Searches for light CP-odd Higgs bosons and dark photons at *BABAR*

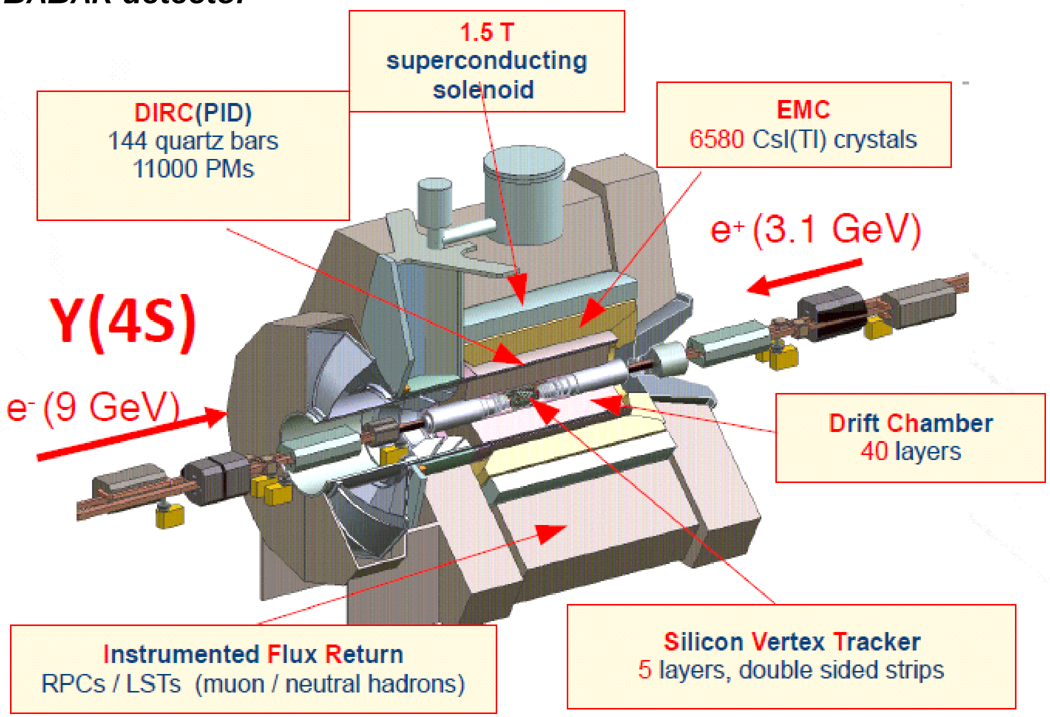
Bertrand Echenard
California Institute of Technology

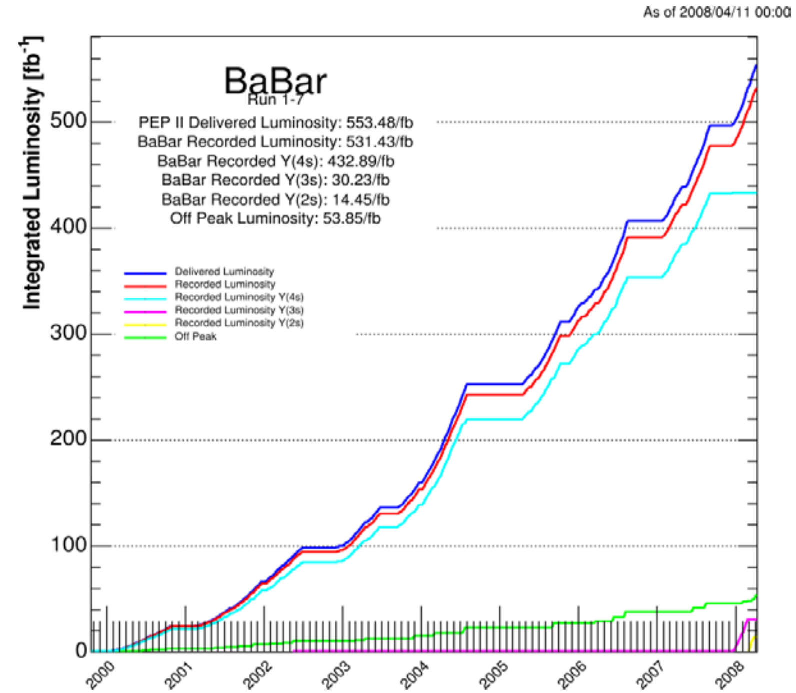
on behalf of the *BABAR* Collaboration

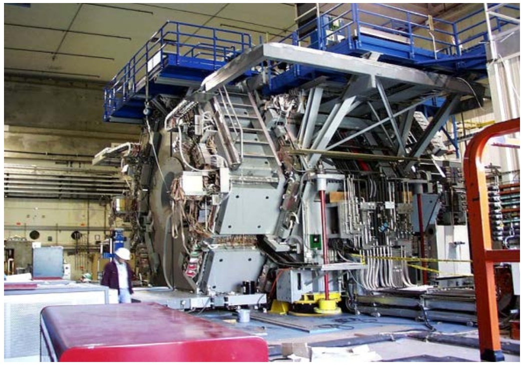
Benasque Workshop 2014




The BABAR detector







BABAR **data sample contains**

~470 x 10^6 Υ(4S)
~120 x 10^6 Υ(3S) (10x Belle)
~100 x 10^6 Υ(2S) (10x CLEO)
~ 23 x 10^6 $\Upsilon(2S,3S)\rightarrow\pi^+\pi^-\Upsilon(1S)$

Better sensitivity to direct production of light degrees of freedom at narrow resonances

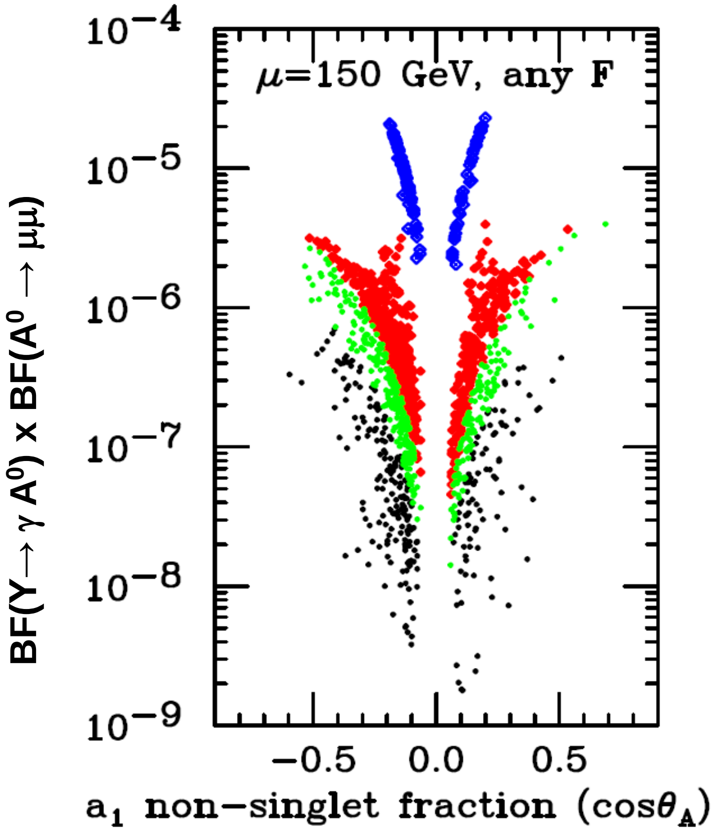
Dermisek et al., PRD 81, 075003 (2010)

A light CP-odd Higgs

- Many SM extensions (NMSSM, 2HDM Type-II,…) include the possibility of additional Higgs boson, which could be light.
- NMSSM proposed to solve the "μ problem", adding one CP-odd Higgs, one CP-even Higgs and one neutralino to the MSSM content
- A light CP-odd Higgs A^0 with mass lower than $2m_b$ is not excluded by LEP constraints.
- Radiative decays $\Upsilon(nS) \to \gamma A^0$ (n=1,2,3) offer an ideal environment to search for light CP-odd Higgs, and more generally a light scalar.
- Possible connection with dark matter connection in $A^0 \to \chi\chi$ decays if $m_\chi < m_A / 2$.
- Branching fractions can be quite large!

Very active program at *BABAR* to search for these possibilities!

tanβ=10, μ=150 GeV, $M_{1,2,3}$ =100,200,300 GeV



$$A^0 = \cos\theta_A A_{MSSM} + \sin\theta_A A_S$$

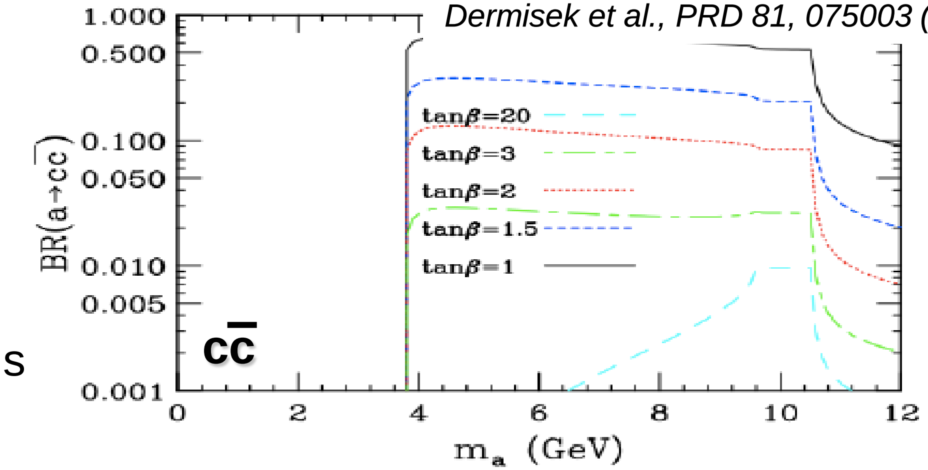
$0 < m_{A0} < 2m_\tau$
$2m_\tau < m_{A0} < 7.5$ GeV
$7.5 < m_{A0} < 8.8$ GeV
$8.8 < m_{A0} < 9.2$ GeV

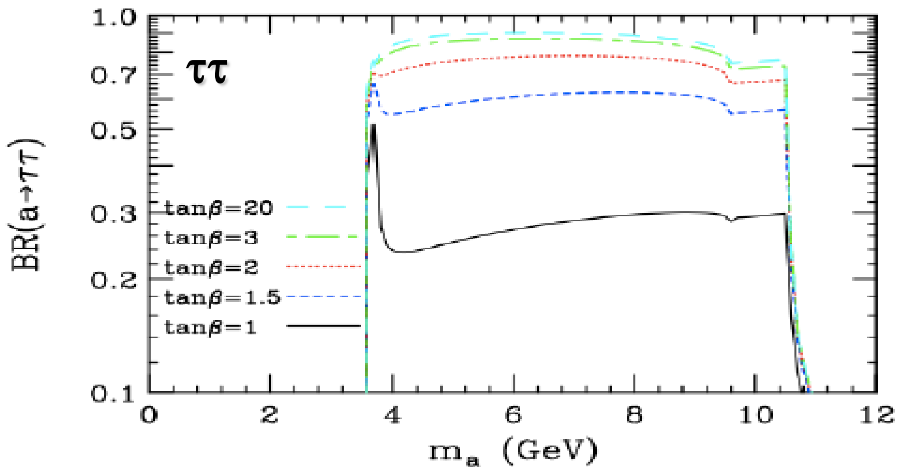
Branching fractions depend on final state and the model parameters

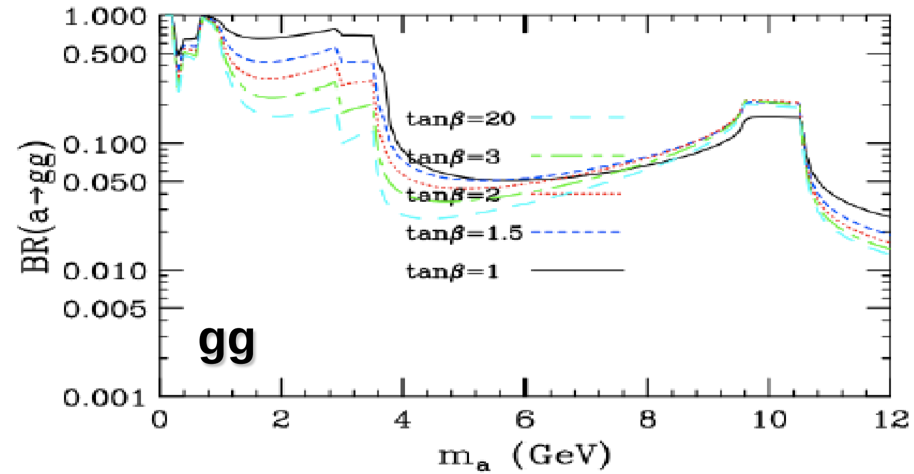
$$BR(A^0 \to f\bar{f}) \propto \cos\theta_A m_f^2 / \tan^2\beta$$ up-type fermions

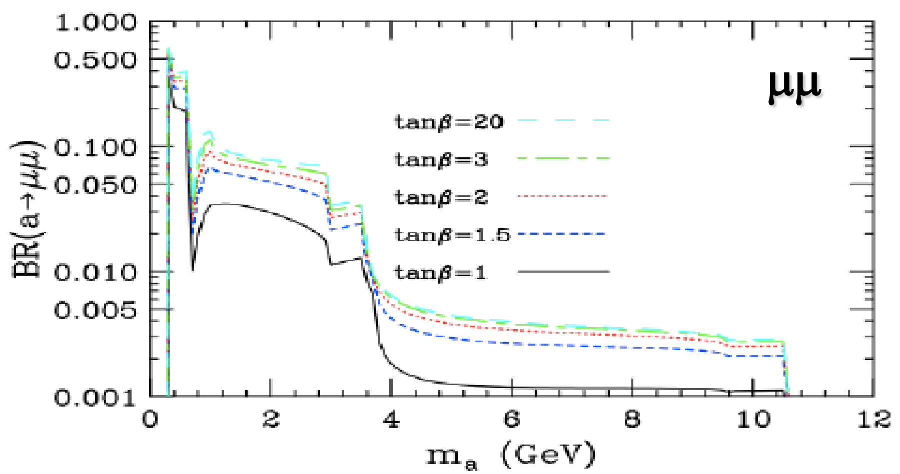
$$BR(A^0 \to f\bar{f}) \propto \cos\theta_A m_f^2 \tan^2\beta$$ down-type fermions

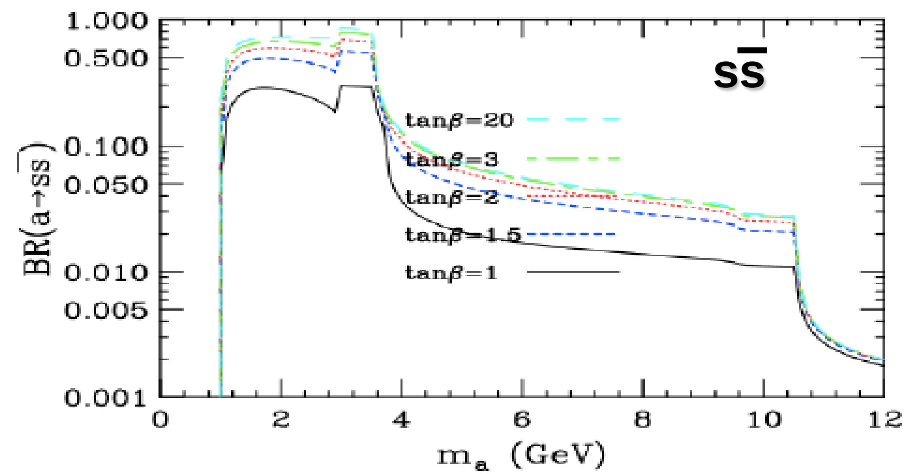
Dermisek et al., PRD 81, 075003 (2010)



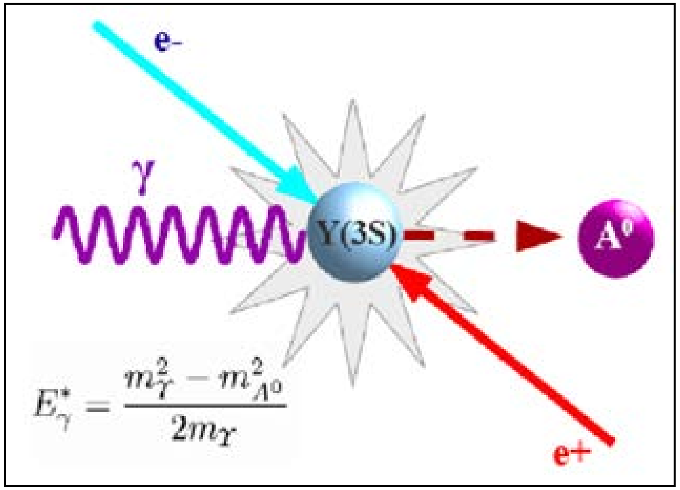




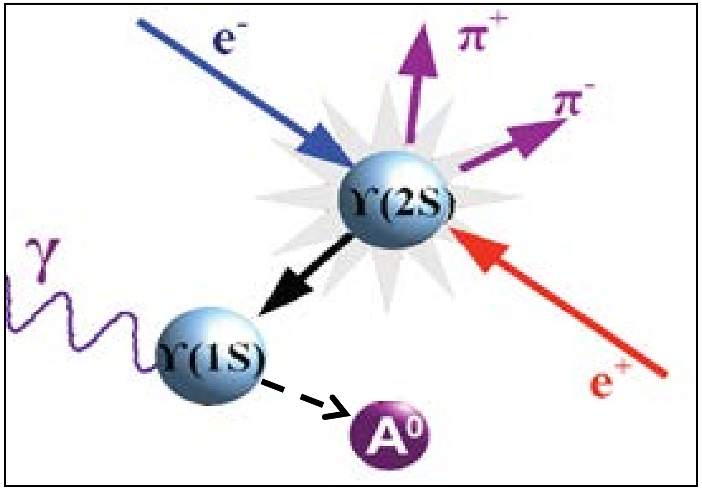




Radiative Υ(2S,3S) decays



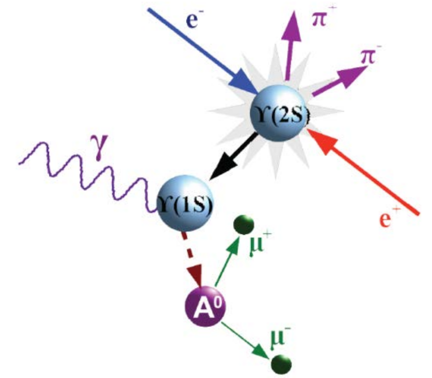
Radiative Υ(1S) decays



- **$\Upsilon(2S,3S) \to \gamma A^0, A^0 \to \mu^+\mu^-$**
  PRL103 (2009) 081803
- **$\Upsilon(3S) \to \gamma A^0, A^0 \to \tau^+\tau^-$**
  PRL103 (2009) 181801
- **$\Upsilon(2S,3S) \to \gamma A^0, A^0 \to$ hadrons**
  PRL107 (2011) 221803
- **$\Upsilon(2S,3S) \to \gamma A^0, A^0 \to$ invisible**
  arXiv: 0808.0017 + new analysis in progress

This talk

- **$\Upsilon(1S) \to \gamma A^0, A^0 \to$ invisible**
  PRL107 (2011) 021804
- **$\Upsilon(1S) \to \gamma A^0, A^0 \to \mu^+\mu^-$**
  PRD 87 (2013) 031102
- **$\Upsilon(1S) \to \gamma A^0, A^0 \to \tau^+\tau^-$**
  PRD 88 (2013) 071102
- **$\Upsilon(1S) \to \gamma A^0, A^0 \to gg$ or $s\bar{s}$**
  PRD 88 (2013) 031701
- **$\Upsilon(1S) \to \gamma A^0, A^0 \to \gamma\gamma$ and $A^0 \to c\bar{c}$**
  in preparation

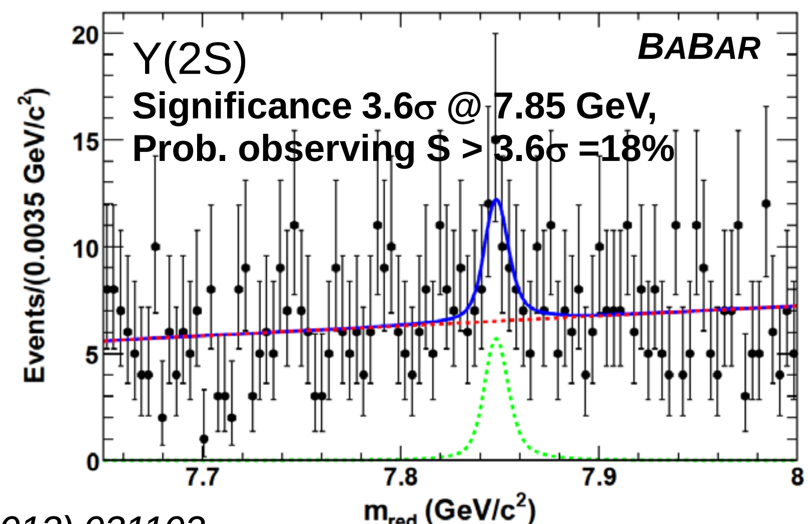


Search for

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

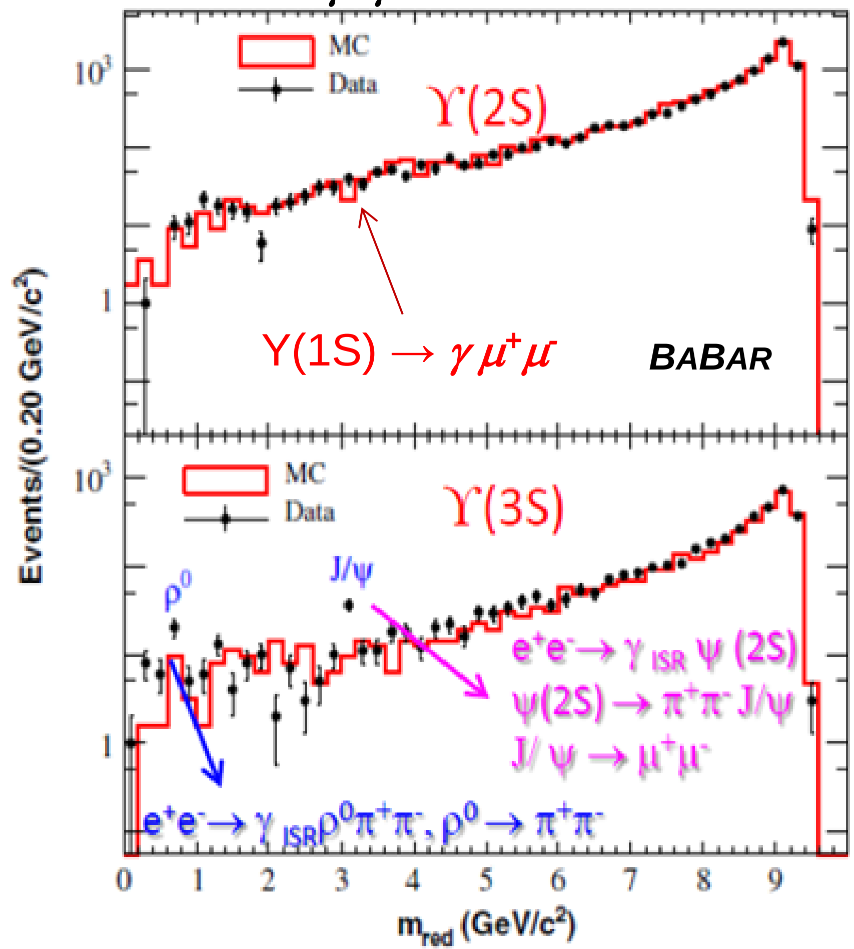
Analysis highlights

- Tag the Y(1S) from the dipion transition:
  one photon with $E\gamma^* > 200$ MeV + 4 tracks with at least one identified as muon
- Require the $\gamma\mu\mu$ system to be compatible with a Y(1S) meson, apply kinematic constraints to improve resolution
- Scan reduced mass $m_r = (m^2_{A0} - 4m^2_{\mu})^{1/2}$



PRD 87 (2013) 031102

$A^0 \to \mu^+\mu^-$: reduced mass



PRL103 (2009) 081803
PRD 87 (2013) 031102

Bayesian upper limits (90% CL) in the range $0.212 \leq m_{A0} \leq 9.20$ GeV

$B(\Upsilon(1S) \to \gamma A^0, A^0 \to \mu^+\mu^-) < (0.1 – 9.7) \times 10^{-6}$

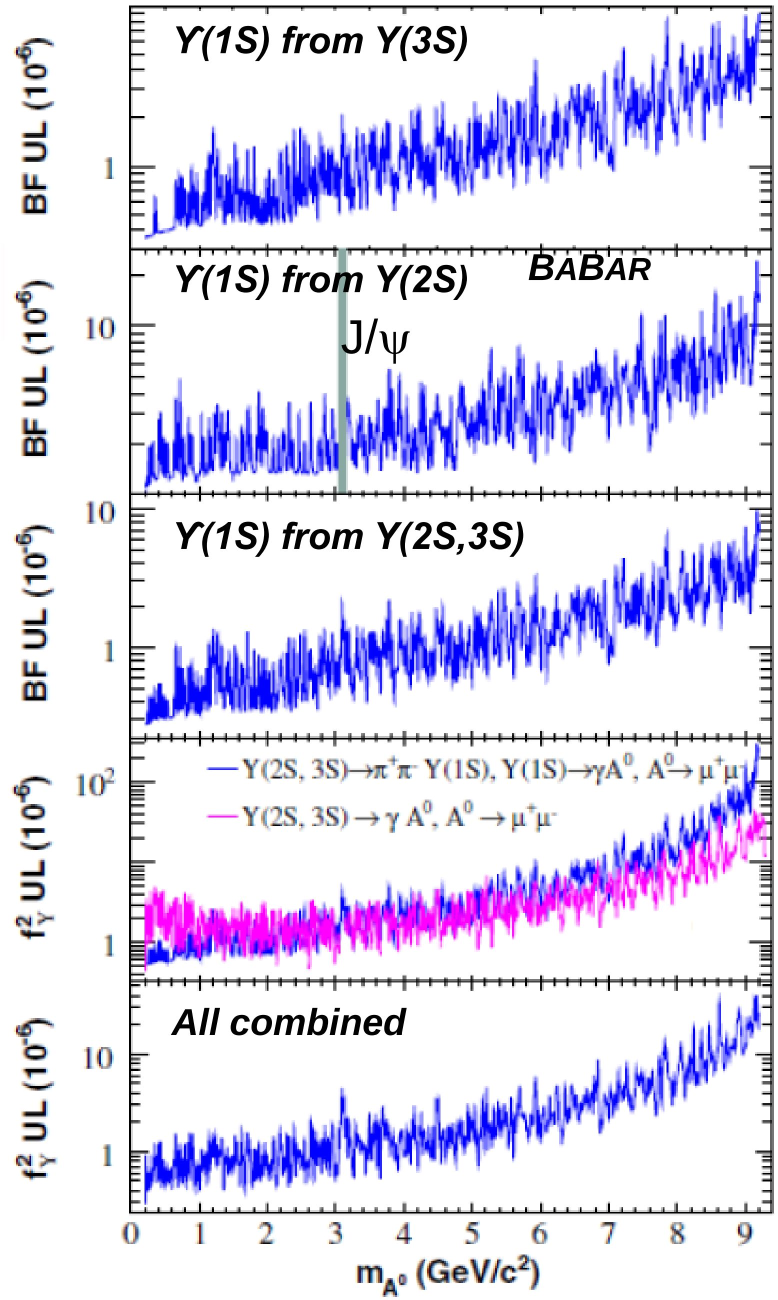
Limits comparable with results from Υ(2S,3S) decays with a slight improvement in the region $m_{A0} < 1.2$ GeV

Combination with the results from Υ(2S,3S) decays to extract a limit on the effective Yukawa coupling (f_Υ) between A^0 – b-quark*:

$$\frac{B(\Upsilon(nS) \to \gamma A^0)}{B(\Upsilon(nS) \to \ell^+\ell^-)} = \frac{f_\Upsilon^2}{2\pi\alpha}\left(1 - \frac{m_{A^0}^2}{m_{\Upsilon(ns)}^2}\right)$$

For $m_{A0} < 9.2$ GeV (90% CL)

$f_\Upsilon^2 \times B(A^0 \to \mu^+\mu^-) = (0.3 – 40) \times 10^{-6}$



* F. Wilczek, Phys. Rev. Lett. 39, 1304 (1977).
M. L. Mangano and P. Nason, Mod. Phys. Lett. A22, 1373 (2007).
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PRL103 (2009) 081803
PRD 87 (2013) 031102

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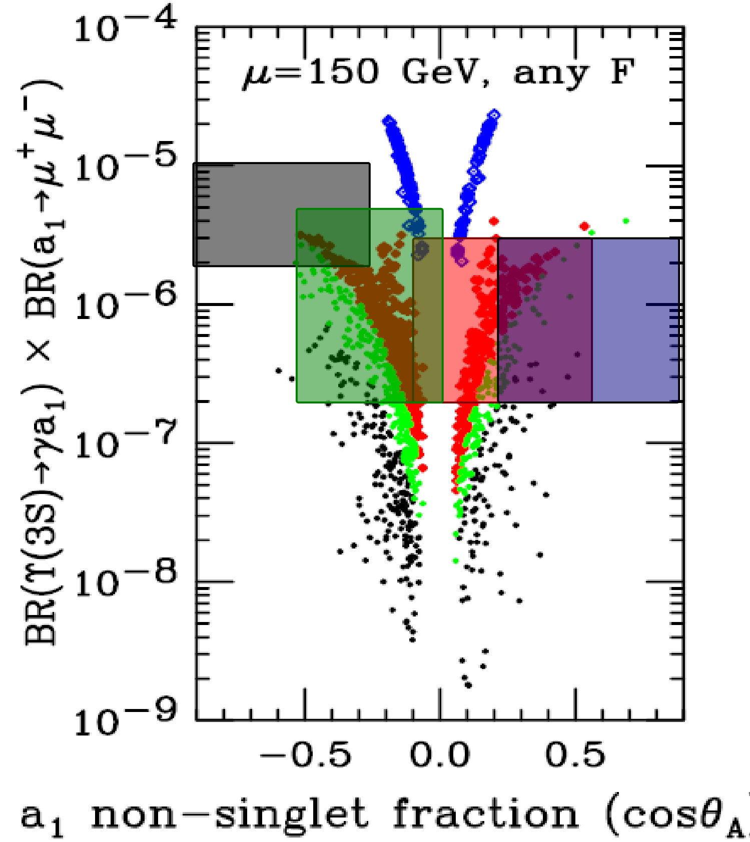
$A^0 \to \mu^+\mu^-$



Upper limits (90% CL)

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

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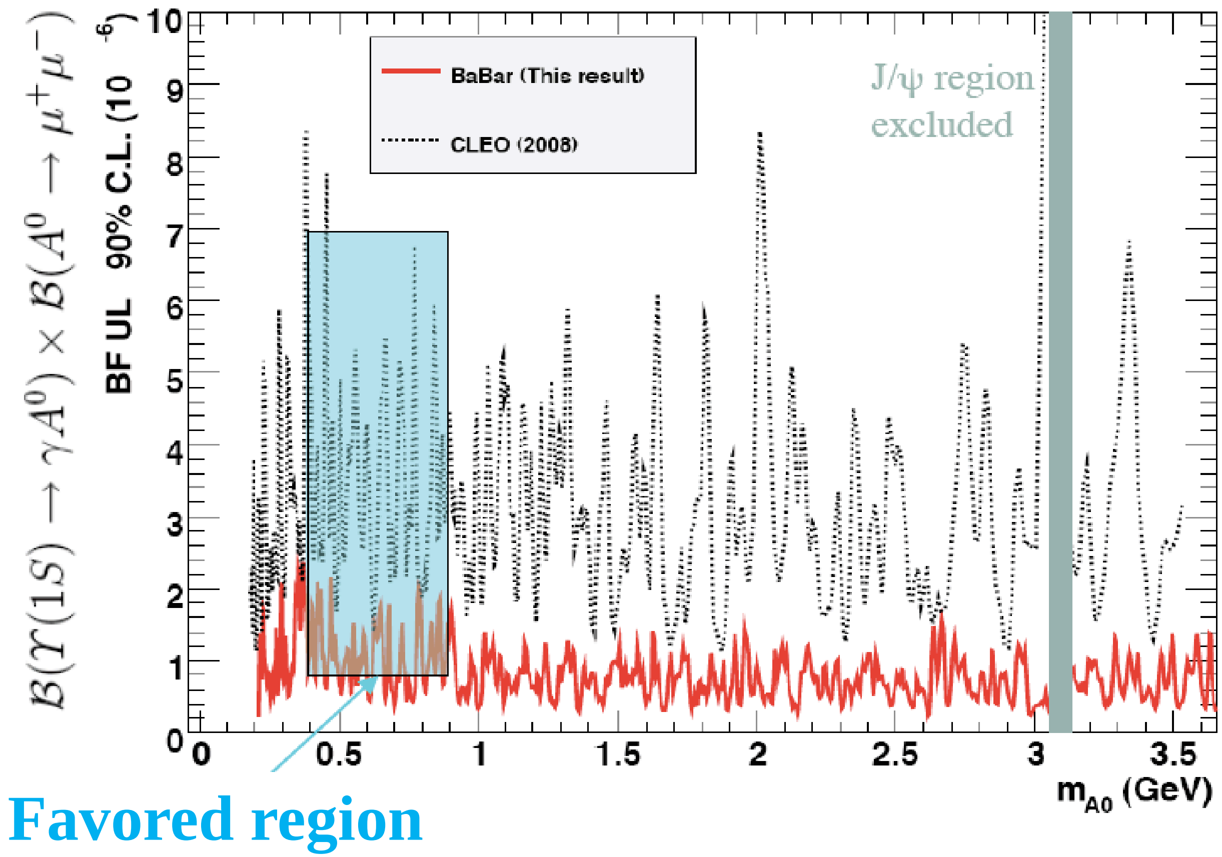
Dark matter model with axion-like particles predicting an axion mass 360 – 800 MeV decaying mainly into a muon pair[1)]



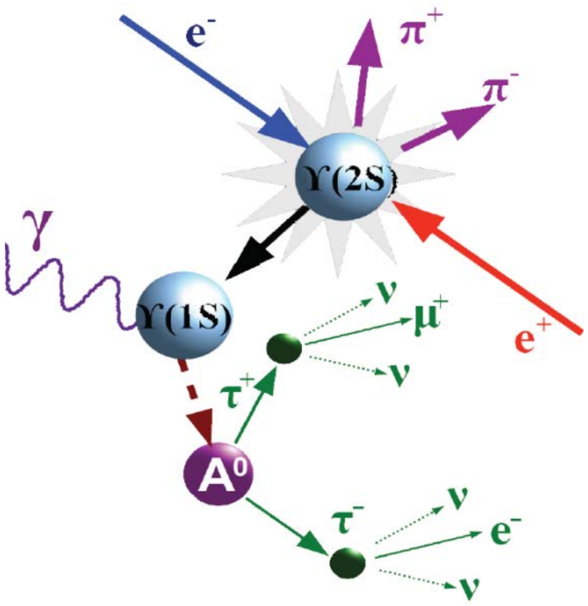
Severe constraints on this type of models

1) *Nomura & Thaler PRD 79, 075008 (2007)*

PRD 88 (2013) 071102

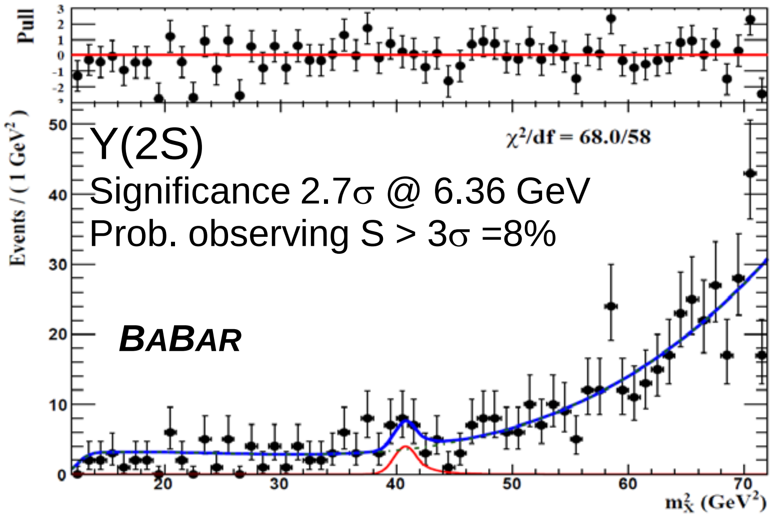
Search for

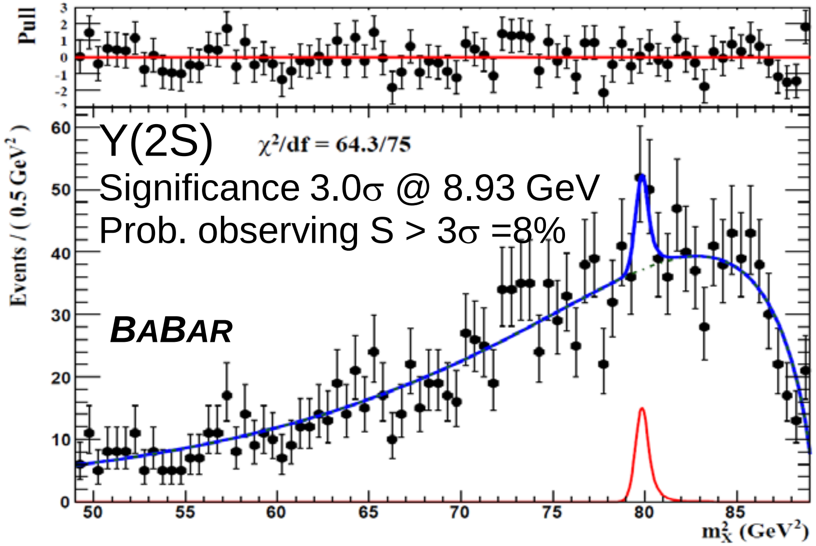
$\Upsilon(2S) \rightarrow \pi^+\pi^- \Upsilon(1S)$, $\Upsilon(1S) \rightarrow \gamma A^0$, $A^0 \rightarrow \tau^+\tau^-$



Analysis highlights

- Tag the Y(1S) from the dipion transition
- Tag 1-prong decay of tau ($\tau \rightarrow \mu\nu\nu$, $\tau \rightarrow e\nu\nu$, $\tau \rightarrow \pi\nu\nu$)
- Optimize analysis in low mass ($3.6 < m_A < 8.0$ GeV) / high mass ($8.0 < m_A < 9.2$ GeV) regions
- Fit for a narrow peak to the photon recoil mass in the Y(1S) system





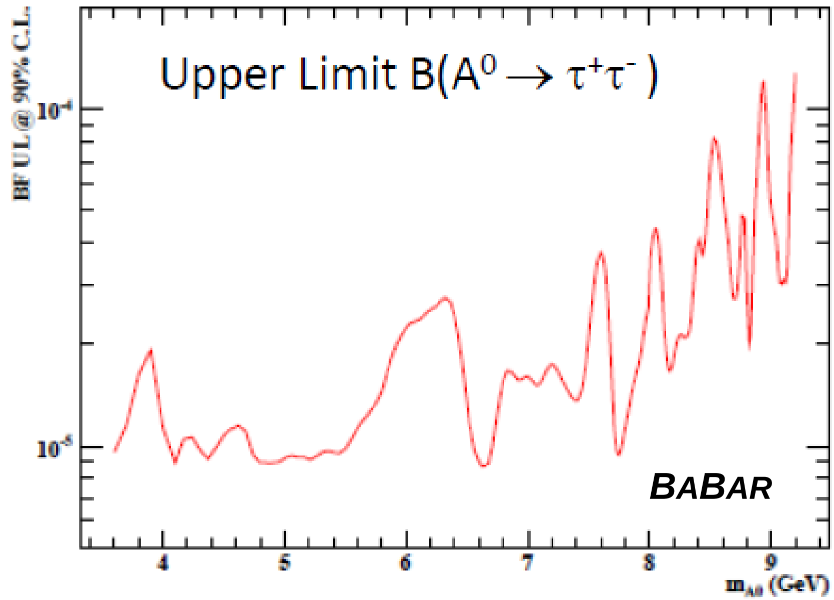
Search for A^0 in $\Upsilon(1S) \rightarrow \gamma A^0$, $A^0 \rightarrow \tau^+\tau^-$

PRL103 (2009) 181801
PRD 88 (2013) 071102

Upper limits (90% CL) in the range
$3.6 \leq m_{A0} \leq 9.20$ GeV

$B(\Upsilon(1S) \rightarrow \gamma A^0, A^0 \rightarrow \tau^+\tau^-) < (0.9 - 13) \times 10^{-5}$

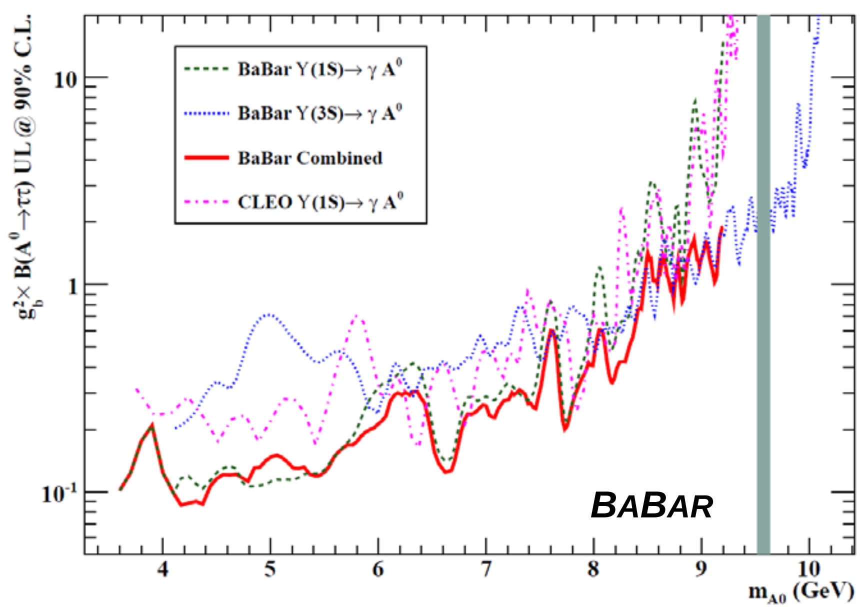
Factor 2-3 improvement in the low mass range with respect to measurement in Y(3S)



Combination with the results from Y(2S,3S) decays to extract a limit on the Yukawa coupling (g_b) between A^0 – b-quark*:

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

$g_b^2 \times B(A^0 \rightarrow \tau^+\tau^-) = 0.1 - 1.9$ @ 90% CL



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PRD 88 (2013) 071102

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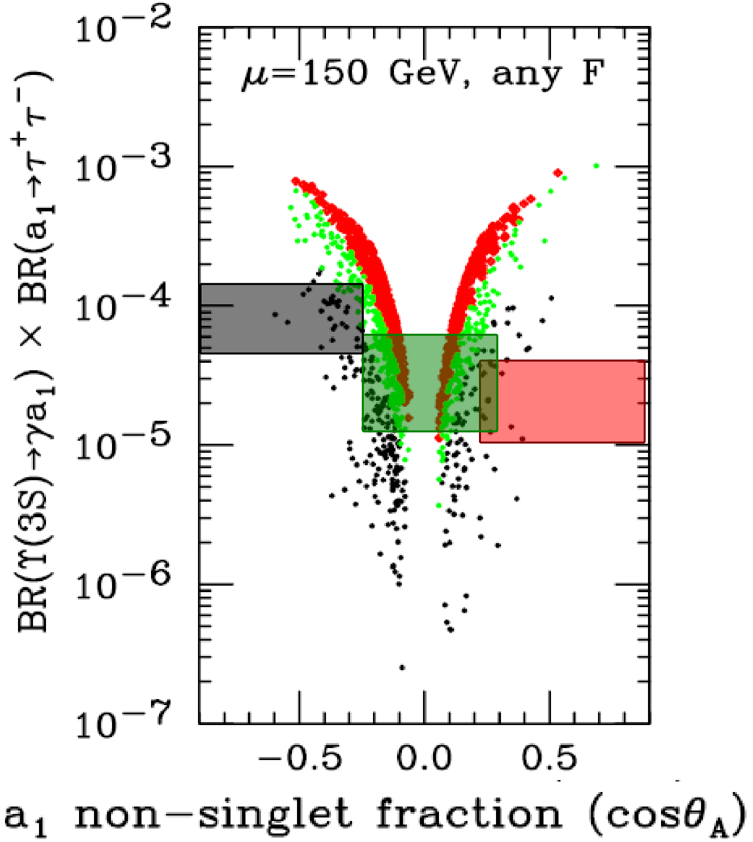
$A^0 \rightarrow \tau^+\tau^-$



Upper limits (90% CL)

$2m_\tau < m_{A0} < 7.5$ GeV
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M. L. Mangano and P. Nason, Mod. Phys. Lett. A22, 1373 (2007).
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Selection

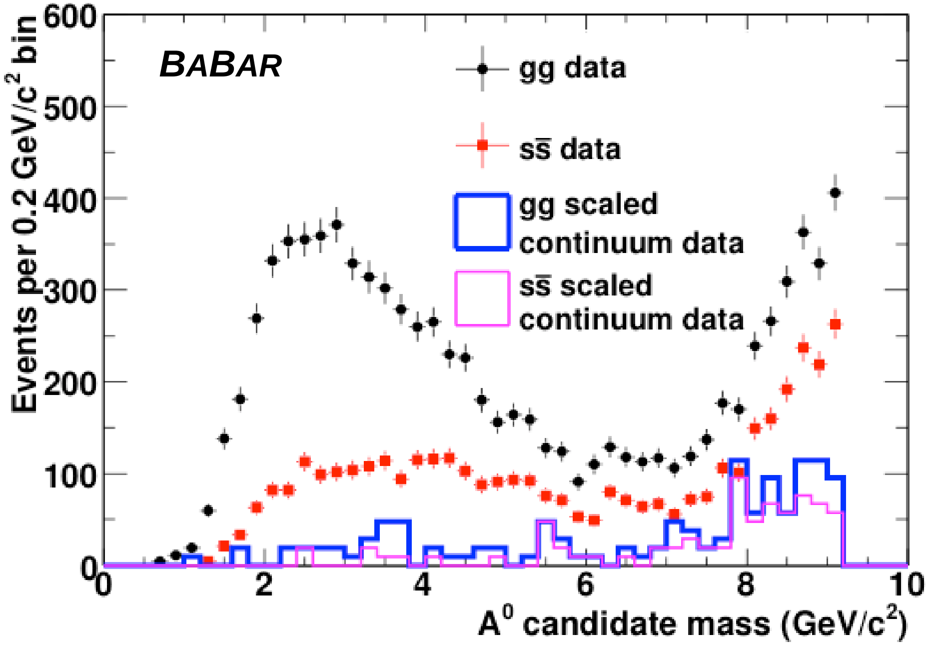
- Exclusive reconstruction of A^0 in 26 /14 different channels for gg/$s\bar{s}$ final state. Two body decays excluded as CP-odd Higgs can not decay into two pseudo-scalars
- Beam-energy constraints to improve A^0 mass resolution

#	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	$K^\pm K^0_S\pi^\mp 2\pi^+2\pi^-\pi^0$
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	$p\bar{p}\pi^+\pi^-$

Main background

- $\Upsilon(1S) \to \gamma gg$ (low masses)
- $\Upsilon(1S) \to ggg$ (high masses)

Extract yield from mass spectrum in the range $0.5 < m_A < 9$ GeV, use cut and count method with background estimated from sidebands.



Large systematic uncertainty from hadronization (~50%)

PRD 88 (2013) 031701R

Most significant signals

- gg: 2.7σ @ 8.1 GeV
- $s\bar{s}$: 2.9σ @ 8.6 GeV

Toy Monte Carlo studies shows that the probability to see a significance as large as the observed one is

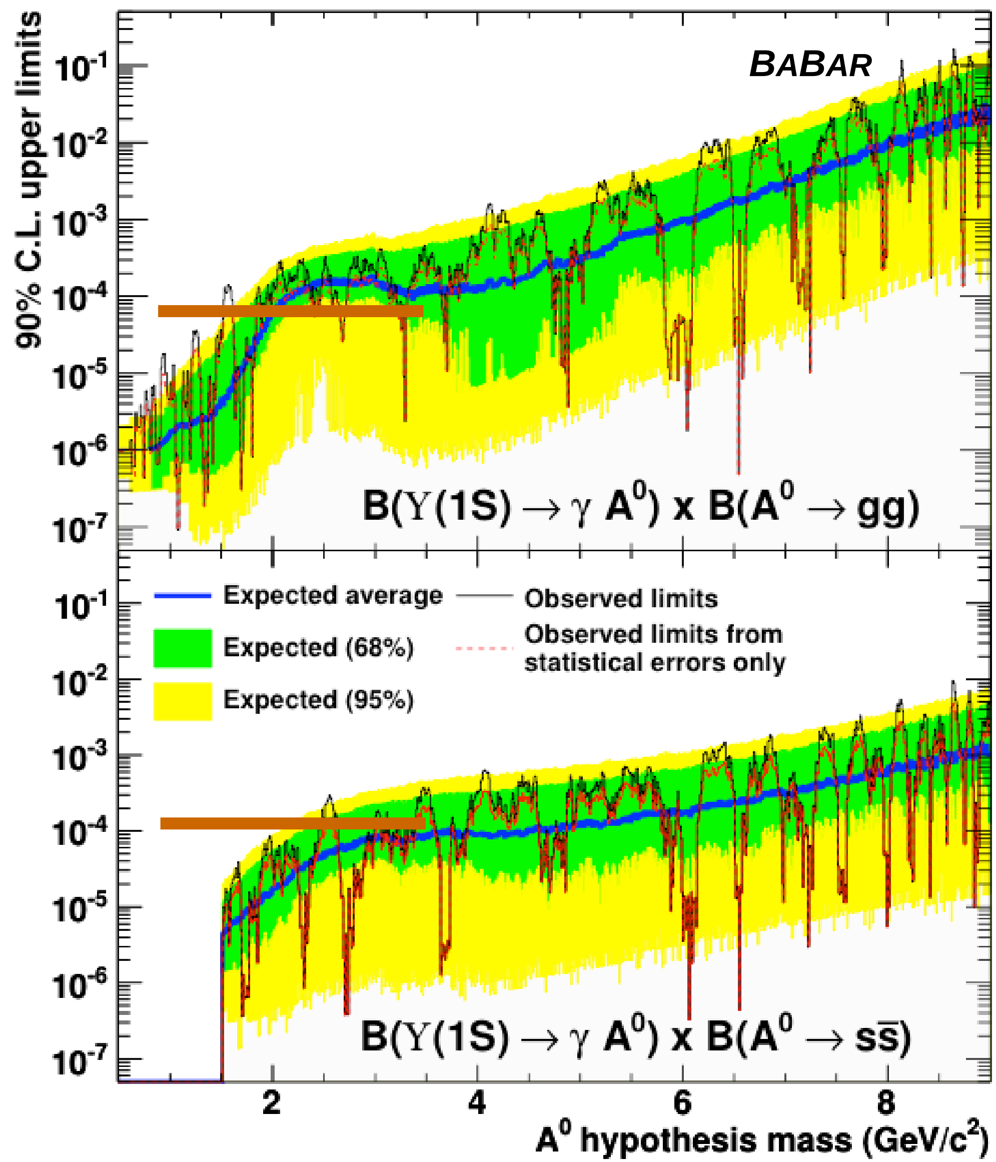
- gg: 86%
- $s\bar{s}$: 59%

No significant signal is observed

Bayesian upper limits (90% CL) in the range $0.5 \leq m_{A0} \leq 9.0$ GeV

$B(\Upsilon(1S) \to \gamma A^0, A^0 \to gg) < 10^{-6} - 10^{-2}$
$B(\Upsilon(1S) \to \gamma A^0, A^0 \to s\bar{s}) < 10^{-5} - 10^{-3}$

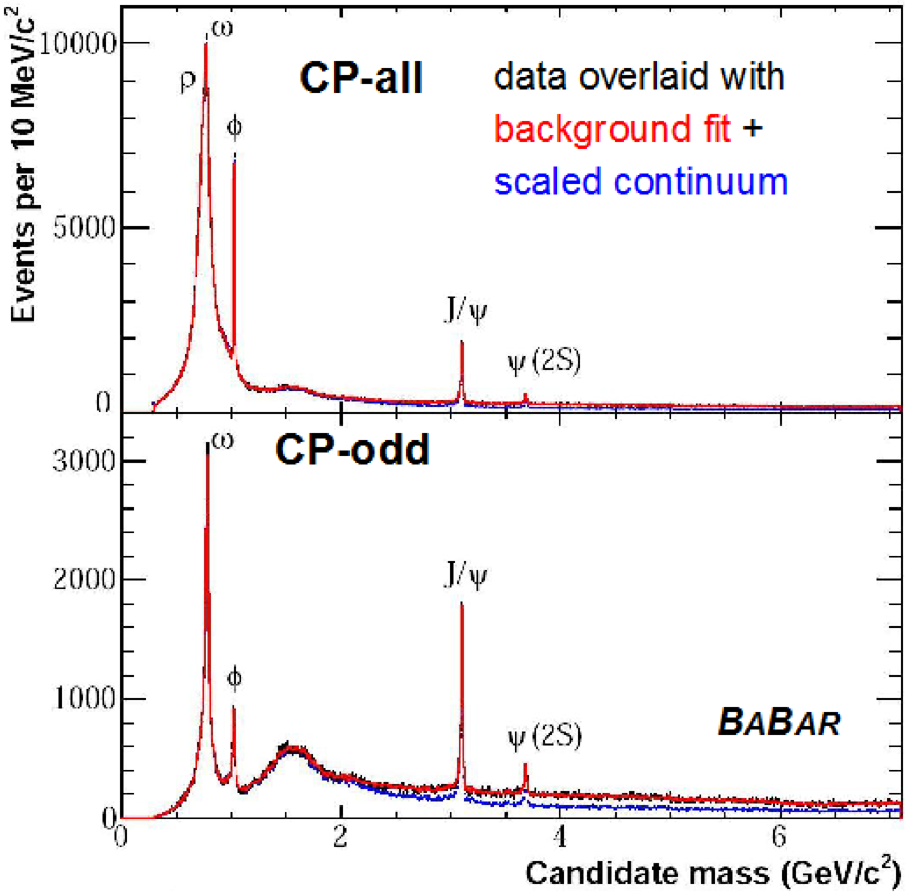
Low mass region excluded

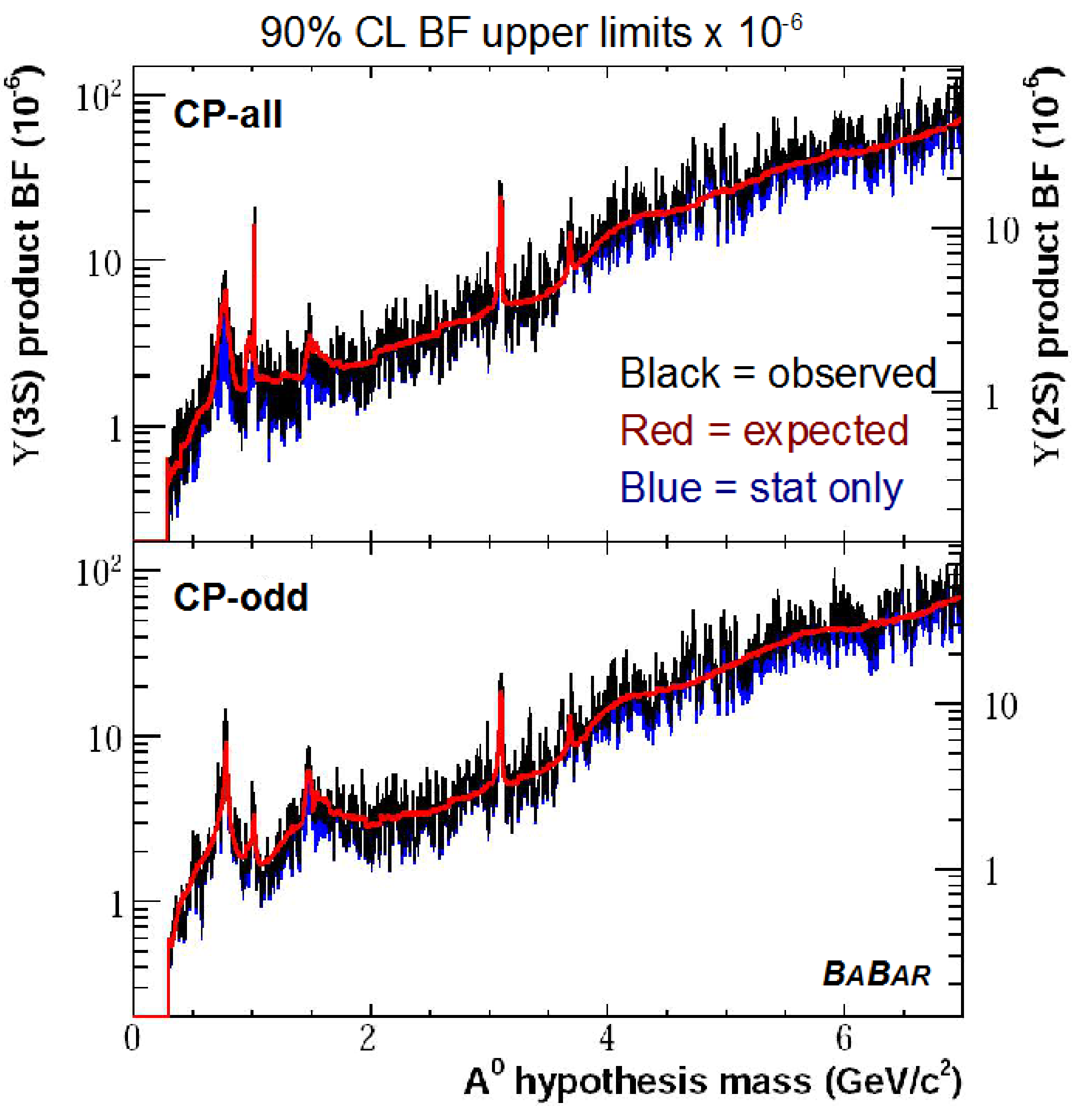


Brown line = approximate predictions

PRL 107, 221803 (2011)

- Reconstructed the full $A^0 \rightarrow$ hadrons candidate
- Consider both CP-all and CP-odd (no $\pi\pi$/KK) hypotheses



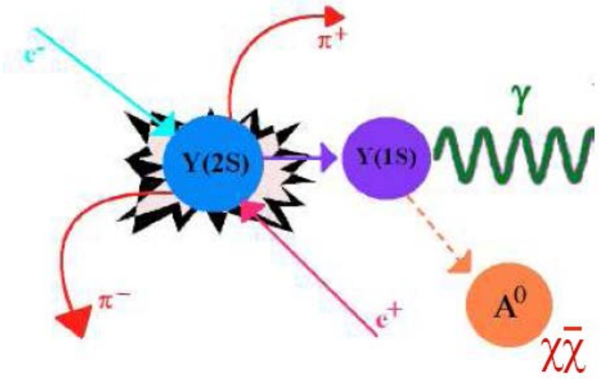


No evidence of light CP-odd Higgs in hadronic decays

PRL107, 021804 (2011)

Search for

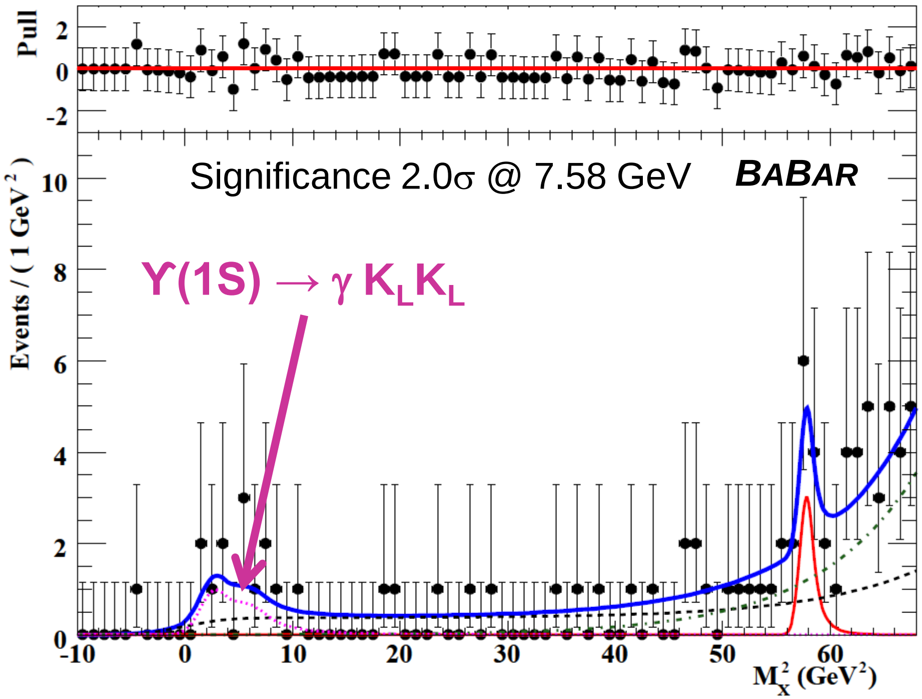
$Y(2S) \to \pi^+\pi^- \Upsilon(1S)$, $\Upsilon(1S) \to \gamma A^0$, $A^0 \to$ invisible



Analysis highlights

- Tag the Y(1S) from the dipion transition
- Require two tracks + one high-energy photon and no additional activity
- Missing energy and momentum

Recoil mass squared

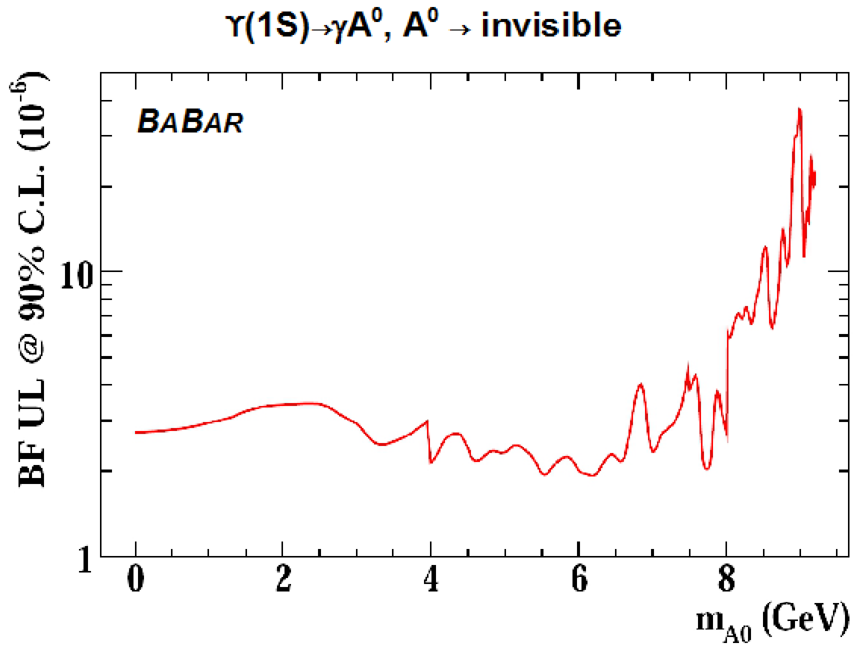


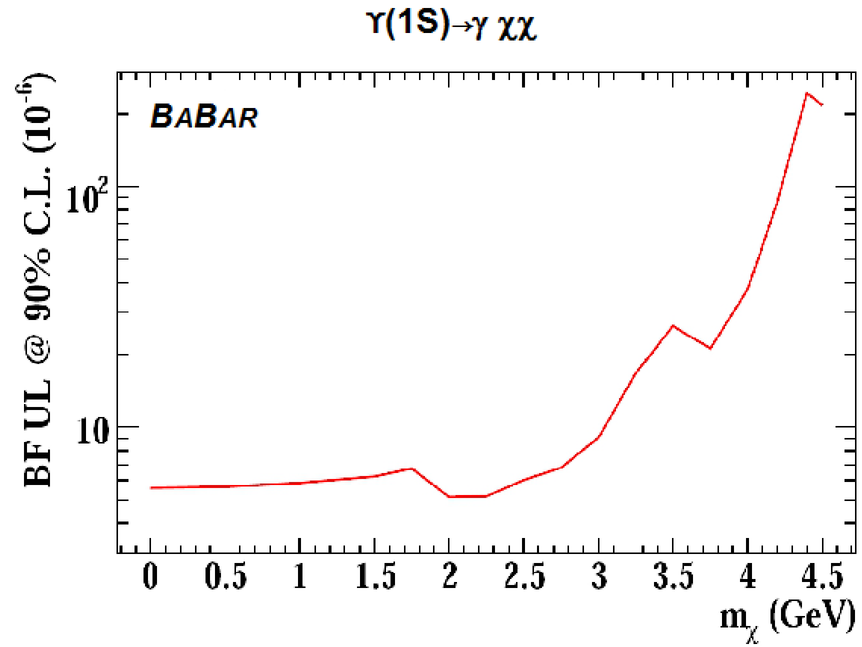
Search strategy

- Consider both $\Upsilon(1S) \to \gamma A^0$ (two-body) and $\Upsilon(1S) \to \gamma\chi\chi$ (multi-body) decays
- 2D fit the the recoil mass squared (M^2_{recoil}) and missing mass (M^2_X) squared

$$M^2_{\rm recoil} = M^2_{\Upsilon(2S)} + m^2_{\pi\pi} - 2M_{\Upsilon(2S)}E^*_{\pi\pi}$$
$$M^2_X = (\mathcal{P}_{e^-e^-} - \mathcal{P}_{\pi\pi} - \mathcal{P}_\gamma)^2$$

PRL107, 021804 (2011)





Upper limits (90% CL)

$BF(\Upsilon(1S) \rightarrow \gamma A^0, A^0 \rightarrow invisible) < (1.9 - 37) \times 10^{-6}$
$BF(\Upsilon(1S) \rightarrow \gamma\chi\chi) < (0.5 - 25) \times 10^{-5}$

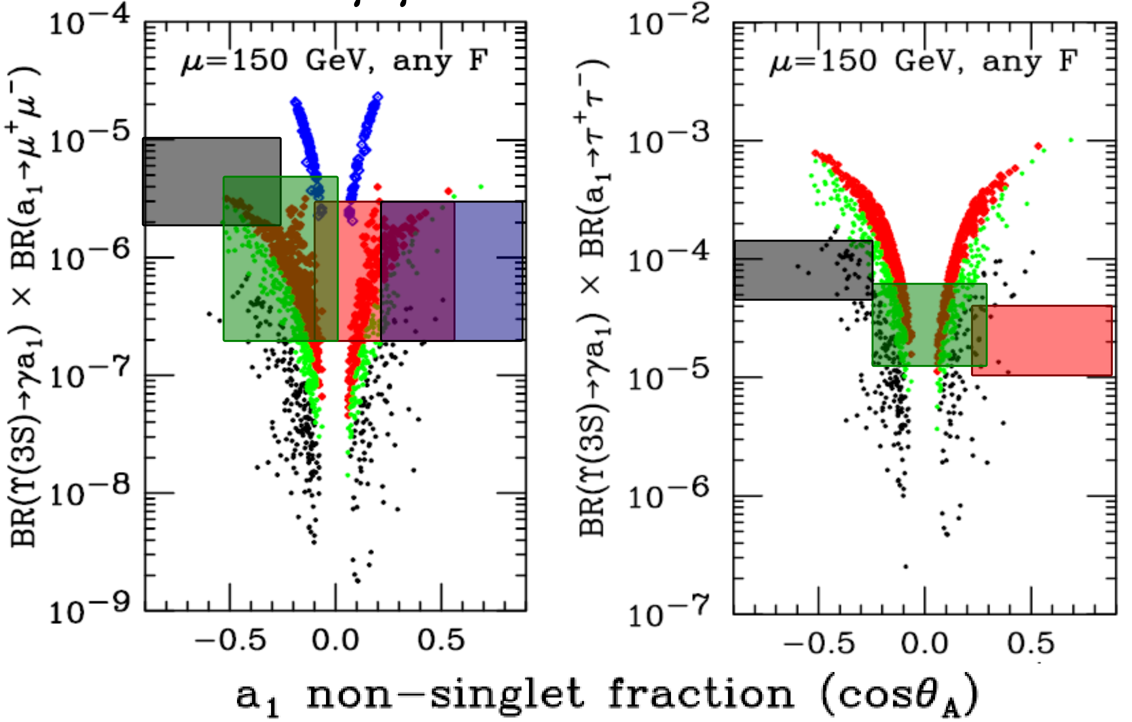
Predictions[1,2)]

$BF(\Upsilon(1S) \rightarrow \gamma A^0, A^0 \rightarrow invisible) \sim 10^{-6} - 10^{-4}$
$BF(\Upsilon(1S) \rightarrow \gamma\chi\chi)$ $10^{-5} – 10^{-4}$

Significant constraints on these models

1) PRD 76, 051105 (2007) 2) PRD 80,115019 (2009)

$A^0 \to \mu^+\mu^-$ **$A^0 \to \tau^+\tau^-$**



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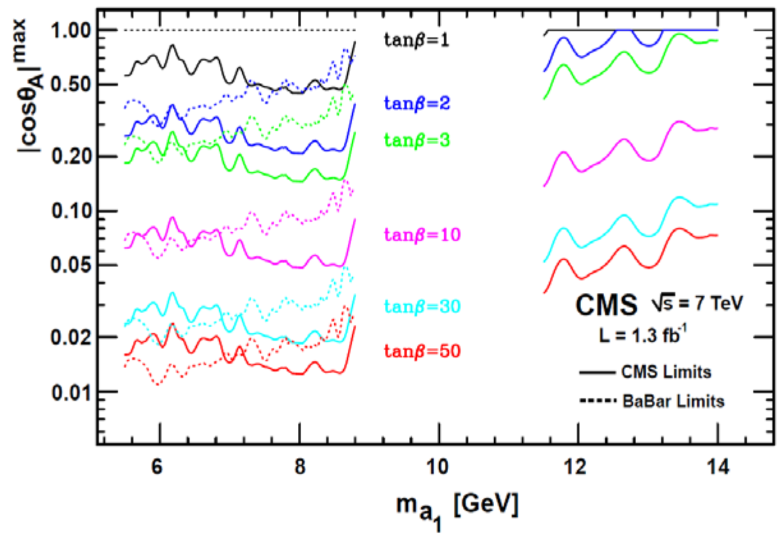
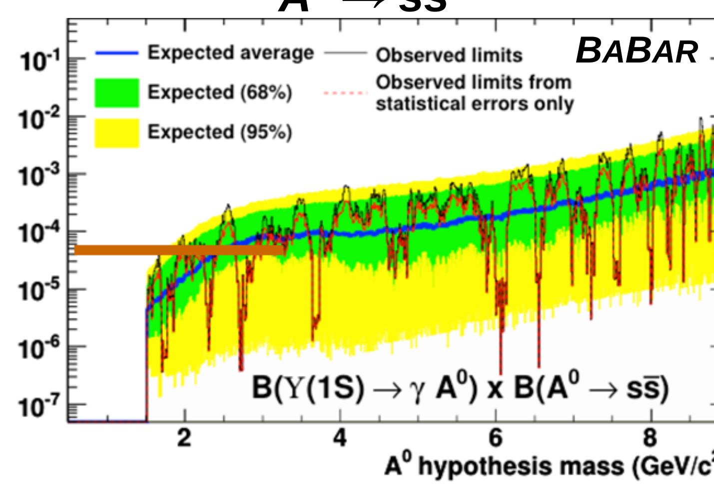
$A^0 \to \mu^+\mu^-$
CMS (PRL 109 (2012) 121801)



$A^0 \to s\bar{s}$

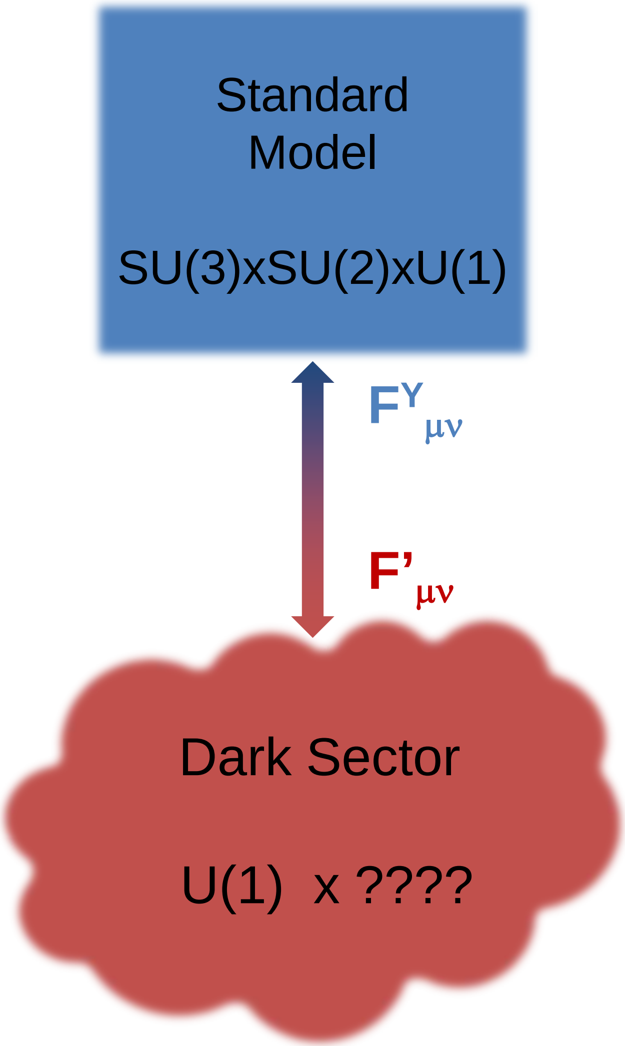


Substantial fraction of the parameter space up to 7-8 GeV is excluded

Dark Sector

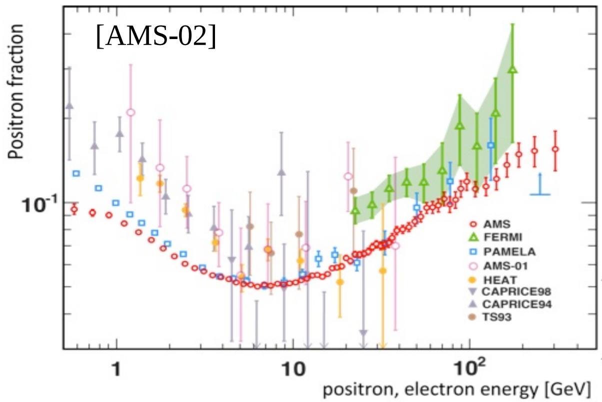
Dark sector in a nutshell

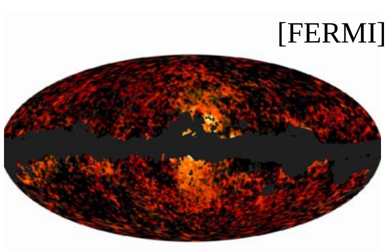
- Recent dark matter model introducing a new dark sector with a new U(1)'.
- The corresponding gauge boson, the so-called dark photon (A'), is light (MeV – GeV mass) in these models.
- Dark sector particles do not couple directly to the SM content. Interaction dark sector - SM via kinetic mixing between the dark photon and photon/Z with a mixing strength ε among other "portals".
- In other words, there is a dark photon – SM fermion coupling $\alpha' = \varepsilon^2 \alpha$.
- Mixing strength typically $\varepsilon \sim 10^{-5} – 10^{-2}$, but could be smaller.
- Dark photon width $\Gamma_{A'} \sim m_A \varepsilon$ and can be very small or very large. Dark photon can be short or long lived.



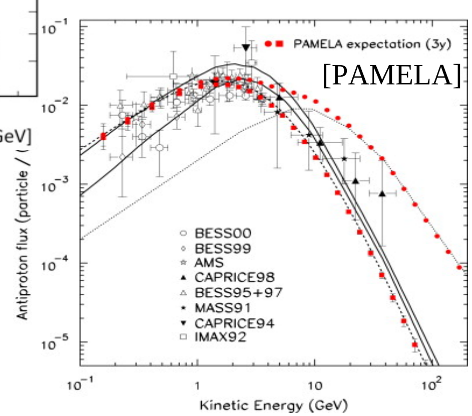
$$\Delta\mathcal{L} = \frac{\varepsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu}$$

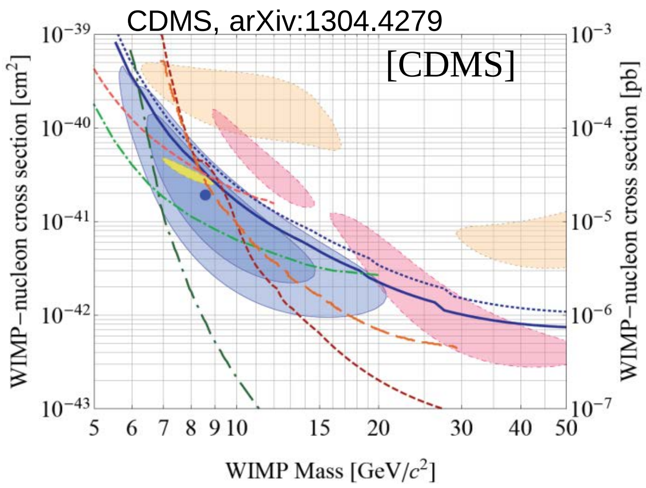
- In this framework, wimp-like TeV-scale dark matter particles can annihilate into pairs of dark photons, which subsequently decay to SM fermions.
- If dark photon is light → can only decay to light states. Could explain the recent observations in cosmic rays (electron excess but no antiprotons) and by ground experiments.
- Other explanations of these anomalies have been proposed, but the possibility of a hidden MeV/GeV-scale sector is poorly constrained and really worth exploring.



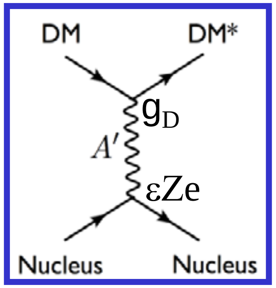


[Finkbeiner Dobler et al.,]





[Slatyer, Schuster&Toro,…]

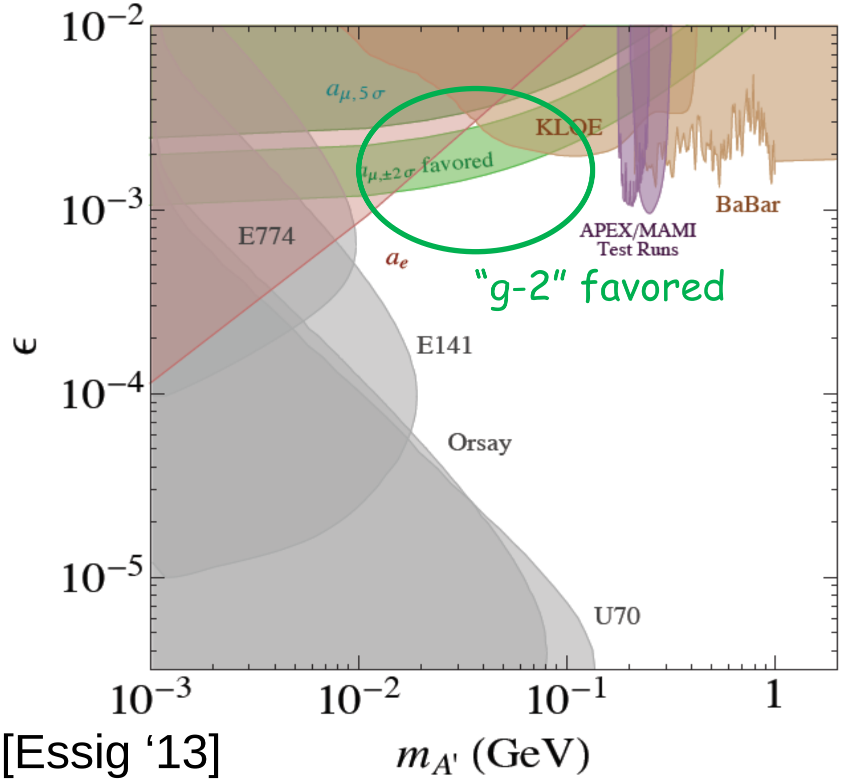


And many others….

Would require another talk to discuss them all…

Particle physics implications

- Can produce dark photons. In fact, photons in any process can be replaced by a dark photon (with an extra factor of ε).
- Decays back to lepton/quark pairs → search for resonances
- Dark photon decay can be prompt or displaced (long-lived)
- Current bounds on the mixing parameter ε are shown as a function of the dark photon mass.
- Constraints from electron/muon g-2, beam dump and fixed target experiments and e^+e^- colliders (some constraints reinterpreted from limits of other measurements by theorists, e.g. *BABAR*)



[Essig '13]

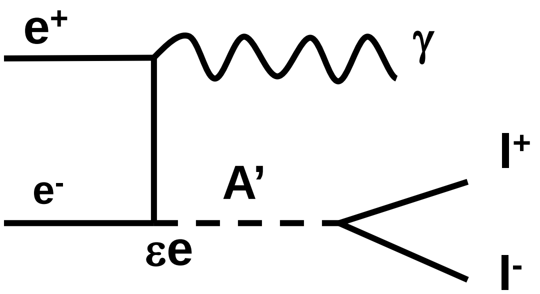
Pospelov;
Bjorken, Essig, Schuster, Toro
Andreas, Niebuhr, Ringwald
Batell, Pospelov, Ritz;
Essig, Harnik, Kaplan, Toro
Blumlein, Brunner;

Dent, Ferrer, Krauss
Essig Schuster, Toro, Wojtsekhowski
KLOE, APEX, MAMI/A1 Collab.
Davoudiasl, Lee, Marciano;
Endo, Hamaguchi, Mishima

Low-energy high-luminosity e^+e^- colliders offer a low-background environment to search for MeV/GeV-scale hidden sector (in particular GeV masses) and probe their structure

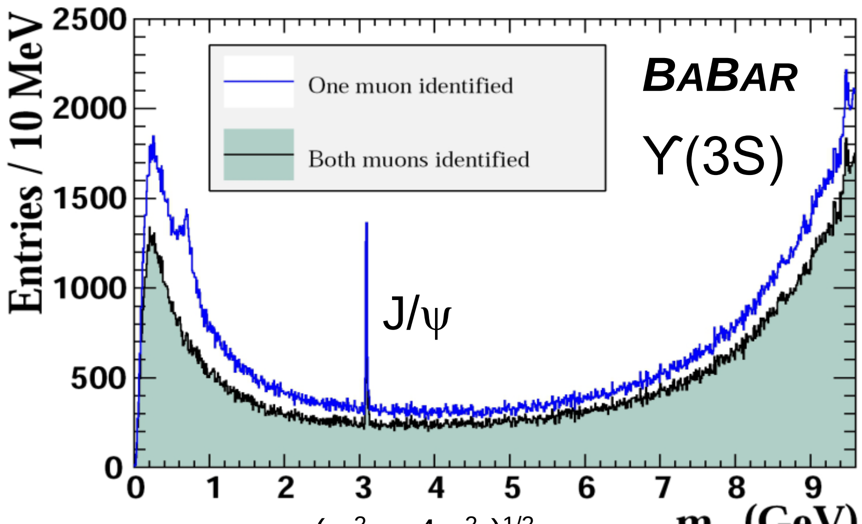
A dark photon can be produced in

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



So far, only one measurement of this final state at *BABAR* from light CP-odd Higgs search in ϒ(2S,3S) decays

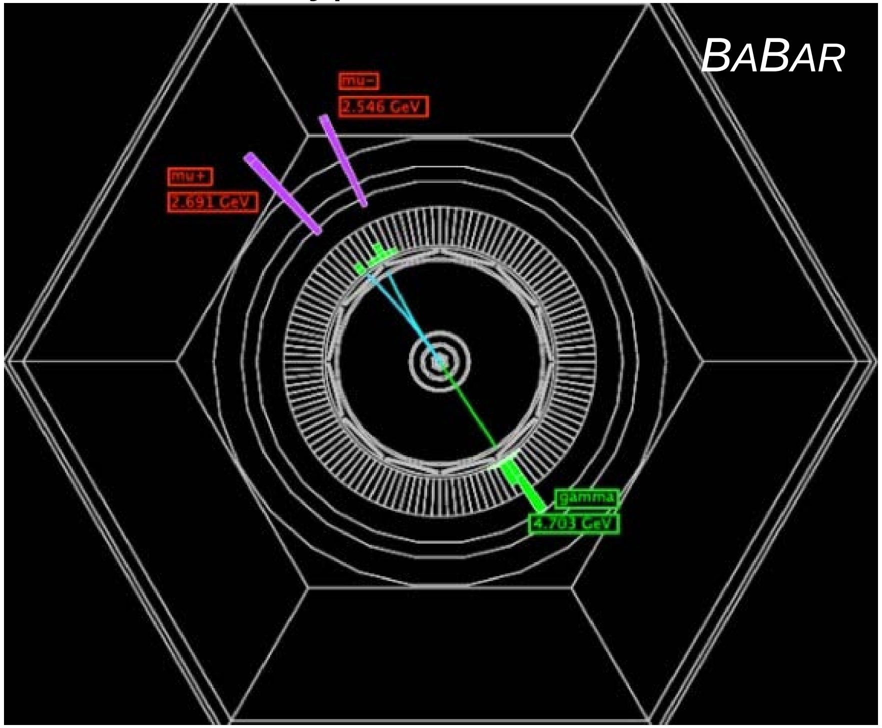
$$e^+e^- \to \gamma\, A^0,\ A^0 \to \mu^+\mu^-$$



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

No significant signal !

Typical event

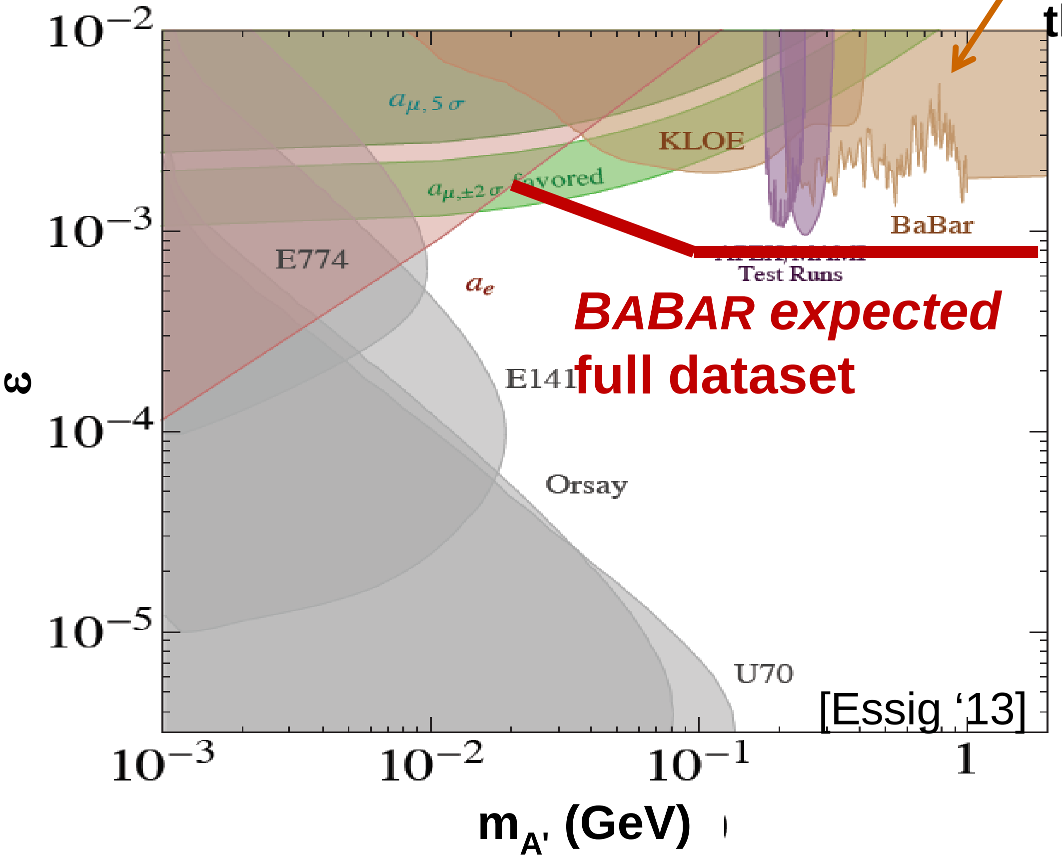


Tracks
Photon
Signal in muon/hadron detector

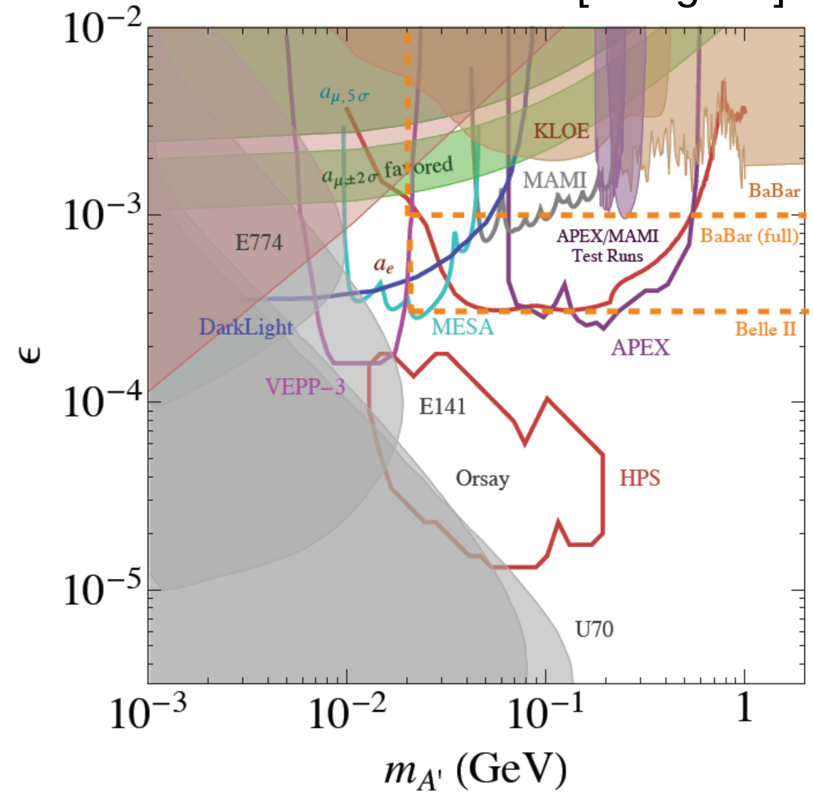
PRL 103 (2009) 081803

Current limits on dark photon

Light Higgs limits reinterpreted by theorists



[Essig '13]



- On-going analysis on the full dataset, should probe almost all "g-2" preferred region and improve bounds down to ~10^{-3} from 20 MeV to 10.2 GeV. Should come soon, stay tuned !
- Planned experiments will further probe the parameter space.

arxiv:0808.0017

Invisible dark sector

- Several scenarios where dark photons decay to invisible final states, e.g lighter dark sector particles (sub-GeV),…
- At e^+e^- colliders, we can search for

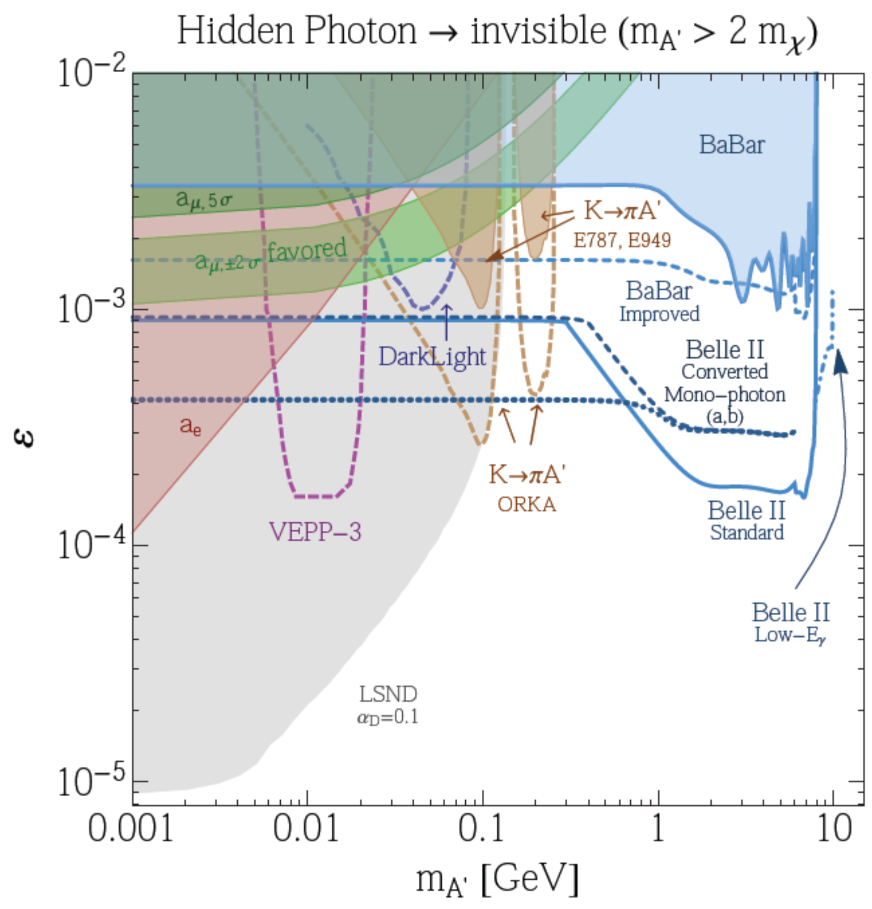
  $$e^+e^- \rightarrow \gamma A' \;,\; A' \rightarrow \text{invisible}$$

  by tagging the recoil photon in "single photon" events.
- Currently only a measurement of

  $$Y(2S,3S) \rightarrow \gamma A^0,\ A^0 \rightarrow \text{invisible}$$

  at *BABAR* with A^0 a light CP-odd Higgs
- Analysis extended to full single photon dataset and the dark photon case, expect limits on ε at the level of 10^{-3}.
- Also constraints from (g-2)e, (g-2)μ, $K \rightarrow \pi\nu\nu$ decays

Essig *et al.*, JHEP 1311 (2013) 167



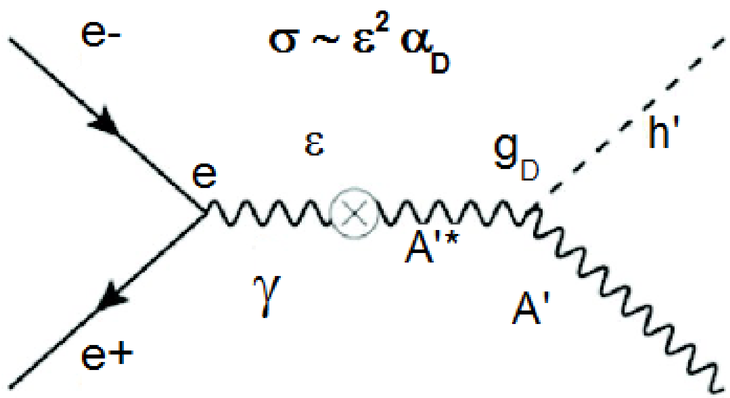
Major improvement possible with future experiments (e.g. Belle II)

- Dark photon mass is generated via the Higgs mechanism, adding a dark Higgs boson (h')
- A minimal scenario has a single dark photon and a single dark Higgs boson.
- Theoretical prejudice for dark Higgs mass at the MeV-GeV scale.
- The Higgsstrahlung process

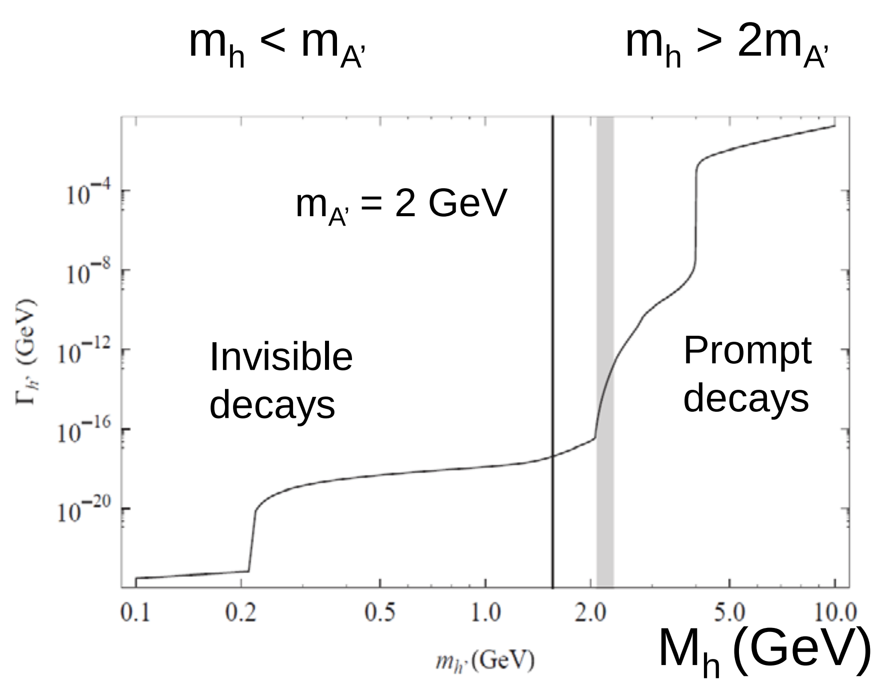
$$e^+e^- \rightarrow A'^* \rightarrow h' A'$$

is only suppressed by ε^2 and should have low background

- Also sensitive to the dark sector coupling constant $\alpha_D = g_D^2 / 4\pi$



Dark Higgs decay topology



Search for prompt h' decays at *BABAR*:
$e^+e^- \rightarrow A'^* \rightarrow h' A', h' \rightarrow A' A', A' \rightarrow l^+l^-, \pi^+\pi^-$

PRL 108 (2012) 211801

- Six candidates are selected from the full *BABAR* dataset (~500 fb^{-1})

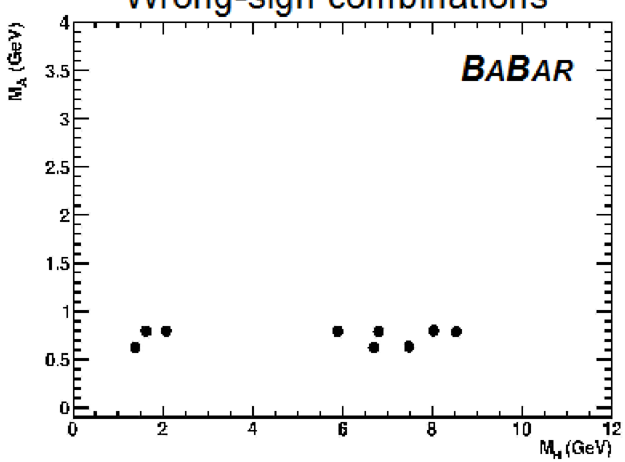
- Three entries for each event, corresponding to the three possible assignments of the h' → A'A' decay

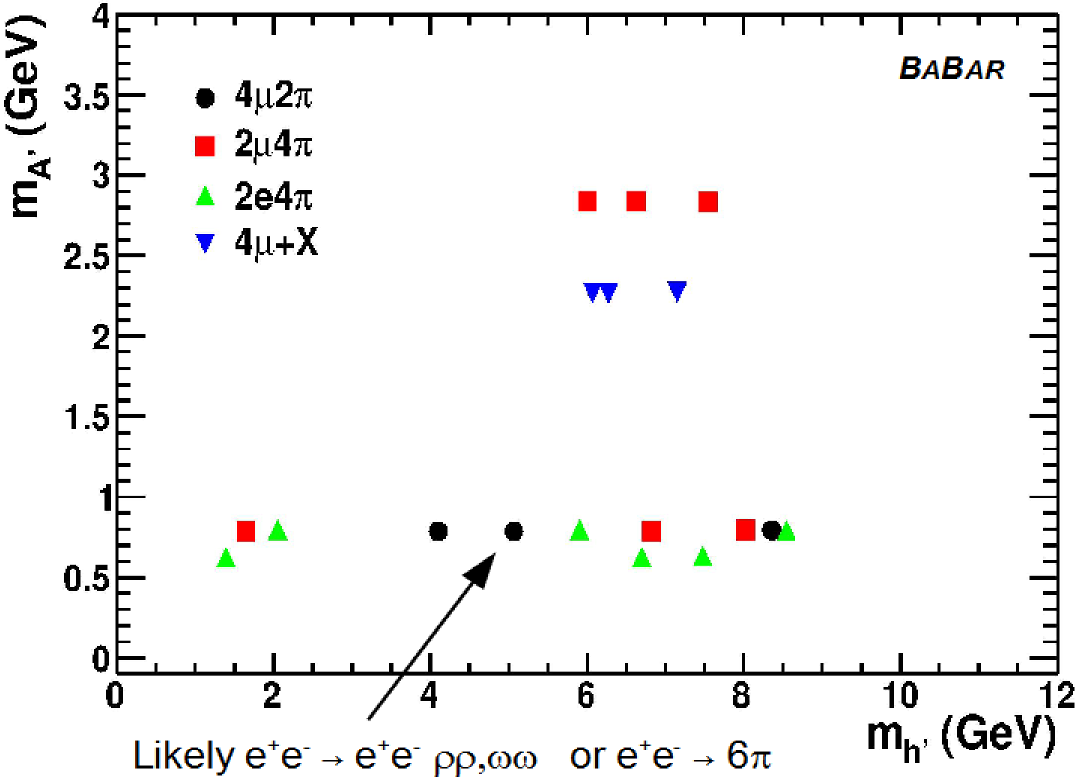
- Estimate background from

  - 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

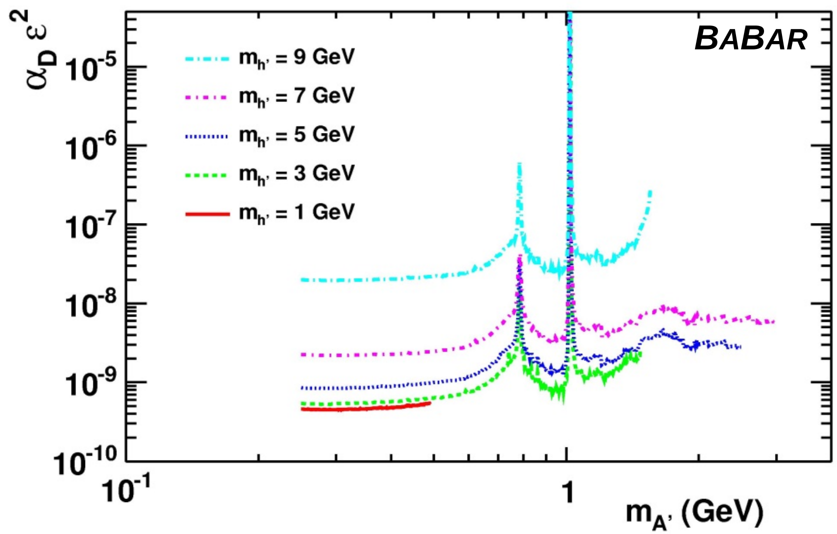




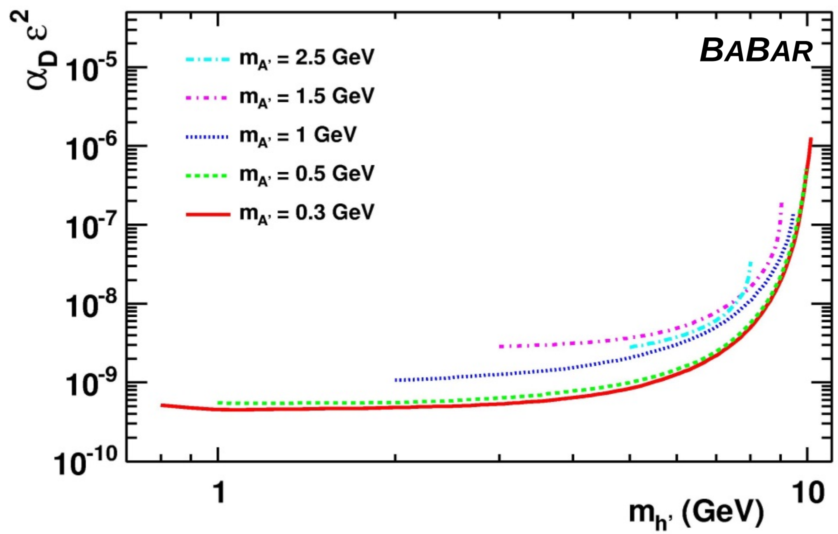
No events with 6 leptons, consistent with the pure background hypothesis

PRL 108 (2012) 21180

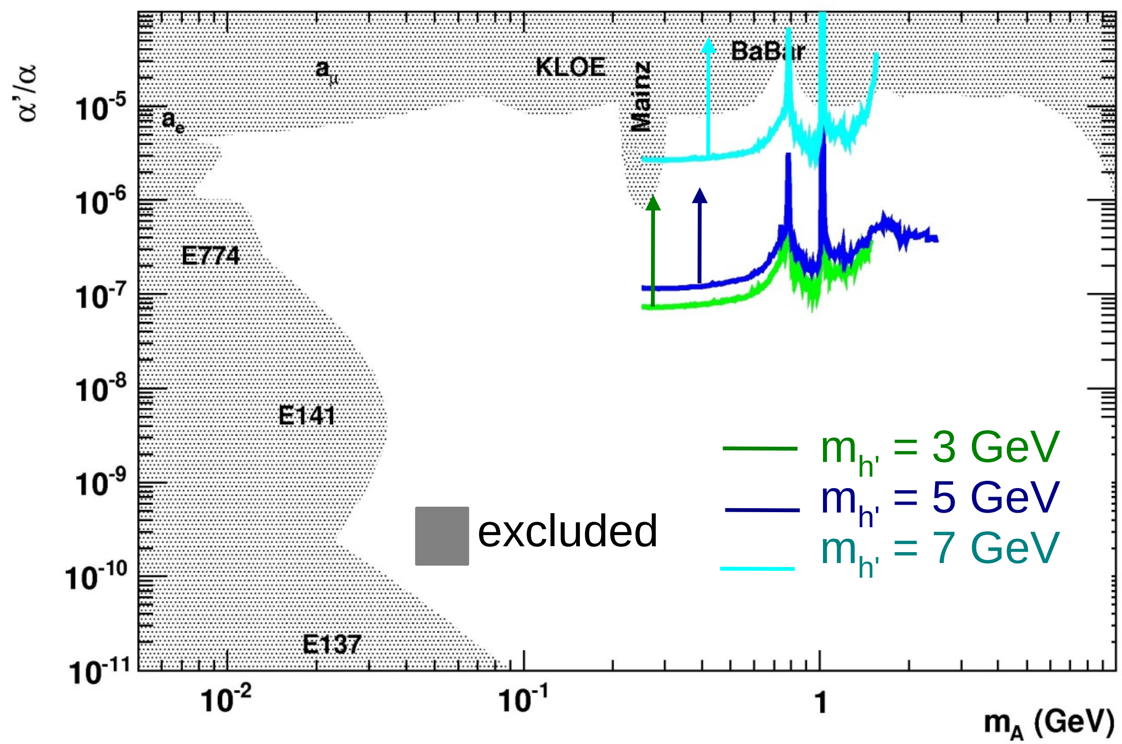
90% CL upper limit on $\alpha_D\varepsilon^2$



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

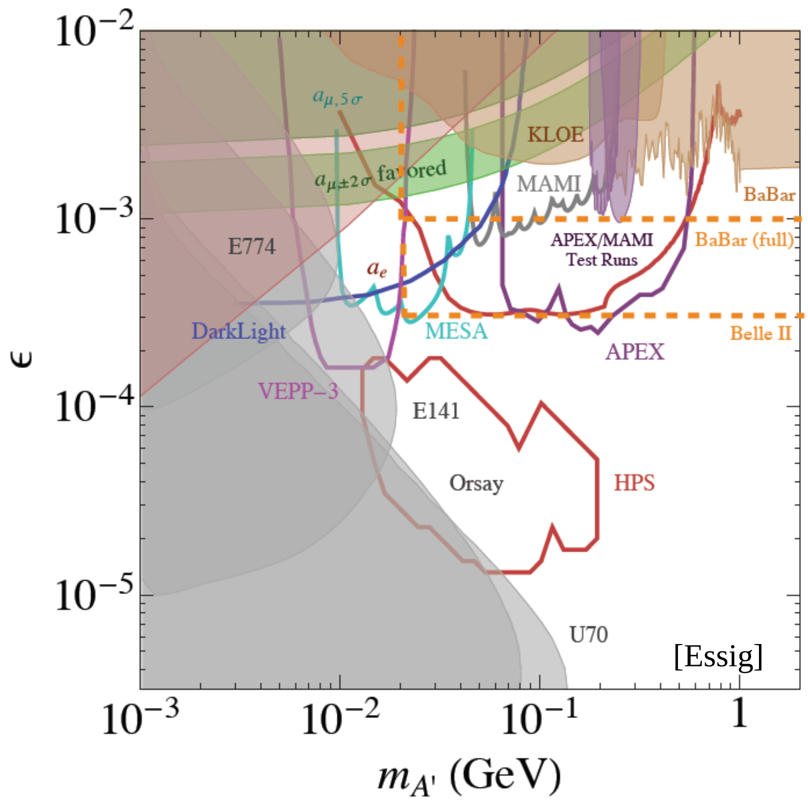


Limit on $\varepsilon^2=\alpha'/\alpha$ assuming $\alpha_D=\alpha_{em}$ for various Higgs mass

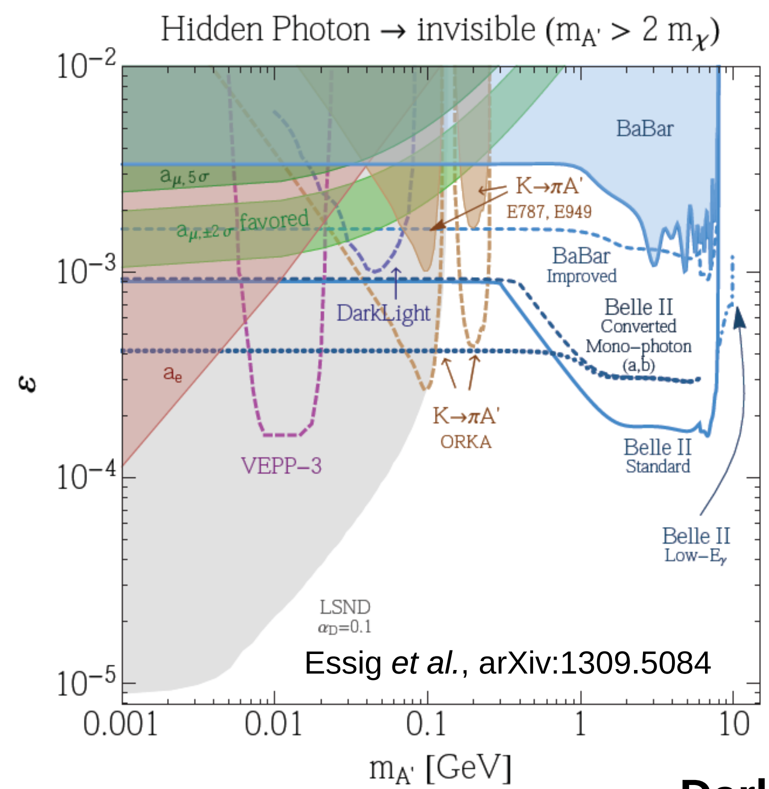


Substantial improvement over existing limits for $m_{h'}$ < 5 - 7 GeV if light dark Higgs boson exists

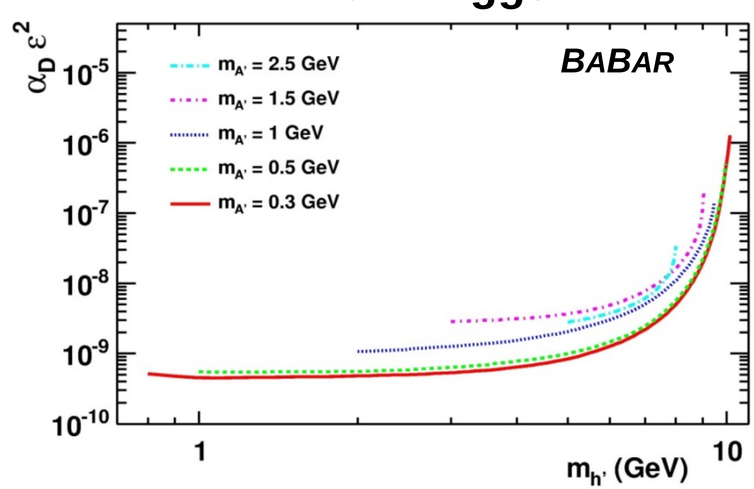
A' → visible



A' → invisible



Dark Higgs



Start excluding some parameter space, but still a large fraction of uncovered territory!

Several new initiatives will further probe this region.

- No significant evidence for light CP-odd Higgs has been found and upper limits have been set with a sizeable improvement over previous measurements.
- Limits are competitive with the LHC at low masses, especially below $2m_\tau$. Low-energy colliders can also probe partially reconstructed / invisible final states.
- Excluded a large fraction of parameters space, exclude almost everything below $2m_\tau$, and a large fraction below 7.5 GeV.
- On-going searches for $A^0 \rightarrow \gamma\gamma$ and $A^0 \rightarrow c\bar{c}$, expect results for the summer
- No sign of dark photon or dark Higgs so far, set stringent constraints on these models. Expect new results soon, stay tuned!

Better luck at the LHC…