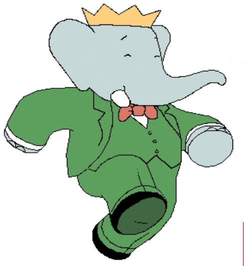
Search for dark photon and dark Higgs at *BABAR*

Bertrand Echenard
California Institute of Technology

on behalf of the *BABAR* Collaboration

8TH Patras Workshop
Chicago, July 2012

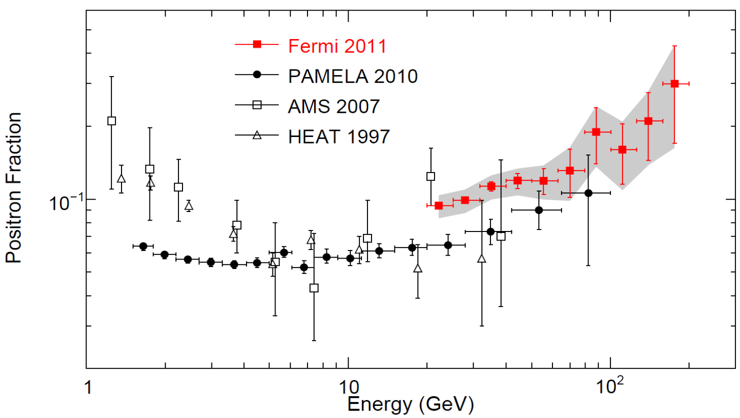


Models introducing a **new 'dark' force** mediated by a **new gauge boson with a mass around a GeV** have been proposed to explain the observations of PAMELA, FERMI, DAMA/LIBRA, CREST,... (see talks from Essig, Hooper).

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

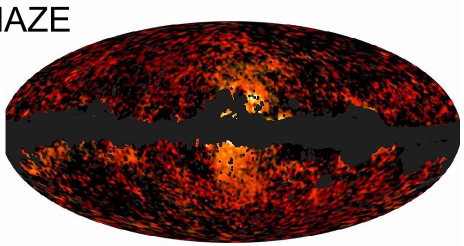
Other explanations of these anomalies have been proposed, but the possibility of a **hidden MeV/GeV-scale sector** is **poorly constrained and worth exploring.**

FERMI



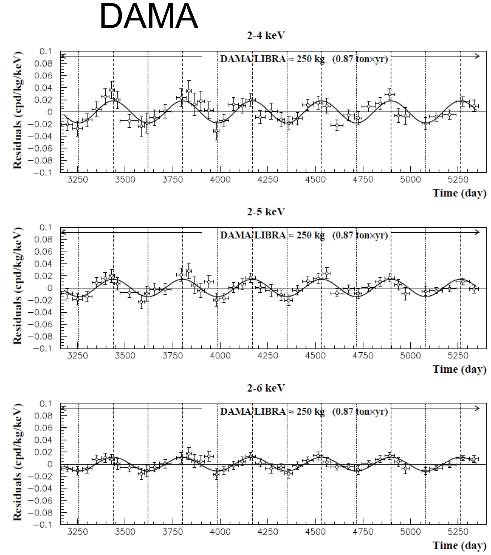
FERMI Collab., PRL 108, 011103 (2012), arXiv:1109.0521

FERMI HAZE



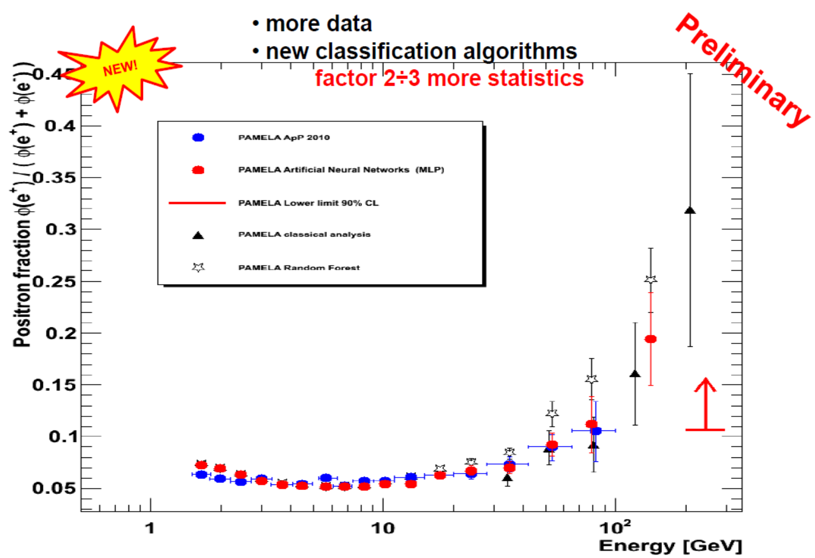
http://www.nasa.gov/mission_pages/planck/multimedia/pia15228.html

DAMA



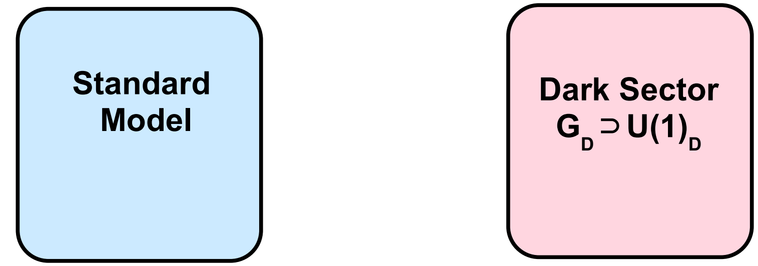
DAMA Collab., Eur. Phys. J. C (2010) 67: 39-49

PAMELA



E. Mocchiutti,
International workshop on positrons in Astrophysics 2012

- ⇨ New dark sector with a $U(1)_D$ gauge group
- ⇨ New gauge boson: **dark photon A' , which could have O(GeV) mass**

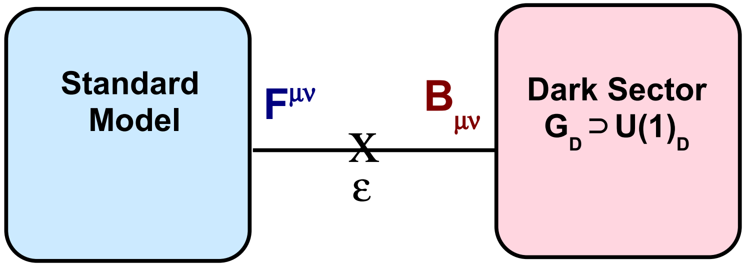


Dark sector and dark forces

- New dark sector with a $U(1)_D$ gauge group
- New gauge boson: **dark photon A' , which could have O(GeV) mass**
- Interaction with the SM is via **kinetic mixing**

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

with a **mixing strength ε.**



$$\Delta\mathcal{L}_{mix} = \varepsilon F^{\mu\nu} B_{\mu\nu}$$

PRD 79, 115008,2009

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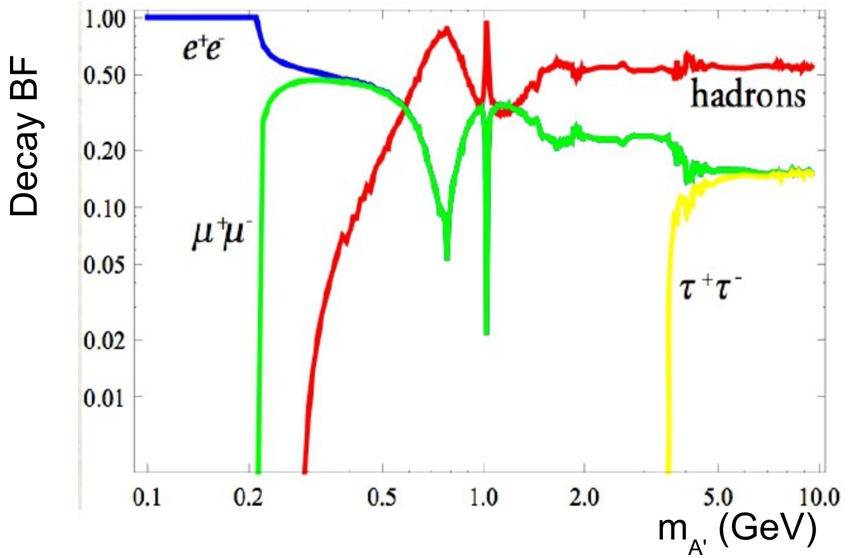
- The dark photon acquires a charge εe, and the **coupling of the dark photon to SM fermions** is characterized by $\alpha' = \alpha\,\varepsilon^2$

dark photon branching fraction



$$BF(A' \to \text{hadrons}) / BF(A' \to \mu\mu) = R(s = m_{A'}^2)$$

Dark sector and dark forces

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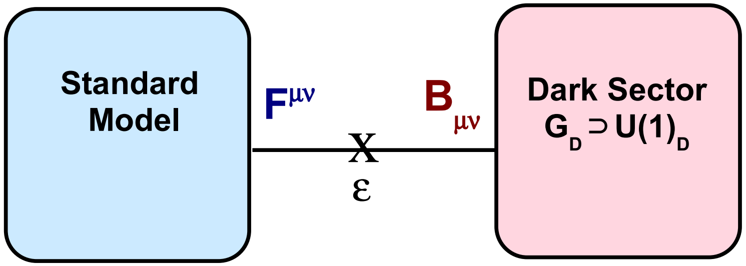
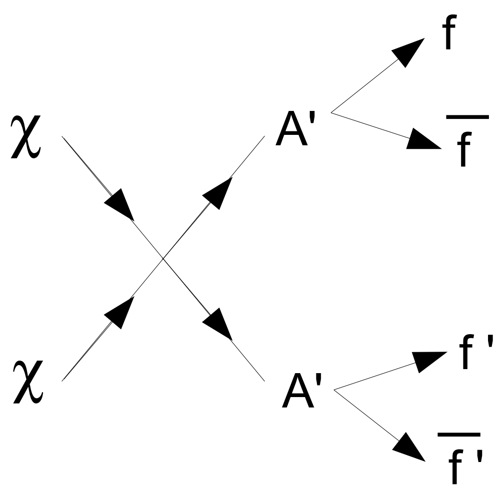


$$\Delta\mathcal{L}_{mix} = \varepsilon\, F^{\mu\nu} B_{\mu\nu}$$



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

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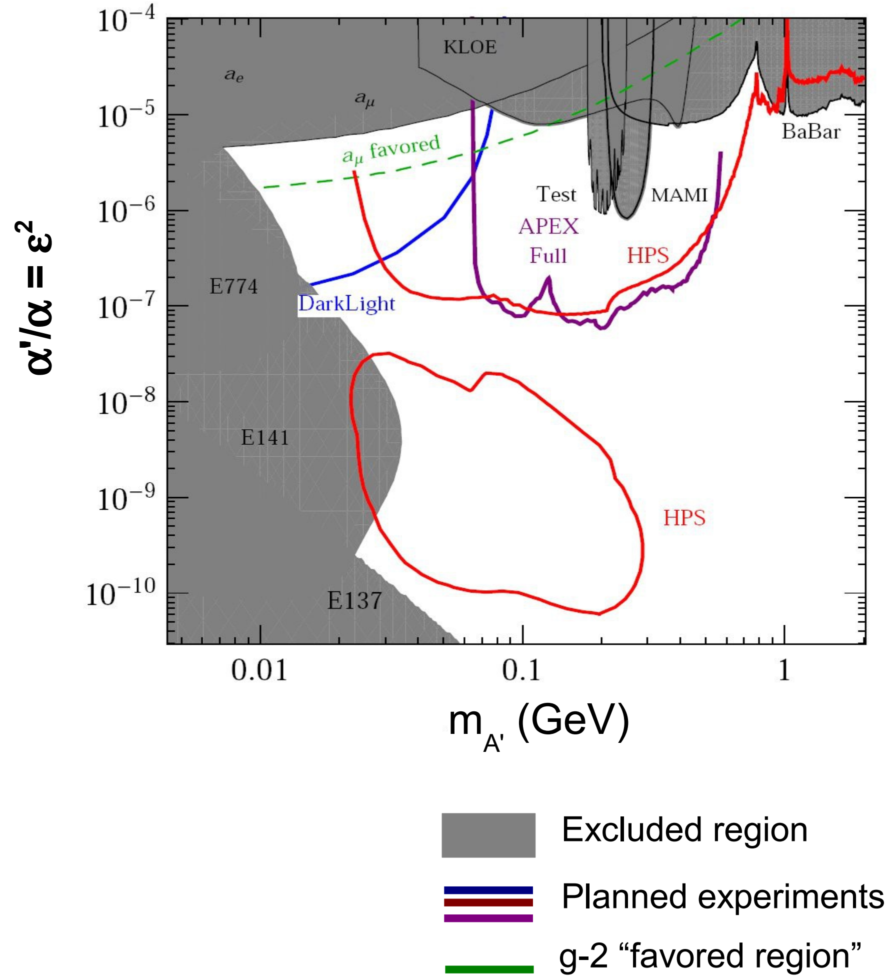
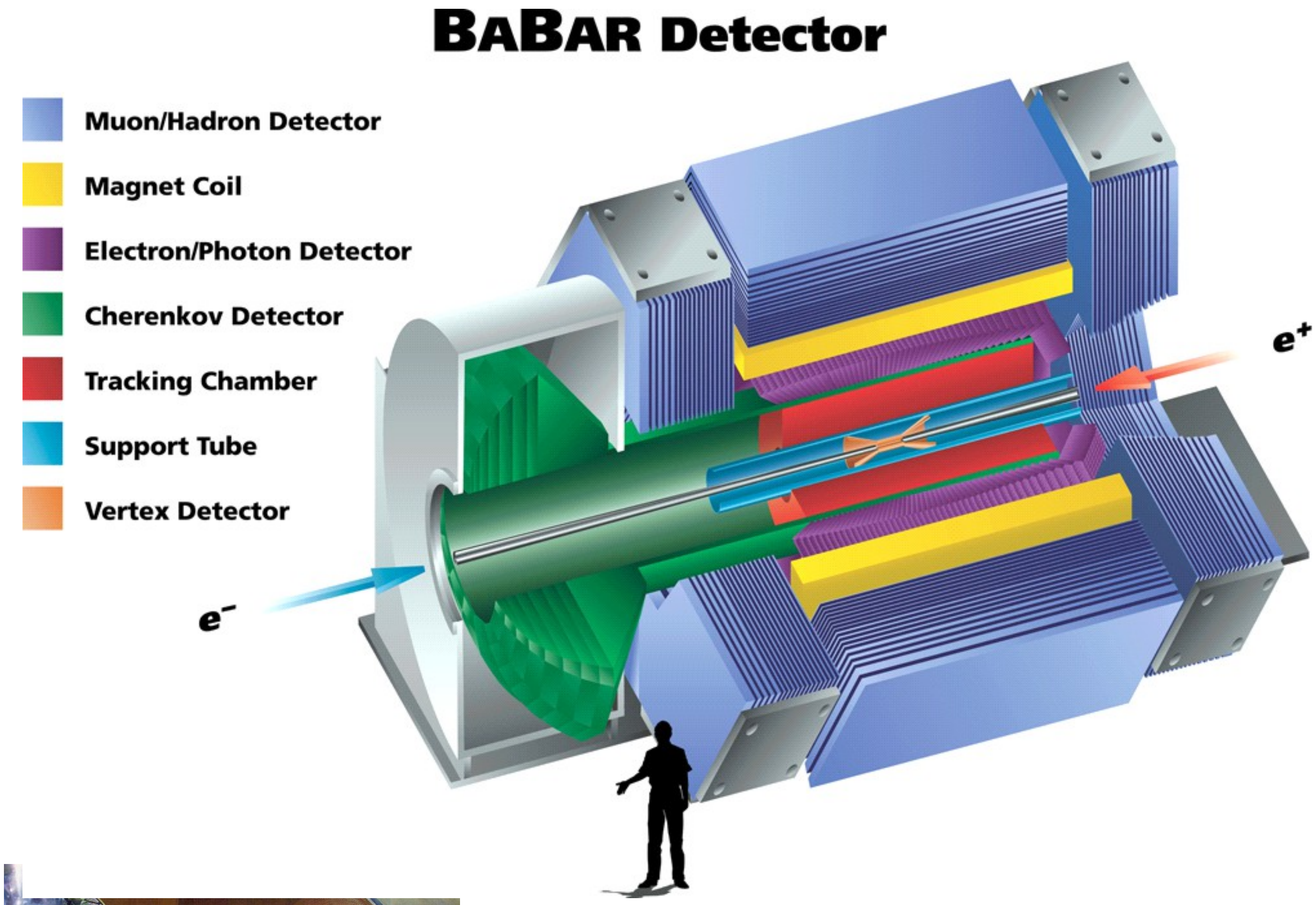
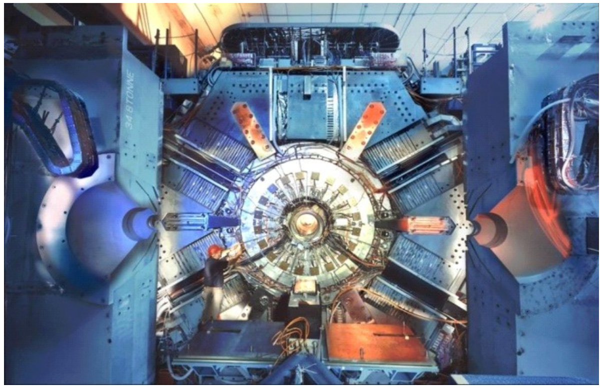
  with a **mixing strength ε.**
- The dark photon acquires a charge εe, and the **coupling of the dark photon to SM fermions** is characterized by $\alpha' = \alpha\,\varepsilon^2$
- TeV-scale dark matter particles can annihilate into a pair of gauge bosons, which subsequently decay into SM fermions
- Current limits on the mixing strength ε^2 are shown as a function of the dark photon mass for existing measurements and a few planned experiments.

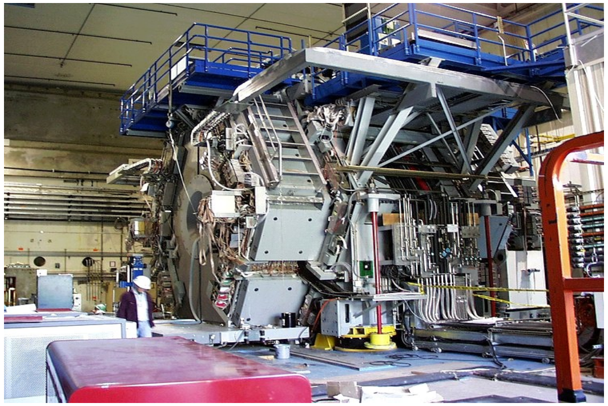
Constraints on $\alpha'/\alpha = \varepsilon^2$

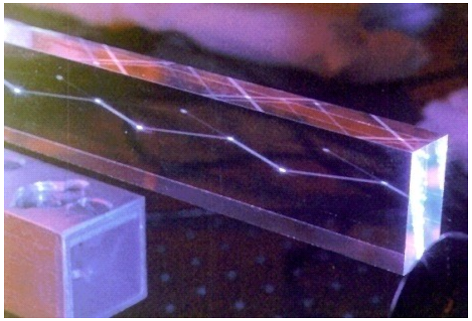


Low-energy high-luminosity e^+e^- colliders offer a low-background environment to search for MeV/GeV-scale hidden sector signatures and probe their structure

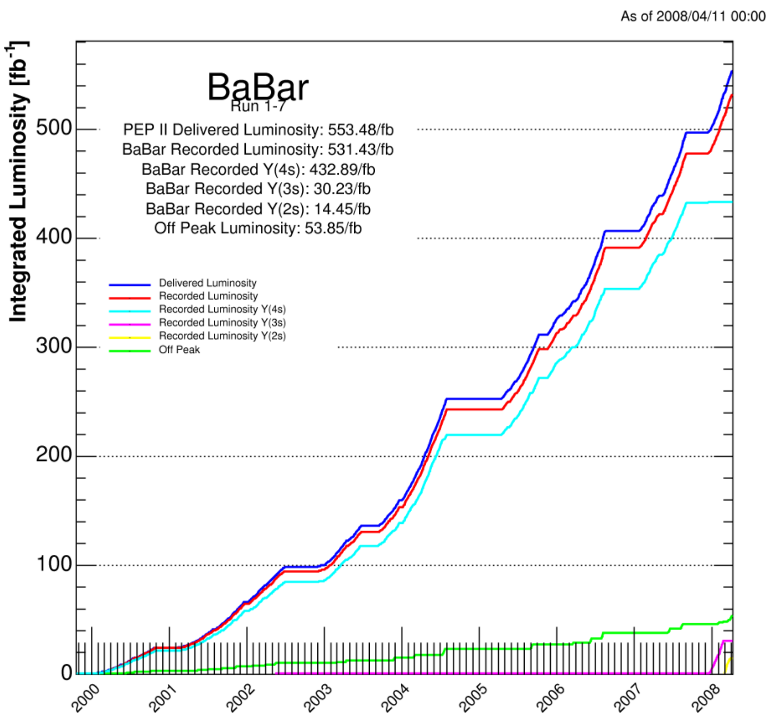

BABAR Detector
Muon/Hadron Detector
Magnet Coil
Electron/Photon Detector
Cherenkov Detector
Tracking Chamber
Support Tube
Vertex Detector
e+
e-

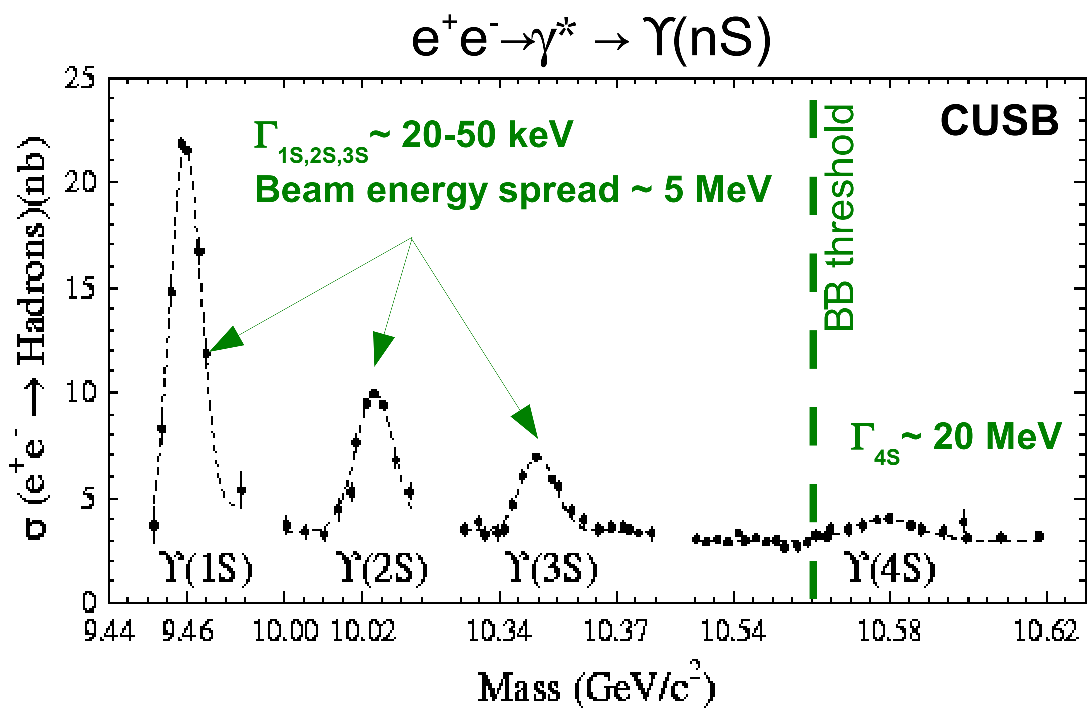






BABAR collected around 533 fb^{-1} of e^+e^- collisions around the ϒ(4S)





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 ϒ(2S) → $\pi^+\pi^-$ ϒ(1S)

Possible searches for dark sector at *BABAR*

Search for dark photon

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

Search for dark boson(s)

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

$e^+e^- \to \gamma A' \to W' W''$

Search for dark Higgs boson

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

Search for dark hadrons

$e^+e^- \to \pi_D + X$, $\pi_D \to e^+e^-, \mu^+\mu^-$

Search for dark photon in meson decay

$\pi^0 \to \gamma l^+l^-$, $\eta \to \gamma l^+l^-$, $\phi \to \eta l^+l^-$,...

Search for dark scalar (s) / pseudoscalar (a)

$B \to K^{(*)}s \to K^{(*)} l^+l^-$ and $B \to K^{(*)}a \to K^{(*)} l^+l^-$
$B \to ss \to 2(l^+l^-)$
$B \to K\, 2(l^+l^-)$
$B \to 4(l^+l^-)$

Search for "invisible" dark photon

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

+ related searches (hidden warped extra dimensions,...)

Can probe the hidden sector structure

Possible searches for dark sector at BABAR

Search for dark photon

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Search for “invisible” dark photon

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+ related searches (hidden warped extra dimensions,...)

Can probe the hidden sector structure

PRL 103 (2009) 081803

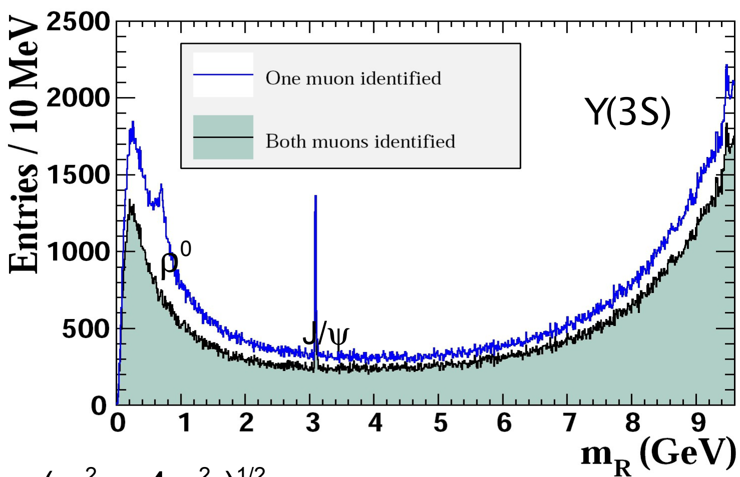
A dark photon can be readily produced in

$$e^+e^- \to \gamma A' \to \gamma\, l^+l^-, \gamma\, q\bar{q}$$

So far, only one measurement of this final state at *BABAR* from light CP-odd Higgs* search in Υ(2S,3S) decays based on ~40 fb^{-1} of data:

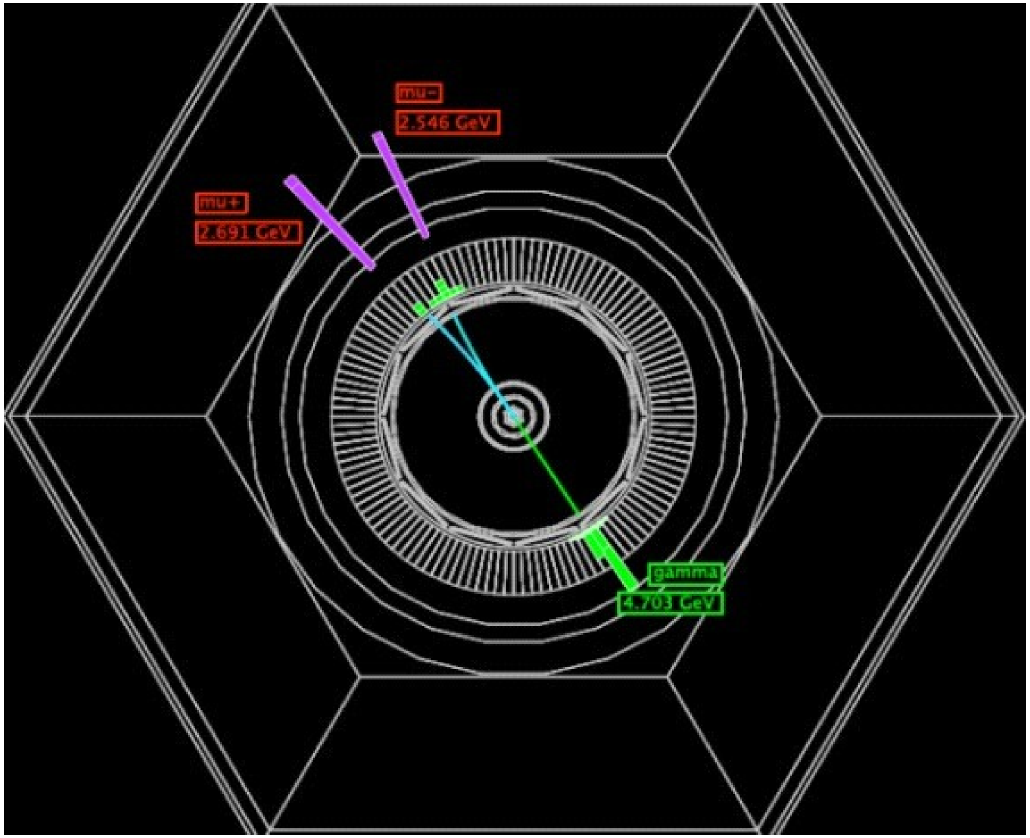
$$e^+e^- \to \gamma A^0,\ A^0 \to \mu^+\mu^-$$

Distribution of dimuon reduced mass



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

Candidate event



Tracks
Photon
Signal in muon/hadron detector

*See Extra material for a discussion on light CP-odd Higgs

PRL 103 (2009) 081803

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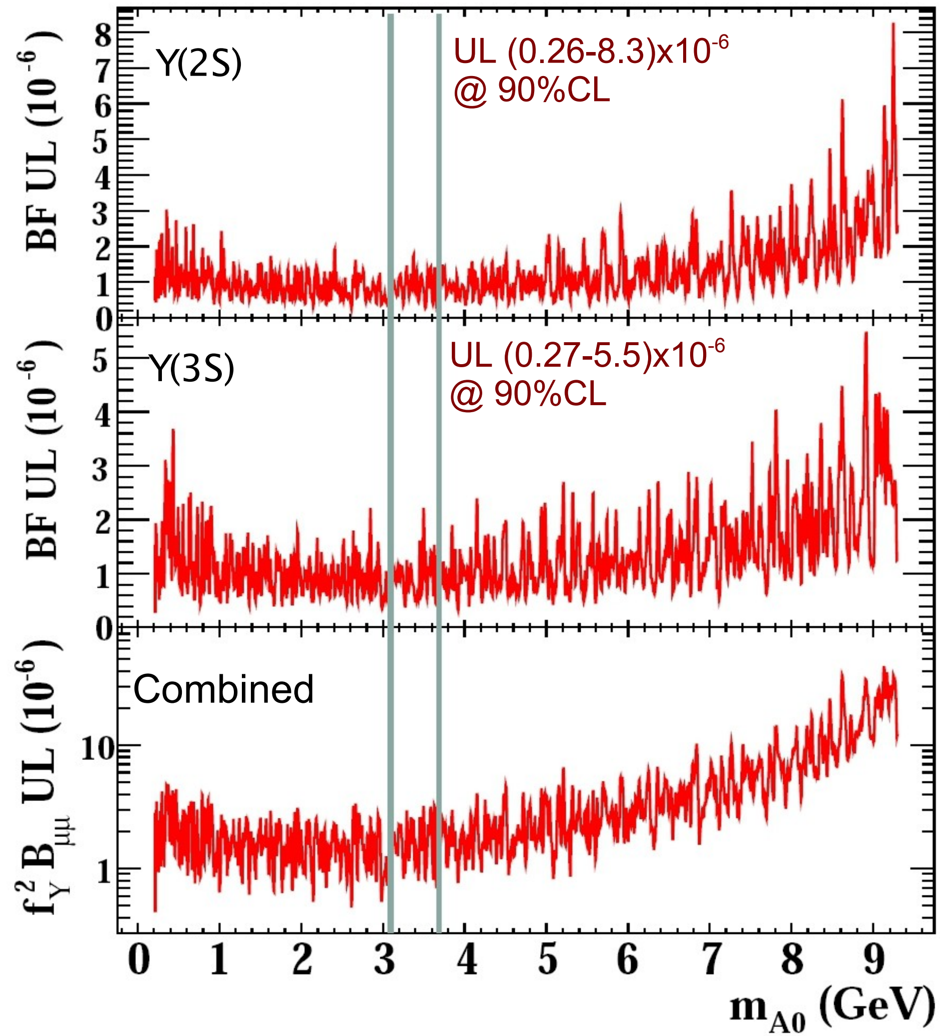

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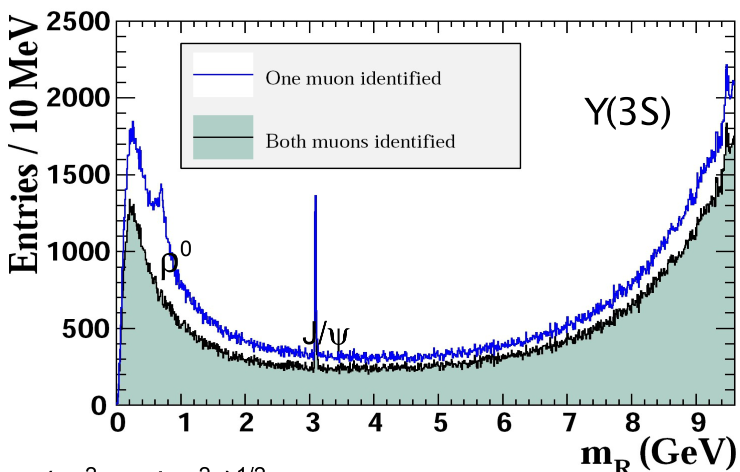
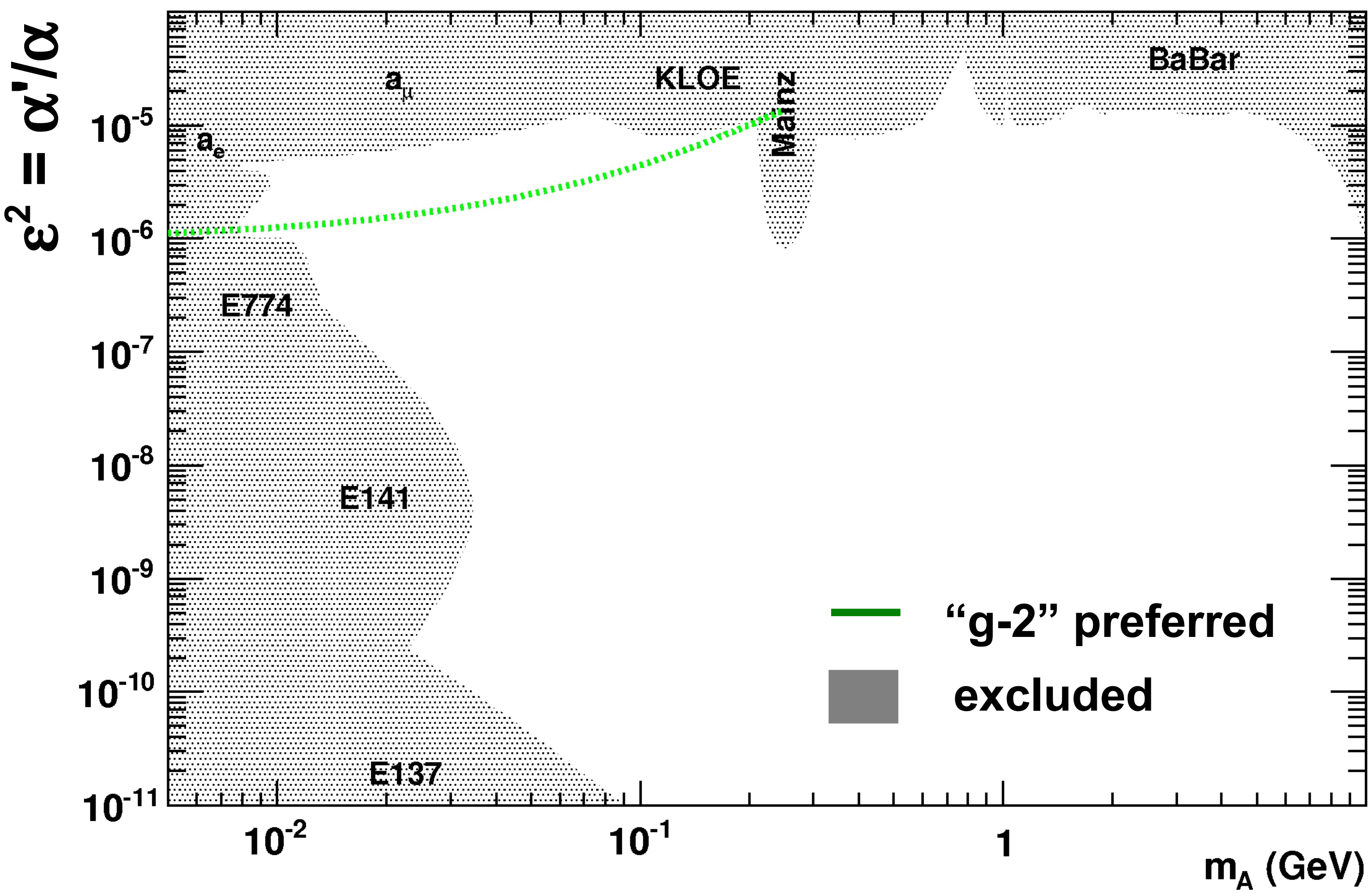


$m_r = (m^2_{A0} - 4m^2_{\mu})^{1/2}$

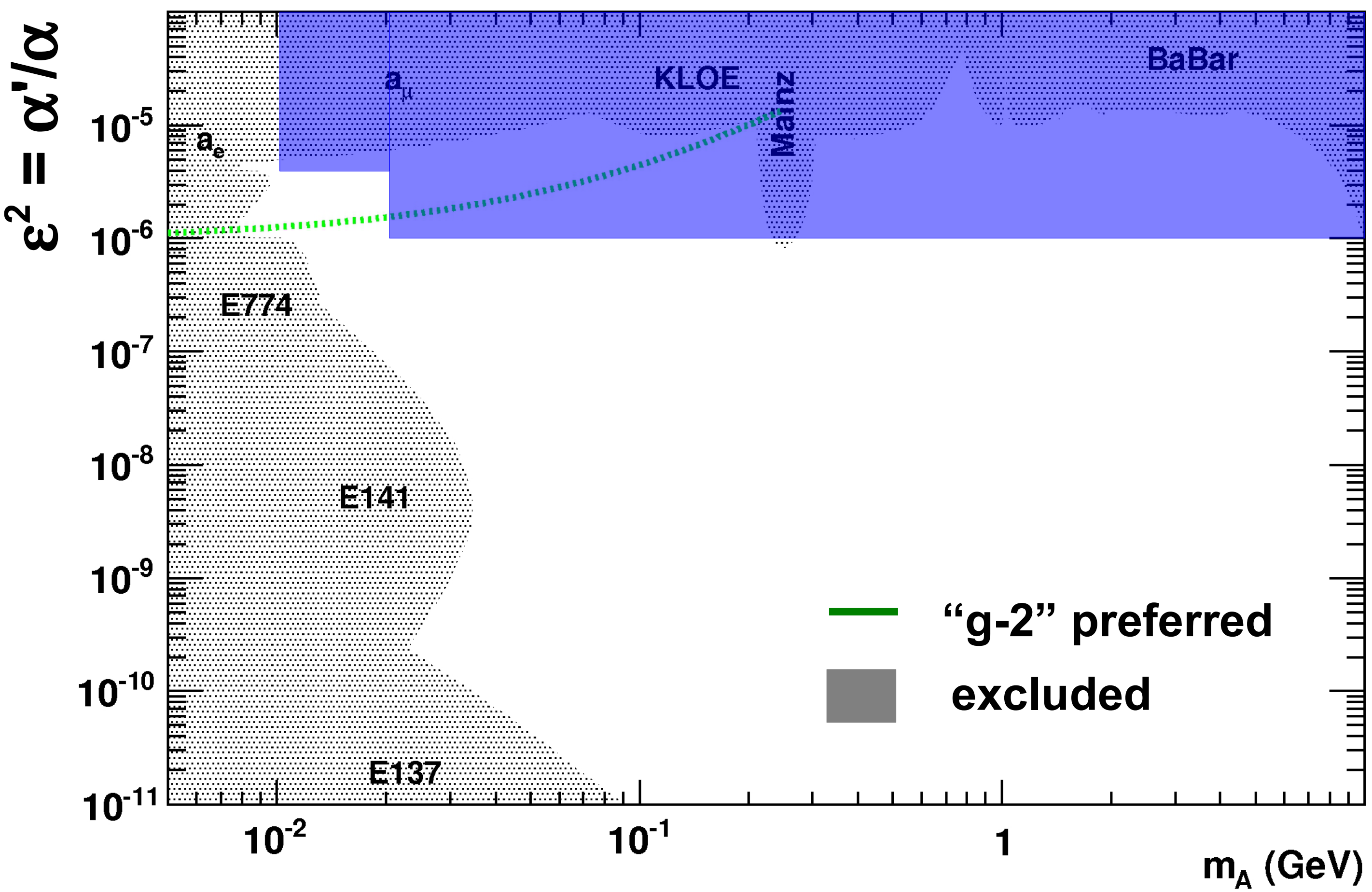
No sign of narrow resonance

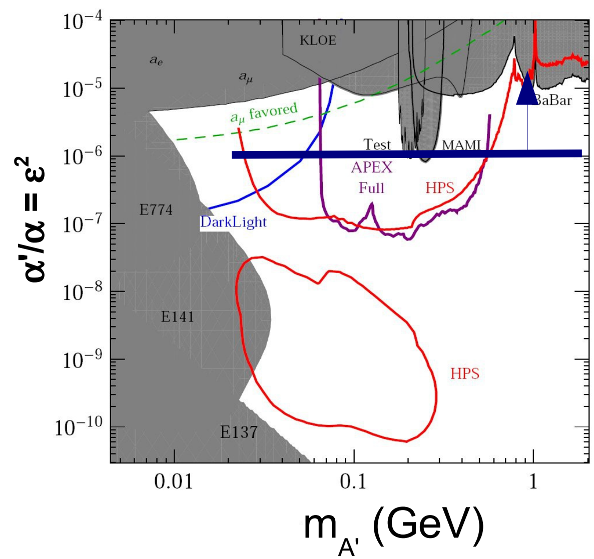
Limit obtained by reinterpreting the $\Upsilon(2S,3S) \to \gamma A^0$, $A^0 \to \mu^+\mu^-$ measurements[1)]



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

Expected limits using the full *BABAR* dataset for $e^+e^- \rightarrow \gamma e^+e^-, \gamma\mu^+\mu^-, \gamma\pi^+\pi^-$



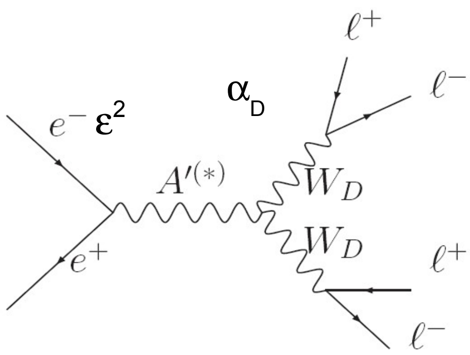


Expect significant improvement, exclude almost all the "g-2" preferred region. Stay tuned!

arXiv:0908.2821

Search for dark gauge boson

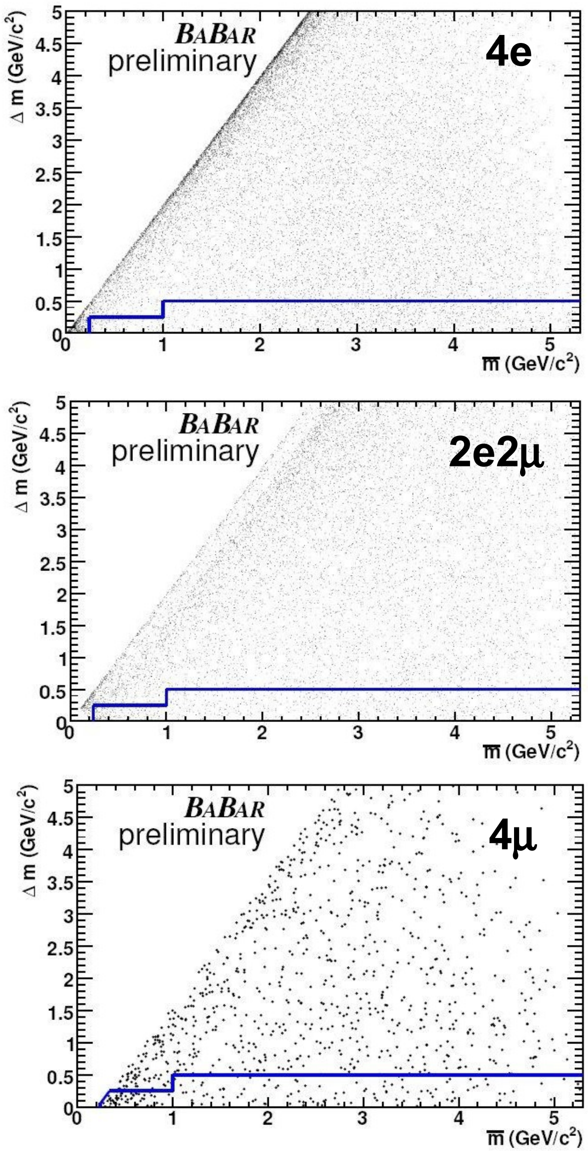
$e^+e^- \to A'^* \to W W', \; W^{(')} \to e^+e^-, \mu^+\mu^-$



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

g_D dark sector gauge coupling

- 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**



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

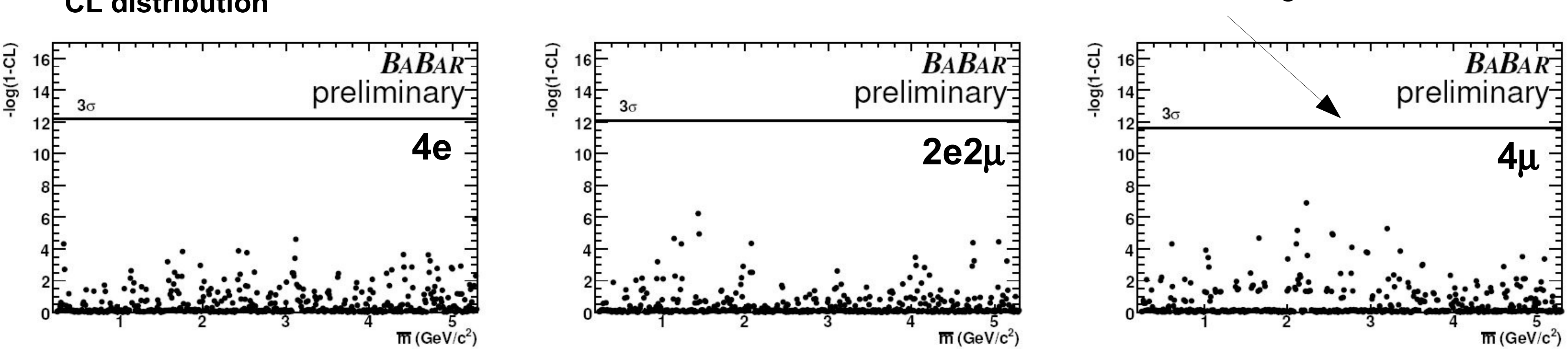
$\Delta m = (m_{max}-m_{min})/2$

arXiv:0908.2821

Scan mass spectrum for signal (507 points)

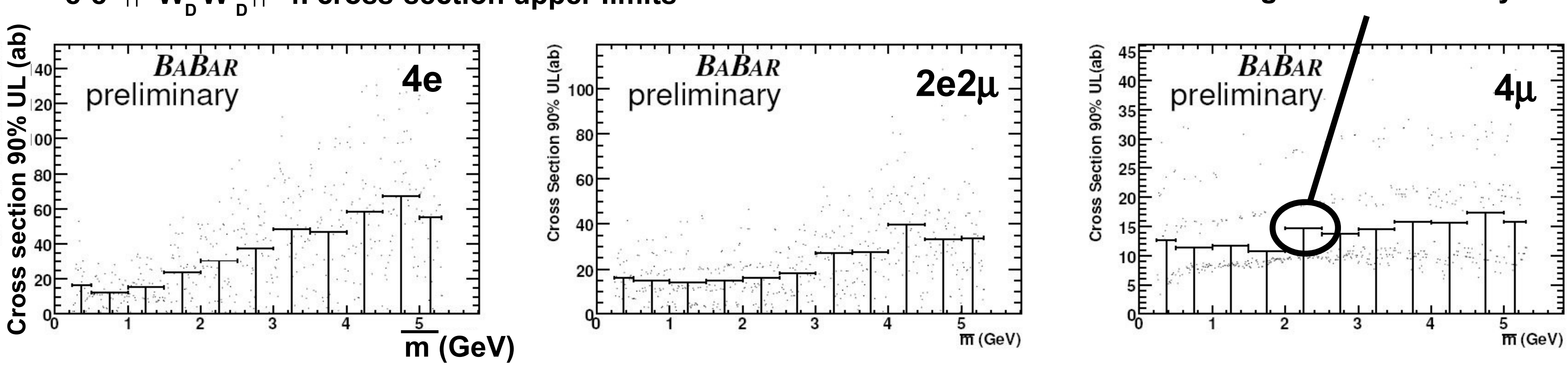
CL distribution

3σ limit, including trial factors



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

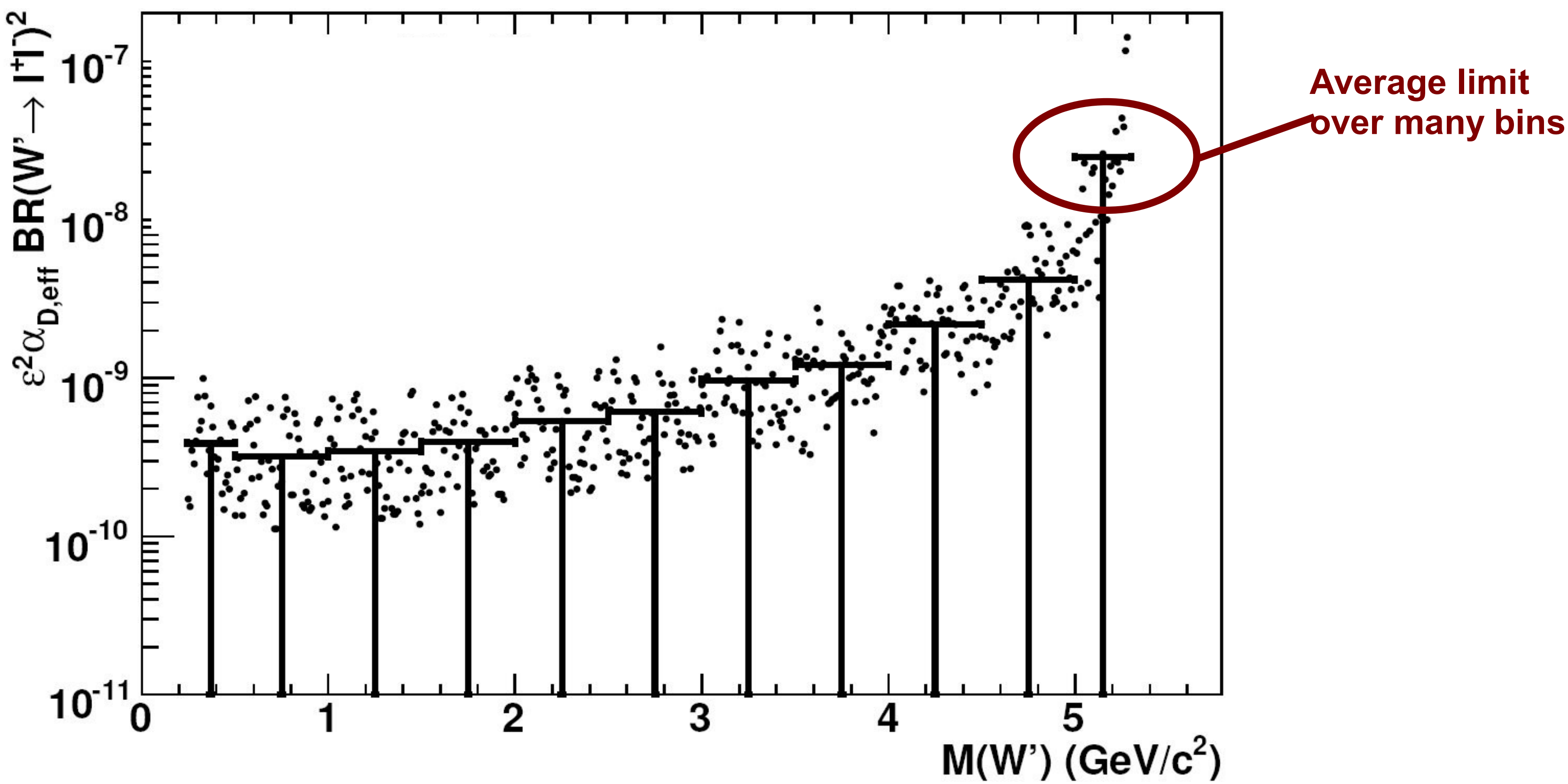
Average limit over many bins



Search for dark gauge boson

arXiv:0908.2821

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



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

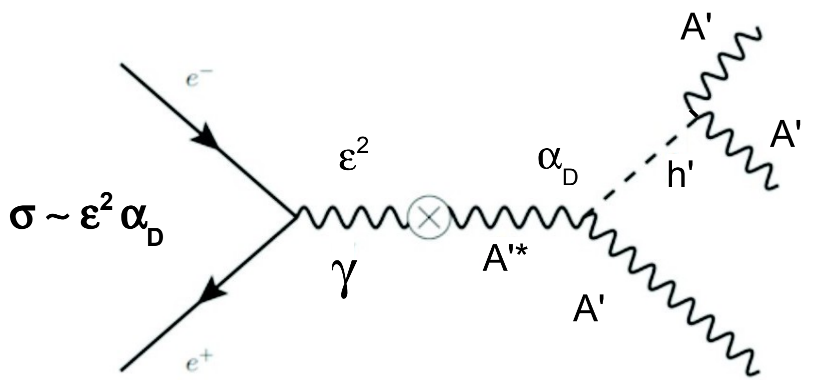
B. Batell et al., PRD 79 (2009) 115008
R. Essig et al., PRD 80 (2009) 015003

- 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**

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

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

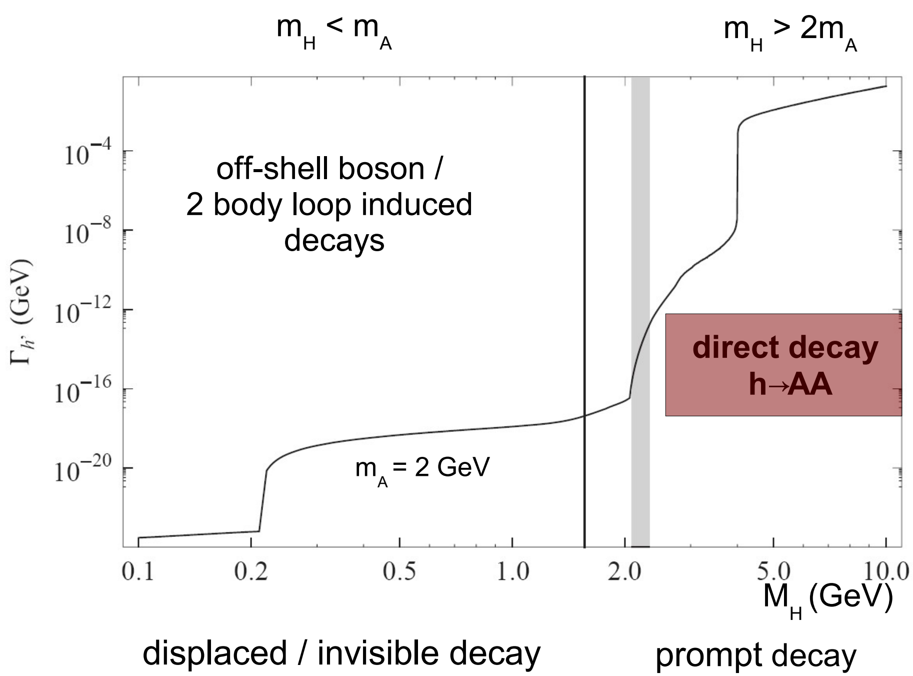
$\sigma \sim \varepsilon^2 \alpha_D$



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

g_D is the dark sector gauge coupling

Higgs decay topology



Focus on prompt decays
$m_h > 2m_A$

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

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

Selection

- 6 tracks with an invariant mass $m_{tot} > 0.95\sqrt{s}$
- apply 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

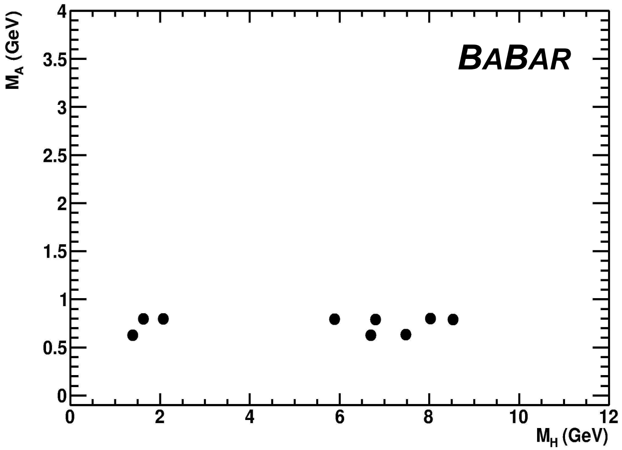
PRL 108 (2012) 211801

- 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 $h' \rightarrow A'A'$ decay
- Estimate background from
  - wrong-sign combinations, e.g.

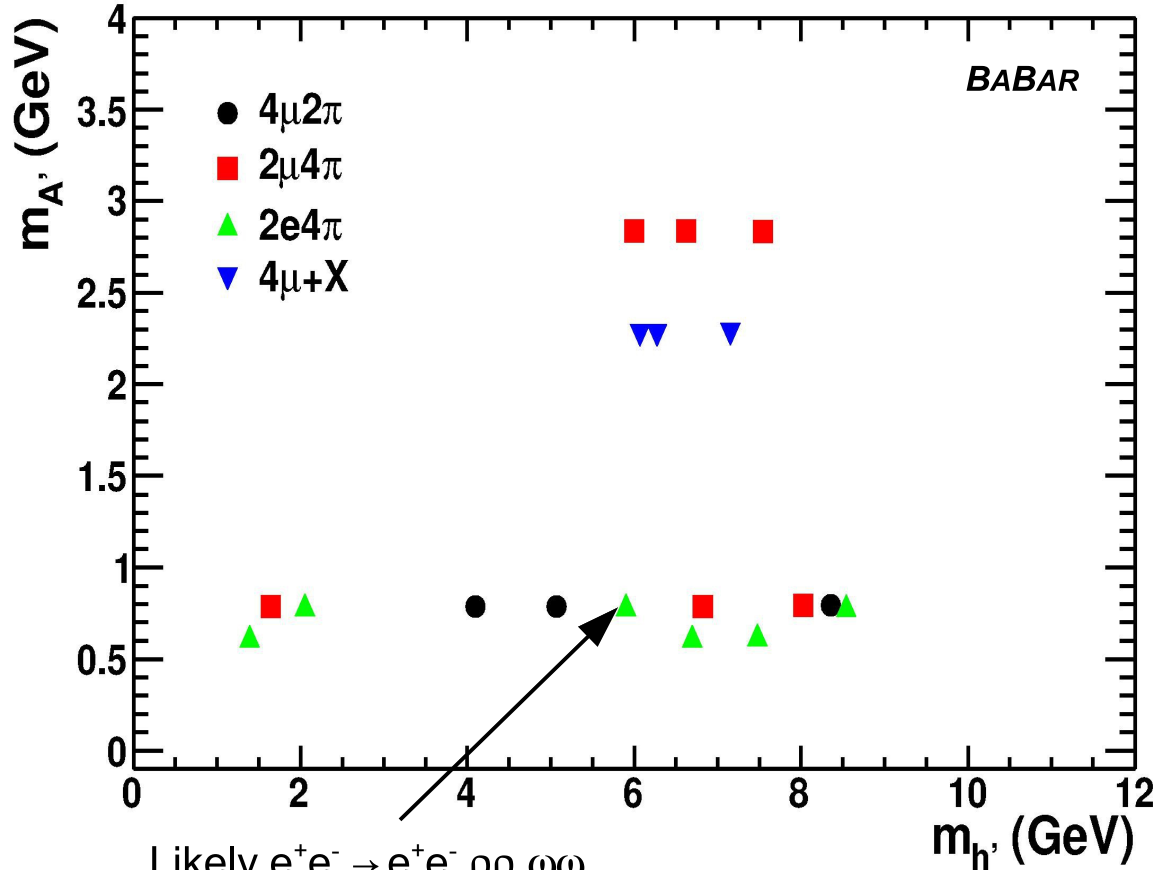
    $e^+e^- \rightarrow (e^+e^+)\ (e^-e^-)\ (\mu^+\mu^-)$

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

Wrong-sign combinations



Signal candidates



Likely $e^+e^- \rightarrow e^+e^-\ \rho\rho,\omega\omega$ or $e^+e^- \rightarrow 6\pi^\pm$

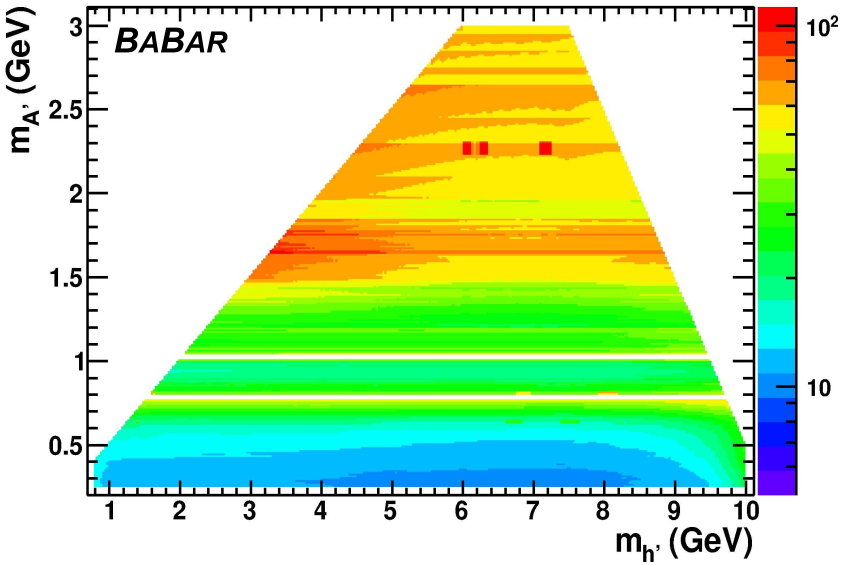
No events with 6 leptons, consistent with the pure background hypothesis

PRL 108 (2012) 211801

Limit on the cross section $e^+e^- \rightarrow h' A'$, $h' \rightarrow A' A'$ 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**

90% CL upper limit on cross section (ab)

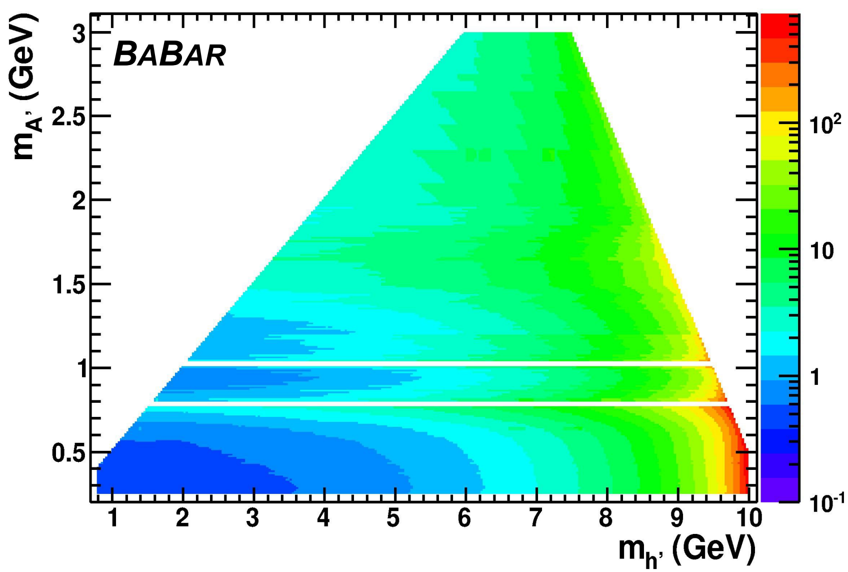


Extract limits[1] on the product $\alpha_D\varepsilon^2$

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

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

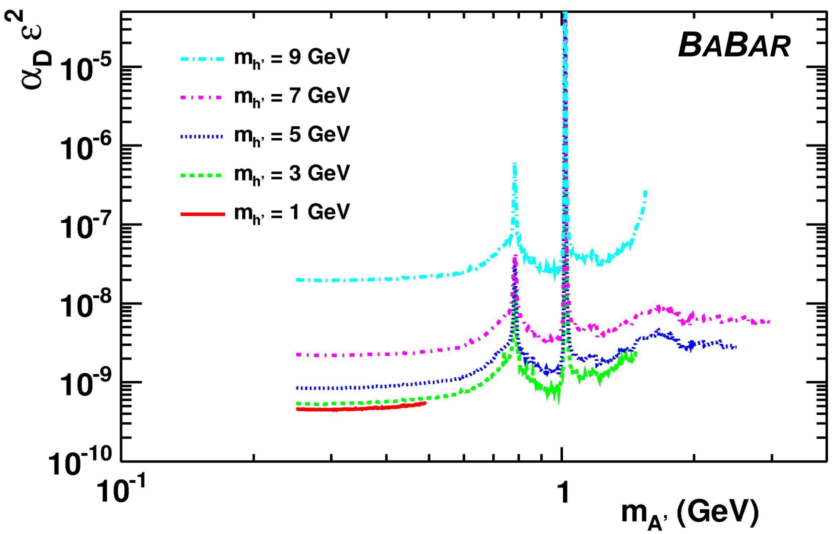
90% CL upper limit on $\alpha_D\varepsilon^2$ (x 10^{-9})



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

PRL 108 (2012) 211801

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



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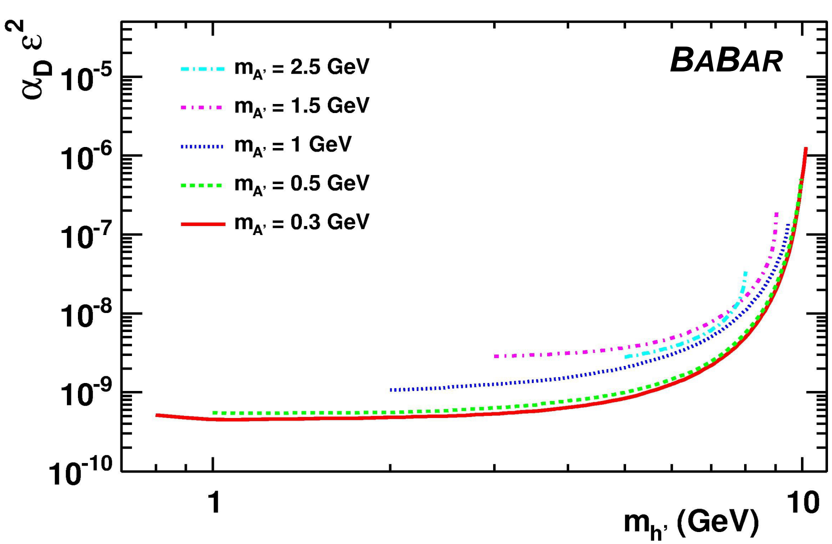
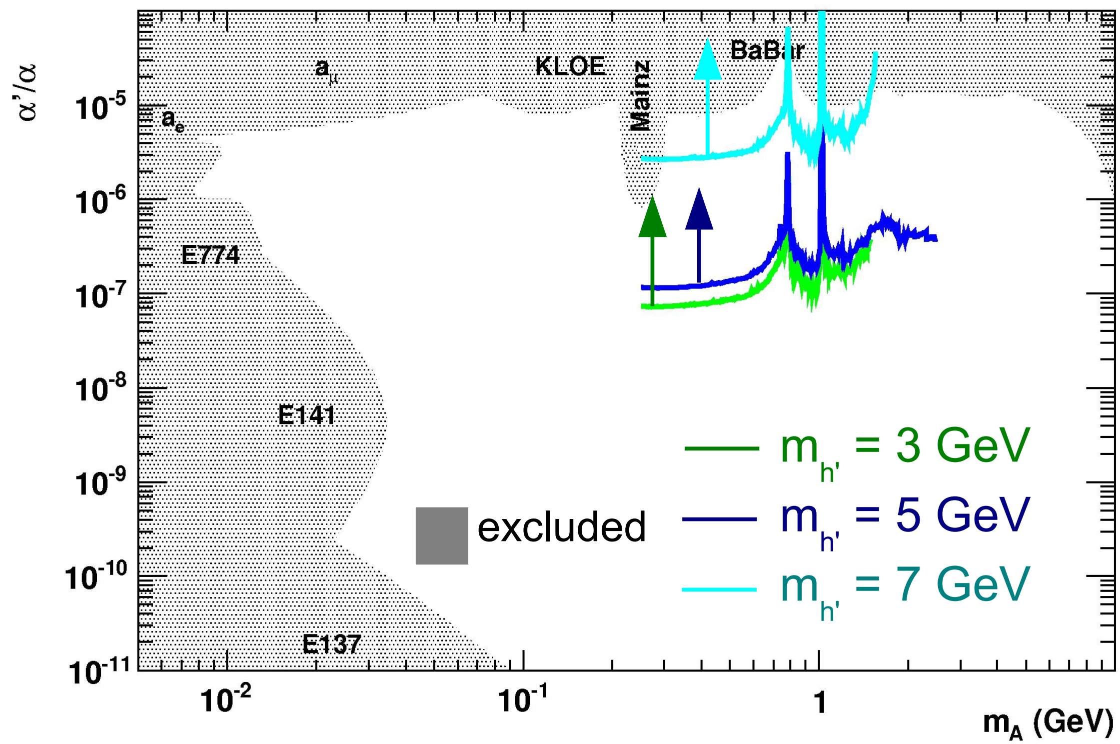


Limit on $\varepsilon^2 = \alpha'/\alpha$ assuming $\alpha_D = \alpha_{em}$ for various Higgs mass



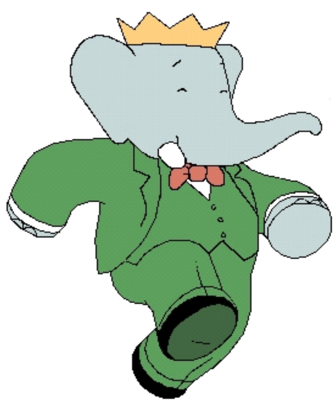
Substantial improvement over existing limits for $m_{h'}$ < 5 - 7 GeV if low-mass dark Higgs boson exists

Summary

Low-energy e^+e^- colliders provide a clean environment to explore MeV-GeV scale hidden sector.

The new generation of super flavor factories (i.e. Super*B* / Belle II) might have a sensitivity to dark photon searches similar to that of some dedicated experiments.

Several searches for dark sector particles are currently performed at *BABAR* and should produce results soon. Stay tuned...



EXTRA MATERIAL

Shrok,Suzuki, PLB 110, 250 (1982)
Hiller, PRD 70, 034018 (2004)
Dermisek et al., PRD 76, 051105 (2007)
Dermisek et al., PRD 81, 075003 (2010)

Light Higgs boson

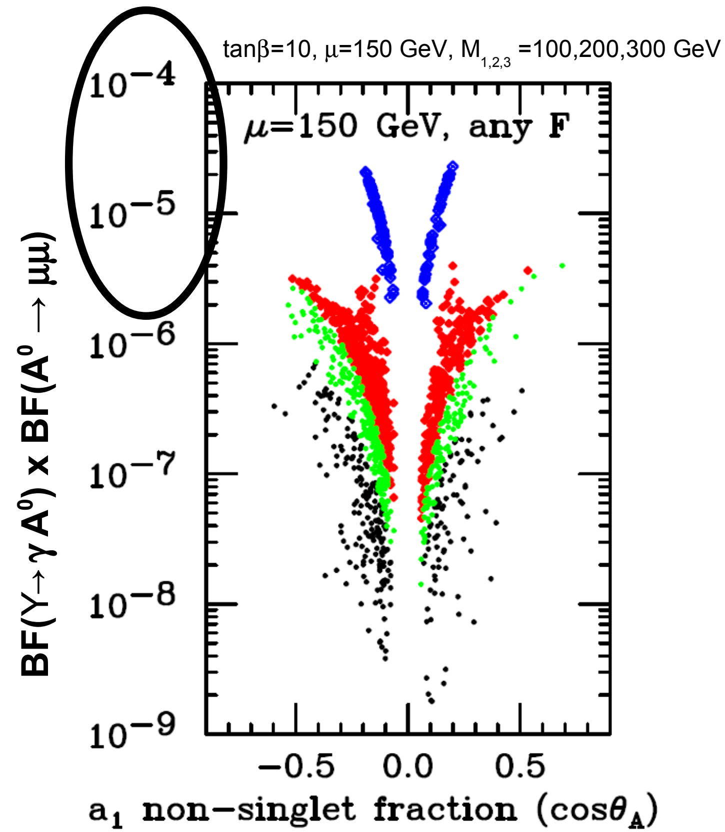
- Many SM extensions (NMSSM, Type II 2HDM,...) include the possibility of a light Higgs

- NMSSM proposed to solve the "μ problem", adding one CP-odd Higgs, one CP-even Higgs and one neutralino to 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 Higgs:
  - Fully reconstructed in $A^0 \to \mu^+\mu^-$
  - Partially reconstructed in $A^0 \to \tau^+\tau^-, q\bar{q}$
  - Invisible decay $A^0 \to \chi_1\chi_1$ if $m_{A0} > 2m_\chi$

Can have a very large branching fraction

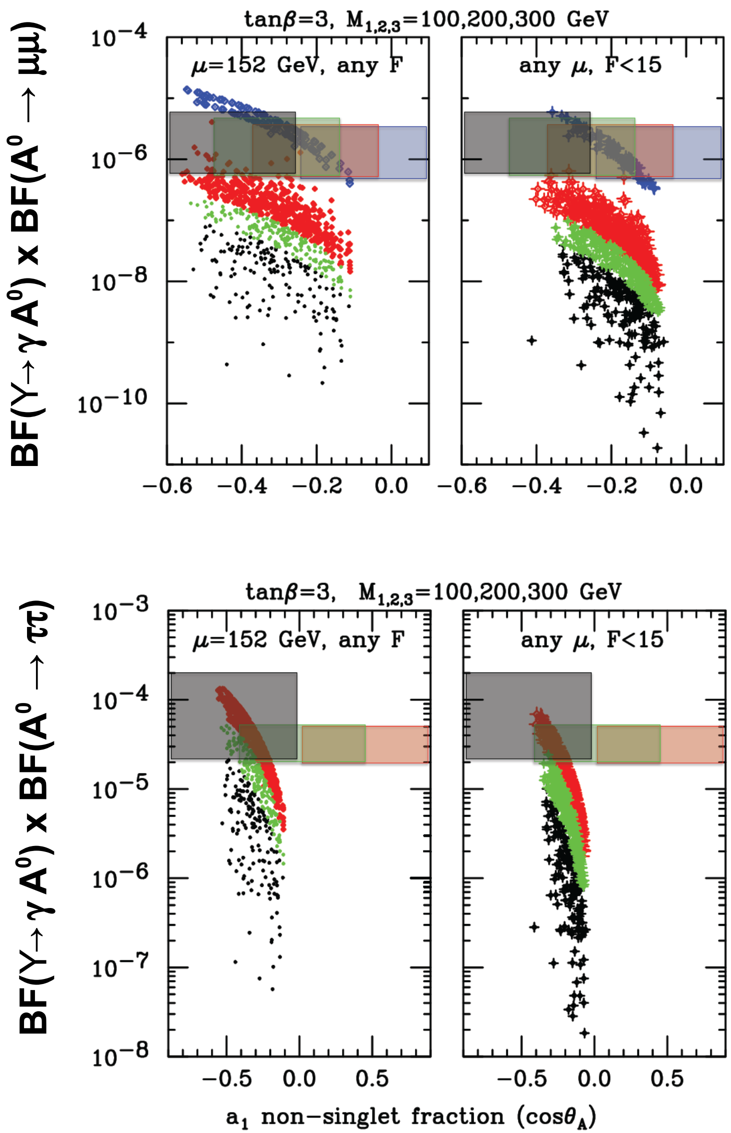


$A^0 = \cos\theta_A A_{MSSM} + \sin\theta_A A_S$

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

Search for light Higgs boson – a few results

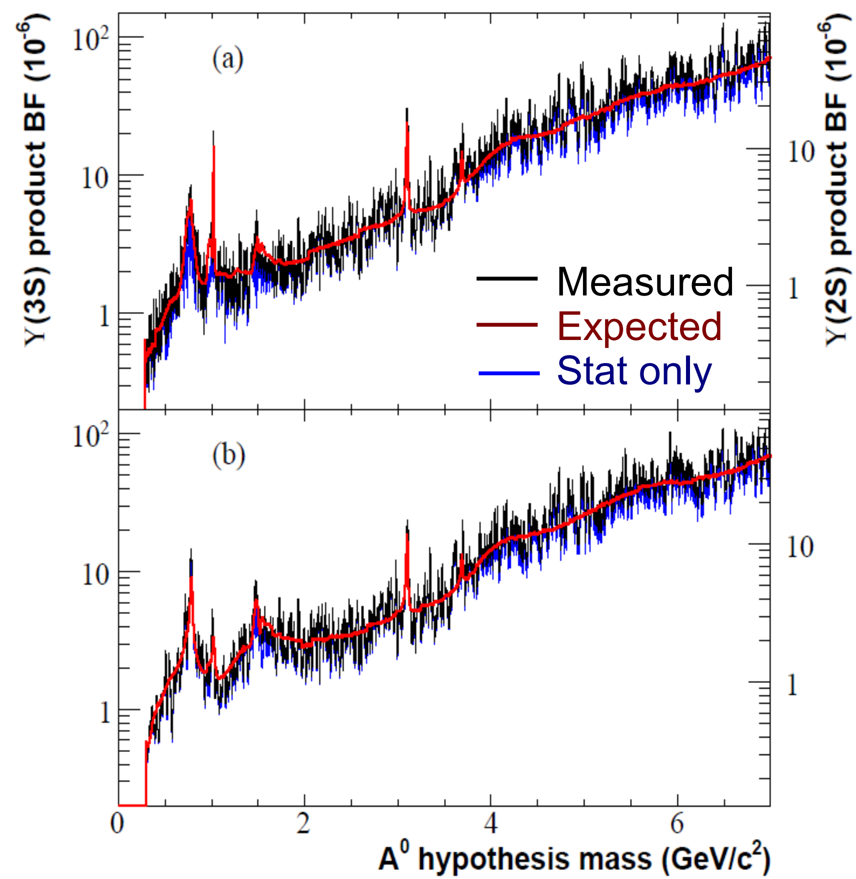
PRL 103 (2009) 081803, PRL 103 (2009) 181801
PRL 107 (2011) 021804, PRL 107 (2011) 221803



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

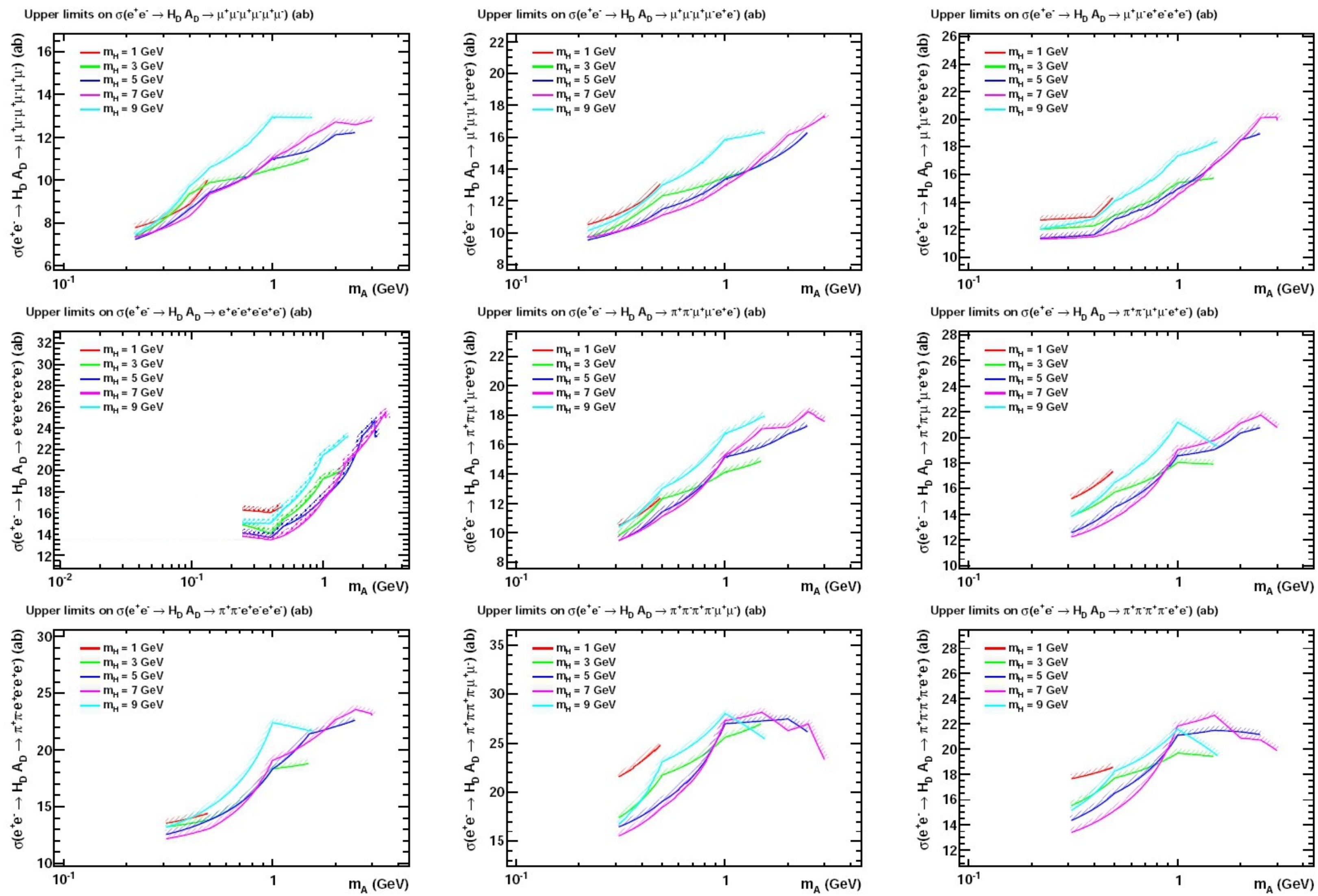
Upper limits (90% CL)

90% CL upper limits on BF(Υ→γ A⁰) x BF(A⁰ → hadrons)



No sign of light Higgs boson

Cross section upper limits for individual channels (90% CL)



Upper limits as low as 10 ab !