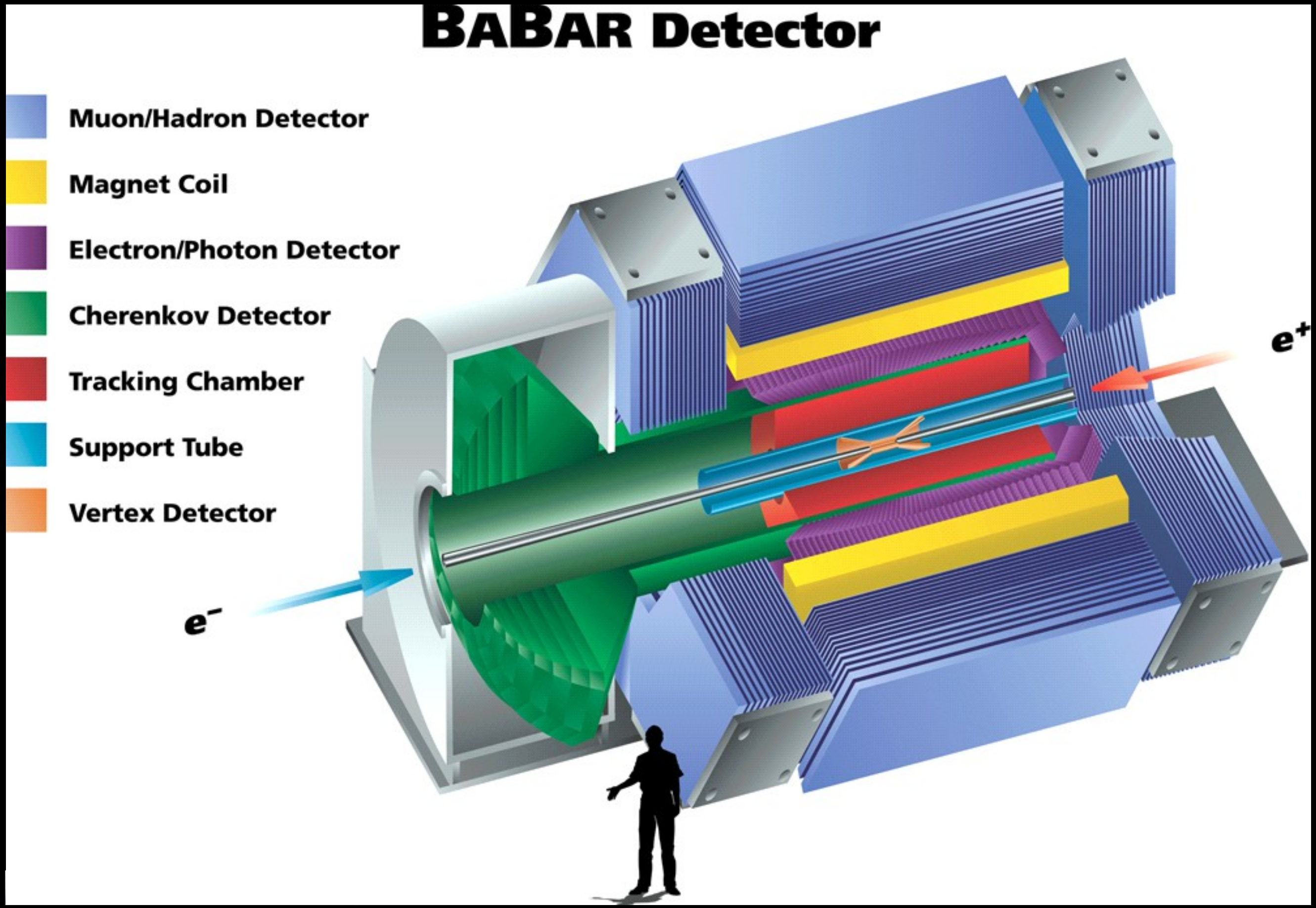
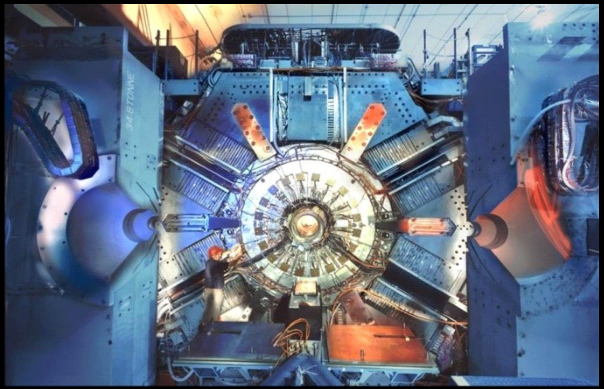
# Searches for dark matter and dark forces at *BABAR*

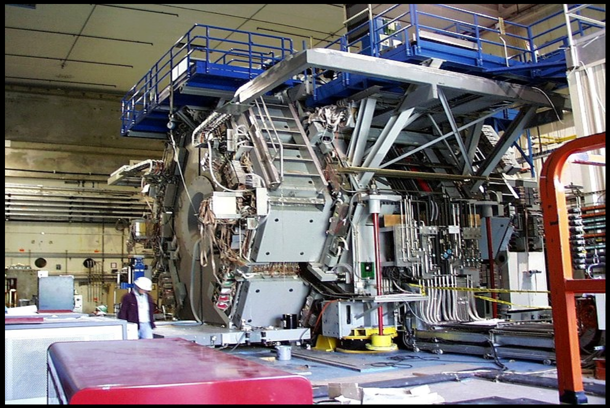
*Bertrand Echenard*
*Caltech*
*on behalf of the BABAR collaboration*

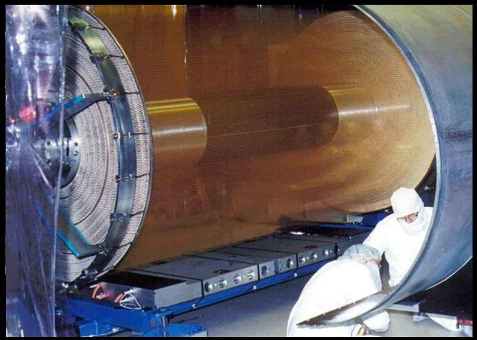
*Closing in on dark matter*
*Aspen, January 2013*

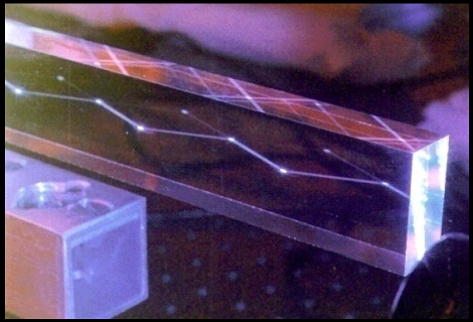
# The BABAR experiment at SLAC

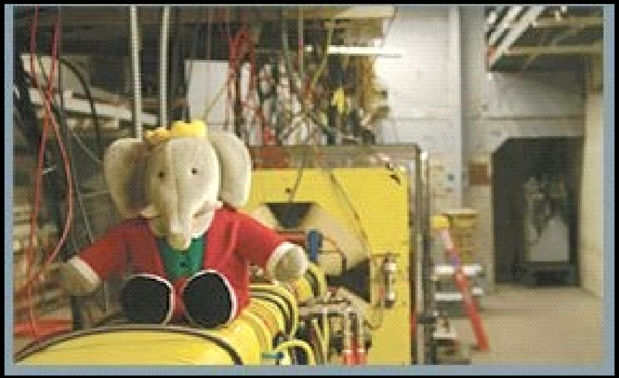


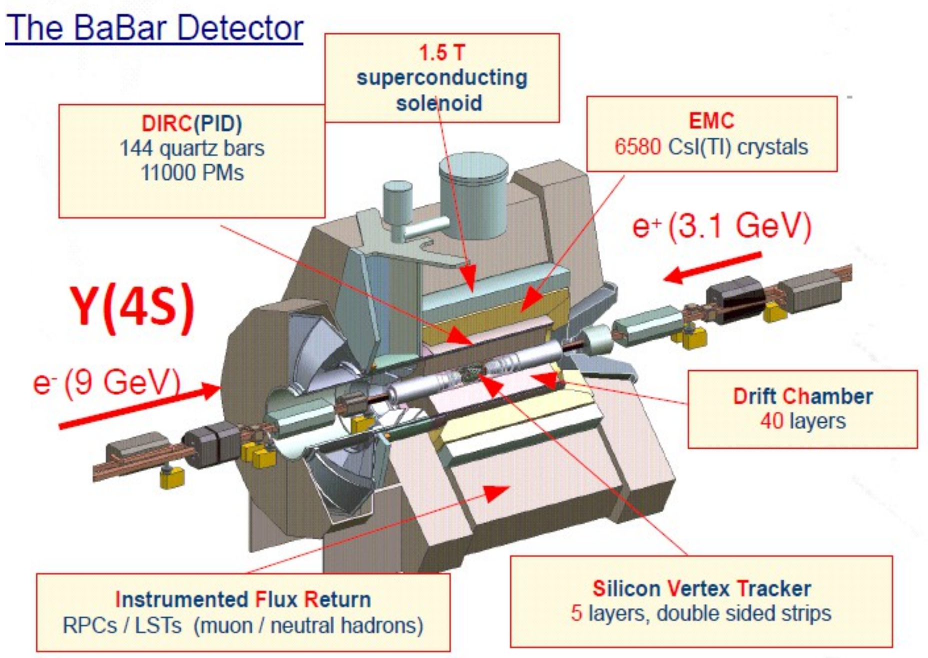


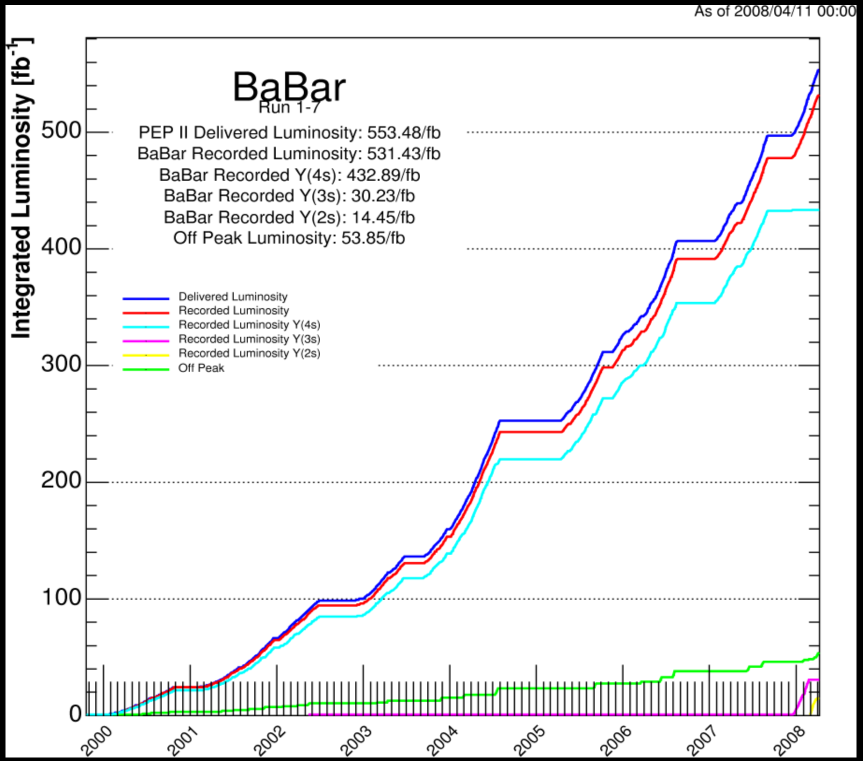


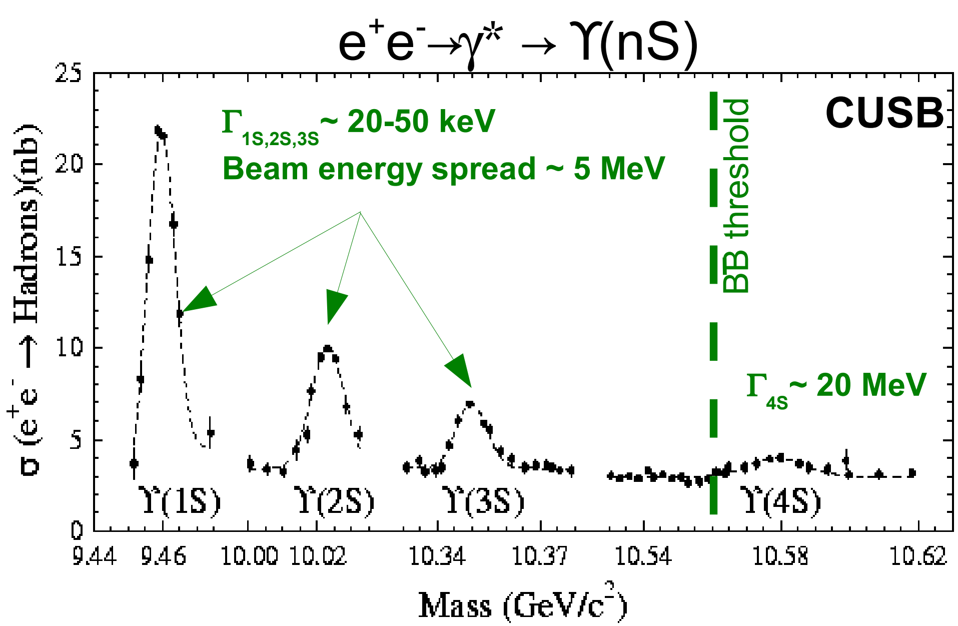




# *The BABAR experiment at SLAC*




***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)
- ~ 18 x $10^6$ $\Upsilon(1S)$ from $\Upsilon(2S) \to \pi^+\pi^- \Upsilon(1S)$

# Search for dark matter in Upsilon decays

*McElrath, PRD 72, 103508 (2005)*

## Generic Dark Matter model

- Minimal model introducing a light dark matter particle $\chi$ ($m_\chi < m_\Upsilon/2$) and a new scalar or gauge boson A' to serve as an s-channel annihilation mediator
- Scalar/boson A' couples to SM via Higgs mixing or kinetic mixing with SM hypercharge
- Could explain 511 keV gamma rays excess from the galactic center reported by INTEGRAL and electon/positron excess by PAMELA/FERMI
- Could increase the invisible decay width of the Y(1S) predicted by SM[1)] by orders of magnitude. Rate estimates are fairly model independent, based on cosmological observations and assuming time-reversal symmetry

## Rate predictions

$BF(\Upsilon(1S)\to\chi\chi) \sim 4.2 \times 10^{-4}$ (s-wave) (*PRD 72, 103508 (2005)*)

$BF(\Upsilon(1S)\to\chi\chi) \sim 1.8 \times 10^{-3}$ (p-wave) (*PRD 72, 103508 (2005)*)

$BF(\Upsilon(1S)\to\nu\nu) \sim 9.9 \times 10^{-6}$ (*PLB 441, 419 (1998)*)

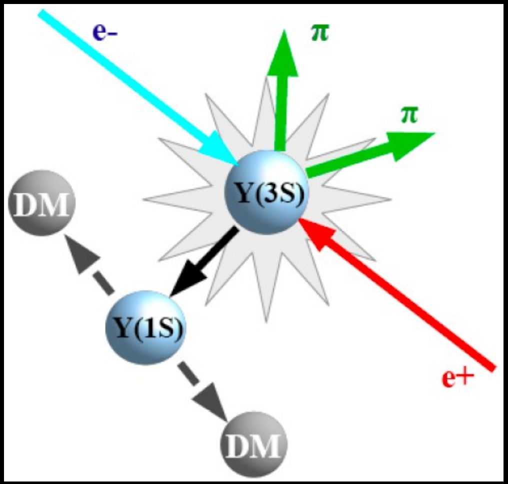
## Large increase from SM predictions

1) PLB 441, 419 (1998).

*PRL 103, 251801 (2009)*

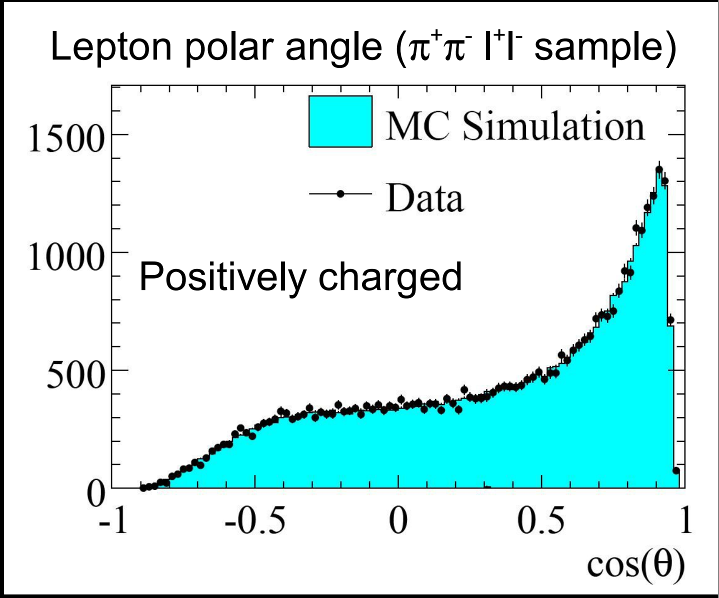
## Analysis strategy

- Tag $\Upsilon(1S)$ mesons in $\Upsilon(3S) \to \pi^+\pi^- \Upsilon(1S)$ transition
- Select event containing two oppositely-charged tracks only (no extra activity)




## Data sample contains

- Non-peaking background from random $\pi^+\pi^-$ combinations
- Peaking background (indistinguishable from signal)
  $\Upsilon(3S) \to \pi^+\pi^- \Upsilon(1S)$, $\Upsilon(1S) \to X$ (X undetected, mainly $l^+l^-$ pairs)
- Signal: $\Upsilon(3S) \to \pi^+\pi^- \Upsilon(1S)$, $\Upsilon(1S) \to$ invisible



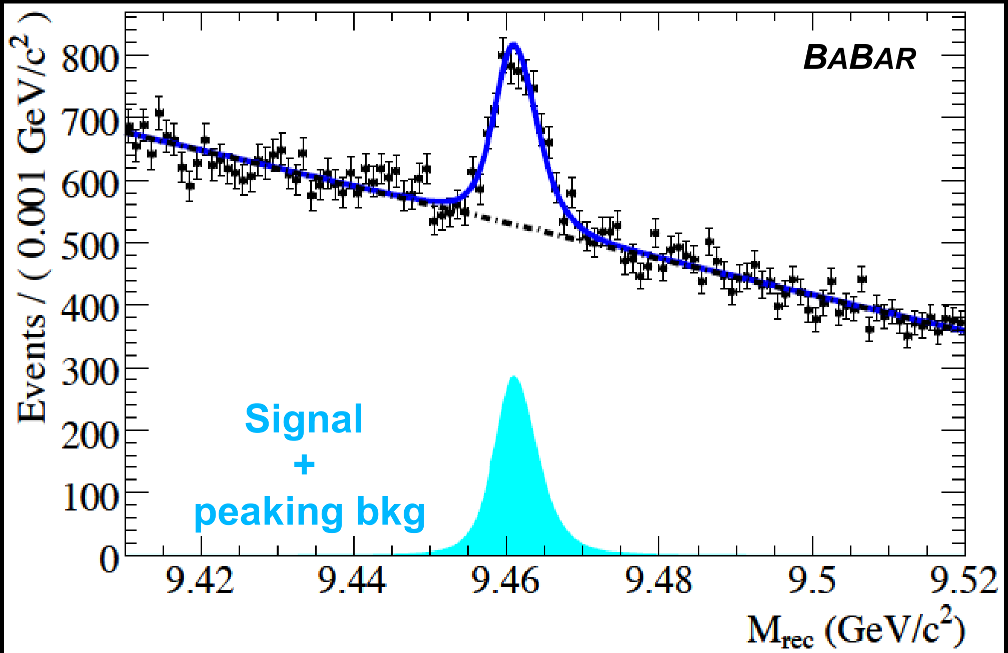

## Signal extraction

- Fit recoil mass $M_{rec} = (s+M^2_{\pi\pi}-2sE^*_{\pi\pi})^{1/2}$, should peak at $\Upsilon(1S)$
- Subtract peaking background estimated from MC. Use $\Upsilon(1S,2S) \to l^+l^-$ with one or two reconstructed leptons to check and correct simulations

*PRL 103, 251801 (2009)*

## Fit

- Extended unbinned maximum likelihood fit of recoil mass $M_{rec}$
- Sum of signal + peaking background
  - Crystal-Ball (Gaussian with power-law tail)
- Non-peaking background
  - 1st order polynomial




## Results

| | |
|---|---|
| Fit yield | 2326 ± 105 |
| Peaking bkg (MC) | 2444 ± 124 |
| **Signal only** | **-118 ± 105 ± 124** |

**Previous measurements BF(ϒ(1S) → invisible)**

| | | |
|---|---|---|
| CLEO: | BF < $3.9 \times 10^{-3}$ @ 90% CL | PRD 75 (2007) 031104 |
| Belle: | BF < $2.5 \times 10^{-3}$ @ 90% CL | PRL 98 (2007) 132001 |

## Upper limit (90% CL)

BF(ϒ(1S) → invisible) < $3.0 \times 10^{-4}$

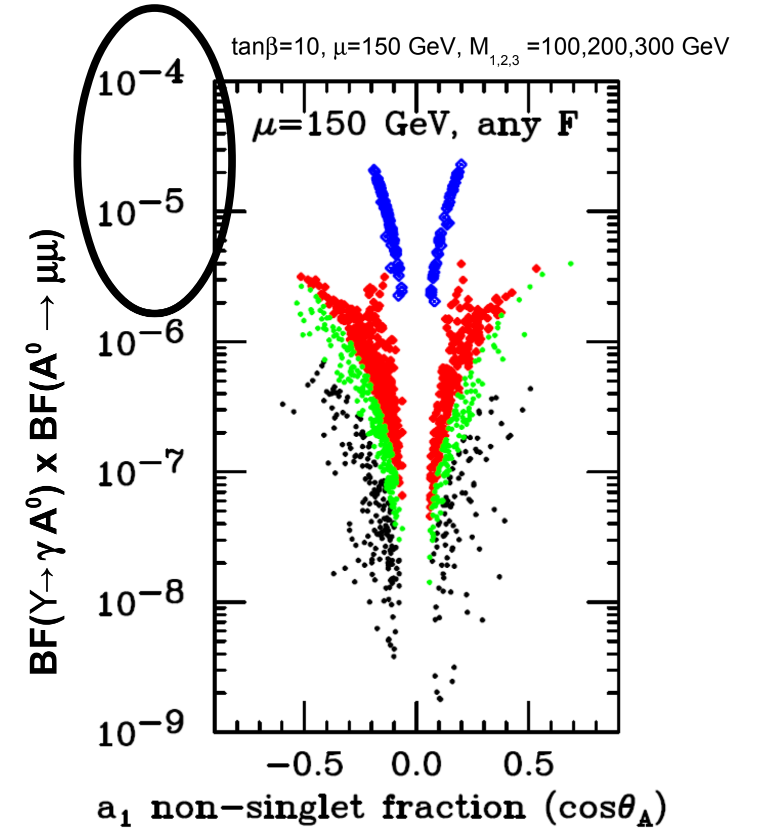
**No evidence of dark matter contribution to invisible ϒ(1S) decays**

# Search for dark matter in radiative Upsilon decays

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

## Dark matter and light Higgs boson

- Many SM extensions, such as the NMSSM, include the possibility of a light Higgs boson
- 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) can have a large branching fraction.
- The lightest neutralino $\chi_1$ is a natural dark matter candidate and the $A^0$ decays dominantly in $A^0 \to \chi_1 \chi_1$ if $m_{A0} > 2m_\chi$
- More generally one can look for dark matter production in radiative $\Upsilon(nS) \to \gamma\chi\chi$ decays (e.g G.K. Yeghiyan, PRD 80 (2009) 115019)



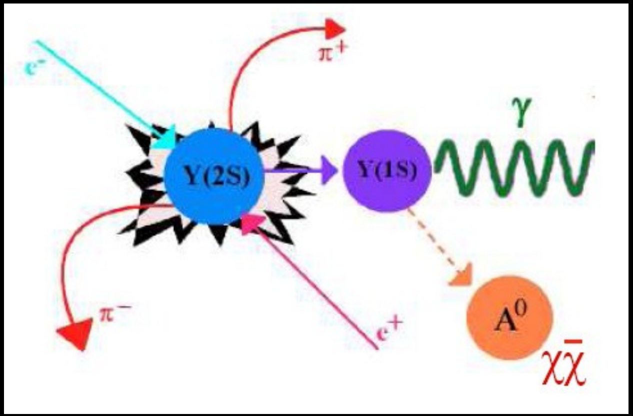

$A^0 = \cos\theta_A A_{MSSM} + \sin\theta_A A_S$

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

PRL107, 021804 (2011)

## Event selection

- Tag the dipion transition $\Upsilon(2S) \to \pi^+\pi^- \Upsilon(1S)$
- Require two charged tracks and one energetic photon, no additional activity
- Missing energy and momentum

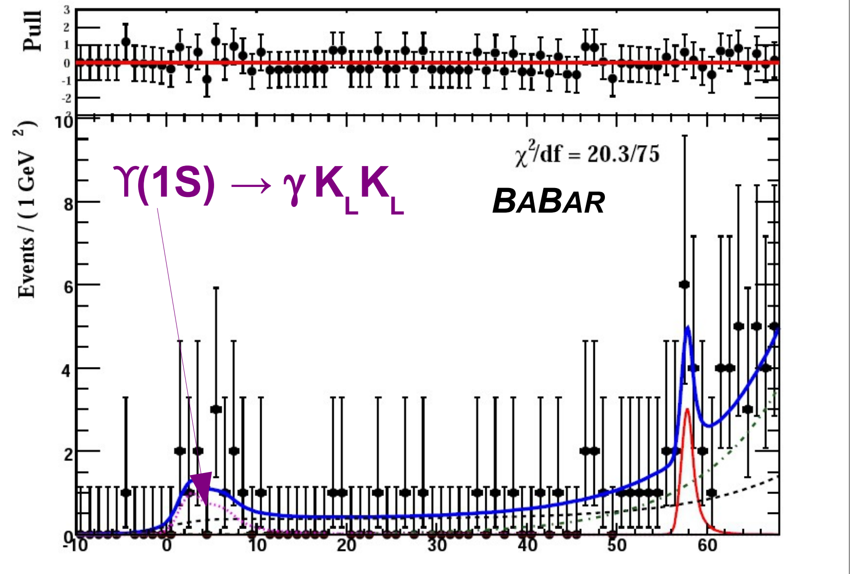



## Signal extraction

- 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

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

Most significant peak ($m_A$ = 7.58 GeV) with local significance 2.0σ.

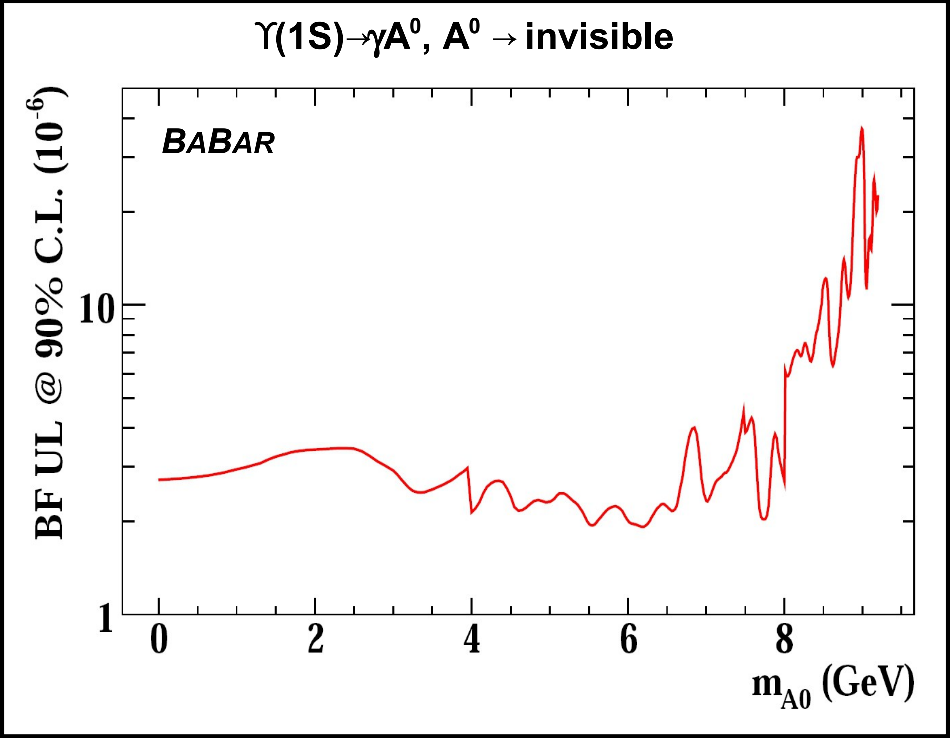


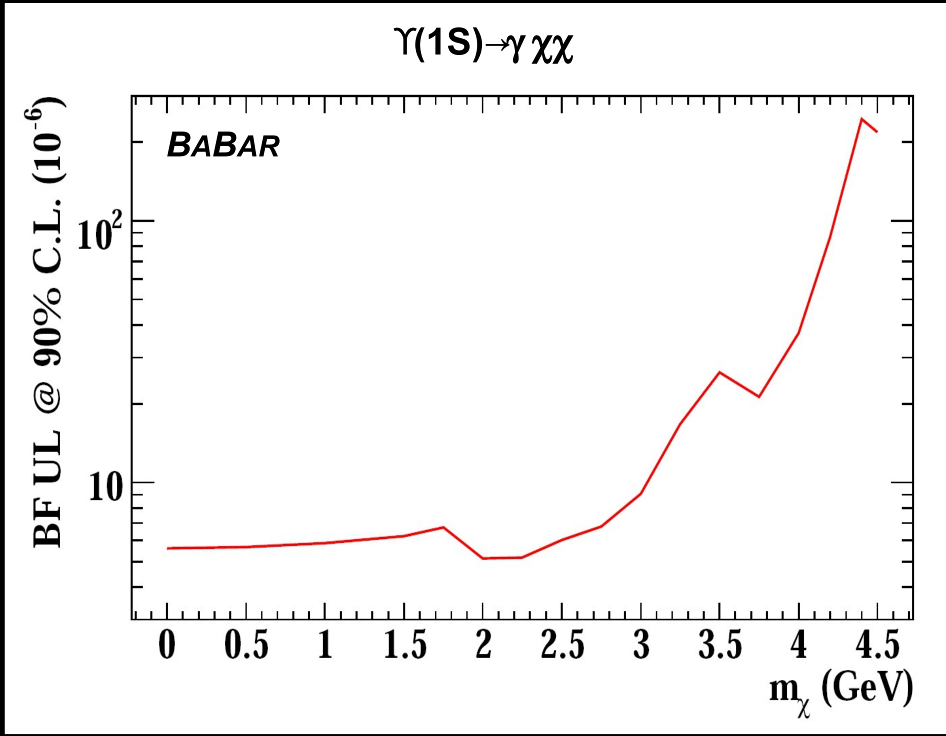

Missing mass squared (GeV²)

**No significant signal observed**

# $\Upsilon(1S) \rightarrow \gamma$ + invisible

*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)]**

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

**Significant constraints on these models**

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

# Search for dark forces

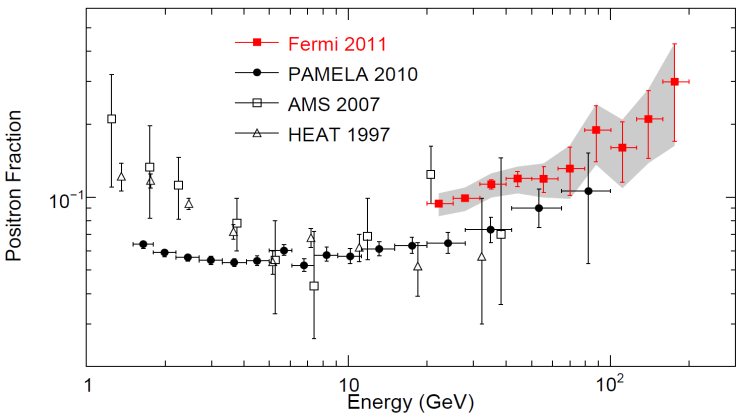
# Dark sector in a nutshell

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, DAMA/LIBRA, CREST,...

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

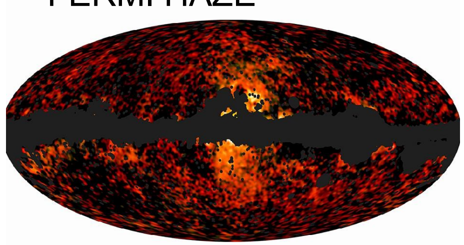
Other explanations of these anomalies have been proposed, but the possibility of a light hidden sector is **poorly constrained** and **I recently learned that this idea only.....**

FERMI



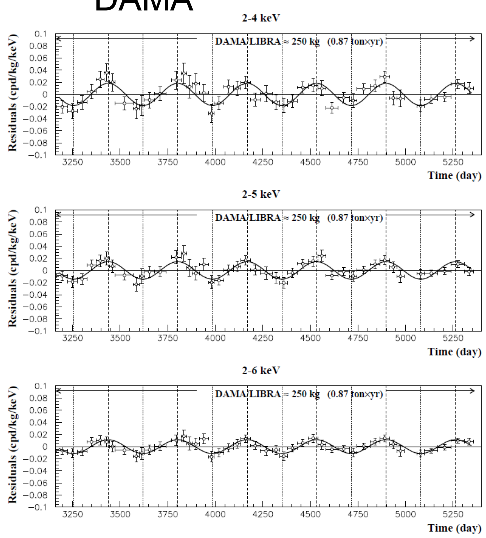

FERMI Collab., PRL 108, 011103 (2012), arXiv:1109.0521

FERMI HAZE



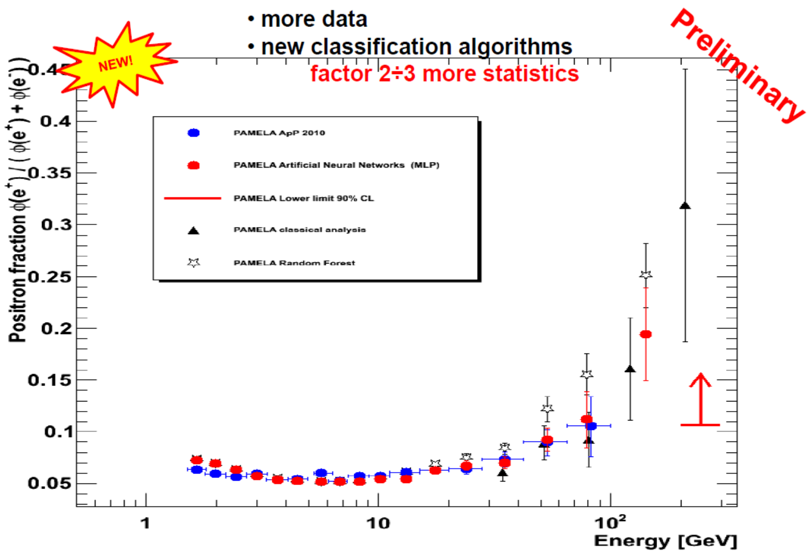
http://www.nasa.gov/mission_pages/planck/multimedia/pia15228.html

DAMA

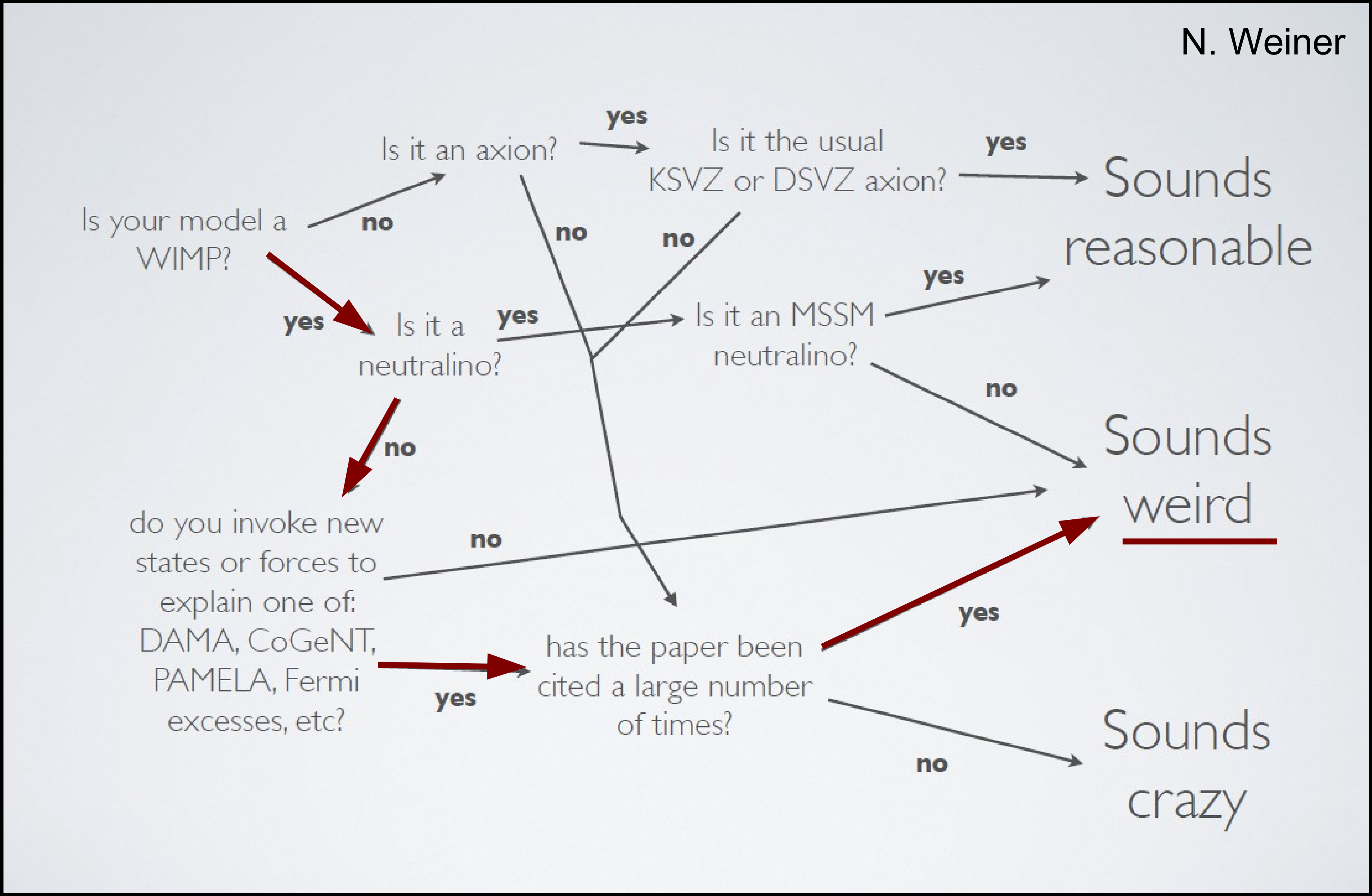



DAMA Collab., Eur. Phys. J. C (2010) 67: 39-49

PAMELA

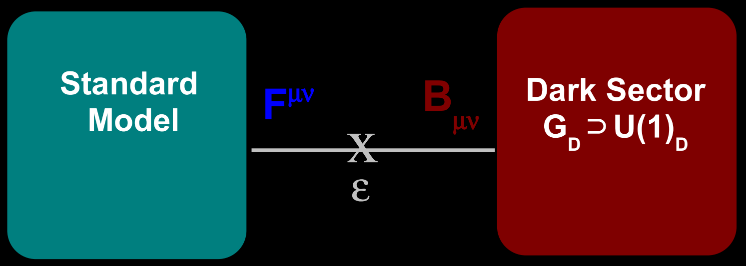



E. Mocchiutti,
International workshop on positrons in Astrophysics 2012


N. Weiner
Is your model a WIMP?
no
yes
Is it an axion?
yes
Is it the usual KSVZ or DSVZ axion?
yes
Sounds reasonable
no
no
Is it a neutralino?
yes
Is it an MSSM neutralino?
yes
no
Sounds weird
no
do you invoke new states or forces to explain one of: DAMA, CoGeNT, PAMELA, Fermi excesses, etc?
no
yes
has the paper been cited a large number of times?
yes
no
Sounds crazy

⇨ New dark sector with a $U(1)_D$ gauge group

⇨ New gauge boson: **dark photon A' , which could have O(GeV) mass**




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

# *Dark sector and dark forces*

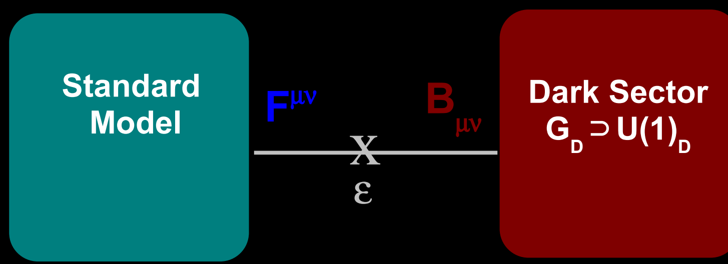
- New dark sector with a $U(1)_D$ gauge group

- 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.**




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

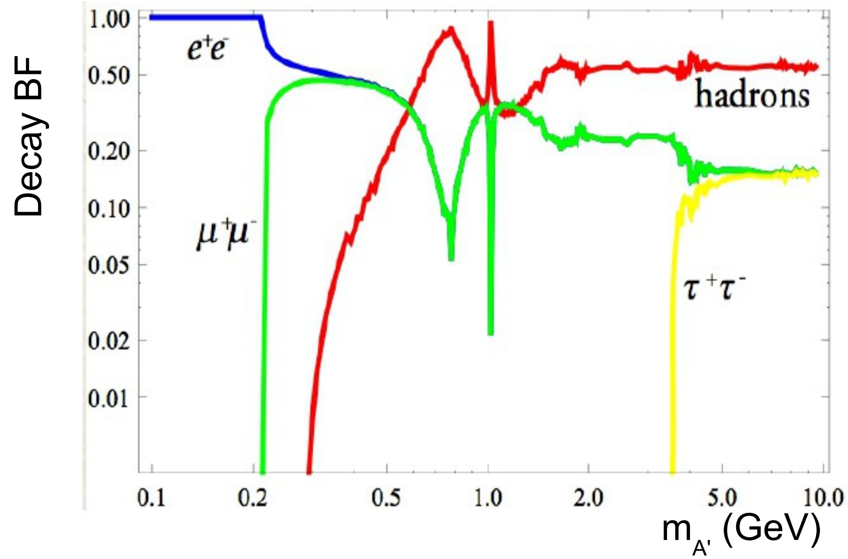
- New dark sector with a $U(1)_D$ gauge group
- New gauge boson: **dark photon A' , which could have O(GeV) mass**
- Interaction with the SM is via **kinetic mixing**

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

with a **mixing strength ε.**

- 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**




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

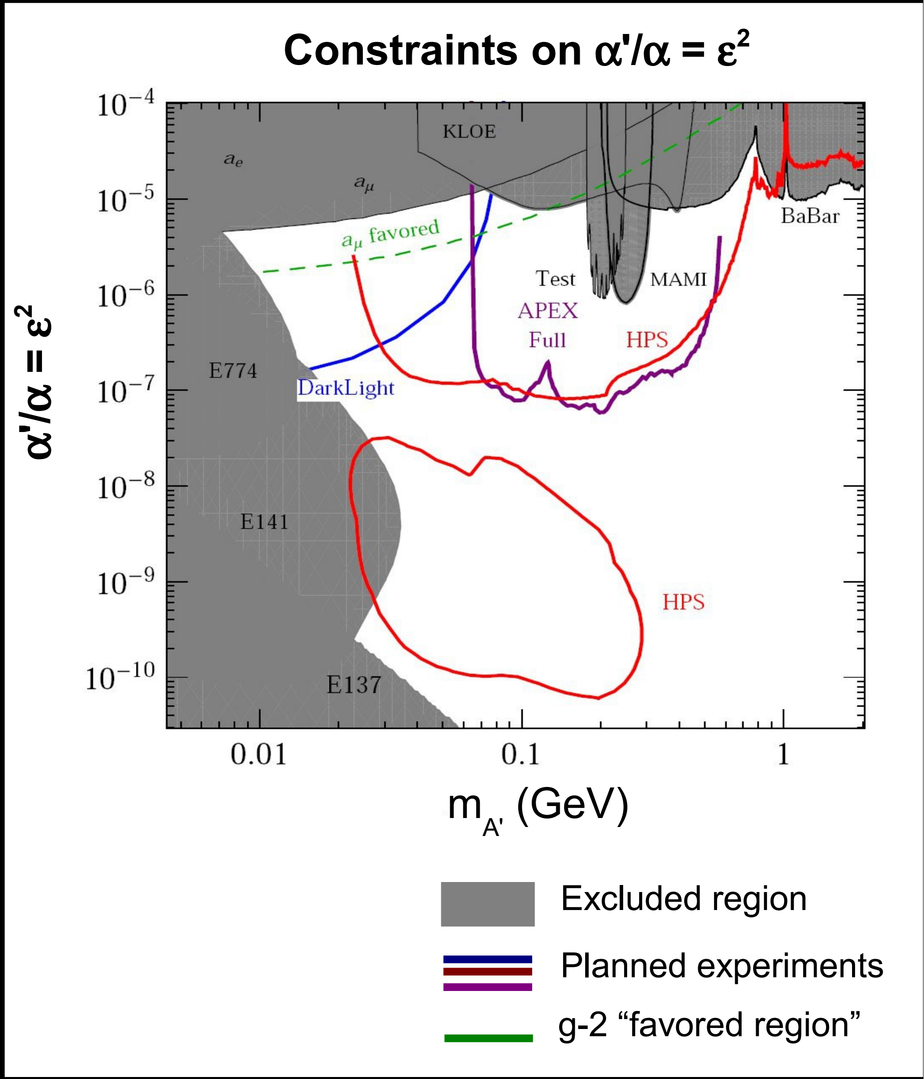
*J.D. Bjorken et al., PRD 80 (2009) 075018*

- 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.**

- The dark photon acquires a charge εe, and the **coupling of the dark photon to SM fermions** is characterized by $\alpha' = \alpha\,\varepsilon^2$
- Current limits on the mixing strength $\varepsilon^2$ are shown as a function of the dark photon mass for existing measurements and a few planned experiments.




**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**

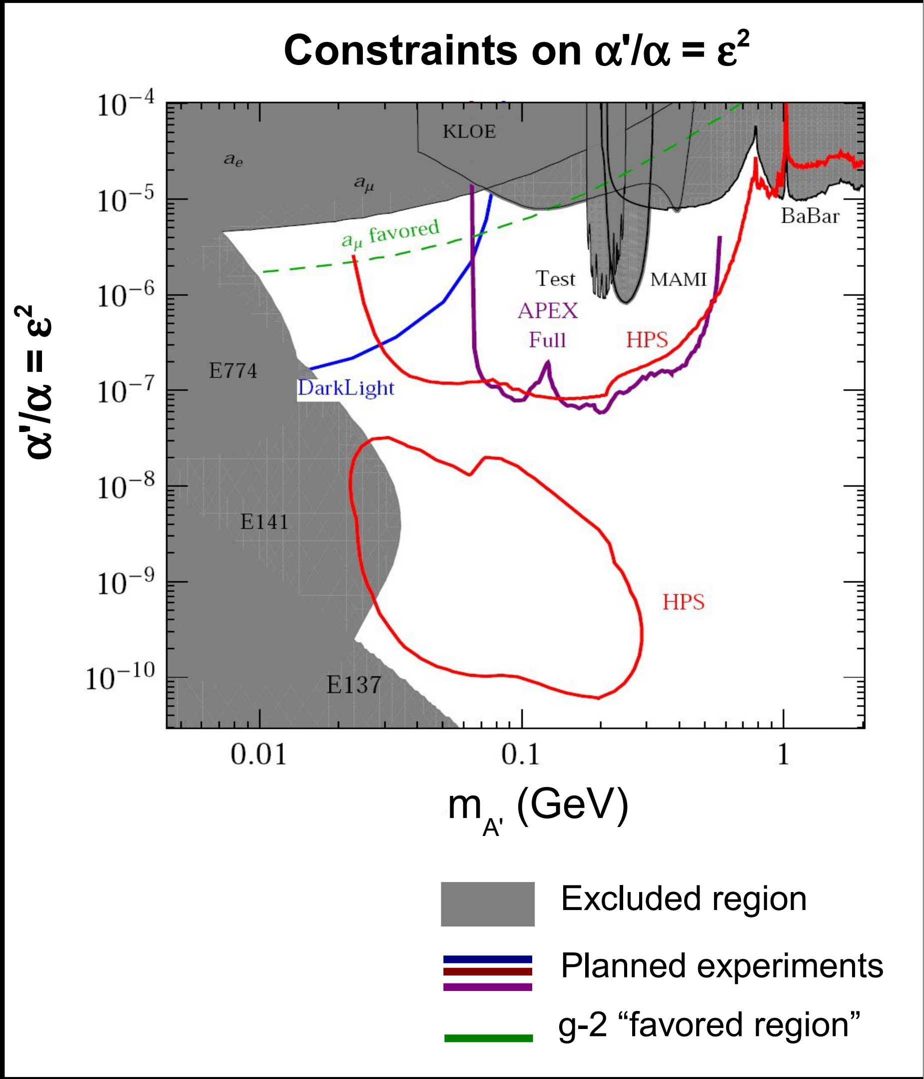
*J.D. Bjorken et al., PRD 80 (2009) 075018*

- 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.**

- The dark photon acquires a charge εe, and the **coupling of the dark photon to SM fermions** is characterized by $\alpha' = \alpha\,\varepsilon^2$
- Current limits on the mixing strength $\varepsilon^2$ are shown as a function of the dark photon mass for existing measurements and a few planned experiments.




**Other portals can connect the dark sector to the SM (Higgs portal, axion portal,...)**
**I'll only discuss the vector portal in this talk**

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

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

Can probe the hidden sector structure

**Search for dark photon**

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

**Search for dark boson(s)**

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

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

**Search for dark Higgs boson**

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

**Search for dark hadrons**

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

**Search for dark photon in meson decay**

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

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

$B \rightarrow K^{(*)}s \rightarrow K^{(*)} l^+l^-$ and $B \rightarrow K^{(*)}a \rightarrow K^{(*)} l^+l^-$

$B \rightarrow ss \rightarrow 2(l^+l^-)$

$B \rightarrow K\ 2(l^+l^-)$

$B \rightarrow 4(l^+l^-)$

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

Can probe the hidden sector structure

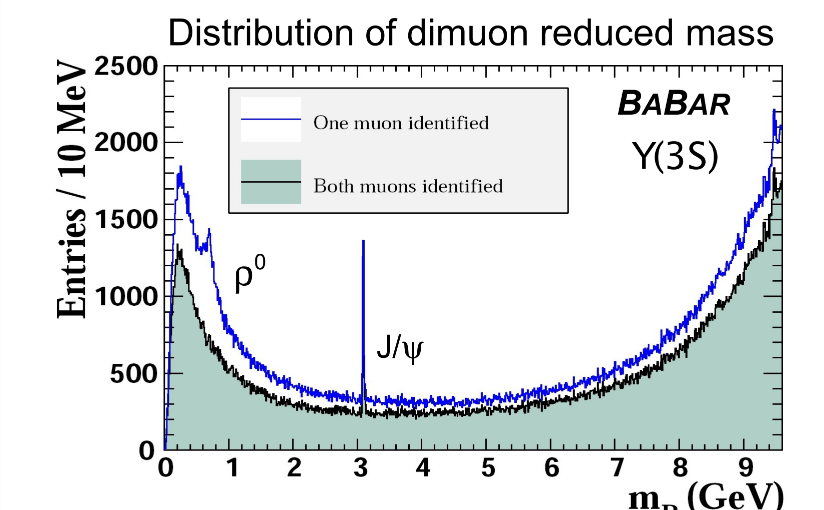
*PRL 103 (2009) 081803*

A dark photon can be readily produced in

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

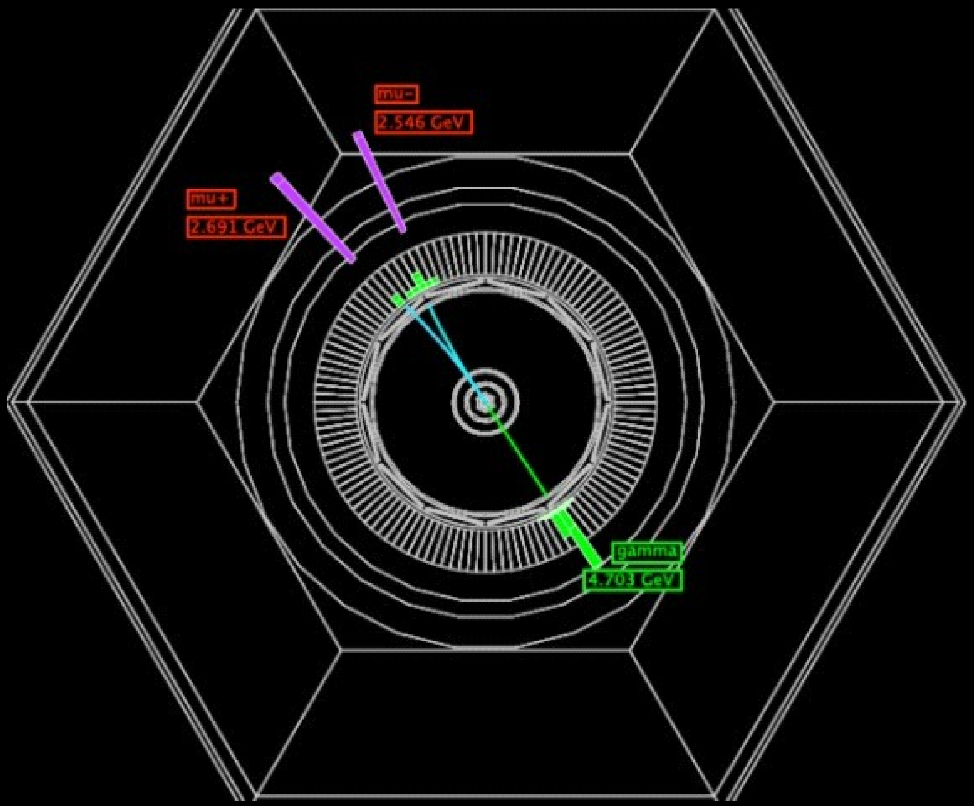
So far, only one measurement of this final state at *BABAR* from light CP-odd Higgs search in $\Upsilon$(2S,3S) decays based on ~45 fb$^{-1}$ of data:

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




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

**Candidate event**




- Tracks
- Photon
- Signal in muon/hadron detector

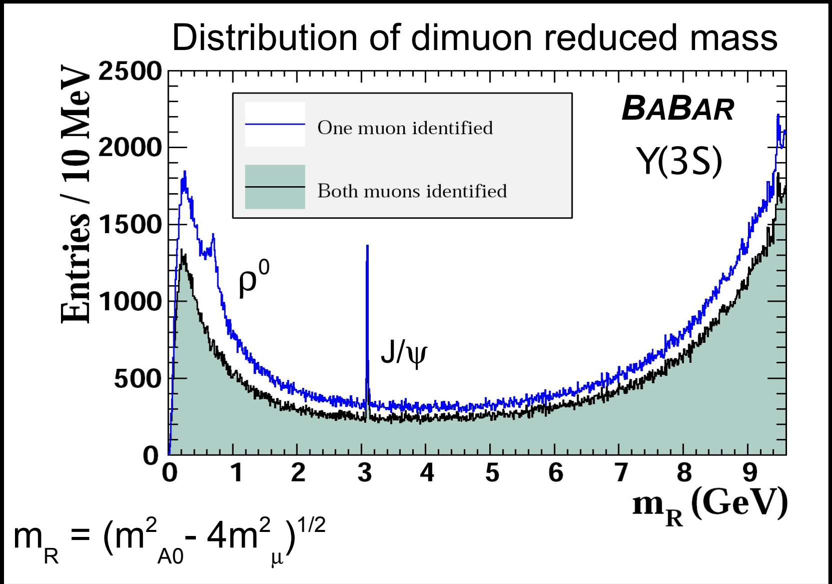
*PRL 103 (2009) 081803*

A dark photon can be readily produced in

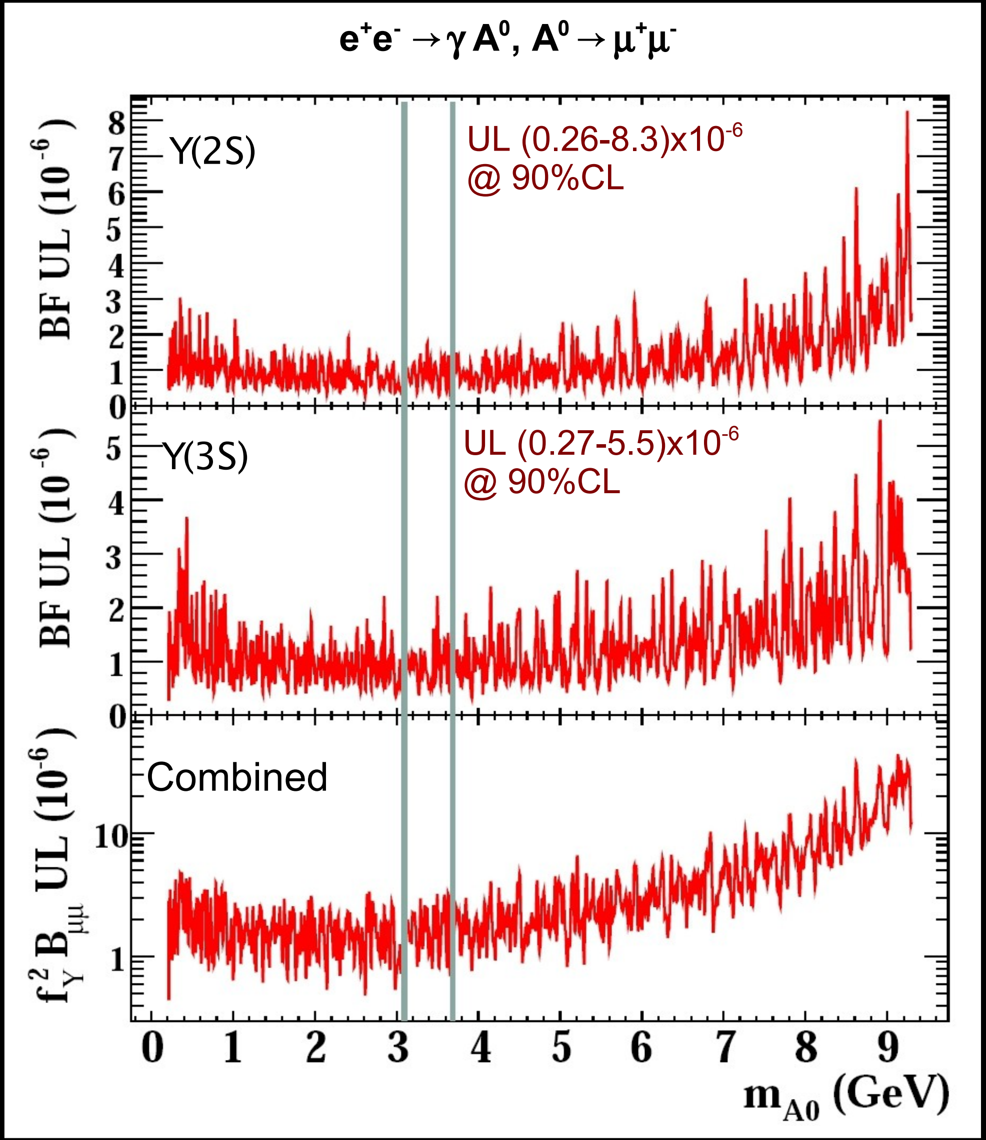
$$e^+e^- \rightarrow \gamma A' \rightarrow \gamma\, l^+l^-,\ \gamma\, q\bar{q}$$

So far, only one measurement of this final state at *BABAR* from light CP-odd Higgs search in ϒ(2S,3S) decays based on ~45 $fb^{-1}$ of data:

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

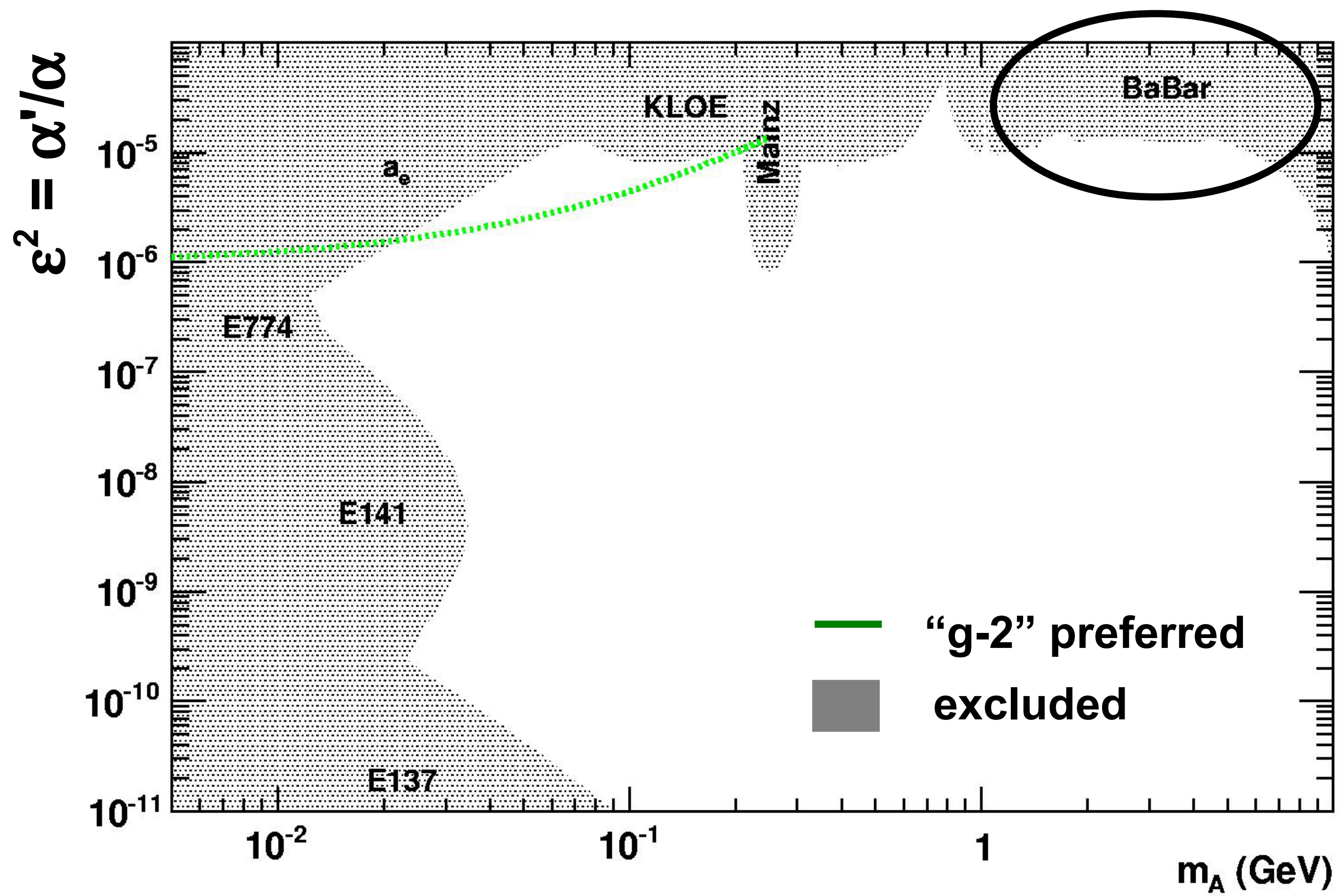



$m_R = (m^2_{A0} - 4m^2_\mu)^{1/2}$




**No sign of narrow resonance**

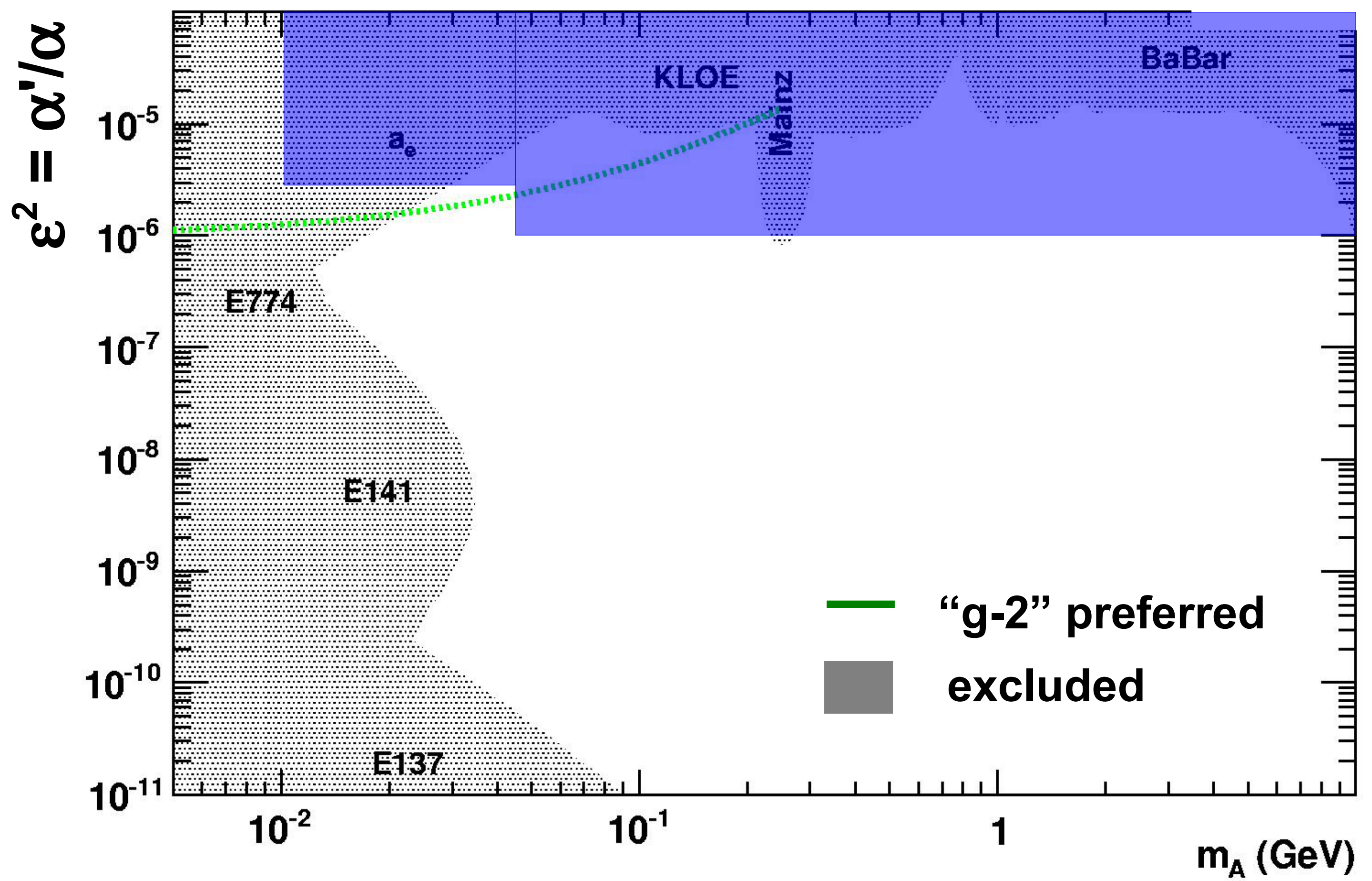
Limit obtained by reinterpreting the $\Upsilon(2S,3S) \rightarrow \gamma A^0$, $A^0 \rightarrow \mu^+\mu^-$ measurements[1)]

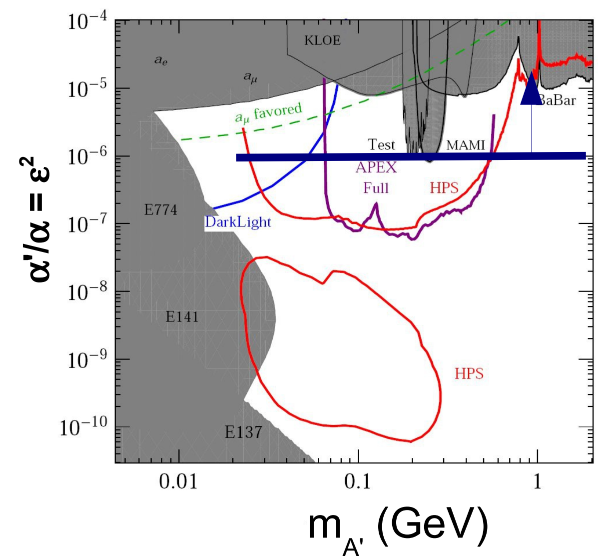



*1) J.D. Bjorken et al., PRD 80 (2009) 075018*

**Note: $\sigma(e^+e^- \rightarrow \gamma A') \sim 1/s$, so need low-energy collider to probe direct production**

**Crude estimate of expected limits using the full *BABAR* dataset for $e^+e^- \to \gamma e^+e^-, \gamma\mu^+\mu^-, \gamma\pi^+\pi^-$**

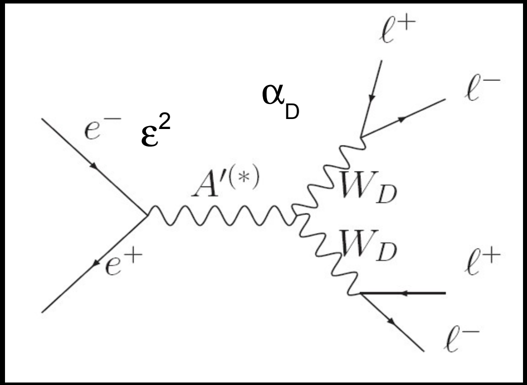



**Expect significant improvement, exclude almost all the "g-2" preferred region. Stay tuned!**

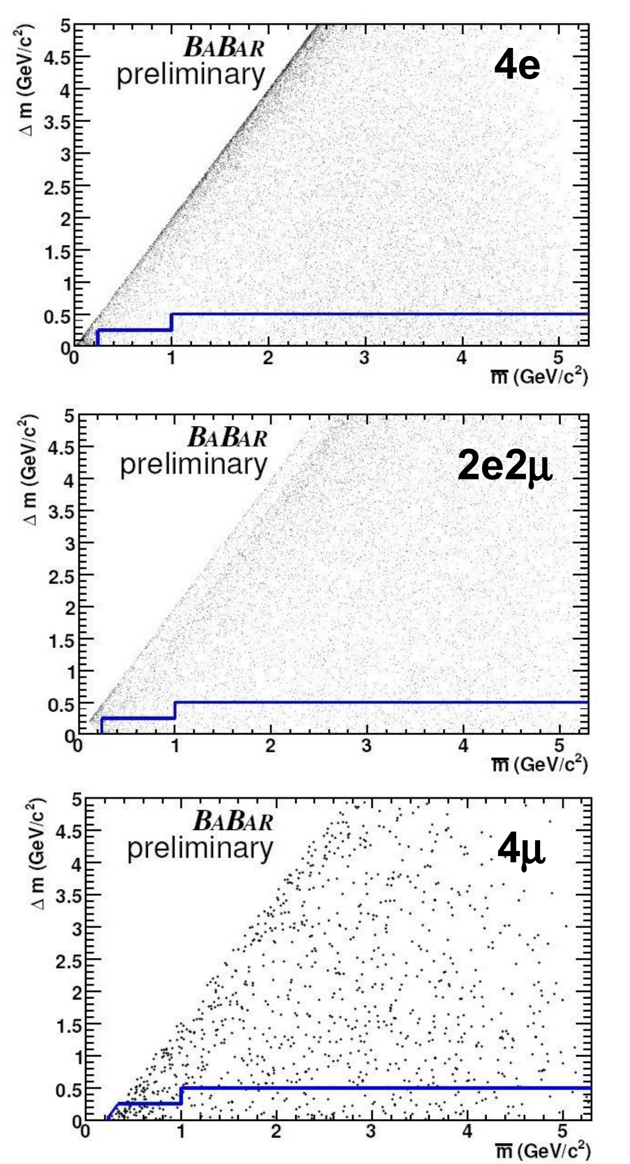
arXiv:0908.2821

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




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

$g_D$ dark sector gauge coupling




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

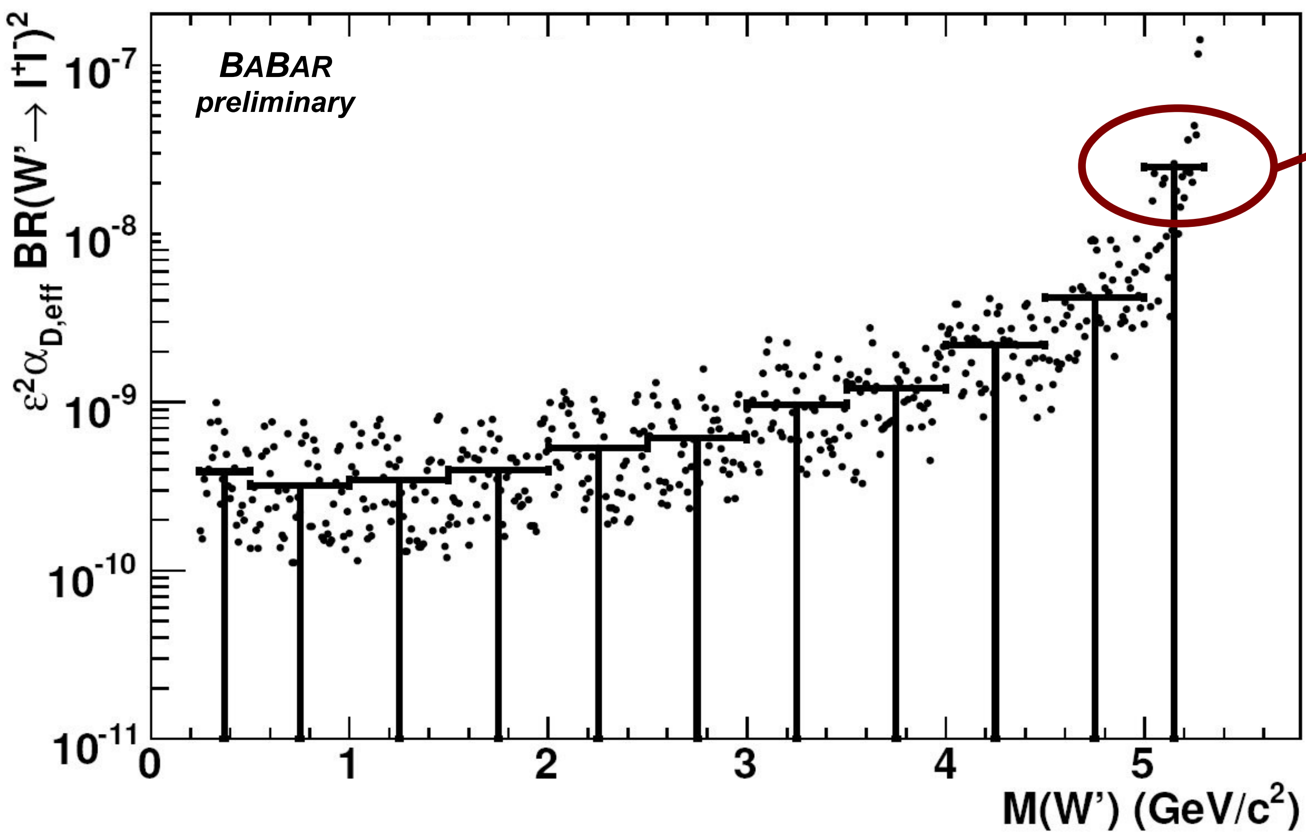
$\Delta m = (m_{max}-m_{min})/2$

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

# Search for dark gauge boson

arXiv:0908.2821

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




Average limit over many bins

Limits on $\varepsilon^2 < 10^{-7} - 10^{-3}$ assuming $\alpha_D = \alpha_{em} = 1/137$

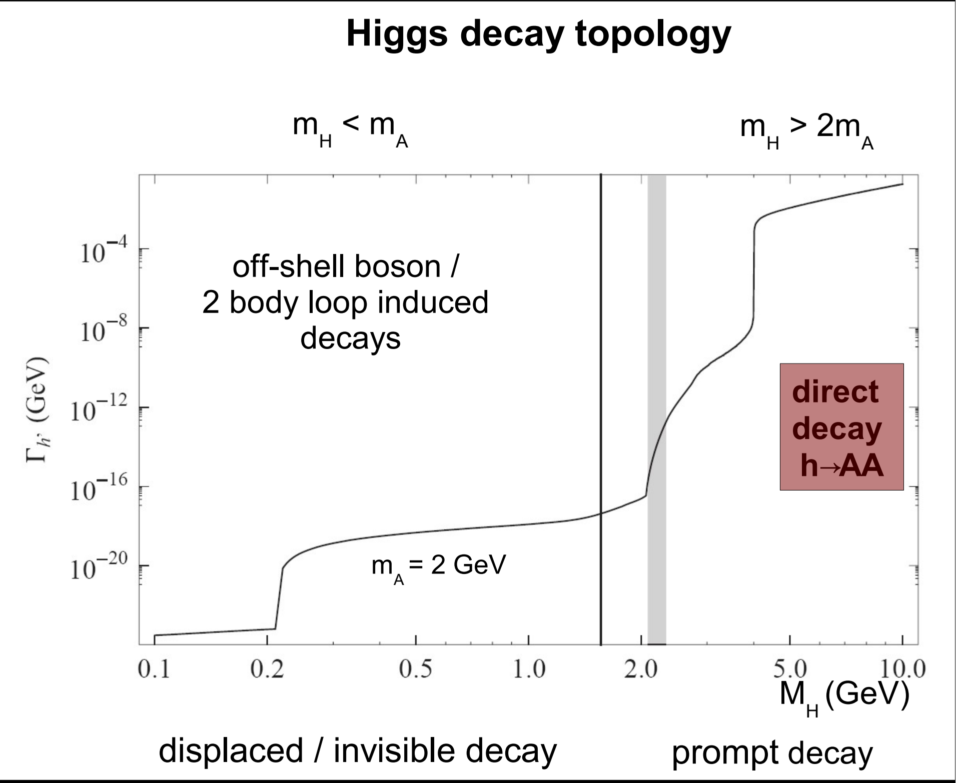
**Expect similar limits for $m_W - m_{W'} >> 0$**

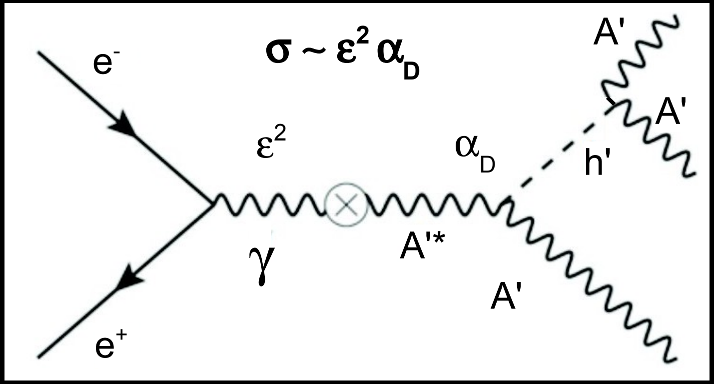
*B. Batell et al., PRD 79 (2009) 115008*
*R. Essig et al., PRD 80 (2009) 015003*

- Dark photon mass is generated via the Higgs mechanism, **adding a dark Higgs boson (h')**
- A minimal scenario has a **single dark photon and a single dark Higgs boson.**
- **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 $\varepsilon^2$** and is expected to have a **very small background.**




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

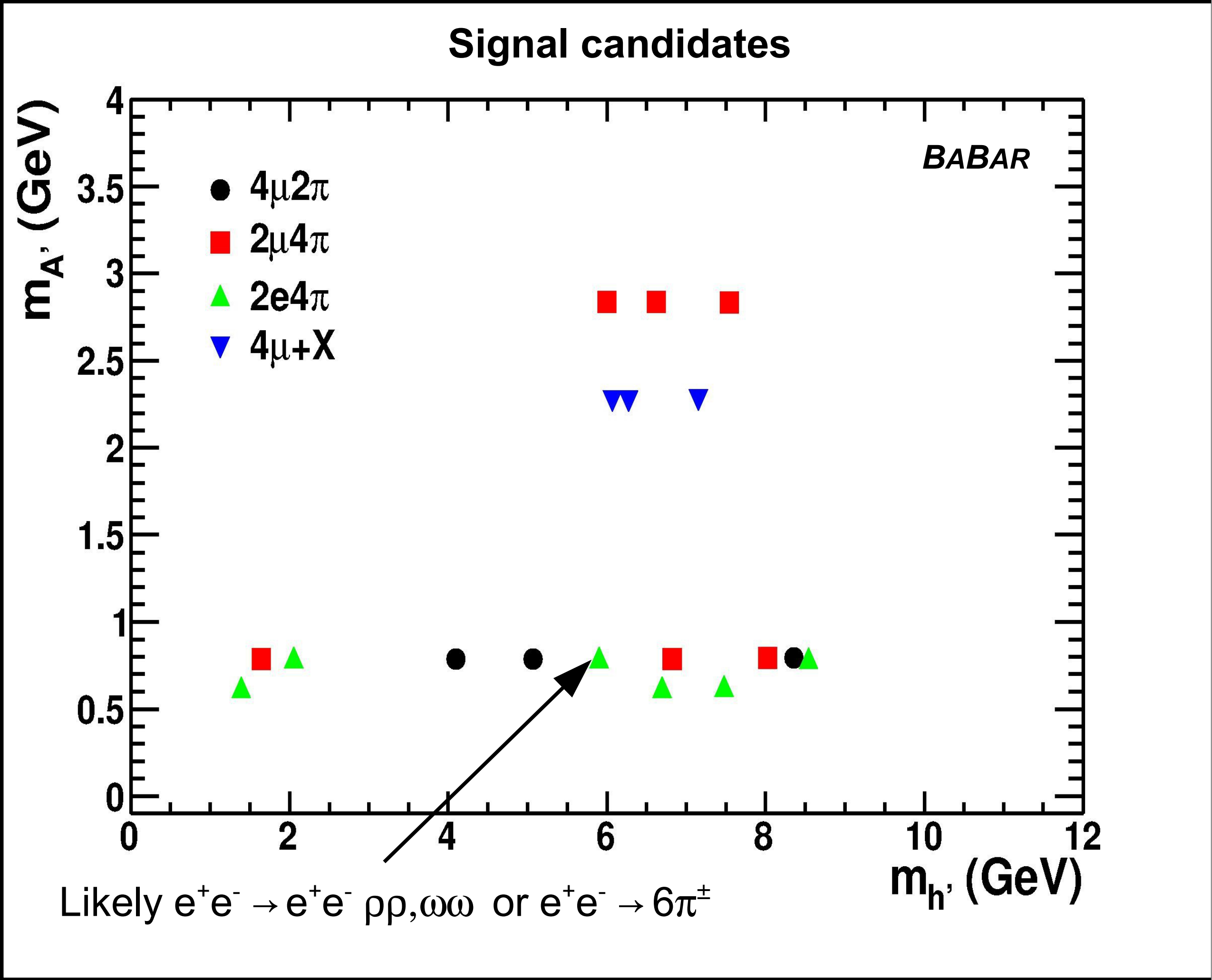
**Focus on prompt decays**
**$m_h > 2m_A$**

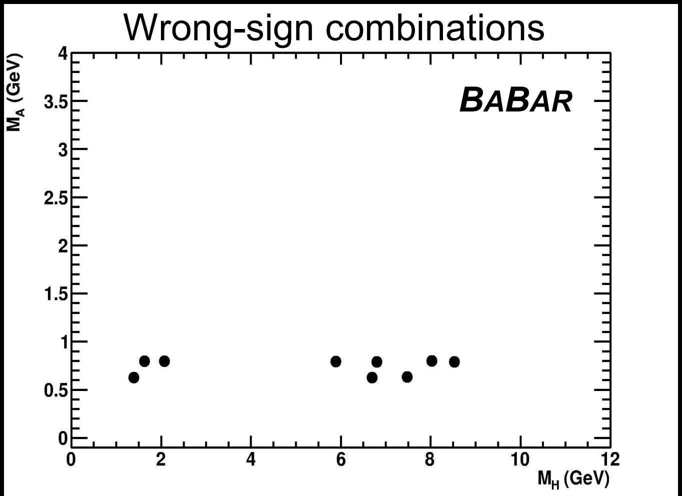
Search for three resonances with similar masses

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.

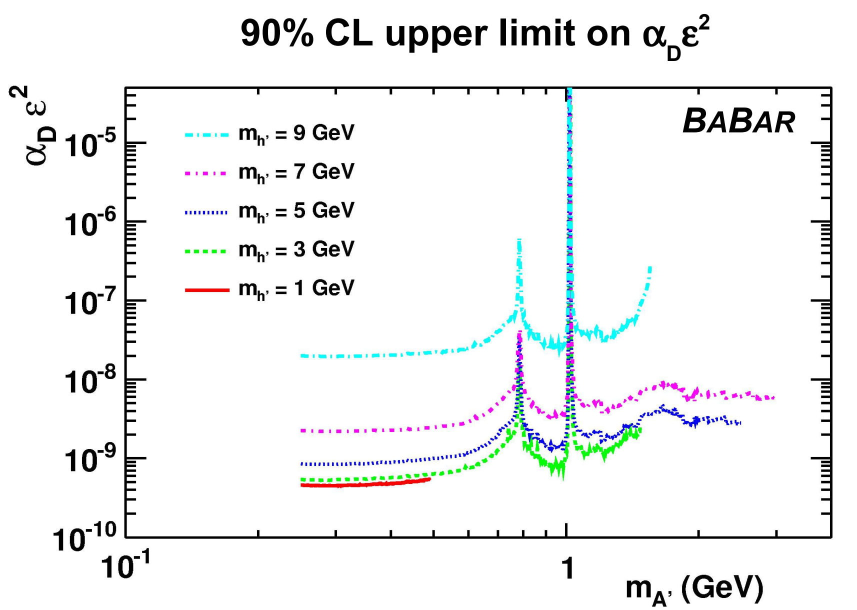
    $e^+e^- \to (e^+e^+)\,(e^-e^-)\,(\mu^+\mu^-)$
  - sidebands from final sample
  - rate for 6 leptons ~ 100x rate for $4\pi$+2l above 1.5 GeV

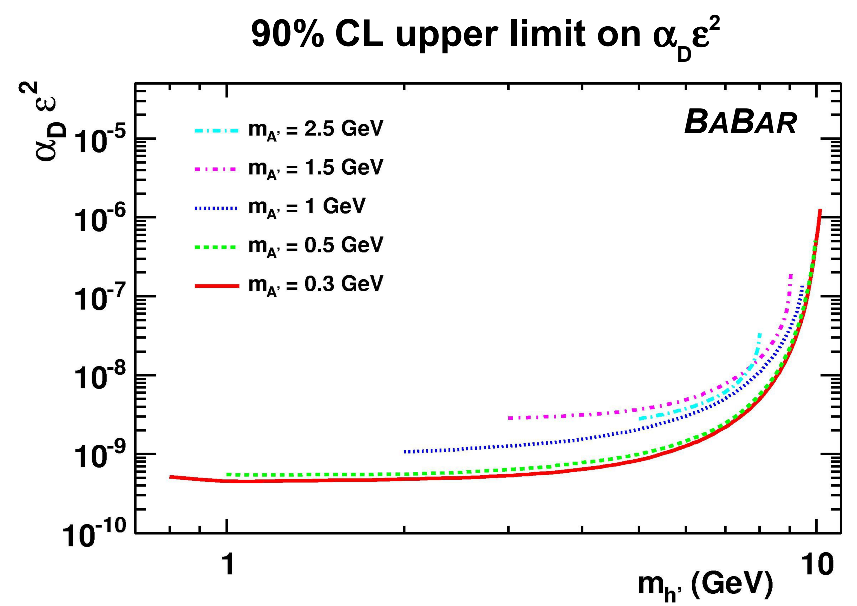


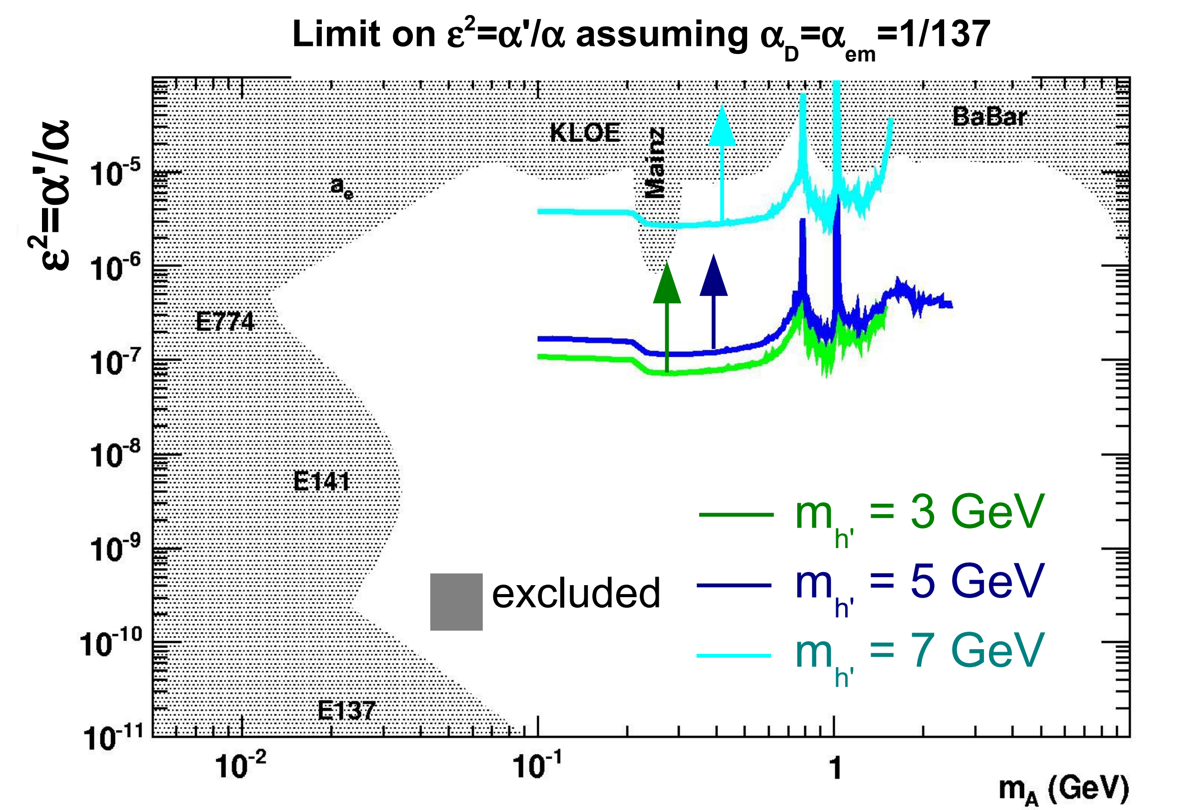




**No events with 6 leptons, consistent with the pure background hypothesis**

*PRL 108 (2012) 211801*




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

Low-energy $e^+e^-$ colliders provide a clean environment to explore MeV-GeV scale dark matter and dark sector. Colliders can not only investigate their existence, but also their structure.

Several results in ϒ decays have already set stringent limits on theoretical models of generic dark matter or BSM physics.

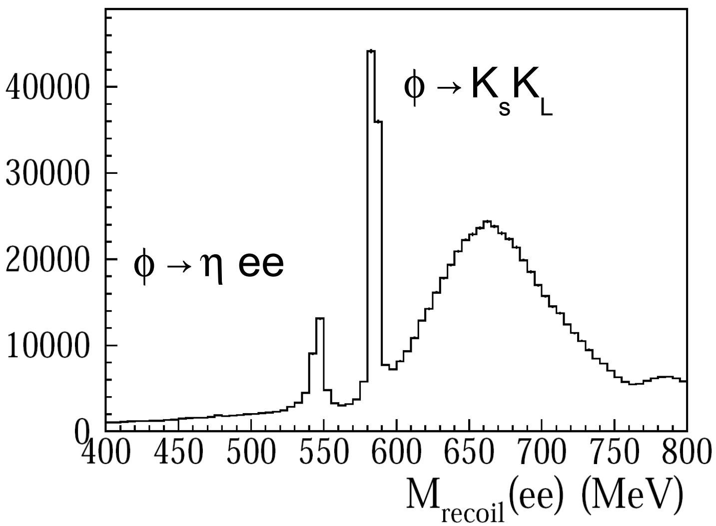
Searches for dark sector particles have already set the best limits on dark sector particles, and many searches are currently being performed at *BABAR.*

# Extra material

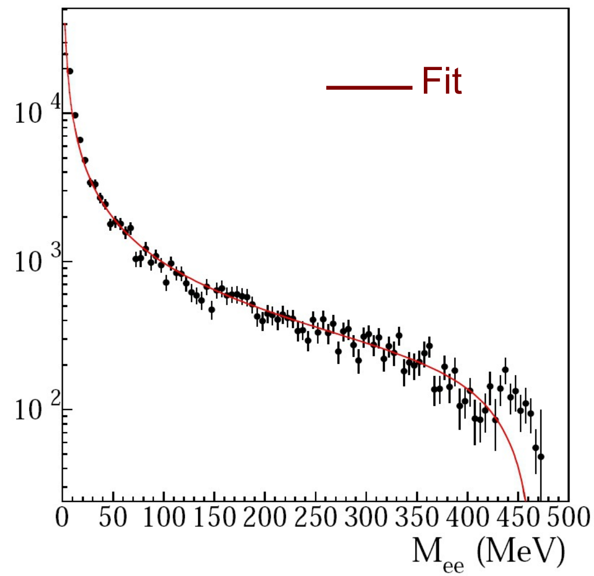
*PLB 706 (2012) 251.*

**Search for dark photon in** $e^+e^- \rightarrow \phi \rightarrow \eta A'$, $\eta \rightarrow \pi^+\pi^-\pi^0$, $A' \rightarrow e^+e^-$ **at KLOE with ~$7\times10^9$ $\phi$ mesons**

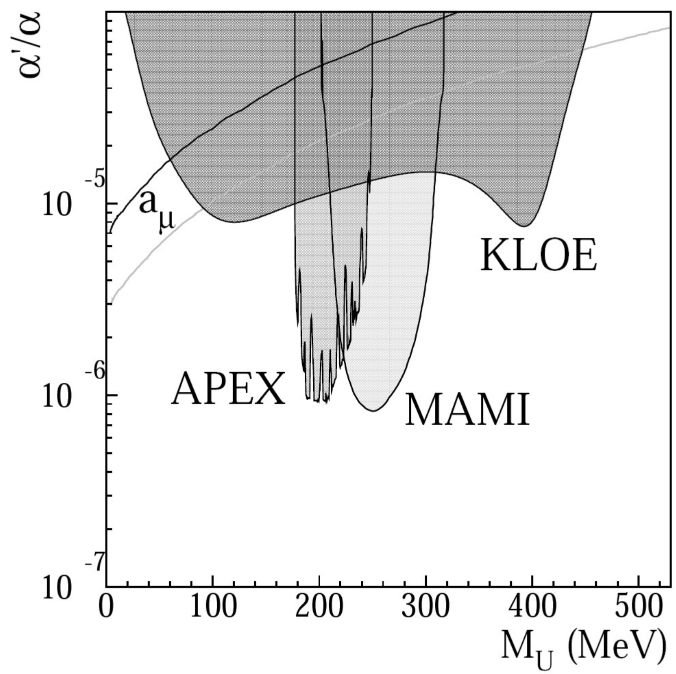
$e^+e^-$ recoil mass spectrum




$e^+e^-$ mass spectrum




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




**Exclude values of $\varepsilon^2$ down to ~$10^{-5}$ for $80 < m_{A'} < 400$ MeV**

**KLOE II is expected to improve these limits by a factor 3-5.**

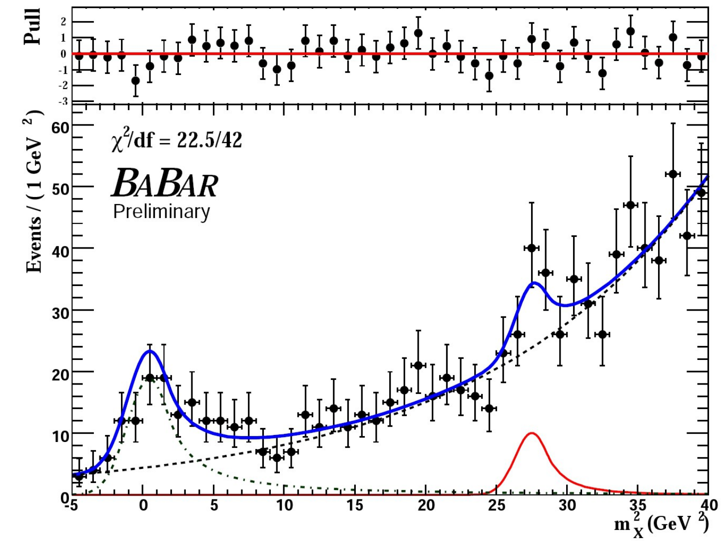
arxiv:0808.0017

## Search for invisible dark photon decay

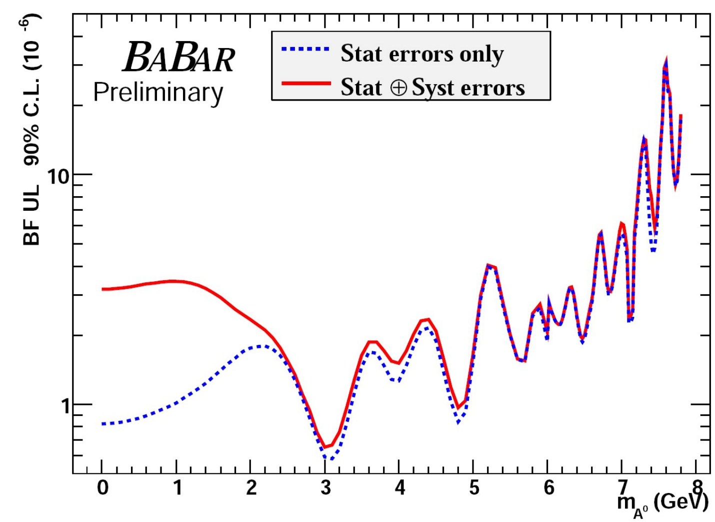
**$e^+e^- \rightarrow \gamma A'$, $A' \rightarrow$ invisible**

- Several scenarios with **dark photon decay to invisible particles** (light dark matter for example, see *Cline et al., arXiv 1108.1391*).
- Dark photon or similar particle may be long lived and escape detector.
- Reinterpret $Y(2S,3S) \rightarrow \gamma$ + invisible measurement from *BABAR*, limits on $\varepsilon^2$ should be at the level of $10^{-5}$ - $10^{-4}$.
- Current analysis will improve the preliminary results by a factor ~2.

**Sample fit $\Upsilon(3S)$**




**$\Upsilon(3S) \rightarrow \gamma A^0$, $A^0 \rightarrow$ invisible**



## Fully reconstructed

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

### Fully reconstructed signal

- ➩ Three dark photons fully reconstructed

### Modes included

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

### Selection

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

## Partially reconstructed

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

### Partially reconstructed signal

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

### Modes included

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

### Selection

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