# Search for Dark Photons and Higgs at *BaBar*


David N. Brown

University of Louisville

On behalf of the *BaBar* Collaboration


# Search for Dark Photons and Higgs at *BABAR*

- **Motivation**
- **The *BABAR* Experiment**
- **Search for Dark Photons, *A'*** Preliminary – to be submitted to PRL
- **Search for Dark Higgs, *h'*** PRL 108 (2012) 21180
- **Measurement of anti-deuteron production**

arXiv:1403.4409, accepted for PRD-RC

# Search for Dark Photons and Higgs at *BABAR*

- **Mot**
- **The**
- **Sea**
- **Sea**
- **Mea**

d to PRL

## Not presented today but worth note…

- **$\Upsilon(2S,3S) \rightarrow \gamma A^0, A^0 \rightarrow \mu^+\mu^-$**
  PRL103 (2009) 081803
- **$\Upsilon(3S) \rightarrow \gamma A^0, A^0 \rightarrow \tau^+\tau^-$**
  PRL103 (2009) 181801
- **$\Upsilon(2S,3S) \rightarrow \gamma A^0, A^0 \rightarrow$ hadrons**
  PRL107 (2011) 221803
- **$\Upsilon(2S,3S) \rightarrow \gamma A^0, A^0 \rightarrow$ invisible**
  arXiv: 0808.0017 + new analysis in progress
- **$\Upsilon(1S) \rightarrow \gamma A^0, A^0 \rightarrow$ invisible**
  PRL107 (2011) 021804
- **$\Upsilon(1S) \rightarrow \gamma A^0, A^0 \rightarrow \mu^+\mu^-$**
  PRD 87 (2013) 031102
- **$\Upsilon(1S) \rightarrow \gamma A^0, A^0 \rightarrow \tau^+\tau^-$**
  PRD 88 (2013) 071102
- **$\Upsilon(1S) \rightarrow \gamma A^0, A^0 \rightarrow gg$ or $s\bar{s}$**
  PRD 88 (2013) 031701
- **$\Upsilon(1S) \rightarrow \gamma A^0, A^0 \rightarrow gg$ and $A^0 \rightarrow c\bar{c}$**
  in preparation

arXiv:1403.4409, accepted for PRD-RC

# Motivation – Search for the Dark Sector

- **Existence of dark matter is well-established from astrophysical evidence, but its nature is not known**

Zwicky, AcHPhys 6 (1933); et al.

- **Collider experiments allow for:**
  - **Direct searches for dark particles through decays to Standard Model (SM) particles**
  - **Study of backgrounds to potential astro-particle searches**
- **Electron collider experiments are particularly clean environments and in many cases provide the best reach in searches for new physics**

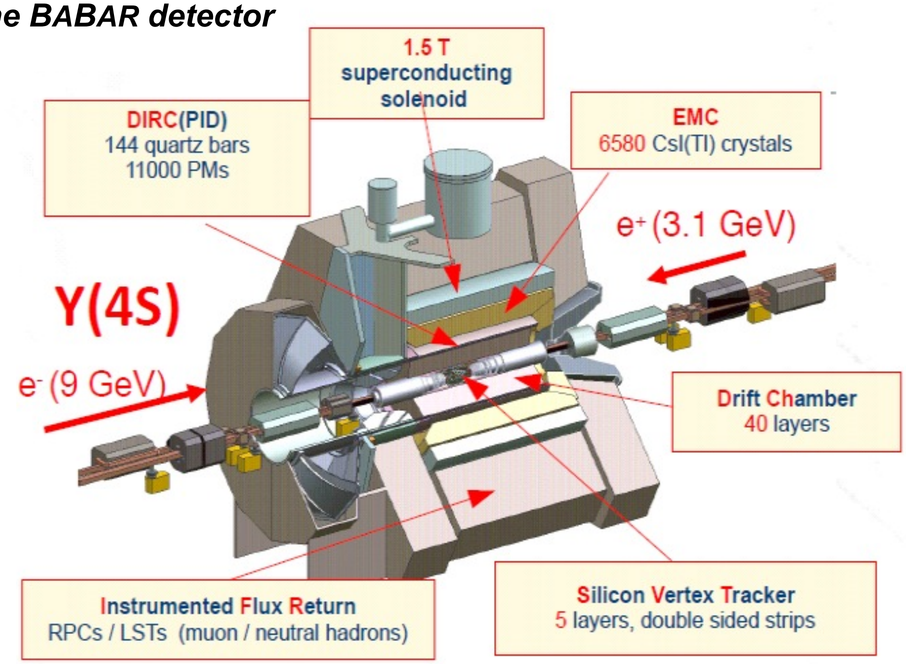
**Embrace the Dark Side**

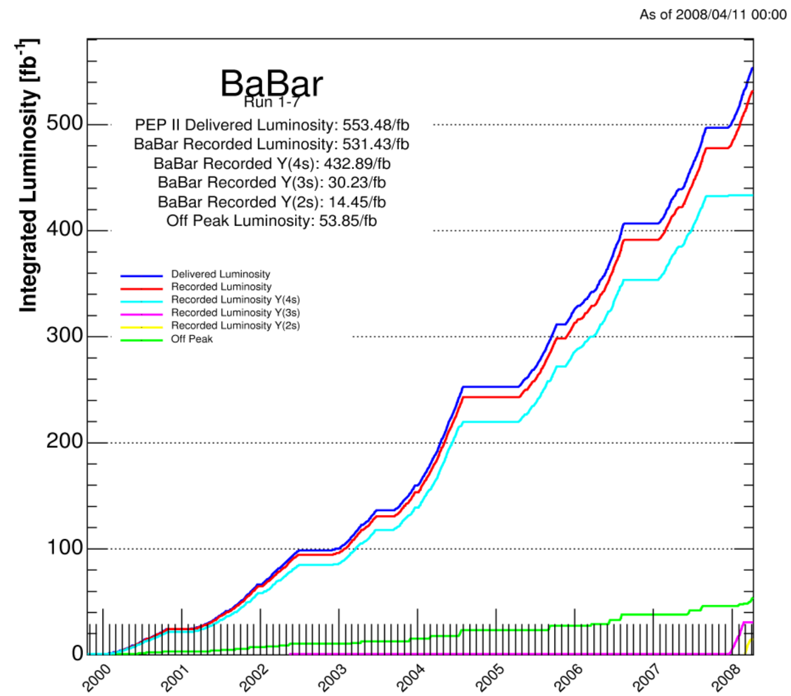
**© Lego, Lucasfilm**

# The *BABAR* Experiment

BABAR

*The BABAR detector*




- Primarily designed for study of *CP*-violation in *B* meson decays
- Quality and general-purpose design make it suitable for a large variety of studies

**BABAR data sample contains**

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

# Dark Sector Overview

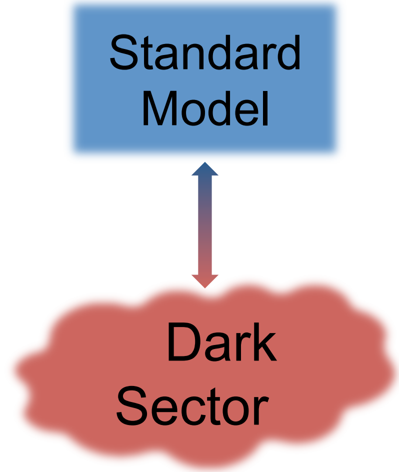
- Recent dark matter models introduce a new dark sector with a new U(1)'.

PLB 166, 196 (1986)

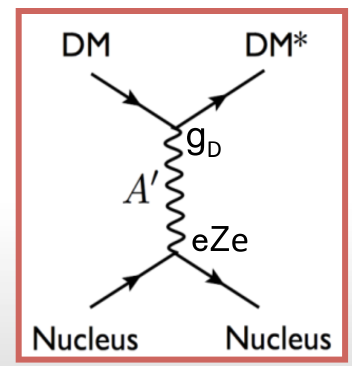
- The corresponding gauge boson, the so-called dark photon (A'), is light (MeV – GeV mass) in these models.

PLB 662, 53 (2008); PRD 79, 015014 (2009; arXiv:1311.0029, for example

- 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 $\varepsilon$ among other "portals".



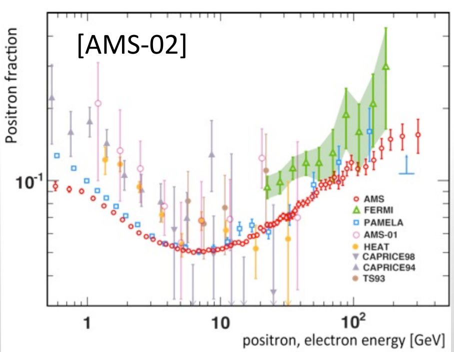

[Slatyer, Schuster&Toro,…]

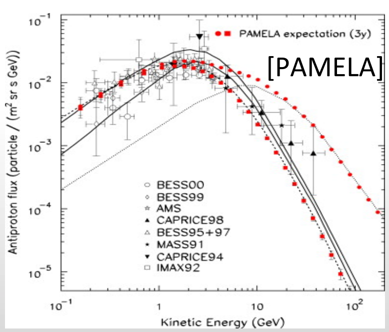


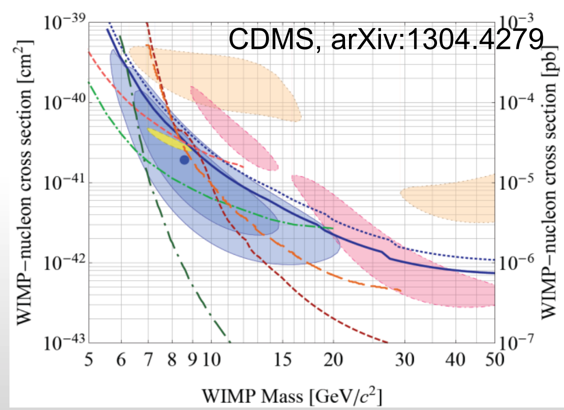

- In other words, there is a dark photon – SM fermion coupling $\alpha' = \varepsilon^2 \alpha$ Strength small, but how small?

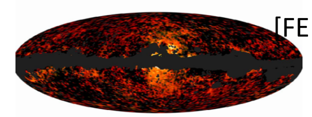
# Dark Sector Overview contd.

- In this framework, wimp-like TeV-scale dark matter particles can annihilate into dark photons, which subsequently decay to SM fermions.
- If the 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.



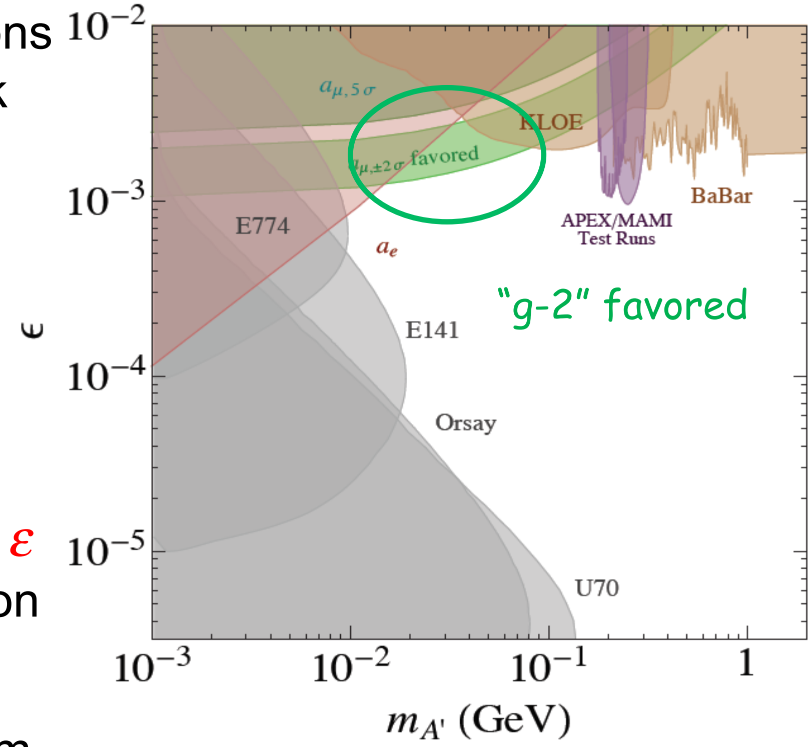




[Finkbeiner Dobler et al., ]

**And many others…**

# 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 $\varepsilon$).
- 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 $\varepsilon$ 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*)

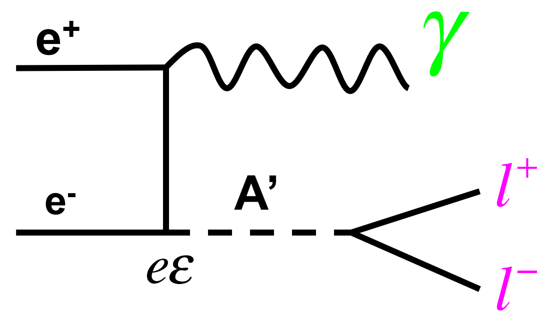



[Essig *et al* 2013]

# Dark Photon Production

A dark photon can be produced in

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

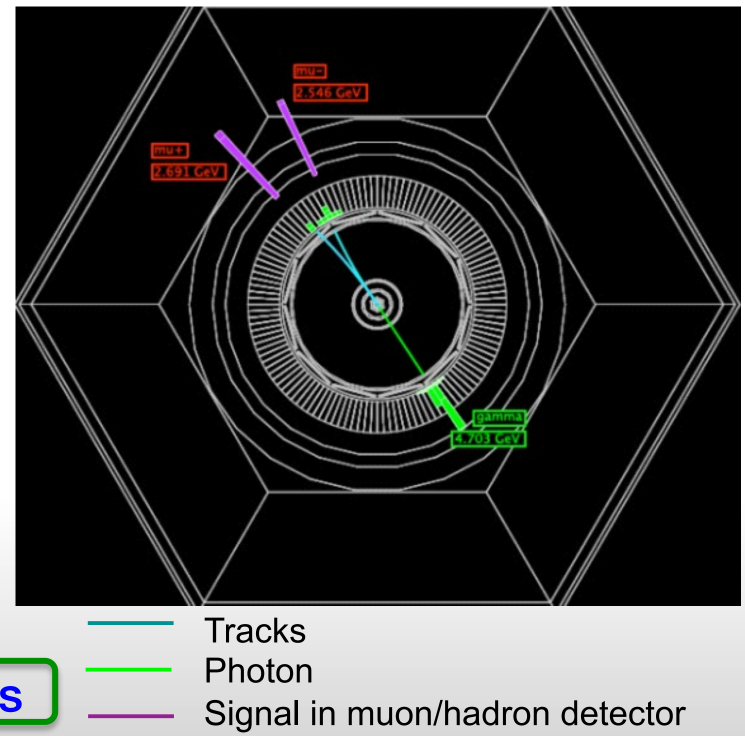



So far, only one measurement of this final state at *BABAR* from light CP-odd Higgs search in ϒ(2S,3S) decays

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

**Select events with one photon and two oppositely charged leptons*. Look at spectrum of dilepton mass. Use reduced mass for muons.**

$$m_R = \sqrt{m_{\mu\mu}^2 - 4m_\mu^2}$$



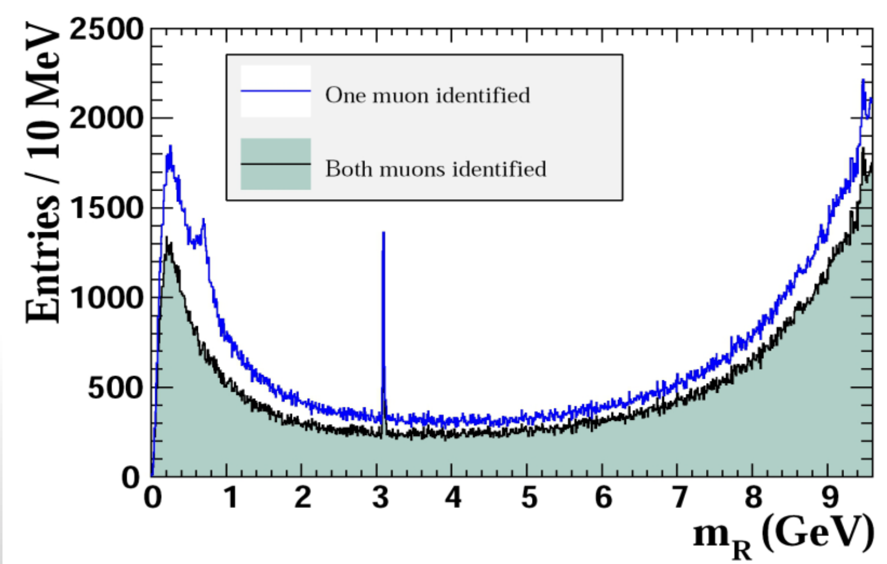

*with further cuts to reduce radiative Bhabhas

# Analysis Technique

Scan the dielectron and dimuon reduced mass spectra and fit a background plus signal function at each step. Background includes resonances - $\rho^0, \phi$ $J/\psi, \psi(2S)$

Mass resolution varies between 1.5 and 8 MeV
Window size 20x mass resolution
Step size approximately half the mass resolution

Electrons: 5704 fits, 0.02 – 10.2 GeV
Muons: 5370 fits, 0.212 – 10.2 GeV



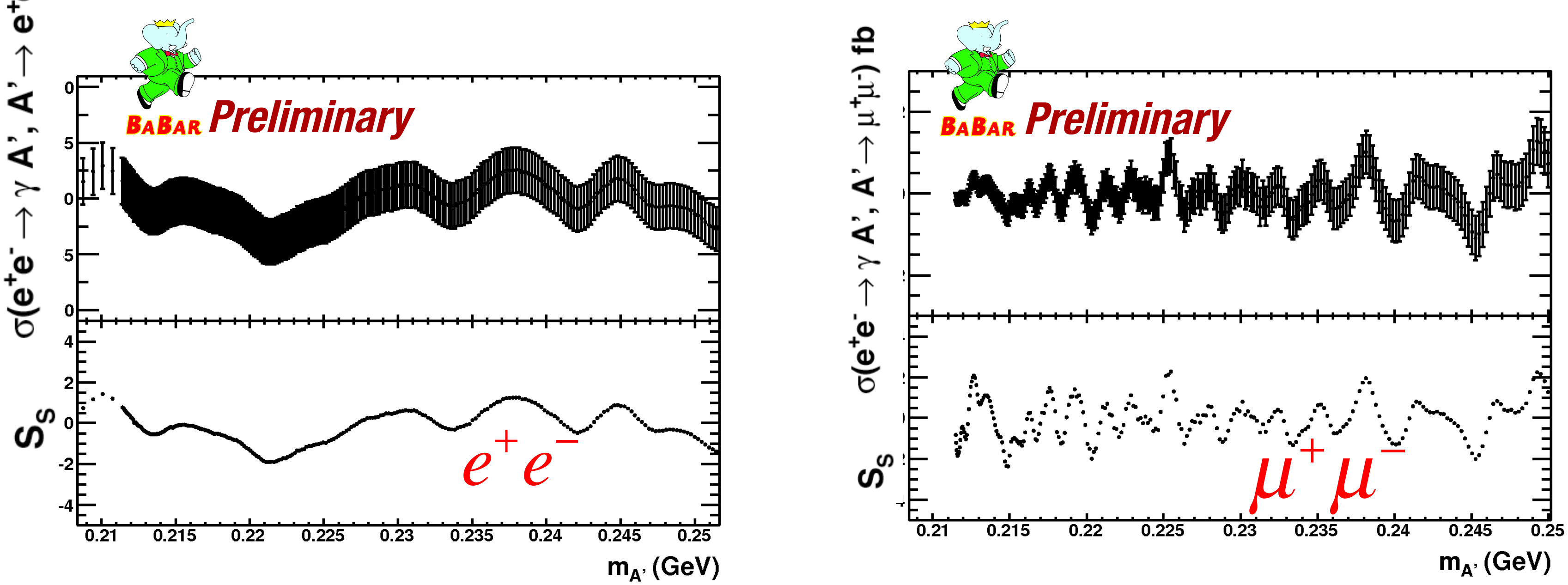

Assign a statistical significance for each fit:

$$S_S = \sqrt{2\log\left(L/L_0\right)}$$

$L$: likelihood w/background + signal
$L_0$: likelihood w/background only

# Dark Photon Results

Results for $\sigma\left(e^+e^- \rightarrow \gamma A', A' \rightarrow l^+l^-\right)$ for combined Y(2S,3S,4S)



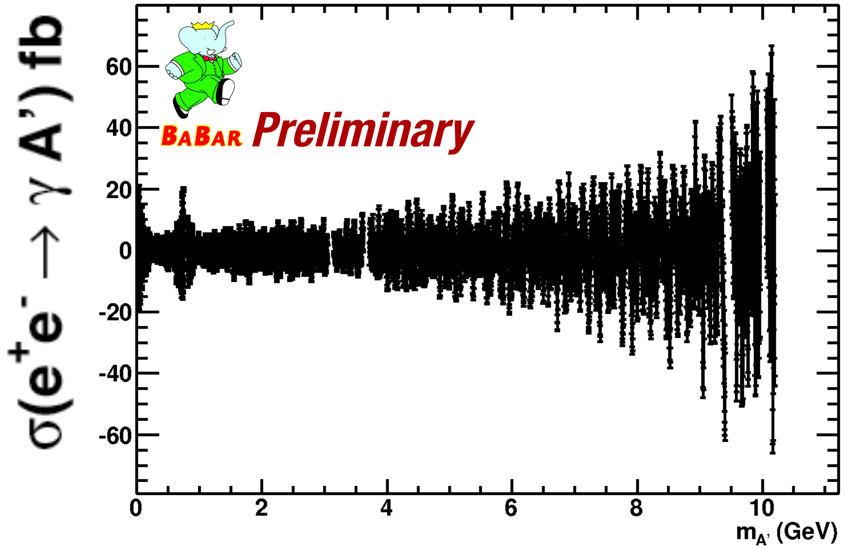

$$S_S = \sqrt{2\log\left(L/L_0\right)}$$

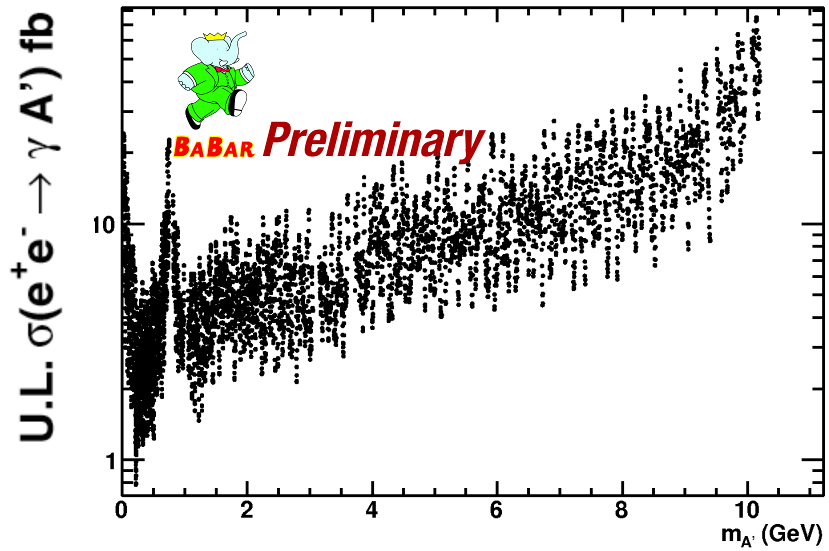
**Here, look in 200 MeV region as suggested by excess in HyperCP results**

PRL 94, 021801 (2005)

**No excess observed**

# Cross-section Results



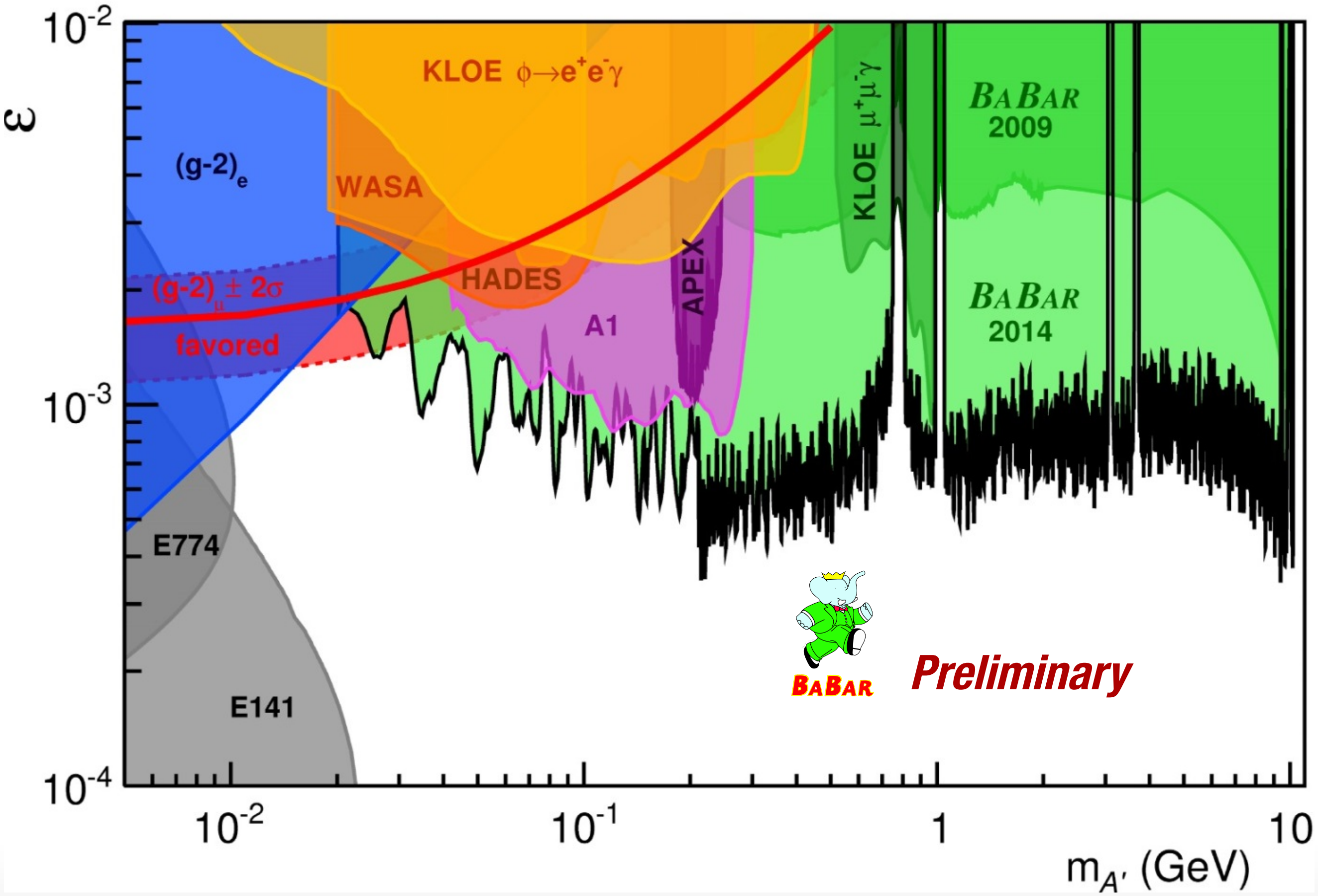

**90% Confidence Level Upper Limit**

**Including Trial factors,**

**Most significant excursion from null hypothesis for electrons:** $0.6\,\sigma$

**Most significant excursion from null hypothesis for muons:** $0.1\,\sigma$

# Dark Sector Mixing Results




Preliminary – to be submitted to PRL

- Further exclude the region favored by the g-2 measurement and improve the existing constraints over a wide range of masses.

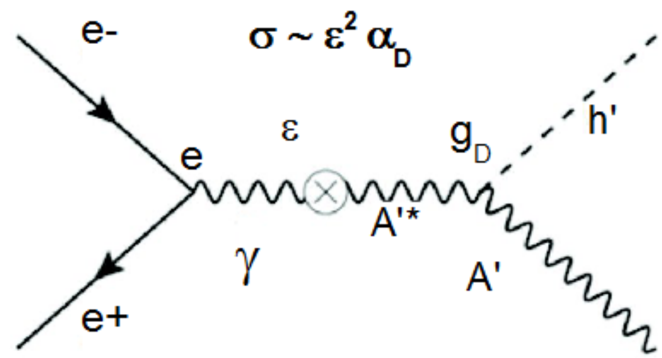
# Dark Higgs Boson

- 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

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

is only suppressed by $\varepsilon^2$ and should have low background

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



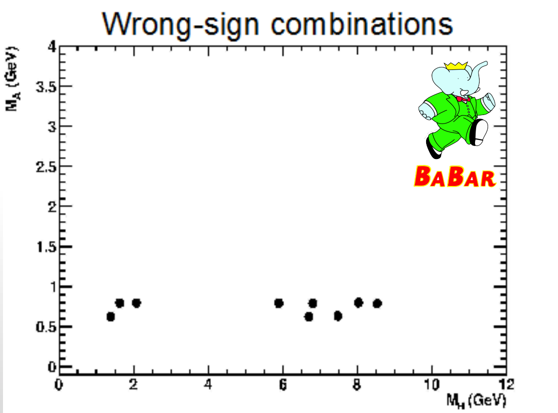

Search for prompt *h*' decays at *BABAR*:
$e^+e^- \to A'^* \to h'A';\ h' \to A'A';\ A' \to l^+l^-, \pi^+\pi^-$

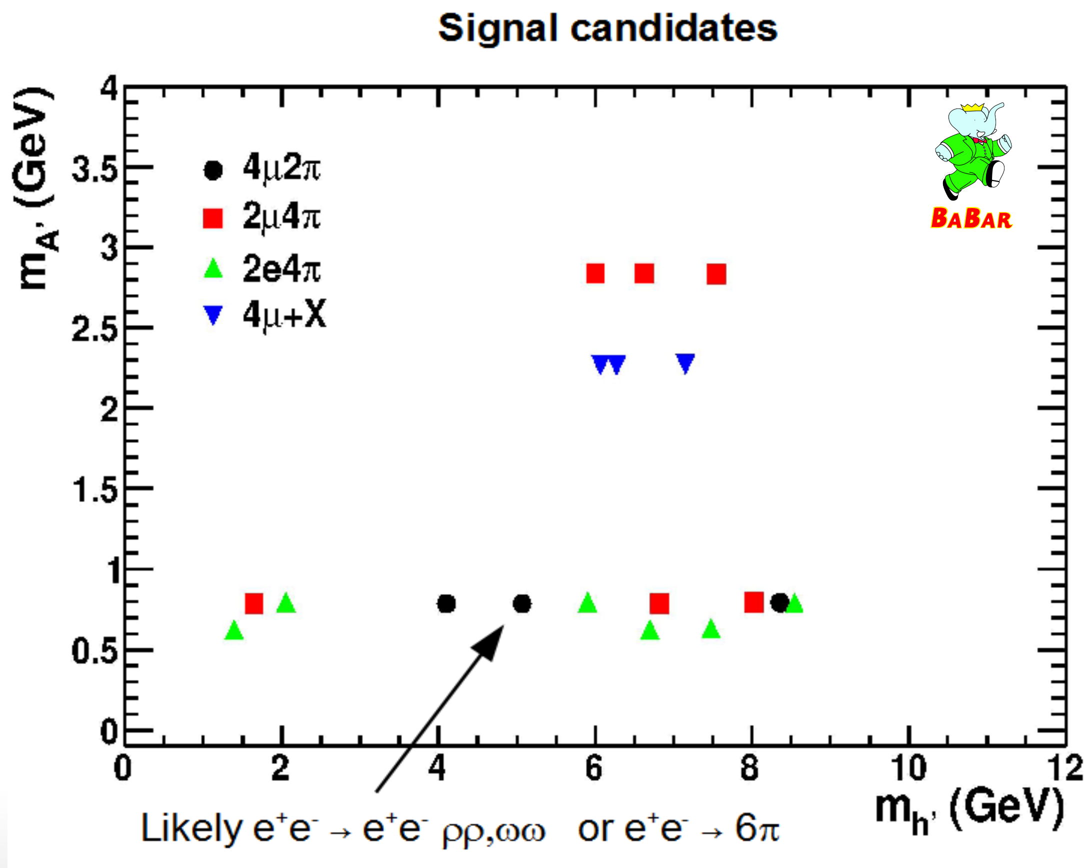
PRL 108 (2012) 21180

# Dark Higgs Search

PRL 108 (2012) 21180

- 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 $h' \rightarrow A'A'$ decay
- Estimate background from
  - wrong-sign combinations, e.g.
    $$e^+e^- \rightarrow (e^+e^+)(e^-e^-)(\mu^+\mu^-)$$
  - sidebands from final sample



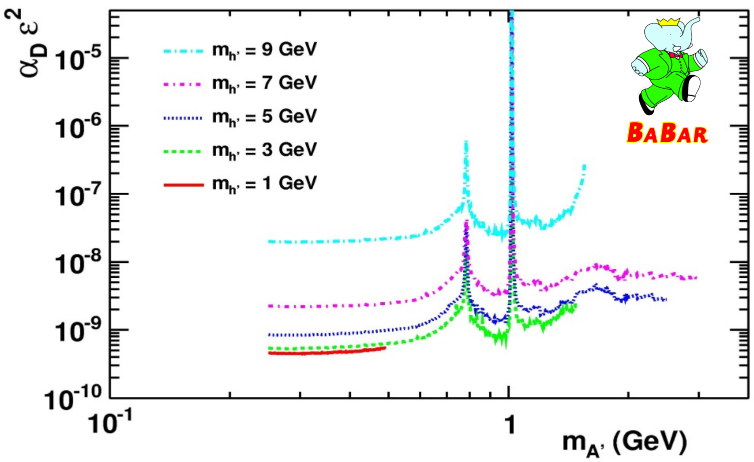




**No events with 6 leptons, consistent with the pure background hypothesis**

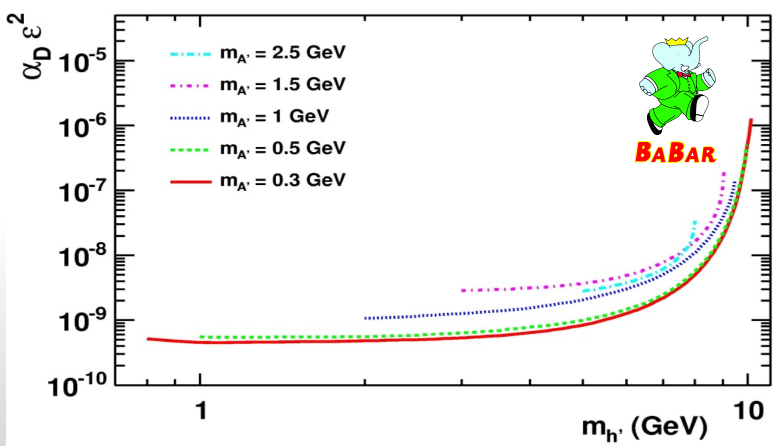
# Dark Higgs Results

PRL 108 (2012) 21180

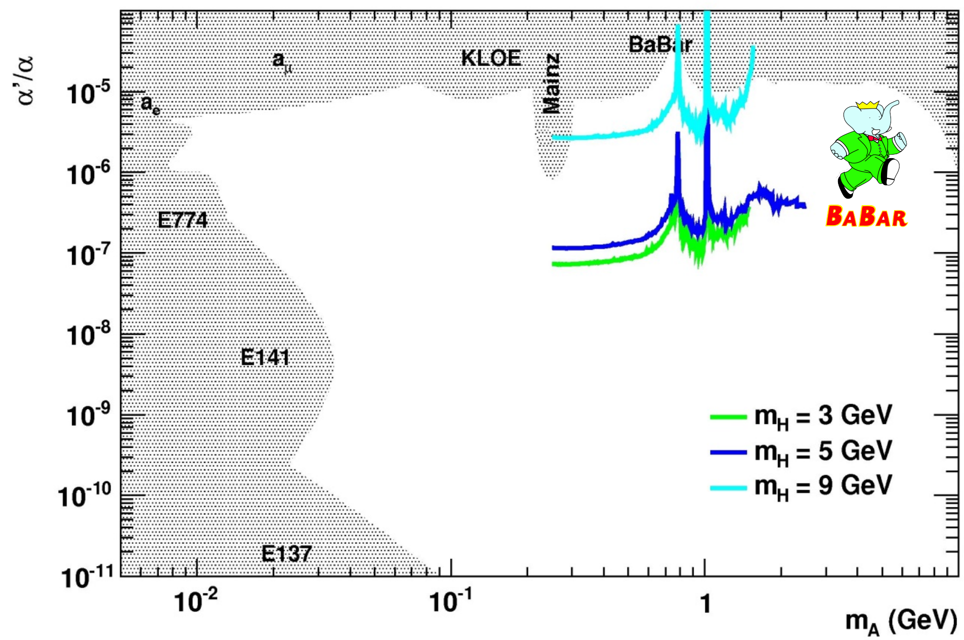
90% CL upper limit on $\alpha_D \varepsilon^2$




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




Limit on $\varepsilon^2 = \frac{\alpha'}{\alpha}$ assuming $\alpha_D = \alpha_{EM}$ for various Higgs masses




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

# Inclusive anti-deuteron Production

**Excess of anti-nuclei in cosmic rays can indirectly probe dark matter annihilation**

JHEP 1011, 017 (2010); PRD 86, 103536(2012); arXiv:1308.4848

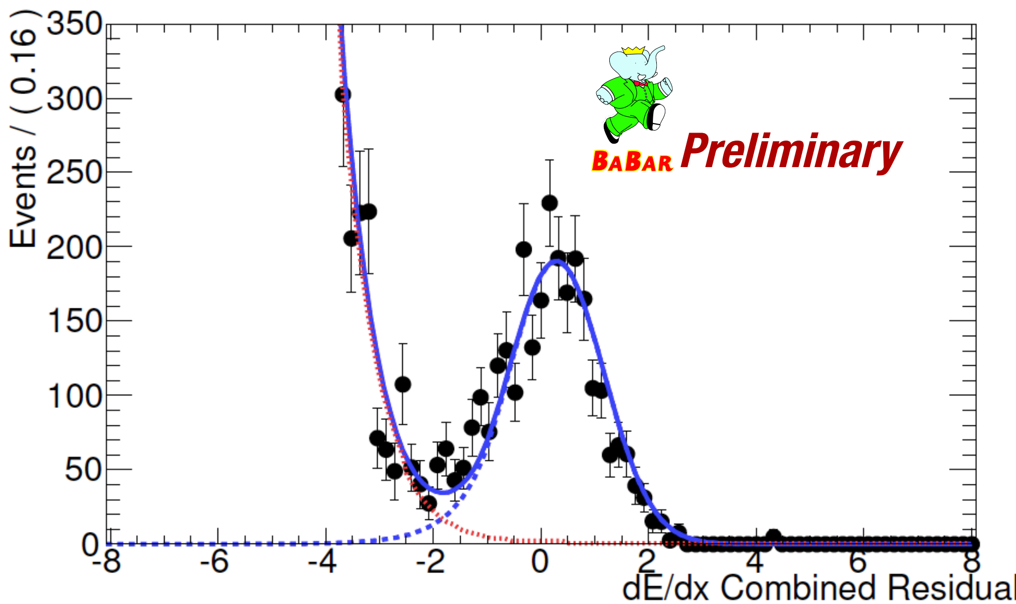
- **Colored partons hadronize into nuclei**
  - **Process requires 6 quarks in close proximity**
- **Before deciphering anti-deuteron results from dark sector sources, need better understanding of ‘standard’ sources**

$e^+e^-$ **annihilation offers a clean environment and ability to separate quark and gluon fragmentation**

# Anti-deuteron identification

**Analyze full BABAR dataset. Restrict attention to anti-deuterons to avoid machine backgrounds.**

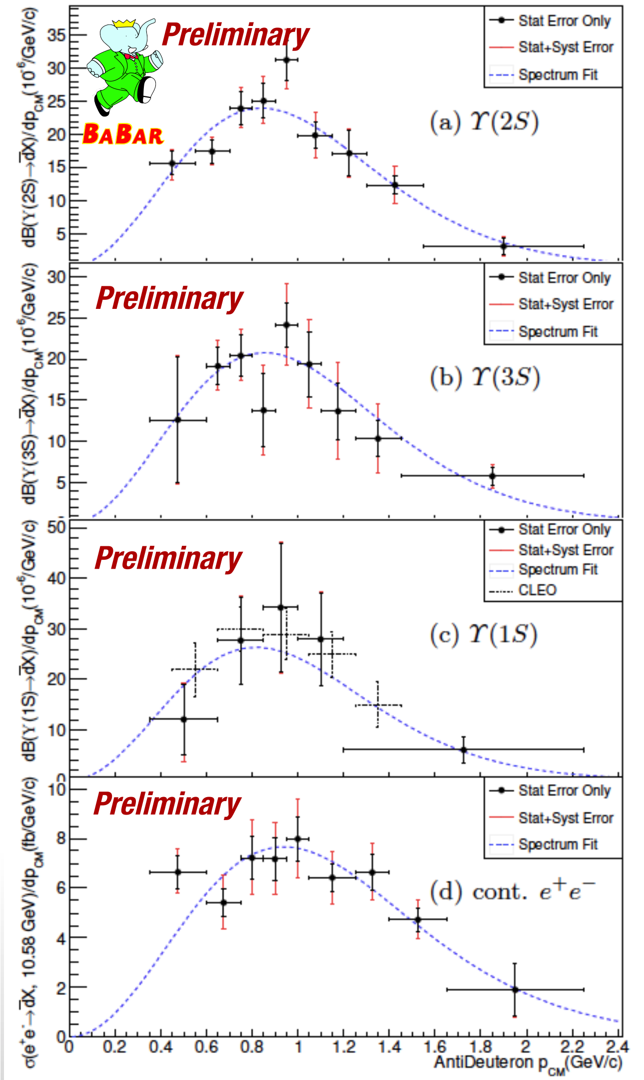
**Anti-deuterons are heavy, highly ionizing, emit ~no Čerenkov photons**




arXiv:1403.4409, accepted for PRD-RC

**Fit *dE/dx* Residual in bins of center of mass momentum**

# Anti-deuteron Results




- First measurement on $\Upsilon(3S)$
- Measurements on $\Upsilon(1S), \Upsilon(2S)$ consistent with previous, but greatly improved uncertainty
- Anti-deuterons suppressed by an order of magnitude in $e^+e^- \rightarrow q\bar{q}$

| Process | |
|---|---|
| $\mathcal{B}(\Upsilon(3S) \to \bar{d}X)$ | $(2.33 \pm 0.15^{+0.31}_{-0.28}) \times 10^{-5}$ |
| $\mathcal{B}(\Upsilon(2S) \to \bar{d}X)$ | $(2.64 \pm 0.11^{+0.26}_{-0.21}) \times 10^{-5}$ |
| $\mathcal{B}(\Upsilon(1S) \to \bar{d}X)$ | $(2.81 \pm 0.49^{+0.20}_{-0.24}) \times 10^{-5}$ |
| $\sigma(e^+e^- \to \bar{d}X)$ $[\sqrt{s} \approx 10.58\,\mathrm{GeV}]$ | $(9.63 \pm 0.41^{+1.17}_{-1.01})$ fb |
| $\dfrac{\sigma(e^+e^- \to \bar{d}X)}{\sigma(e^+e^- \to \mathrm{Hadrons})}$ | $(3.01 \pm 0.13^{+0.37}_{-0.31}) \times 10^{-6}$ |

**arXiv:1403.4409, accepted for PRD-RC**

# Summary

- Dark matter is well-established but mysteries remain
- *BABAR* has completed searches for the dark photon and dark Higgs
  - No evidence for either, but
  - Tighten constraints on dark sector models
- *BABAR* has measured anti-deuteron production in $e^+e^-$ annihilation, improving understanding of standard backgrounds to potential dark sector signals
- The dark sector is an exciting field, to which electron collider experiments can make significant contributions


wordpress.com


**Thanks!**