Searches for Low-mass Higgs and Dark-sector Bosons at *BABAR*

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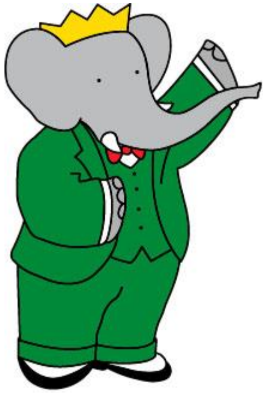
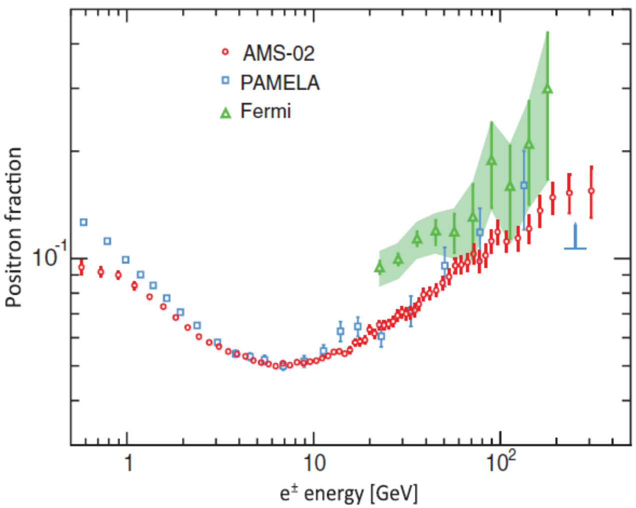


Dark sector in a nutshell

- 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, AMS-02, DAMA/LIBRA, PLANCK, etc.; e.g, Arkani-Hamed *et al.*, Phys. Rev. D **79**, 015014 (2009).

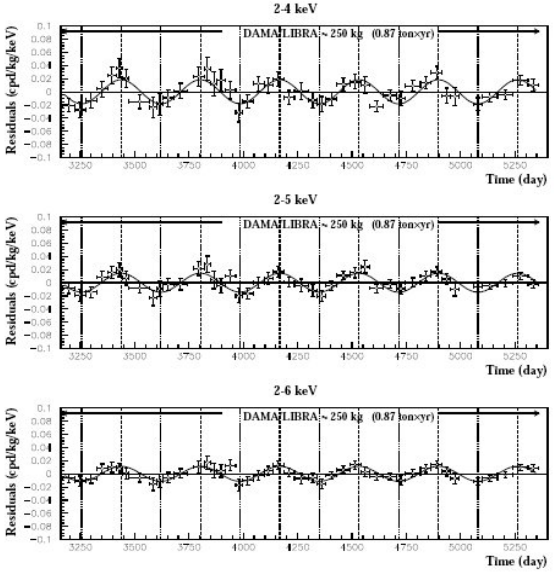
- **The possibility of hidden MeV/GeV scale sector is poorly constrained and worth exploring.**

AMS-02, PAMELA, Fermi Positron Excess



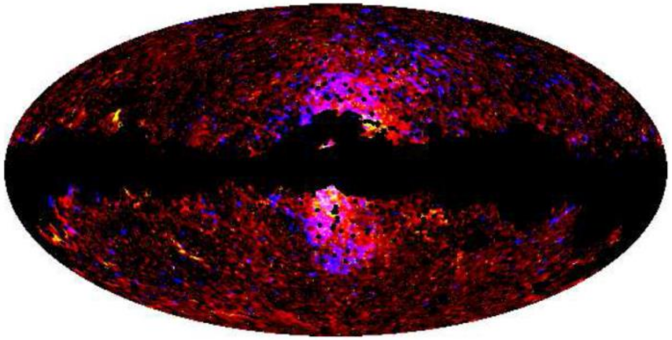
AMS, Phys. Rev. Lett. 110, 141102 (2013)

DAMA/LIBRA Annual Modulation



DAMA Collab., Eur. Phys. J. C (2010) 67

Fermi / Planck Galactic Haze



Ade *et al.*, Astron.Astrophys., 554 (2012) A139

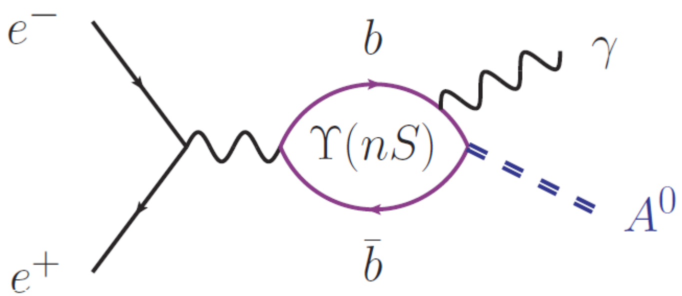
Dobler *et al.*, Astrophys.J.717 (2010) 825-842

- Excess of electrons / positrons
- Few / no antiprotons
- Large annihilation cross section

Low-mass Higgs searches

- *BaBar* has searched for a low-mass, CP-odd, non-singlet Higgs **A^0**, a generic feature of many NMSSM models, in the Upsilon decays (n=1,2,3)

$$\Upsilon(nS) \rightarrow \gamma A^0 \longrightarrow$$



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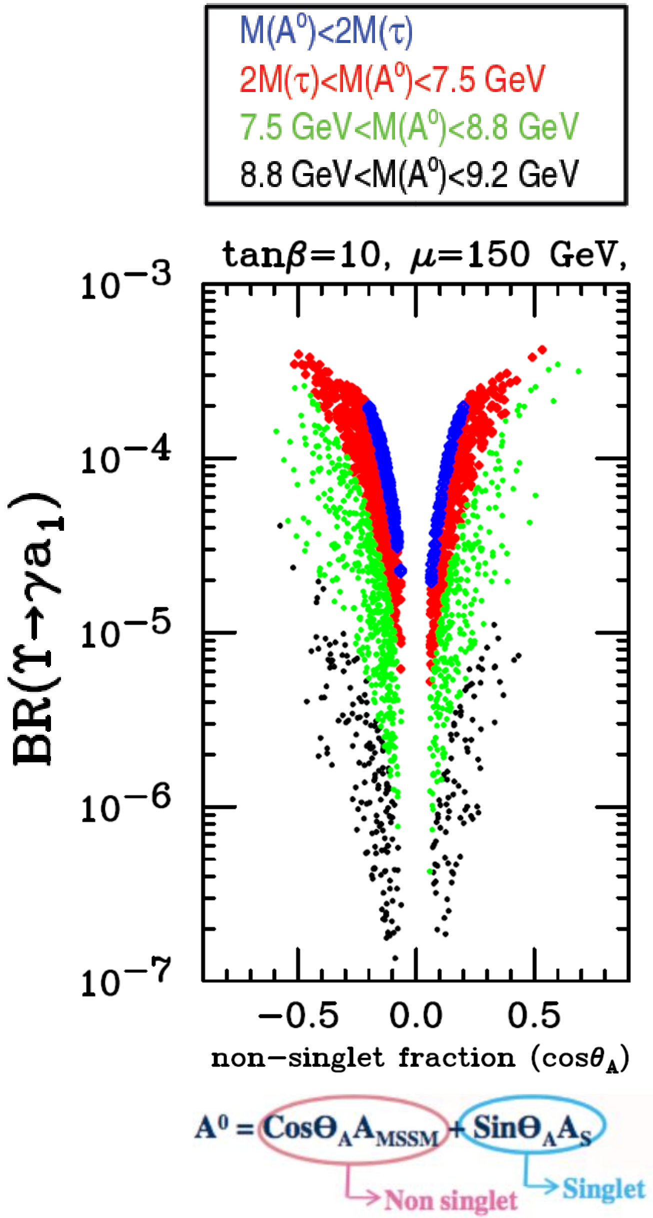
- Branching fraction predictions for this process range over several orders of magnitude depending on the non-singlet fraction and NMSSM parameter values.



Low-mass Higgs searches

Gunion et al, PRD 81 (2010) 075003

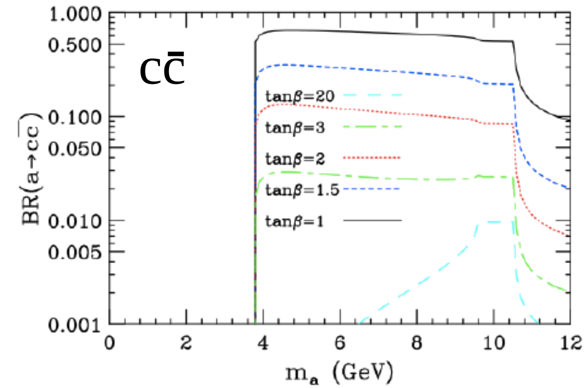
- Babar has searched for a low-mass, CP-odd, non-singlet Higgs A^0, a generic feature of many NMSSM models, in the Upsilon decays (n=1,2,3)

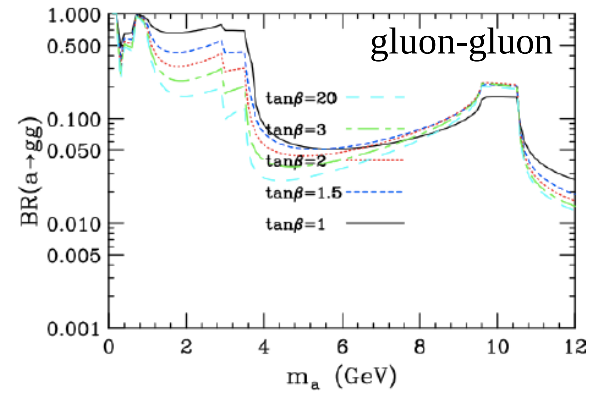
$$\Upsilon(nS) \rightarrow \gamma A^0$$

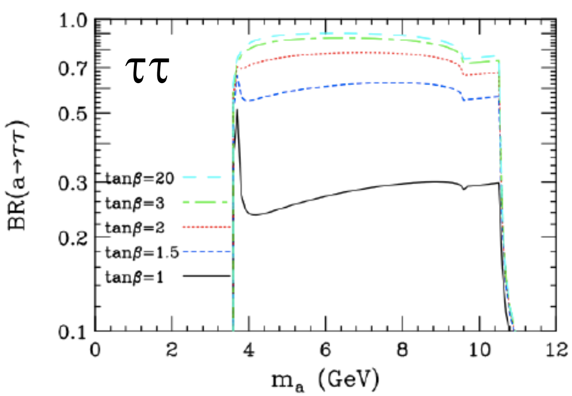
- Branching fraction predictions range over several orders of magnitude depending on the non-singlet fraction and NMSSM parameter values.

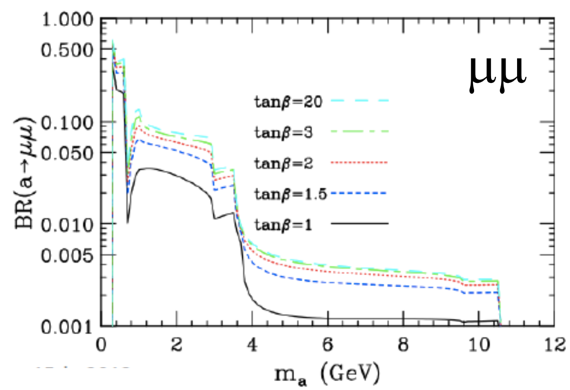
- Several different final states (depending on the A^0 mass) are accessible in Upsilon decays, with branching ratios dependent on properties of the final state fermions as well as on NMSSM parameters.

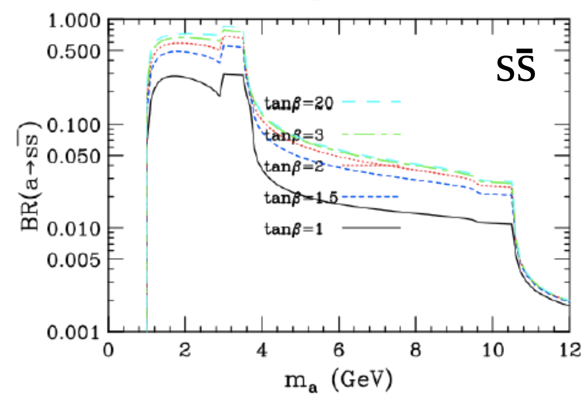
$$B\left(A^0 \rightarrow f\bar{f}\right) \propto m_f^2 / \tan^2\beta \quad \text{up-type fermions}$$
$$B\left(A^0 \rightarrow f\bar{f}\right) \propto m_f^2 \tan^2\beta \quad \text{down-type fermions}$$



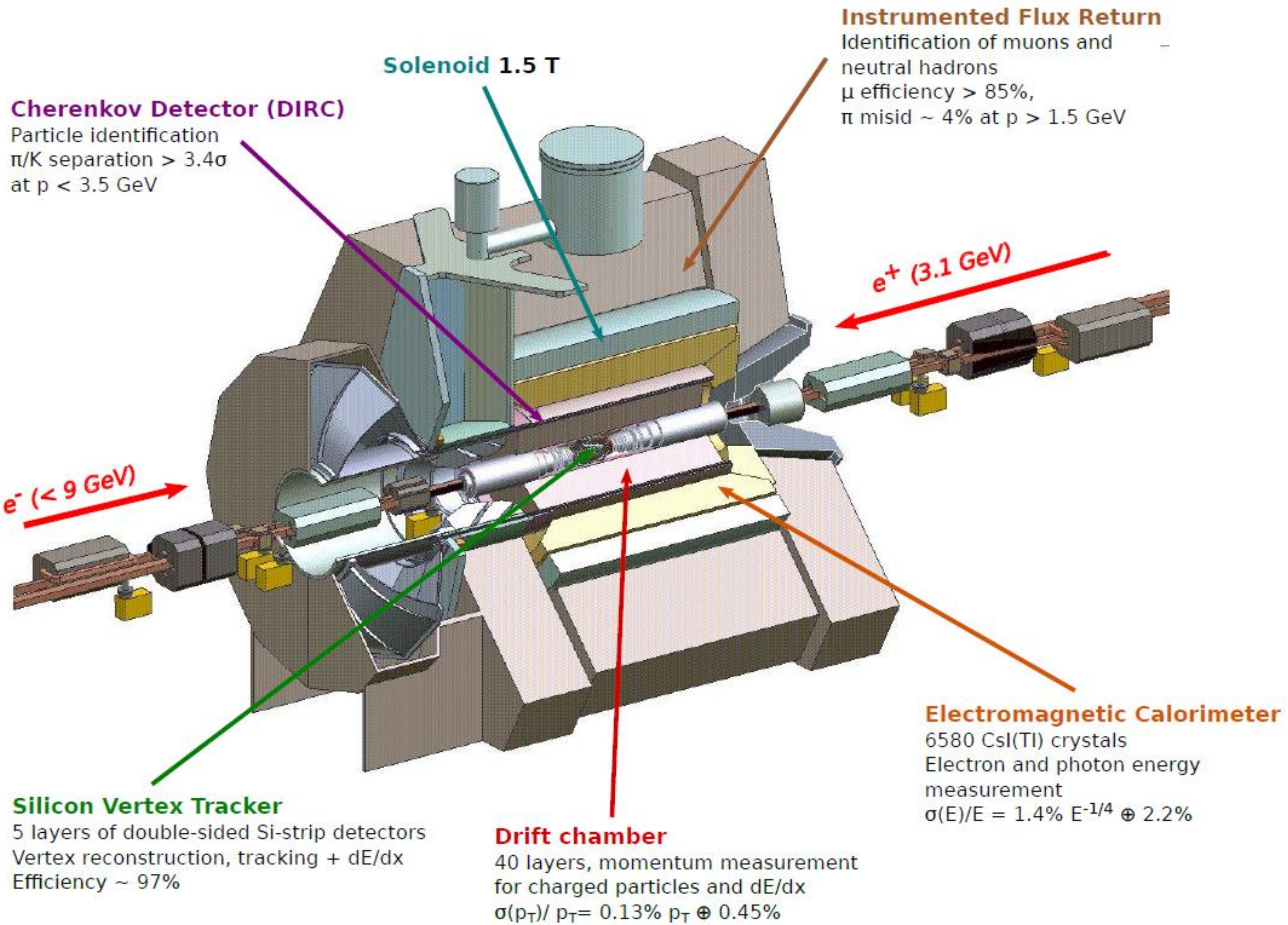




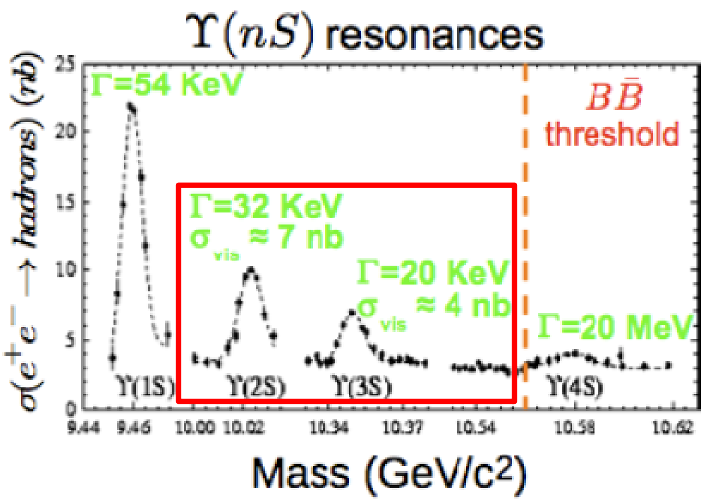




The *BaBar* Detector at PEP-II (SLAC)

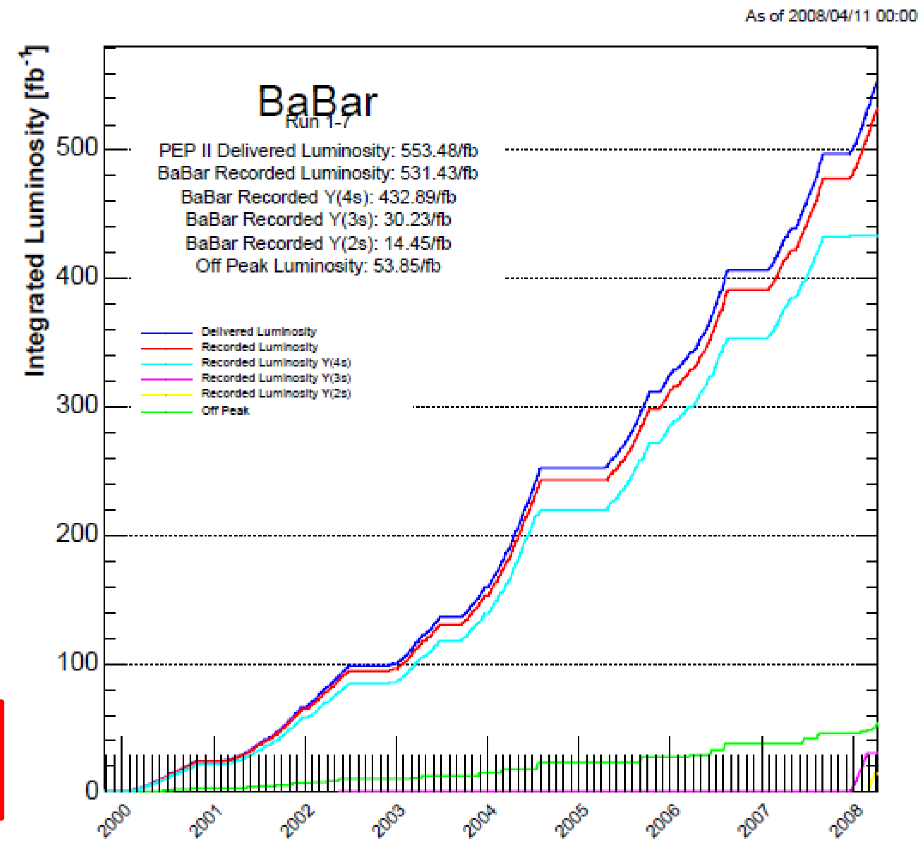


PEP-II: asymmetric e^+e^- collider, running mostly on $\Upsilon(4S)$



$425.6\ \mathrm{fb}^{-1}$	at $\Upsilon(4S)$	➡	467×10^6	$B\bar{B}$
$28.0\ \mathrm{fb}^{-1}$	at $\Upsilon(3S)$	➡	122×10^6	$\Upsilon(3S)$
$13.6\ \mathrm{fb}^{-1}$	at $\Upsilon(2S)$	➡	99×10^6	$\Upsilon(2S)$

BABAR recorded luminosity



Data taking finished April 2008

Low-mass Higgs searches at *BABAR*

⇨ ***BABAR*** has an on-going program, in place for several years now, to systematically search for low-mass Higgs in all kinematically accessible final states.

Older analyses	
$\Upsilon(2,3S) \rightarrow \gamma\, A^0; A^0 \rightarrow \mu^+\mu^-$	PRL 103, 081803 (2009)
$\Upsilon(3S) \rightarrow \gamma\, A^0; A^0 \rightarrow \tau^+\tau^-$	PRL 103, 181801 (2009)
$\Upsilon(1S) \rightarrow \gamma\, A^0; A^0 \rightarrow$ invisible	PRL 107, 021804 (2011)
$\Upsilon(2,3S) \rightarrow \gamma\, A^0; A^0 \rightarrow$ hadrons	PRL 107, 221803 (2011)
Today's Presentation	
$\Upsilon(1S) \rightarrow \gamma\, A^0; A^0 \rightarrow \mu^+\mu^-$	PRD 87, 031102(R) (2013)
$\Upsilon(1S) \rightarrow \gamma\, A^0; A^0 \rightarrow \tau^+\tau^-$	PRD 88, 071102(R) (2013)
$\Upsilon(1S) \rightarrow \gamma\, A^0; A^0 \rightarrow gg$ or $s\bar{s}$	PRD 88, 031701(R) (2013)

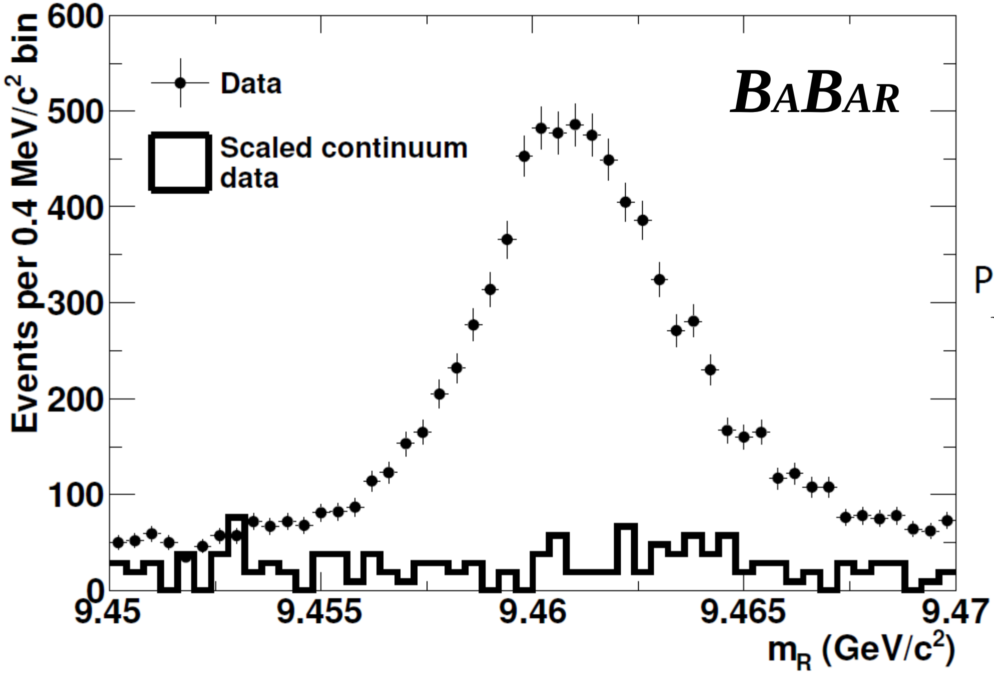
Υ(1S) Reconstruction

- Although *BABAR* did not run at the Υ(1S), a sample of Υ(1S) is available through radiative di-pion decays of Υ(2S) and Υ(3S)

Υ(2S) → $\pi^+\pi^-$ Υ(1S)	Υ(3S) → $\pi^+\pi^-$ Υ(1S)
18 x 10^6 Υ(1S)	5 x 10^6 Υ(1S)

- Di-pion tagging removes most continuum backgrounds using recoil mass

$$M^2_{recoil} = M^2_{\Upsilon(2S)} + M^2_{\pi\pi} - 2M_{\Upsilon(2S)}E_{\pi\pi}$$



PRD 88, 031701(R) (2013)
Υ(1S) → γ A^0 (→ gg, $s\bar{s}$)

Gaussian with long tail on both sides

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

- Gluon-gluon decays are accessed as a sum-over-exclusive-modes through reconstruction of 26 exclusive final states.

- All hadronic systems are CP-odd, with up to 8 final-state particles of which no more than two are π^0.

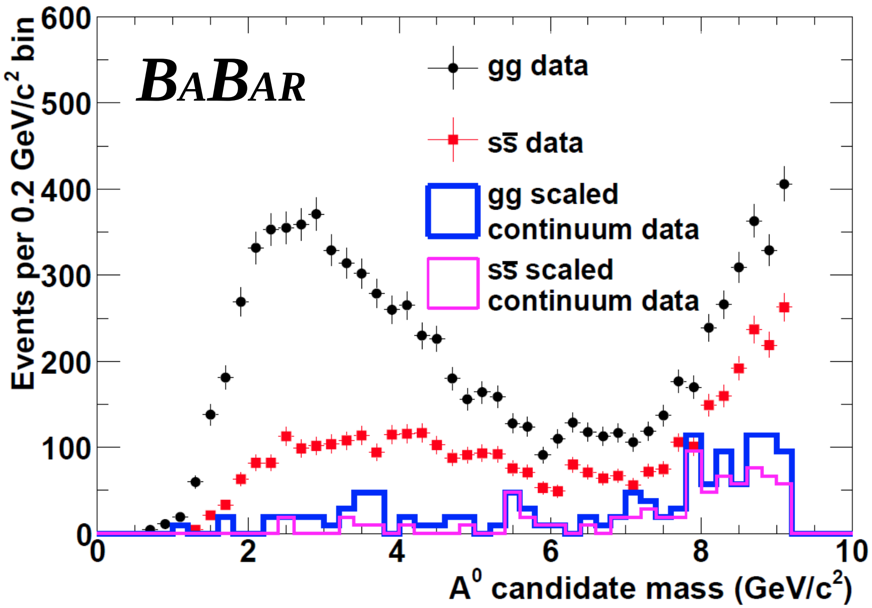
- Decays to $s\bar{s}$ are reconstructed using only decays which contain 2 or 4 kaons.

- The hadronic system is combined with a photon, with the mass of the combined system required to be consistent with the $\Upsilon(1S)$ mass in order to improve the A^0 mass resolution.

#	Channel	#	Channel
1	$\pi^+\pi^-\pi^0$	14	$K^+K^-\pi^+\pi^-$
2	$\pi^+\pi^-2\pi^0$	15	$K^+K^-\pi^+\pi^-\pi^0$
3	$2\pi^+2\pi^-$	16	$K^\pm K^0_S\pi^\mp\pi^+\pi^-$
4	$2\pi^+2\pi^-\pi^0$	17	$K^+K^-\eta$
5	$\pi^+\pi^-\eta$	18	$K^+K^-2\pi^+2\pi^-$
6	$2\pi^+2\pi^-2\pi^0$	19	$K^\pm K^0_S\pi^\mp\pi^+\pi^-2\pi^0$
7	$3\pi^+3\pi^-$	20	$K^+K^-2\pi^+2\pi^-\pi^0$
8	$2\pi^+2\pi^-\eta$	21	$K^+K^-2\pi^+2\pi^-2\pi^0$
9	$3\pi^+3\pi^-2\pi^0$	22	$K^\pm K^0_S\pi^\mp2\pi^+2\pi^-\pi^0$
10	$4\pi^+4\pi^-$	23	$K^+K^-3\pi^+3\pi^-$
11	$K^+K^-\pi^0$	24	$2K^+2K^-$
12	$K^\pm K^0_S\pi^\mp$	25	$p\bar{p}\pi^0$
13	$K^+K^-2\pi^0$	26	$p\bar{p}\pi^+\pi^-$

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

- Plot below shows A^0 mass spectra after applying all selection criteria and selecting one signal candidate per event.
- The mass resolution is ~100 MeV/c^2 for all masses.
- Efficiences range from a few percent at low mass to ~10^{-4} at the highest masses.

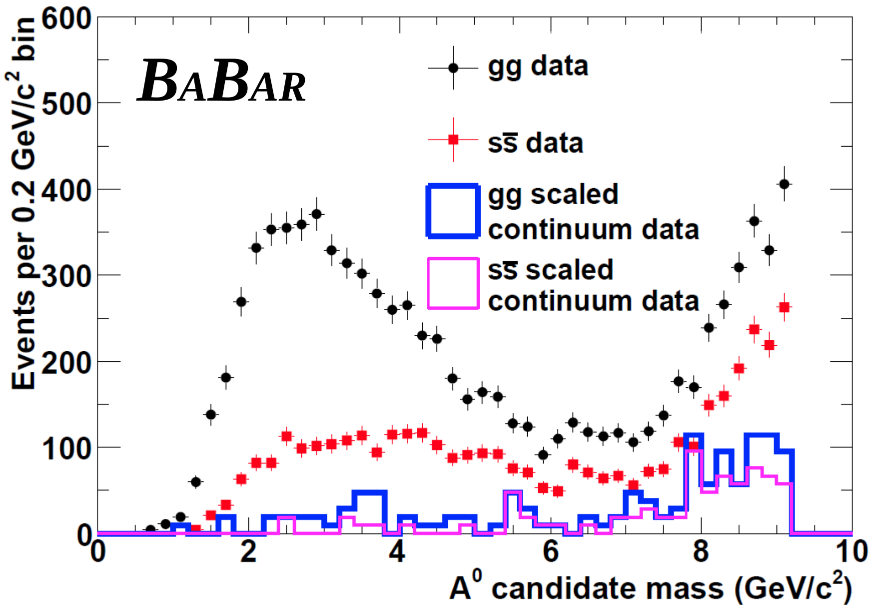


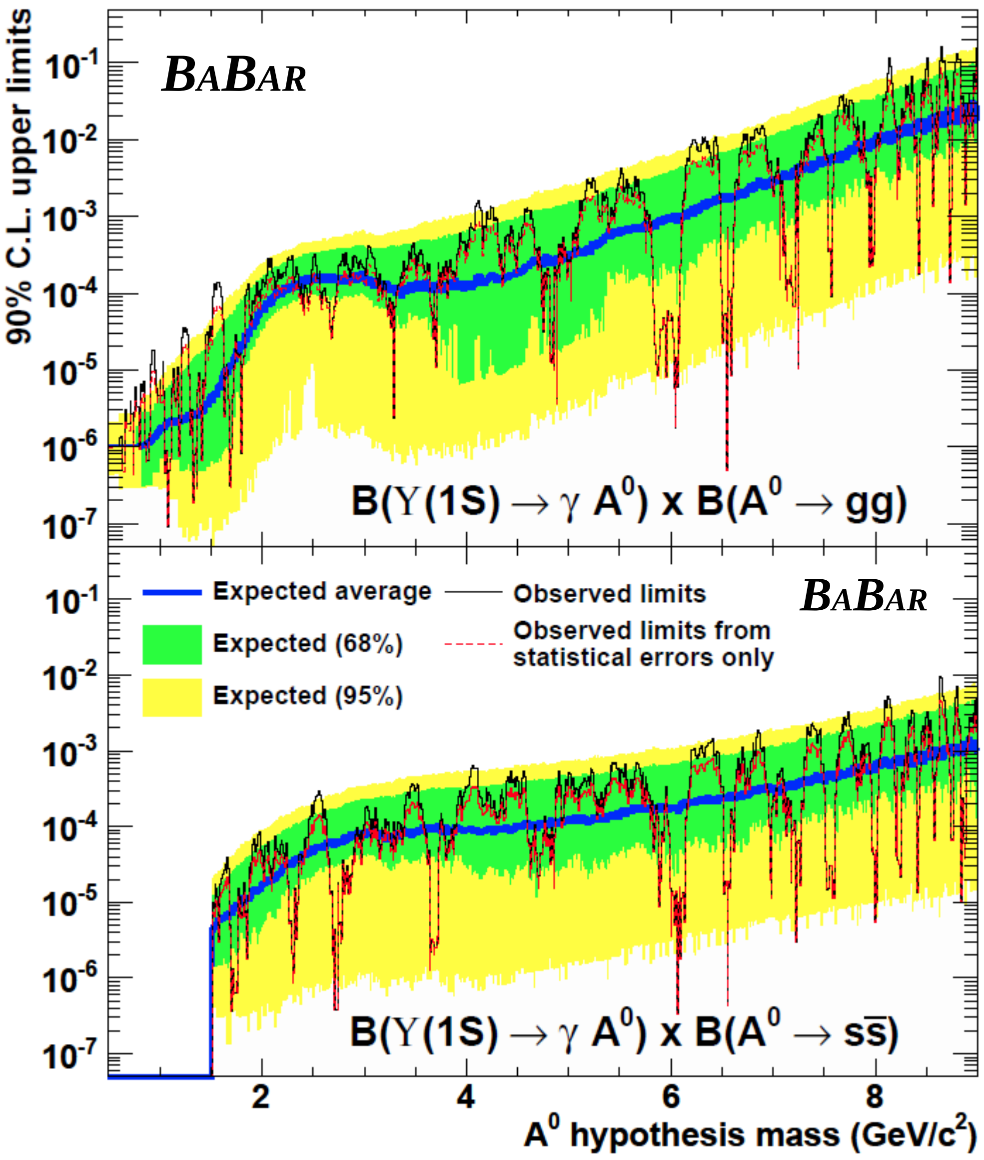
$\Upsilon(1S) \rightarrow \gamma A^0 (\rightarrow gg, s\bar{s})$

- 90% CL upper limits on the product branching fractions

$$\mathcal{B}(\Upsilon(1S) \rightarrow \gamma A^0) \cdot \mathcal{B}(A^0 \rightarrow gg)$$
$$\mathcal{B}(\Upsilon(1S) \rightarrow \gamma A^0) \cdot \mathcal{B}(A^0 \rightarrow s\bar{s})$$

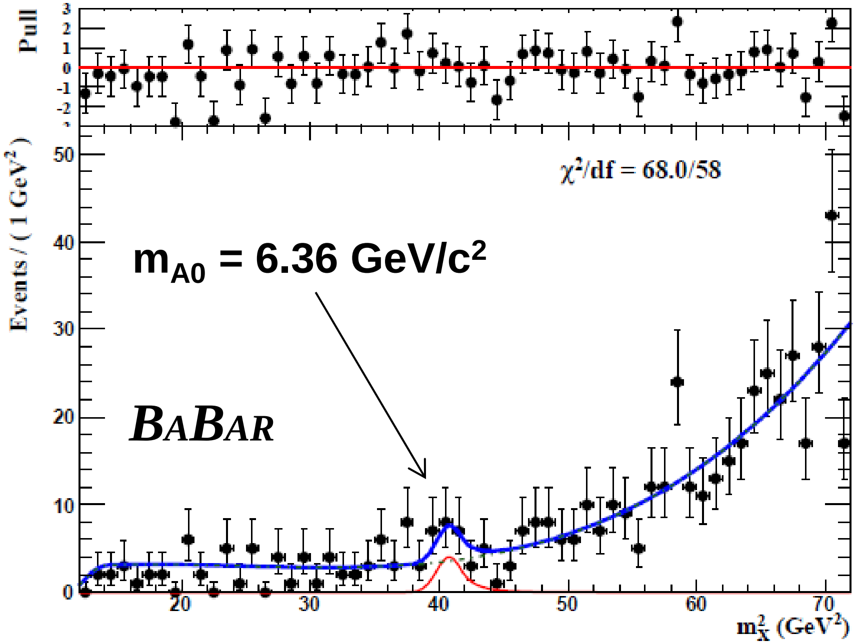
- Scanned in 5 MeV/c^2 steps.
- **Limits exclude parts of the NMSSM parameter space for $M(A^0) < M(\tau\tau)$.**

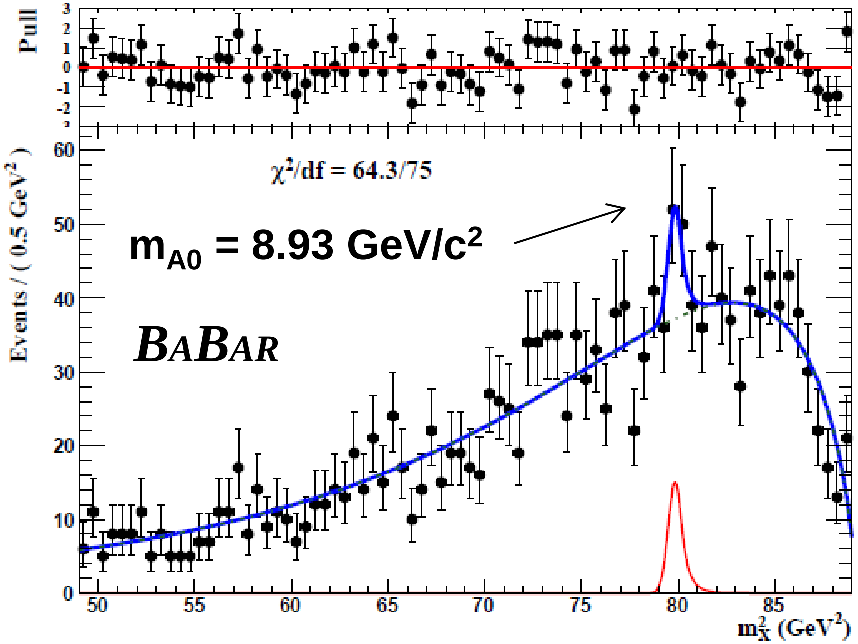




$\Upsilon(1S) \rightarrow \gamma A^0 (\rightarrow \tau\tau)$

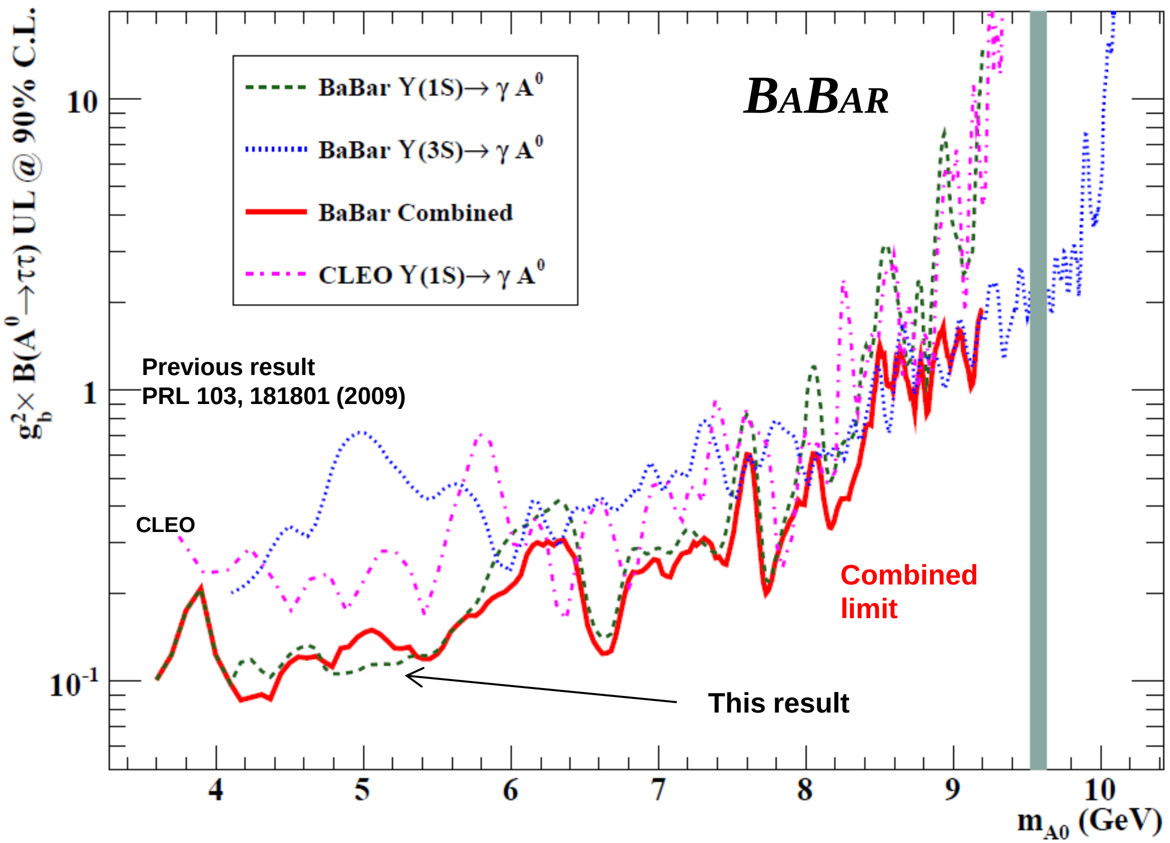
- An analysis similar to the previous one looks at final-state tau pairs reconstructed in ee, eμ, eπ, $\mu\mu$ and $\mu\pi$ final states.
- Search for A^0 candidates using m_x^2 , the mass recoiling against the signal photon in the $\Upsilon(1S)$ frame, $m_X^2 = (P_{e^+e^-} - P_{\pi\pi} - P_\gamma)^2$
- Fits to the largest fluctuations in low and high A^0 mass regions are shown below.
  - 2.7σ, $m_{A0} = 6.36$ GeV/c²
  - 3.0σ, $m_{A0} = 8.93$ GeV/c²
- Fluctuations of at least 3.0σ occur in 7.5% of pseudo-experiments that simulate a scan of 201 mass points with an average correlation of 94.5% between adjacent mass points.





$\Upsilon(1S) \to \gamma A^0 (\to \tau\tau)$

- 90% CL upper limits are shown below for this analysis alone and also in combination with the earlier *BABAR* analysis of $\Upsilon(3S) \to \gamma A^0(\to \tau\tau)$ decays.
- Combined upper limits rule out much of the parameter space preferred by NMSSM $g_b = \tan\beta \cos\theta_A > 1$.



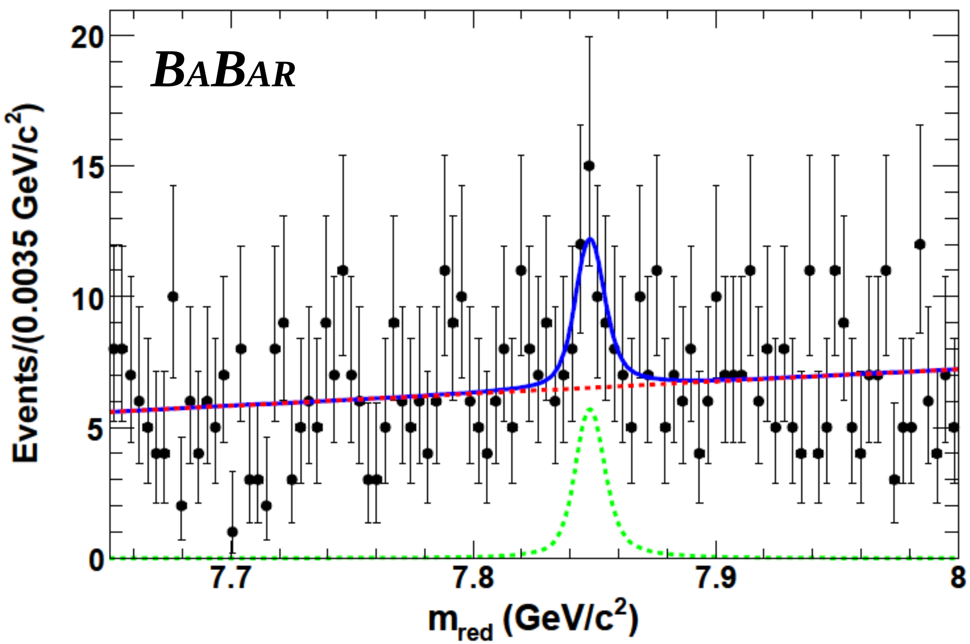
$\Upsilon(1S) \rightarrow \gamma A^0 (\rightarrow \mu\mu)$

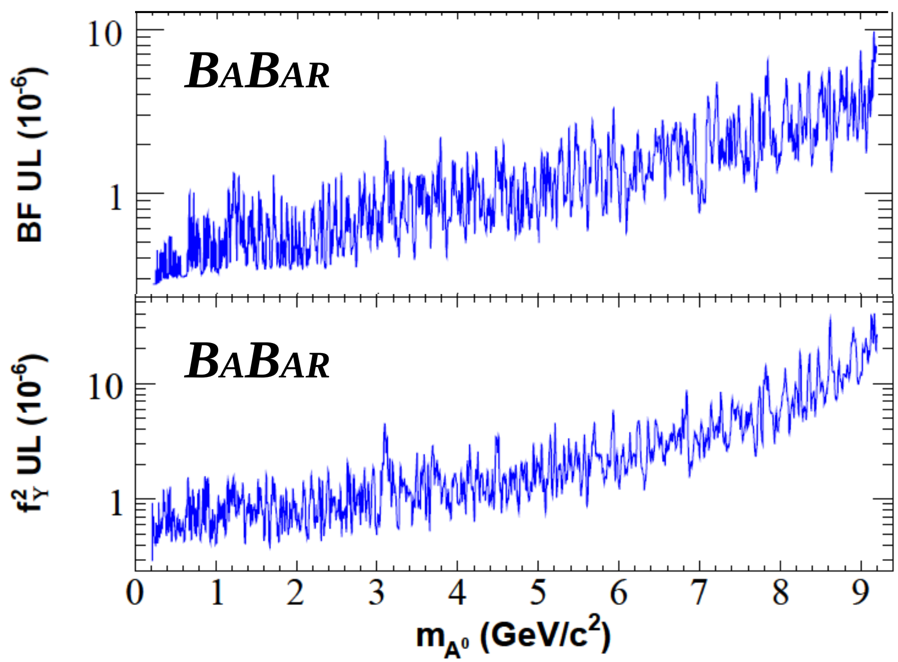
- Similarly to the previous analyses, we look at A^0 decaying into final-state mu-pairs.
- Search for A^0 candidates using reduced mass,

$$m_{\rm red} = \sqrt{m^2_{\mu^+\mu^-} - 4m^2_\mu}$$

- Plot below shows a 1d unbinned maximum likelihood fit of the mass range around the largest observed fluctuation, m_{A0} = 7.85 GeV/c^2.
- The probability, including a trials factor, of finding a peak with at least this local significance is 18%.

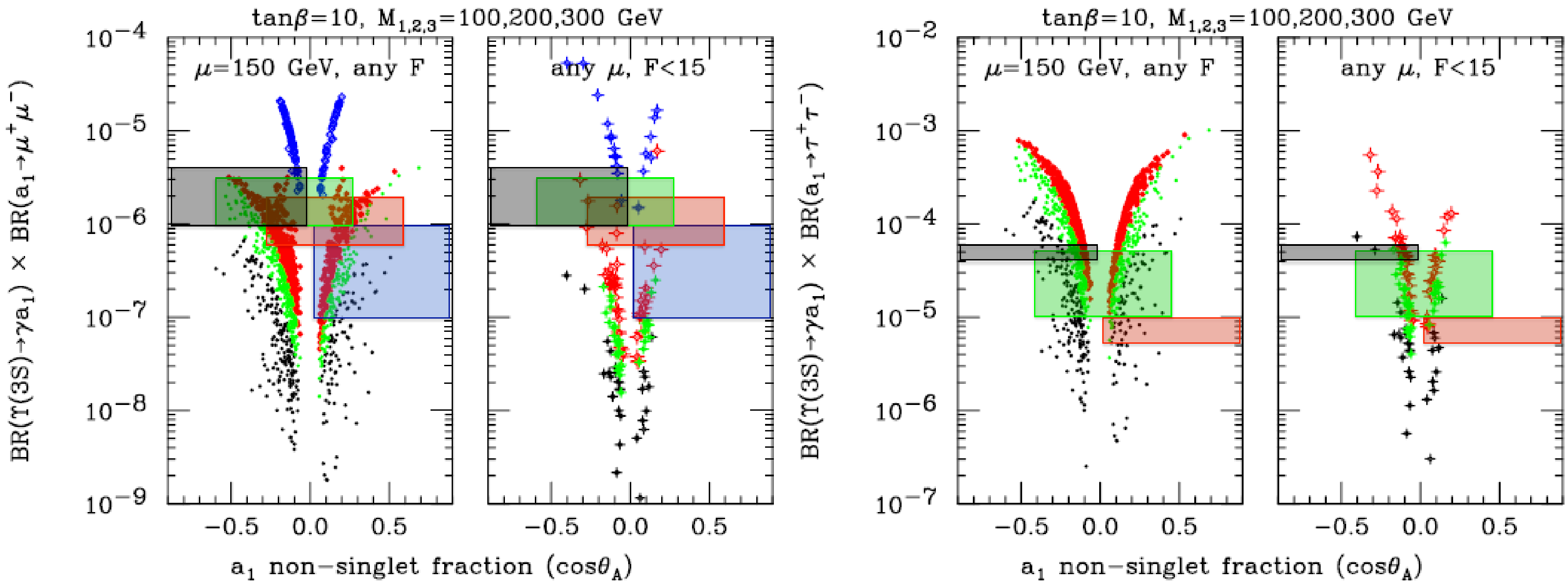
- 90% CL upper limits for:
  - (top) $\Upsilon(1S) \rightarrow \gamma A^0 (\rightarrow \mu\mu)$ branching fraction
  - (bottom) the effective Yukawa coupling f_Υ^2 x BF($A^0 \rightarrow \mu\mu$) for the combination of this result with the previous *BaBar* results from Y(2S) and Y(3S) to the same final state as here.





NMSSM Constraints

$\mu^+\mu^-$ PRD 81, 075003 (2010) $\tau^+\tau^-$



$$F = \max_a F_a \equiv \max_a \left| \frac{d \log m_Z}{d \log a} \right|$$

$0 < m_A < 2m_\tau$

$7.5 < m_A < 8.8\,\text{GeV}$

$2m_\tau < m_A < 7.5\,\text{GeV}$

$8.8 < m_A < 9.2\,\text{GeV}$

Dots = prediction at different masses

Box = range of exclusion by data at different masses

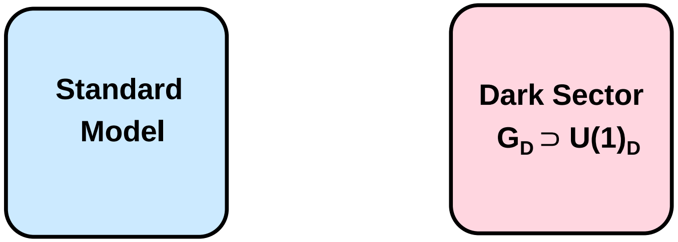
We reject the space above the boxes

(horizontal location of boxes separated for visual purposes)

Dark sector and dark forces

Dark sector and dark forces

- ⇨ New dark sector with a $U(1)_D$ gauge group (or something more complicated...)
- ⇨ New gauge boson: **dark photon A' with O(GeV) mass**

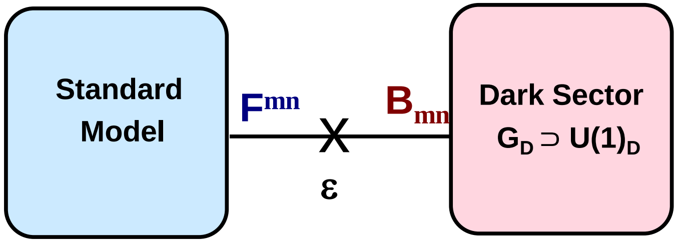


Dark sector and dark forces

- New dark sector with a $U(1)_D$ gauge group (or something more complicated...)
- New gauge boson: **dark photon A' with O(GeV) mass**
- Interaction with the SM is via **kinetic mixing**

$$\varepsilon F^{\mu\nu} B_{\mu\nu}$$

with a **mixing strength ε.**



$$\Delta L_{mix} = \varepsilon F^{\mu\nu} B_{\mu\nu}$$

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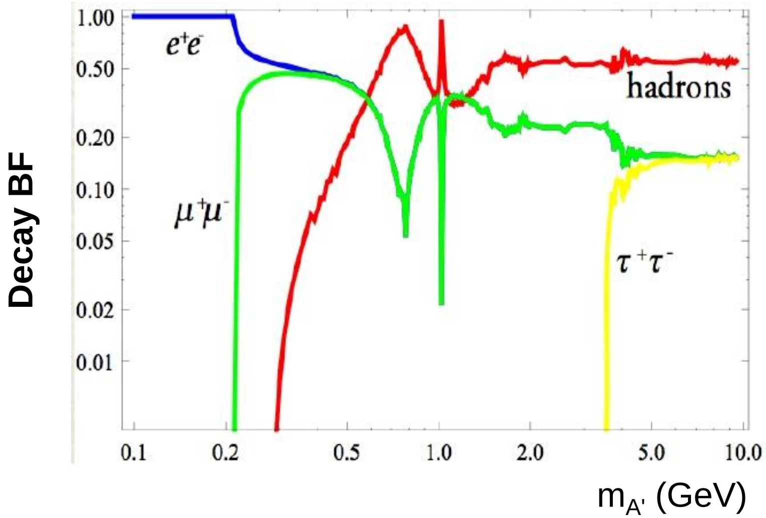
- The dark photon acquires a charge εe, and the **coupling of the dark photon to SM fermions** is characterized by $\alpha' = \alpha\, \varepsilon^2$.

Dark photon branching fraction



Dark sector and dark forces

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- New gauge boson: **dark photon A' with O(GeV) mass**
- Interaction with the SM is via **kinetic mixing**

$$\varepsilon F^{\mu\nu} B_{\mu\nu}$$

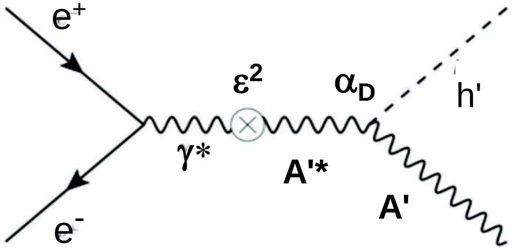
  with a **mixing strength** ε**.**

- The dark photon acquires a charge εe, and the **coupling of the dark photon to SM fermions** is characterized by $\alpha' = \alpha \varepsilon^2$ **.**

- Dark boson 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**, possibly at the GeV scale.

- The **Higgsstrahlung process** is **suppressed only by** ε^2 and is expected to have **small backgrounds.**

$\sigma \sim \varepsilon^2 \alpha_D$



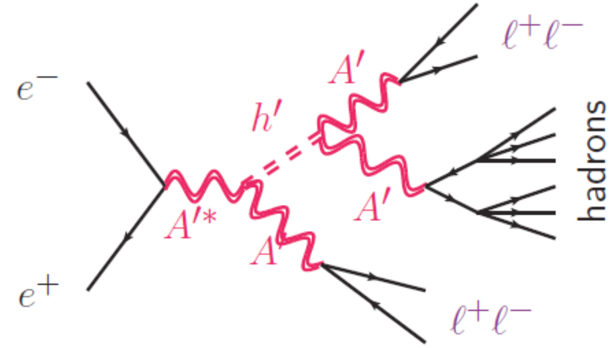
$\alpha_D = g_D^2 / 4\pi$

g_D is the dark sector gauge coupling

Fully reconstructed

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

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



Partially reconstructed

$e^+e^- \to h' A_1'$, $h' \to A_2' A_3'$

with $A'_{1,2} \to e^+e^-, \mu^+\mu^-$, $A'_3 \to X$

Fully reconstructed signal

- Three dark photons fully reconstructed

Modes included

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

Selection

- 6 tracks with an invariant mass $m_{tot} > 0.95\sqrt{s}$
- apply lepton 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 $A' \to q\bar{q}$
- Reconstruct 2 A' decaying to leptons and 1 A' to $q\bar{q}$
- Reconstruct four-momentum $P_3 = P_{ee} - P_1 - P_2$

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

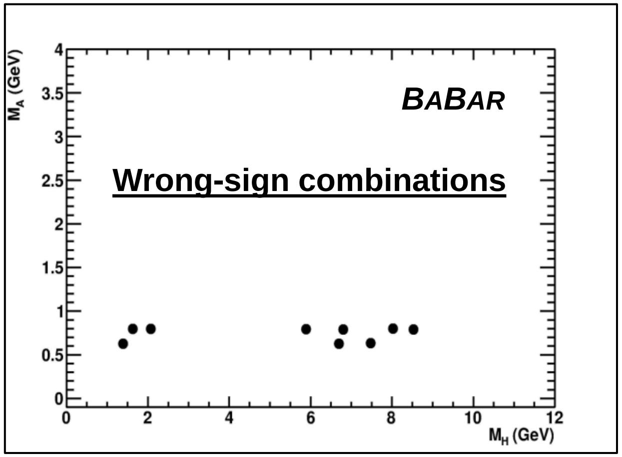
- **Six events** are selected from the full *BABAR* dataset (517 fb^{-1})

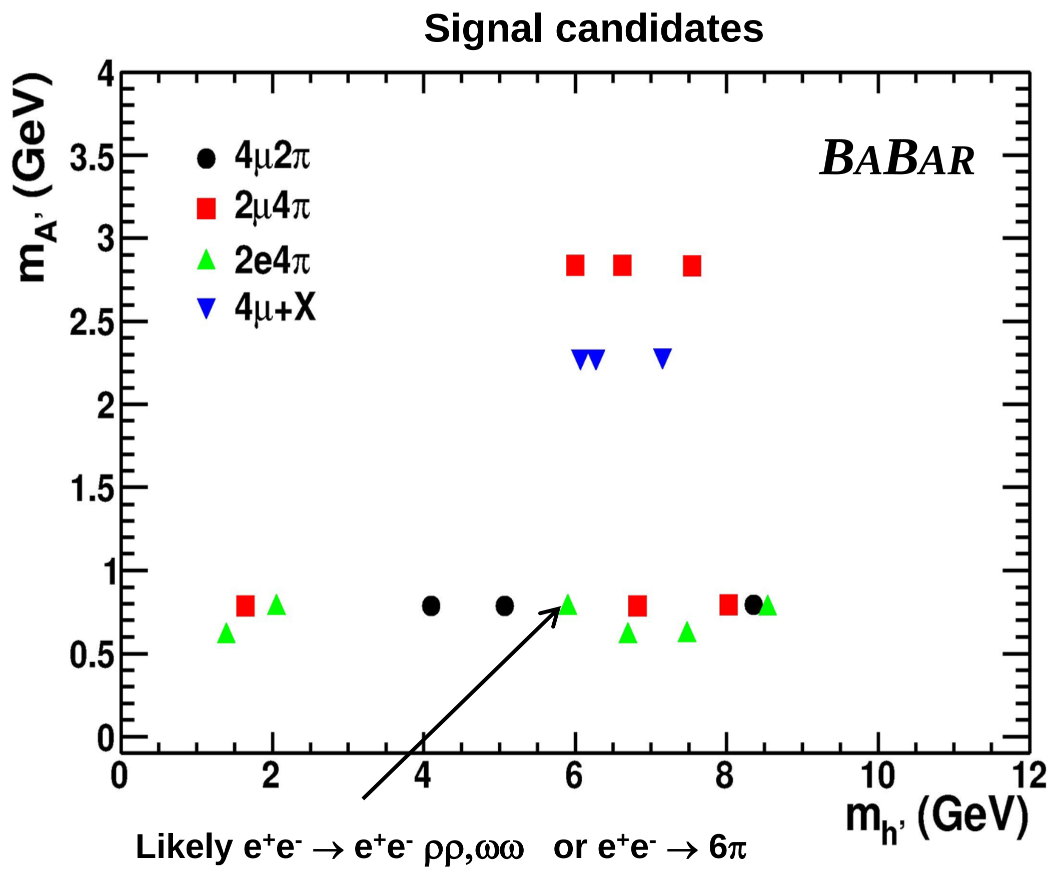
- **Three entries for each event**, corresponding to the three possible assignments of the $h \rightarrow A'A'$ decay

- **Estimate background from**
  - **wrong-sign combinations**, e.g.

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

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



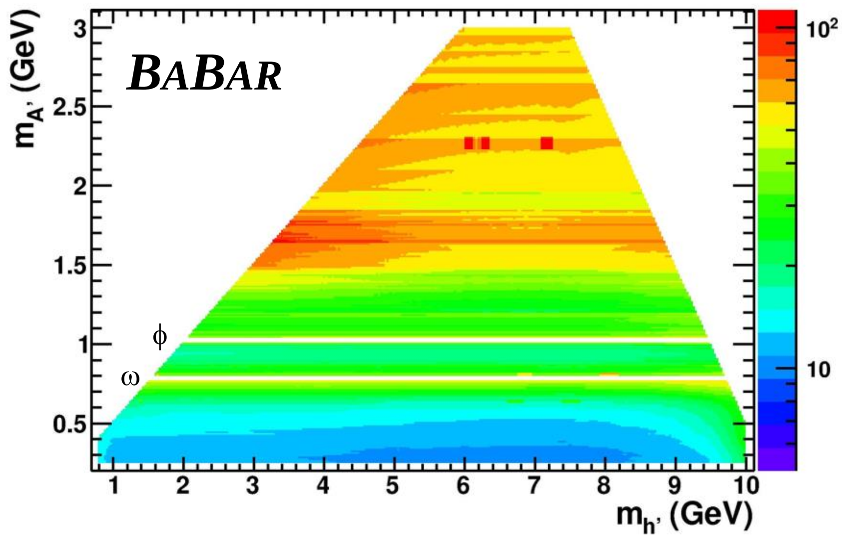


No events with 6 leptons, consistent with the pure background hypothesis

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)
- **Cross section limits from 10 to ~100 ab**

90% CL upper limit on cross section (ab)



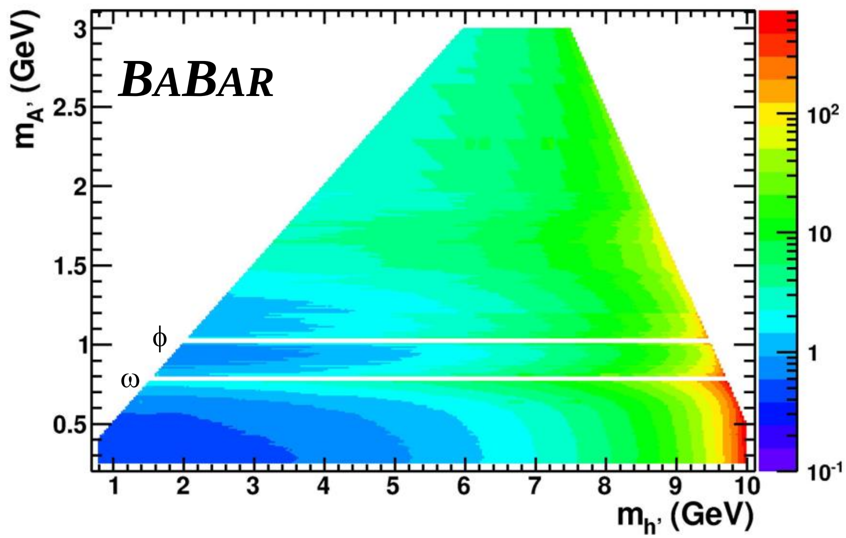
Extract limits[1] on the product $\alpha_D \varepsilon^2$

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

$\alpha_D = g_D^2 / 4\pi$

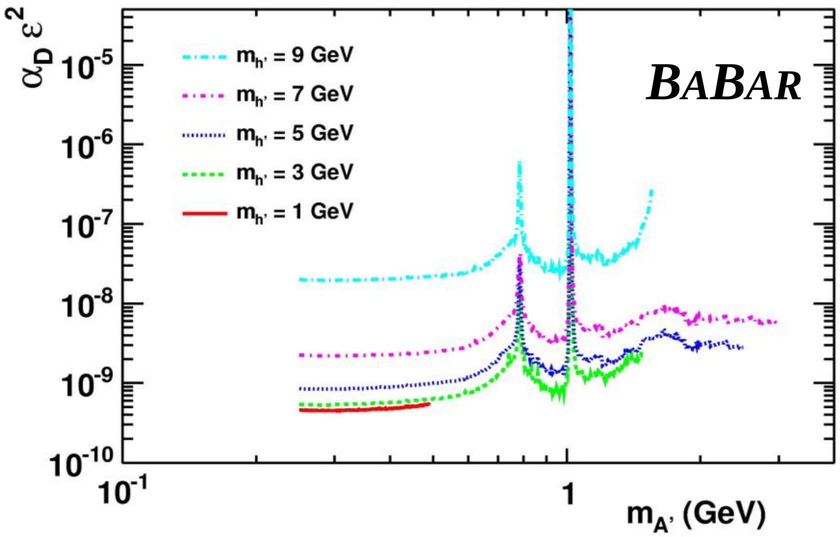
g_D is the dark sector gauge coupling

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

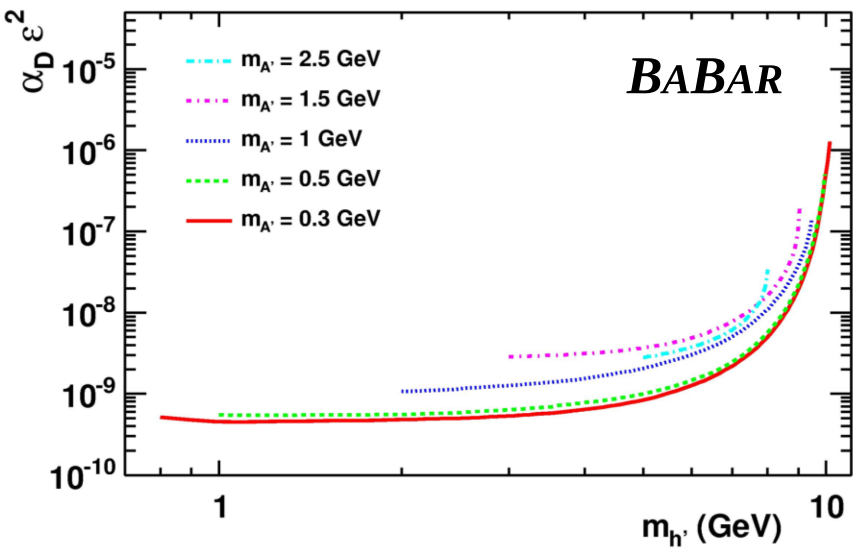


1. B. Batell, M. Pospelov and A. Ritz, Phys.Rev.D79:115008,2009.

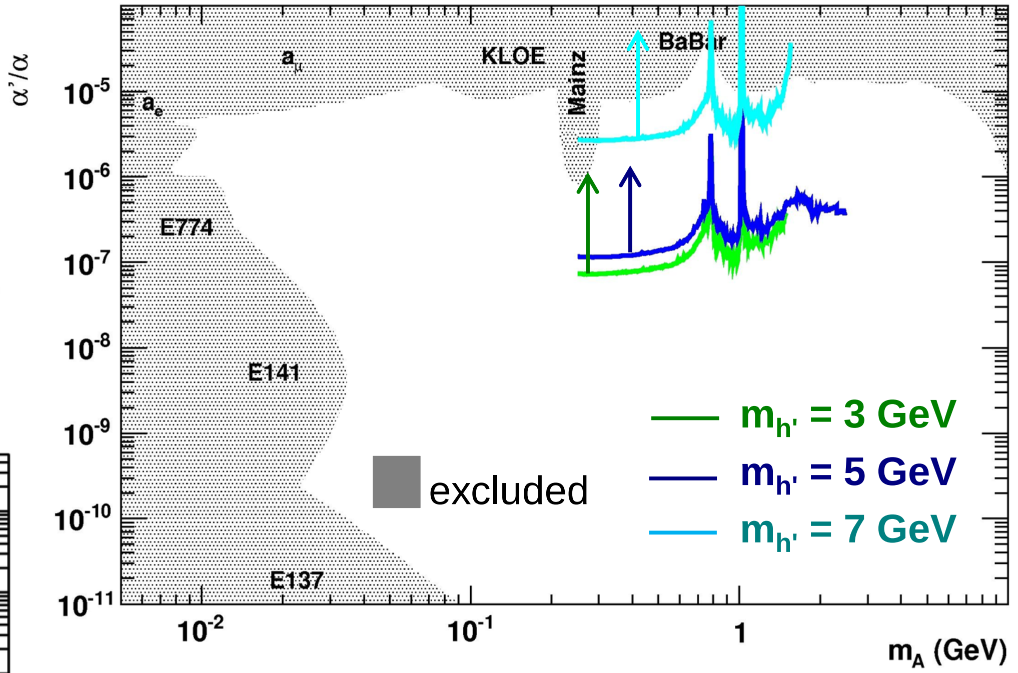
90% CL upper limit on $\alpha_D \varepsilon^2$ vs $m_{A'}$



90% CL upper limit on $\alpha_D \varepsilon^2$ vs $m_{h'}$



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



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

Summary

- The clean environment of low-energy e+e- colliders allows sensitive searches for an MeV/GeV scale dark sector.
- ***BaBar*** results from searches for a low-mass, CP-odd non-singlet Higgs and dark bosons exclude significant parts of NMSSM parameter space which are not covered by other experiments.
- Several A^0 searches in additional final states are in progress:
  - $\Upsilon(1S) \rightarrow \gamma A^0 (\rightarrow \gamma\gamma)$
  - $\Upsilon(1S) \rightarrow \gamma A^0 (\rightarrow c\bar{c})$
  - $\Upsilon(3S) \rightarrow \gamma A^0 (\rightarrow \text{invisible})$