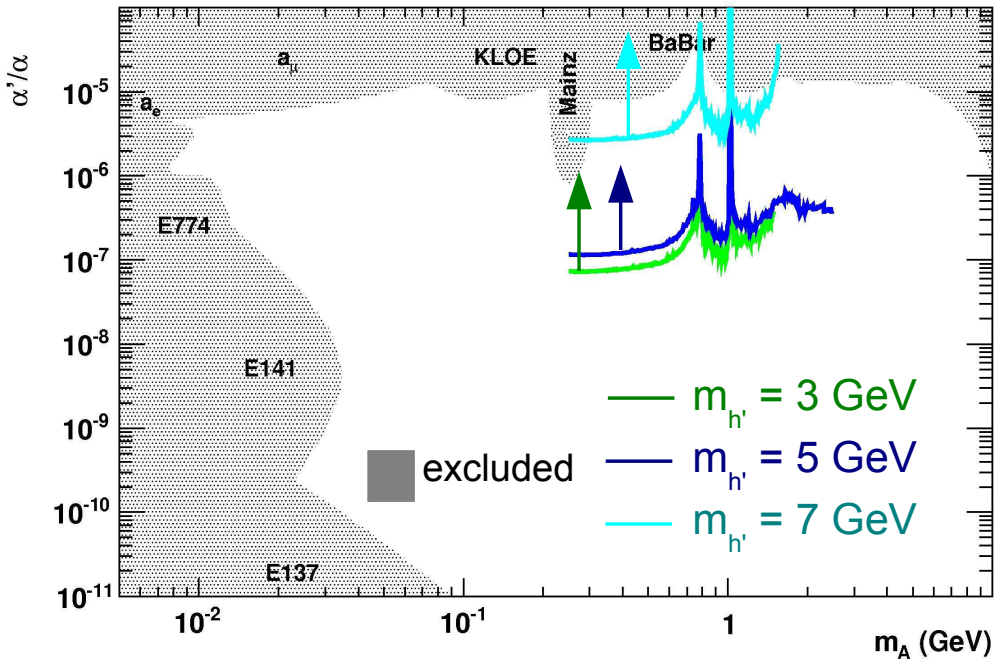
90% CL upper limit on $\alpha_D\varepsilon^2$



90% CL upper limit on $\alpha_D\varepsilon^2$



Limit on $\varepsilon^2=\alpha'/\alpha$ assuming $\alpha_D=\alpha_{em}$ for various Higgs mass



Substantial improvement over existing limits for $m_{h'}$ < 5 - 7 GeV if low-mass dark Higgs boson exists

BABAR light Higgs searches that can be interpreted as dark photon searches

Search for N-MSSM CP-odd Light Higgs in $\mu^+\mu^-$ in *BABAR* PRL 103 (2009) 081803

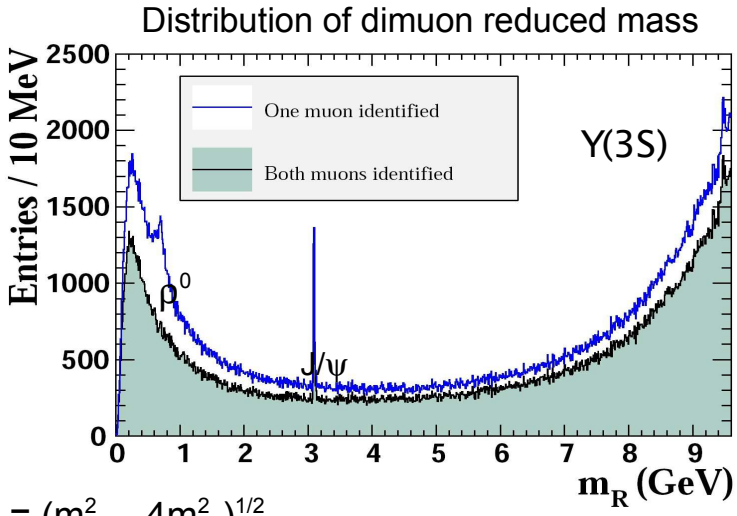
can be interpreted as $e^+e^- \to \gamma A'$, $A' \to \mu^+\mu^-$

use $99 \cdot 10^6$ $\Upsilon(2S)$ and $122 \cdot 10^6$ $\Upsilon(3S)$ events

limits on $B(\Upsilon(nS) \to \gamma A') \cdot B(A' \to \mu^+\mu^-)$

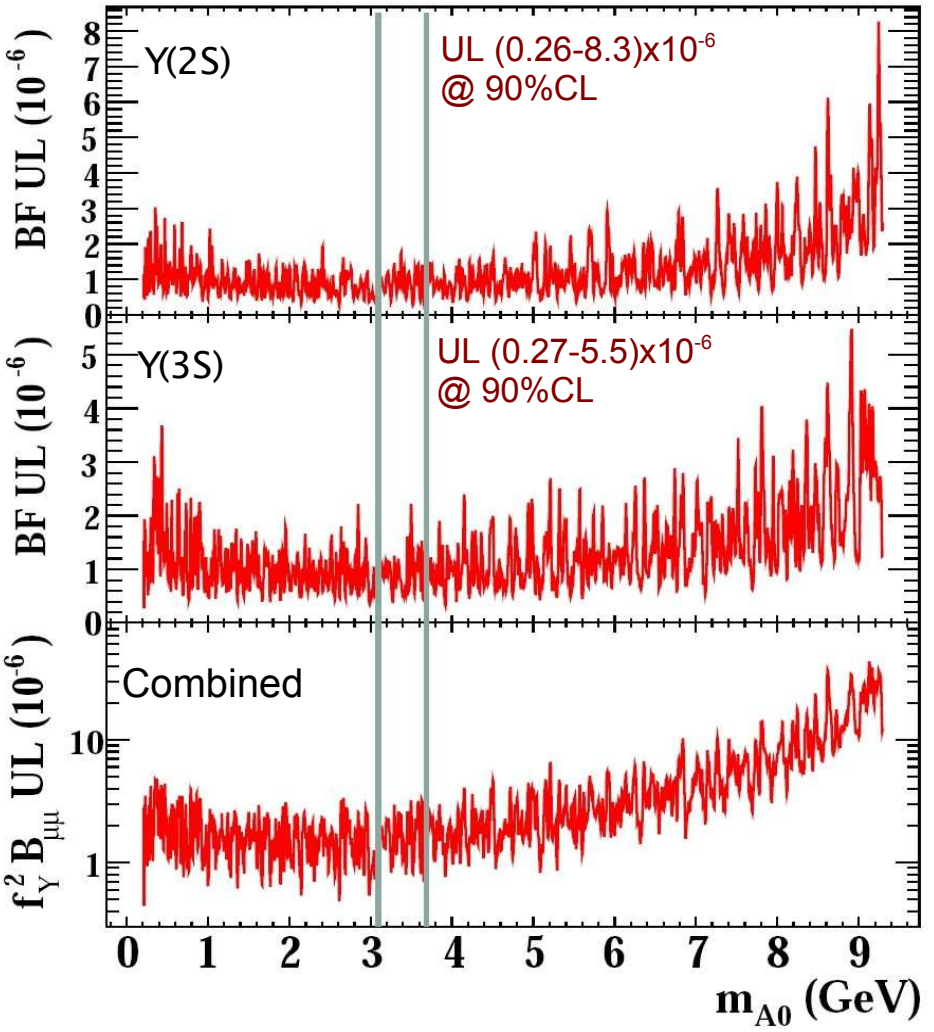
limits on effective coupling $f_\Upsilon^2 \cdot B(A' \to \mu^+\mu^-)$

$$\frac{\Upsilon(nS) \to \gamma A'}{\Upsilon(nS) \to \ell^+\ell^-} = \frac{f_\Upsilon^2}{2\pi\alpha}\left(1 - \frac{m_{A'}}{m_{\Upsilon(nS)}}\right)$$



$m_r = (m^2_{A0} - 4m^2_\mu)^{1/2}$

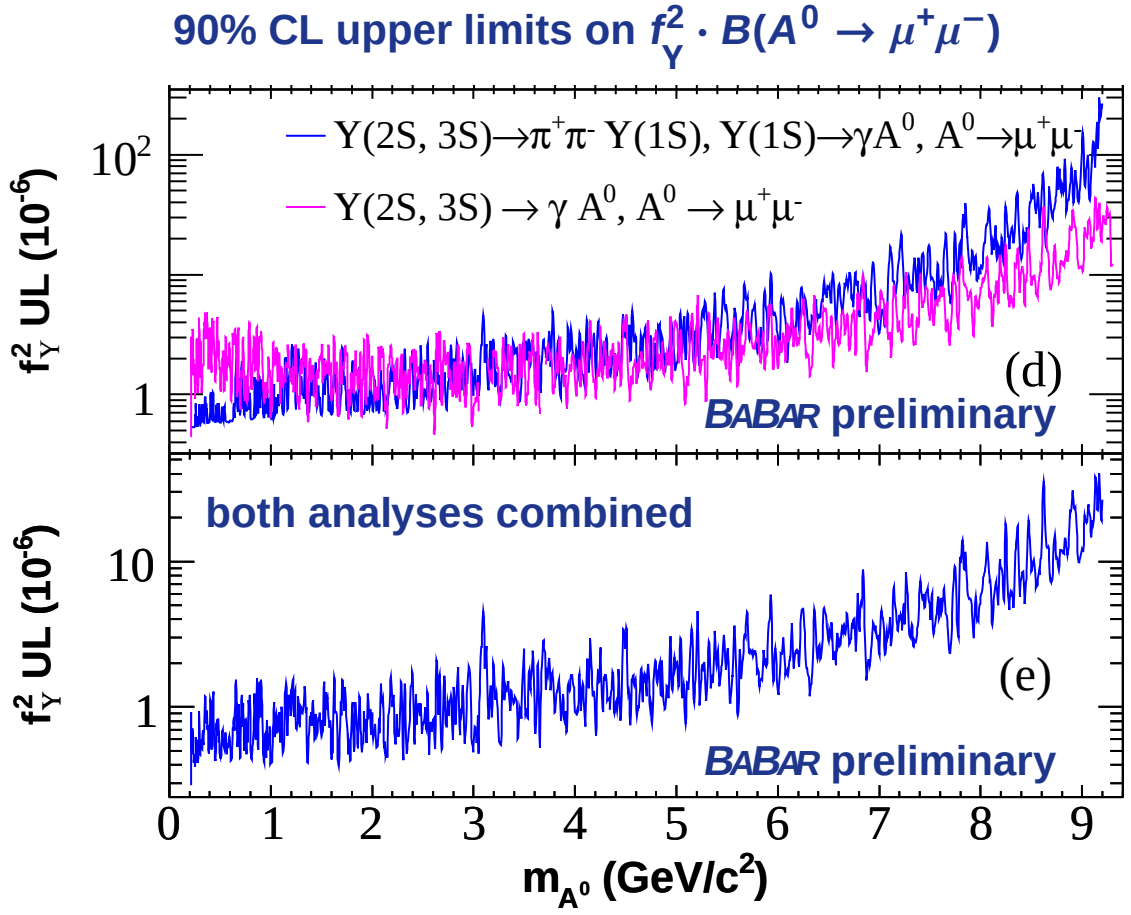
upper limits on $B(e^+e^- \to \gamma A') \cdot B(\quad A' \to \mu^+\mu^-)$



Search for $e^+e^- \to \Upsilon(2S,3S) \to \pi^+\pi^-\Upsilon(1S)$, $\Upsilon(1S) \to \gamma A^0$, $A^0 \to \mu^+\mu^-$ new

- A^0 = low-mass NMSSM Higgs, can be reinterpreted as as dark photon A'
- smaller $\Gamma_{\Upsilon(1S)}$ ➡ larger $B(\Upsilon(1S) \to \gamma A^0)$ ➡ better sensitivity
- tagging $\Upsilon(2S,3S) \to \pi^+\pi^-\Upsilon(1S)$ ➡ more bkg suppression
- use sample of $93{\cdot}10^6$ $\Upsilon(2S)$ and $117{\cdot}10^6$ $\Upsilon(3S)$ events
- select events with 4 tracks $\pi^+, \pi^-, \mu^+, \mu^-$ and one photon with $E_\gamma > 200\,\text{MeV}$
  - ► muon-id required for at least one muon
- constrained fit with event $\sqrt{s}$, $m(\Upsilon(2S,3S))$, $m(\Upsilon(1S))$
- full simulation, data control samples, sidebands used for estimating efficiency and bkg
- search for A^0 peak in 4585 ~half-resolution steps for $0.212 \le m_{A^0} \le 9.20\,\text{GeV}/c^2$,
- $\boldsymbol{B(\Upsilon(1S) \to \gamma A^0) \cdot B(A^0 \to \mu^+\mu^-) < (0.28\text{–}9.7) \times 10^{-6}}$ at 90% CL
- effective coupling can be defined with $$\frac{\Upsilon(nS) \to \gamma A'}{\Upsilon(nS) \to \ell^+\ell^-} = \frac{f_\Upsilon^2}{2\pi\alpha}\left(1 - \frac{m_{A'}}{m_{\Upsilon(nS)}}\right)$$
- $\boldsymbol{f_\Upsilon^2 \cdot B(A^0 \to \mu^+\mu^-) < (0.29\text{–}40) \times 10^{-6}}$ at 90% CL
- 2–3 times better than previous 2009 analysis for $m_{A^0} \le 1.2\,\text{GeV}/c^2$

Search for $e^+e^- \to \Upsilon(2S,3S) \to \pi^+\pi^-\Upsilon(1S)$, $\Upsilon(1S) \to \gamma A^0$, $A^0 \to \mu^+\mu^-$ new



arXiv:1210.0287, sub. PRD-RC, *BABAR* preliminary

Search for $e^+e^- \to \Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$, $\Upsilon(1S) \to \gamma A^0$, $A^0 \to \tau^+\tau^-$ new

- A^0 = low-mass NMSSM Higgs, can be reinterpreted as dark photon A'
- use sample of $(98.3 \pm 0.9)\cdot 10^6$ e^+e^- collisions at the $\Upsilon(2S)$ peak
- select events with:
  - four tracks: $\pi^+\pi^-$ and two 1-prong tau decay products
    at least one tau 1-prong decay must be a lepton
  - one photon from $\Upsilon(2S)$ decay, plus extra photons from tau-decay π^0 and accelerator bkg
- $\Upsilon(1S)$ and A^0 masses reconstructed from event $\sqrt{s}$, $\pi^+\pi^-$ momenta, $\Upsilon(1S)$-decay photon momentum
- signal efficiency estimated with full simulation
- expected bkg estimated with full simulation, data control samples, sidebands
- significance assessed with toy MC simulated experiments with full simulation
- fit for $m(A^0)$ peak for $3.6\,\text{GeV} < m(A^0) < 9.2\,\text{GeV}$ in 201 steps (half resolution): no significant signal
- $\boldsymbol{B(\Upsilon(1S) \to \gamma A^0) \cdot B(A^0 \to \tau^+\tau^-) < (0.9\text{–}13)\cdot 10^{-5}}$ at 90% CL for $3.6\,\text{GeV} < m(A^0) < 9.2\,\text{GeV}$
- upper limits combined with former analysis $\Upsilon(3S) \to \gamma A^0$, $A^0 \to \tau^+\tau^-$, PRL 103 (2009) 181801

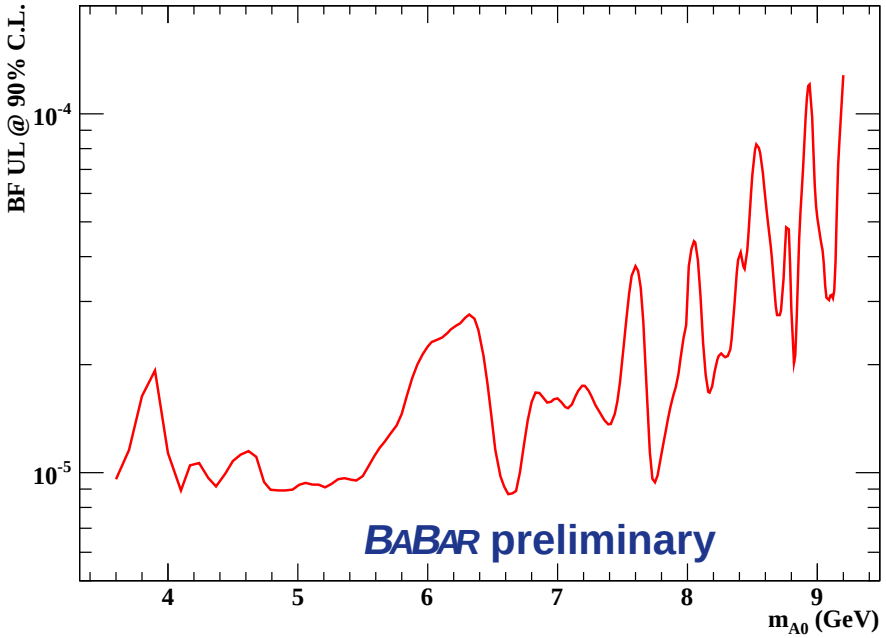
Search for $e^+e^- \to \Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$, $\Upsilon(1S) \to \gamma A^0$, $A^0 \to \tau^+\tau^-$ new

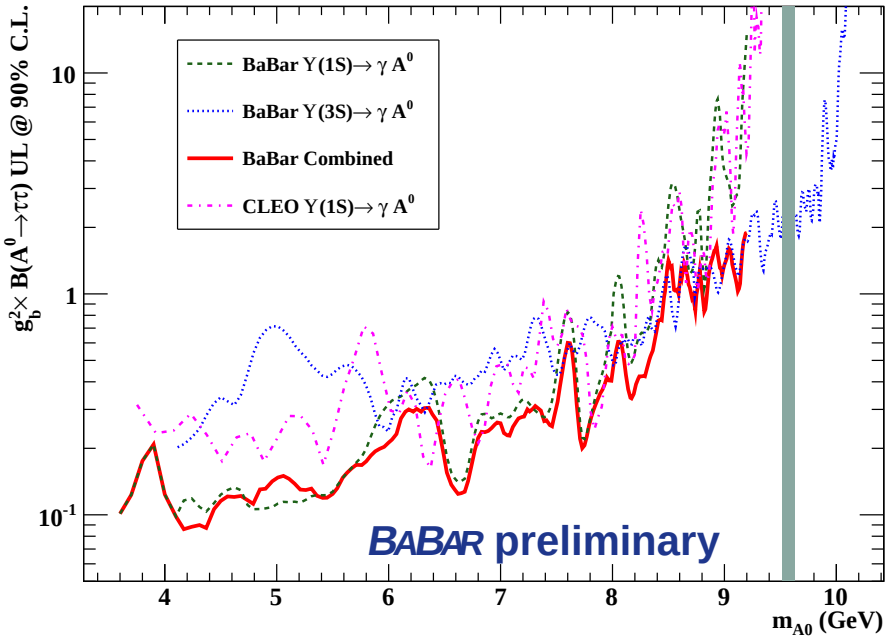
90% CL limits on
$B(\Upsilon(1S) \to \gamma A^0) \cdot B(A^0 \to \tau^+\tau^-)$
(this analysis only)

90% CL limits on $b - A^0$ Yukawa coupling g_b^2

$$\frac{\Upsilon(nS) \to \gamma A^0}{\Upsilon(nS) \to \ell^+\ell^-} = \frac{g_b^2 G_F m_b^2}{\sqrt{2}\pi\alpha} \mathcal{F}_{QCD} \left(1 - \frac{m_{A^0}}{m_{\Upsilon(nS)}}\right)$$

also combined with PRL 103 (2009) 181801





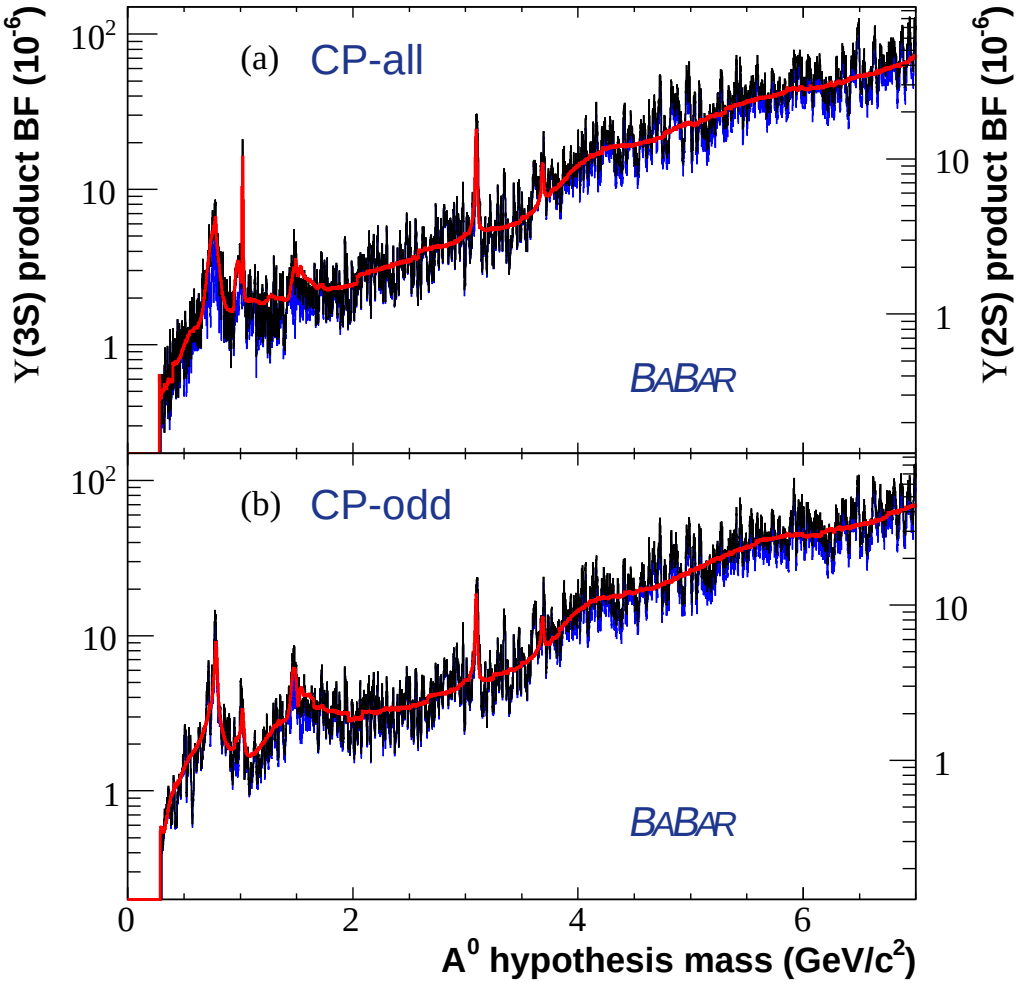
arXiv:1210.5669, sub. PRD-RC, *BABAR* preliminary

Search for $e^+e^- \to \Upsilon(2S, 3S) \to \gamma A^0$, $A^0 \to$ hadrons, PRL 107 (2011) 221803

- A^0 = low-mass CP-odd or CP-even NMSSM Higgs, can be reinterpreted as dark photon A'
- sensitive channel for high mass Higgs below the $\Upsilon(4S)$ peak
- use sample of $98 \cdot 10^6$ $\Upsilon(2S)$ and $121 \cdot 10^6$ $\Upsilon(3S)$ events
- A^0 candidate built from:
  - $K_S \to \pi^+\pi^-$ candidates,
  - remaining hadrons identified as pions, kaons or protons
  - $\pi^0 \to \gamma\gamma$ candidates and extra photons
- $A^0 - \gamma$ fit with constraint to event $\sqrt{s}$, $m(A^0)$-dependent fit χ^2 cut
- two parallel analyses: CP-odd considers only CP-odd final states, CP-all all final states
- signal efficiency estimated with full simulation
- expected bkg estimated with full simulation, data control samples, sidebands
- significance assessed with toy MC simulated experiments with full simulation
- fit for $m(A^0)$ peak for $0.3\,\text{GeV} < m(A^0) < 7\,\text{GeV}$ with about 6700 steps: no significant signal
- **$B(\Upsilon(nS) \to \gamma A^0) \cdot B(A^0 \to \text{hadrons}) < (1\text{–}80) \cdot 10^{-6}$** at 90% CL for $0.3\,\text{GeV} < m(A^0) < 7\,\text{GeV}$

Search for $e^+e^- \to \Upsilon(2S, 3S) \to \gamma A^0$, $A^0 \to$ hadrons, PRL 107 (2011) 221803

90% CL upper limits on $B(\Upsilon(nS) \to \gamma A^0) \cdot B(A^0 \to \text{hadrons})$



Conclusions

- *BABAR* has set constraints on the mass and couplings of “dark-sector” light bosons
- searches for N-MSSM CP-odd Higgs can be reinterpreted as constraints on “dark-sector” bosons
  - *BABAR* will provide further results soon
- 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