Searches for Low-Mass New Physics: CP-odd Higgs and Dark Photons

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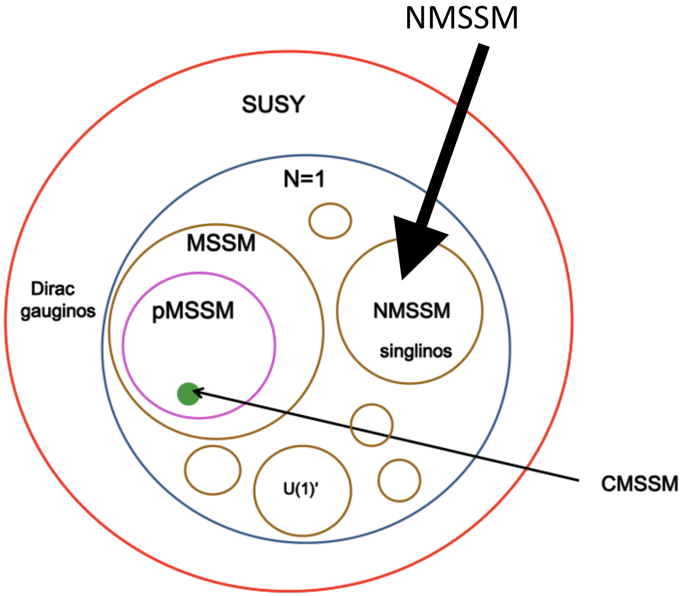
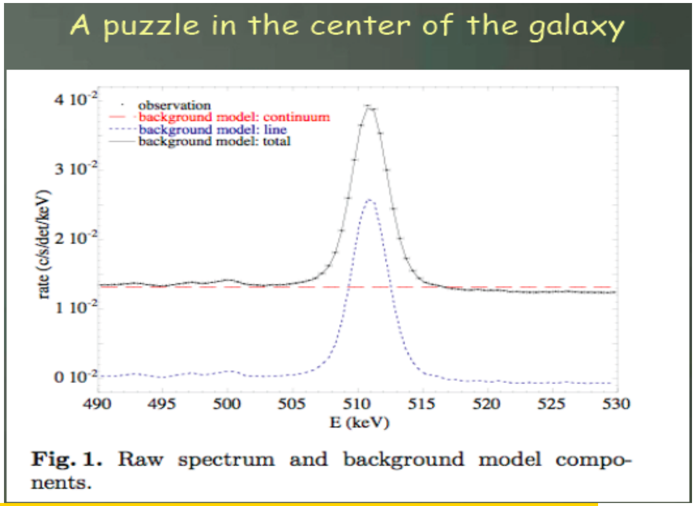
Why CP-Odd Low-Mass Higgs

- Higgs seems to be at hand -- but the fun is just beginning…
  - ❑ Is this a Higgs ? Or THE Higgs ?
    - ☞Need guidance from both low and high energies
- E.g. NMSSM models with light CP-odd Higgs
  - ❑ Solve fine-tuning problems in MSSM
  - ❑ Also help explain some astro-particle observations
    - ☞ INTEGRAL x-rays, Fermi and PAMELA excesses, direct DM claims, …



T. Rizzo (SLAC Summer Institute 2012)



A puzzle in the center of the galaxy

Fig. 1. Raw spectrum and background model components.

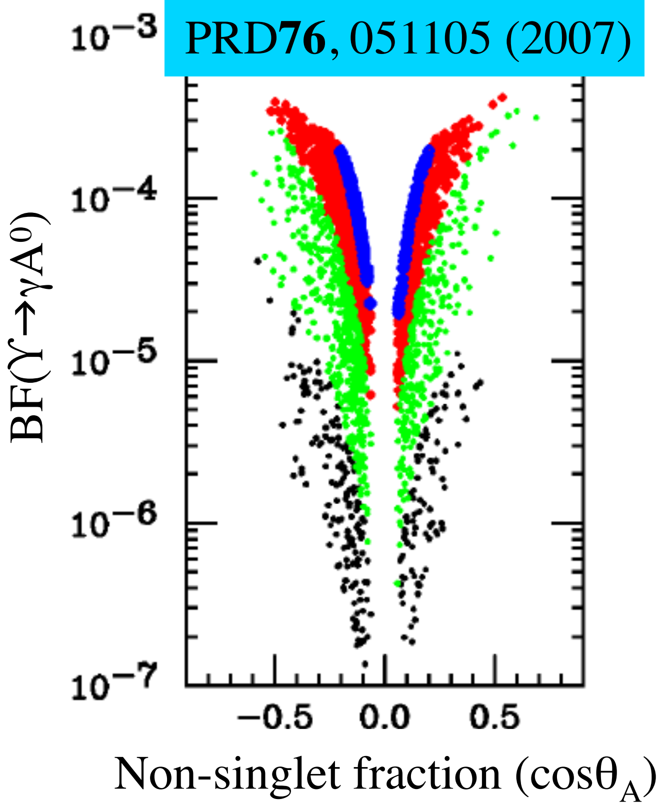
CP-Odd Low-Mass Higgs

- NMSSM parameter space
  - 7 scalar fields
    - ☞ 6 MSSM fields plus singlet A_S
    - ☞ Visible CP-odd component:

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

- CP-odd Higgs, A0, below $2m_b$ is not constrained by LEP
- Observable Branching Fraction (BF) for $\Upsilon \to \gamma A^0$ possible in 10^{-7}–10^{-4} range
- Accessible at B-Factories in e^+e^- annihilations or bottomonium decays
  - Subject of a comprehensive campaign of searches in BABAR since 2008

R.Dermisek et al
PRD**76**, 051105 (2007)



$m_{A0}<2m_\tau$

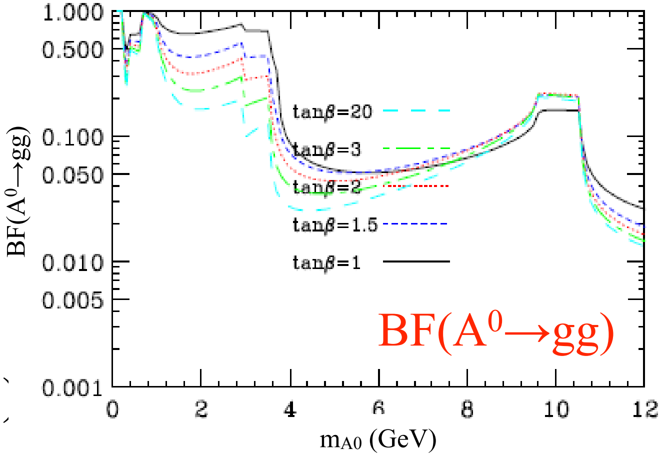
$2m_\tau<m_{A0}<7.5$ GeV

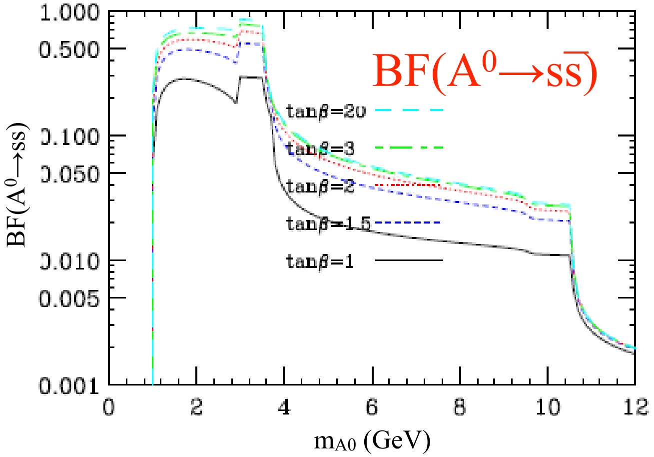
7.5 GeV$<m_{A0}<8.8$ GeV

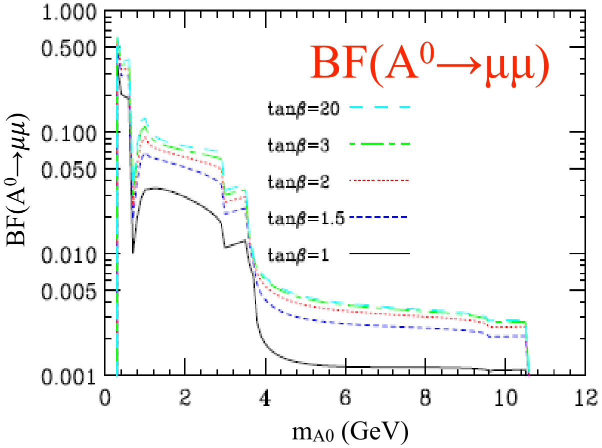
8.8 GeV$<m_{A0}<9.2$ GeV

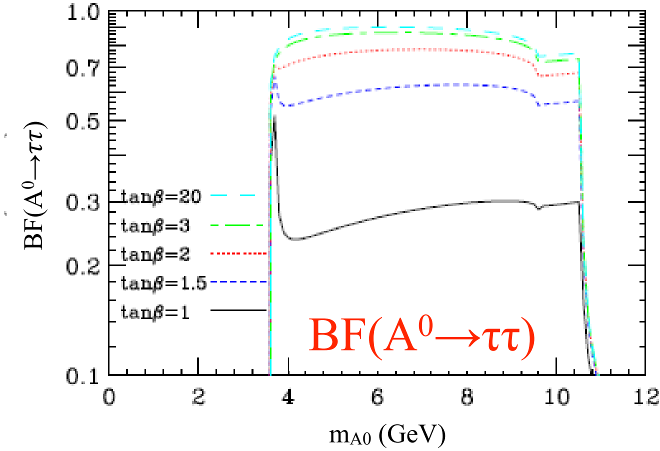
Low-Mass Higgs Decays

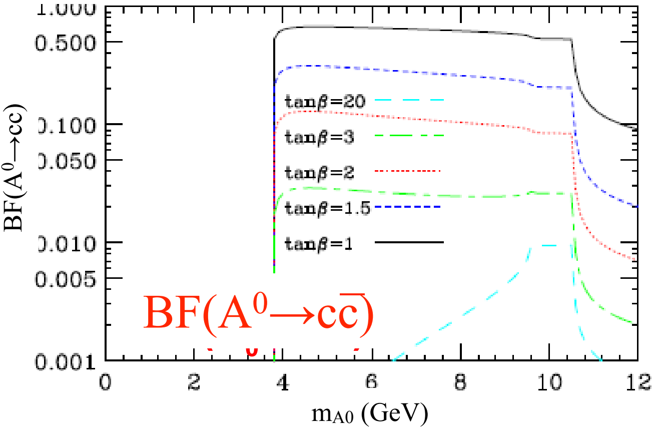
- Pattern of decays depends on A^0 mass and couplings (tanβ)
  - ☞ Dermisek & Gunion, PRD 81, 075003 (2010)
- Comprehensive search in a variety of final states
  - ❑ Leptonic and hadronic





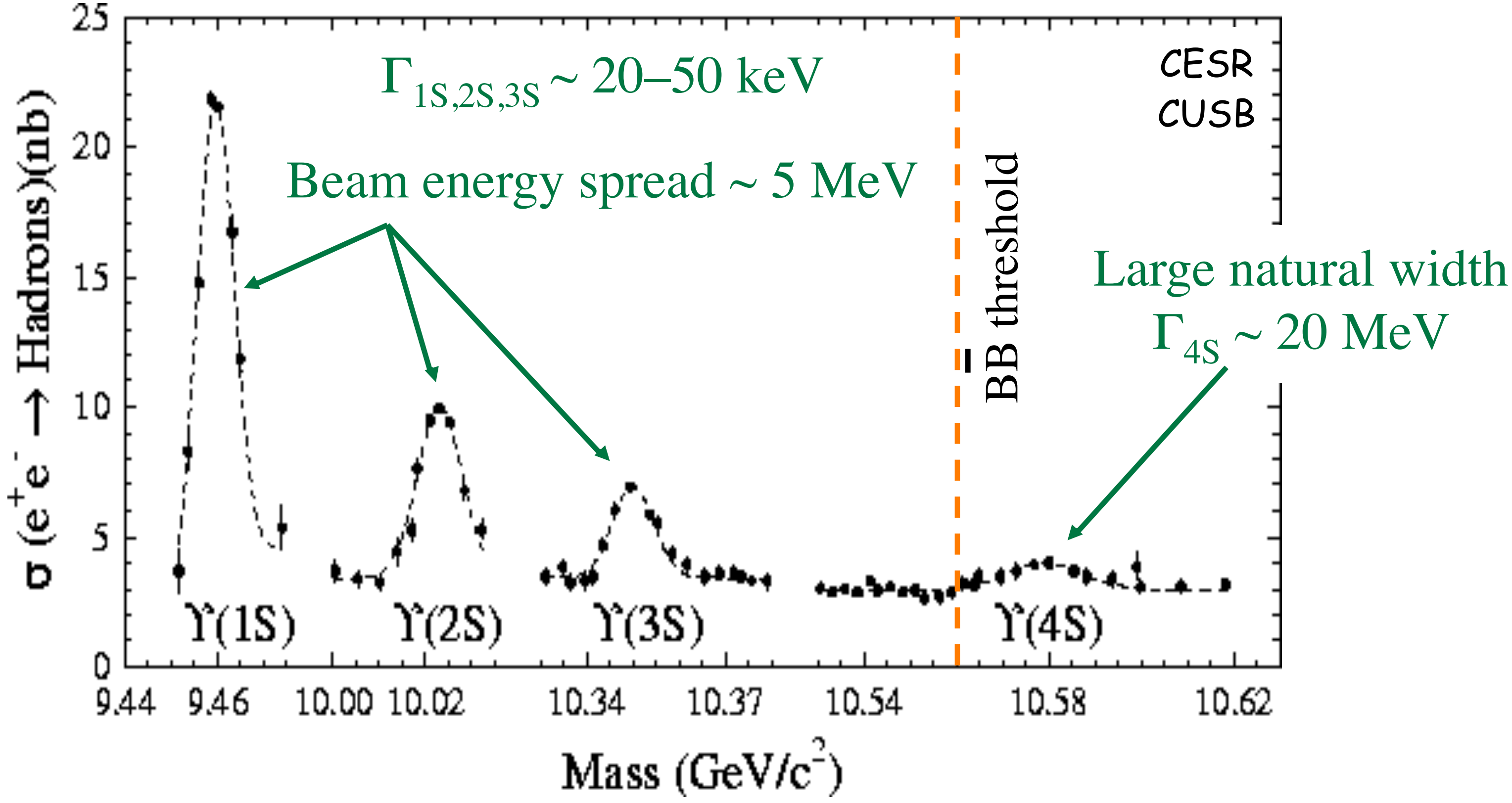






Upsilon Resonances

- Electron-Positron collider: $e^+e^- \rightarrow \gamma^* \rightarrow \Upsilon(nS)$



$\Gamma_{1S,2S,3S} \sim$ 20–50 keV

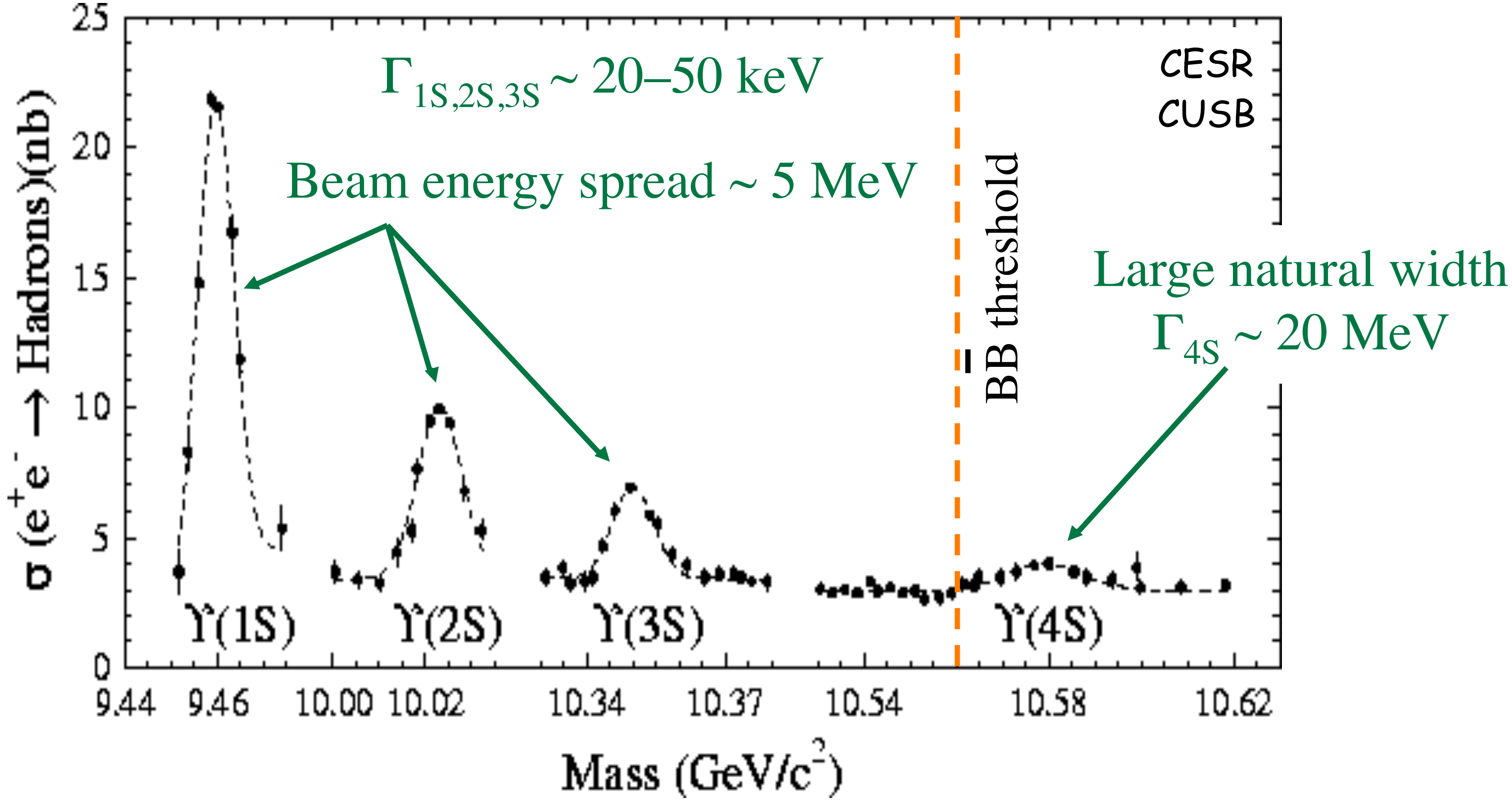
Beam energy spread ~ 5 MeV

Large natural width

$\Gamma_{4S} \sim$ 20 MeV

Upsilon Resonances

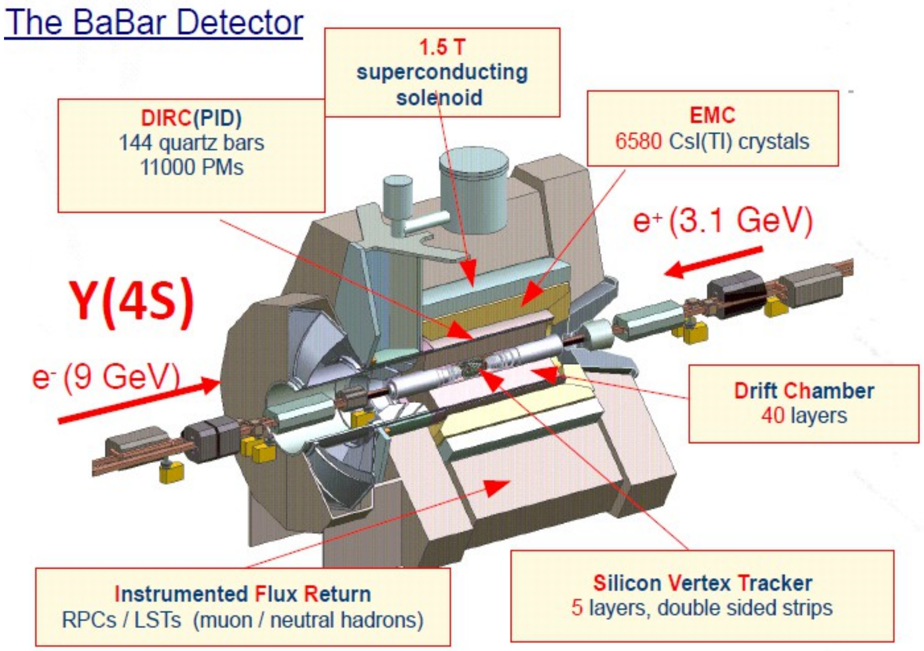
- Electron-Positron collider: $e^+e^- \rightarrow \gamma^* \rightarrow \Upsilon(nS)$

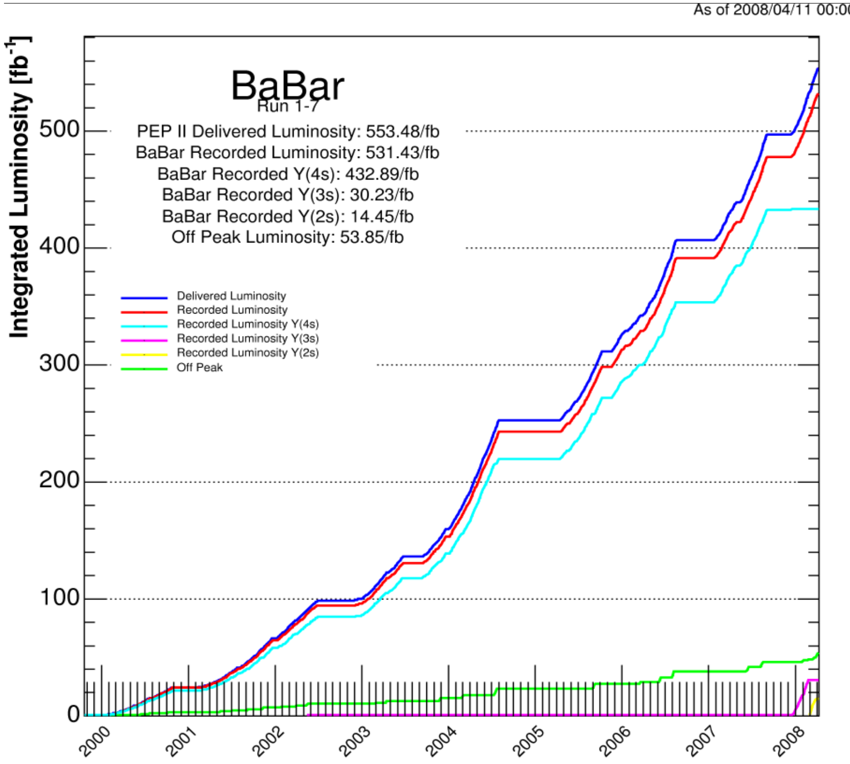


For any bottomonium process $BF_{nS}=\Gamma_{nS}/\Gamma_{tot} >> BF_{4S}$, n=1,2,3

Significantly better sensitivity to direct production of light degrees of freedom @ narrow resonances. Focus of BaBar's Run7 (2008)

BaBar Experiment: 1999-2008





BaBar dataset: 531 fb^{-1} total recorded luminosity

~470M $\Upsilon(4S)$ decays

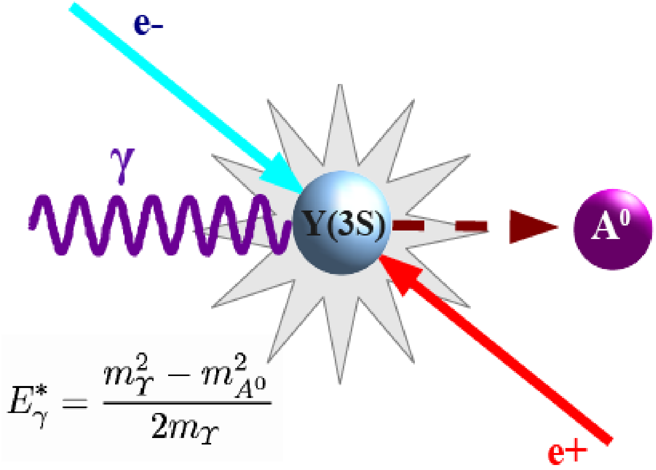
~120M $\Upsilon(3S)$ decays

~100M $\Upsilon(2S)$ decays

Searches for a Light Higgs in BABAR

Radiative Decays of ϒ(nS)

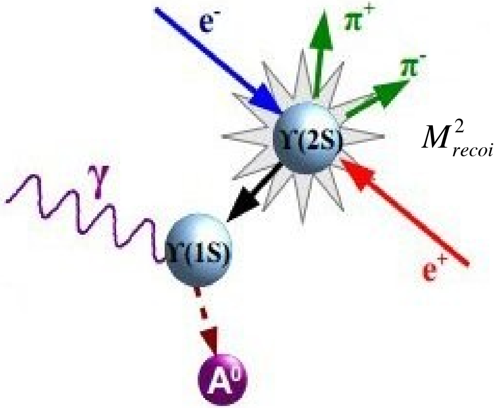
Signature: monochromatic photon



$$E^*_\gamma = \frac{m^2_\Upsilon - m^2_{A^0}}{2m_\Upsilon}$$

Additional constraints: ϒ(1S) from ϒ(2S,3S)→$\pi^+\pi^-$ϒ(1S) transitions

Signature: two low-momentum pions, recoiling against ϒ(1S)



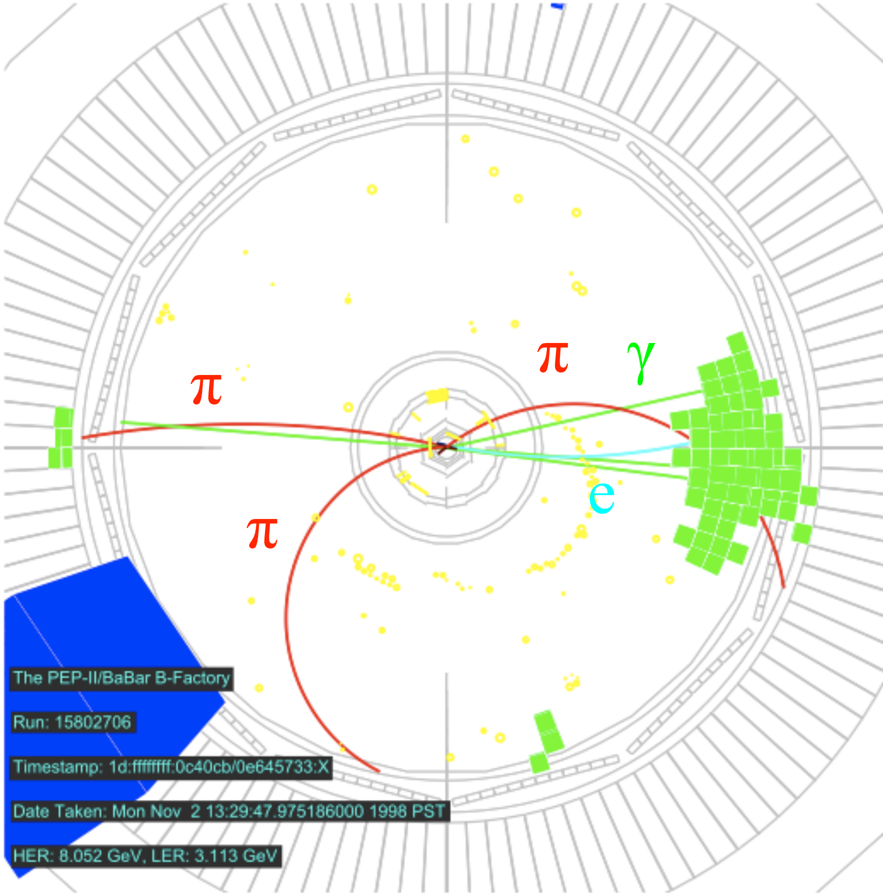
$$M^2_{recoil} = M^2_{\Upsilon(2S)} + M^2_{\pi\pi} - 2M_{\Upsilon(2S)}E_{\pi\pi}$$

- ✔ $A^0\to\mu^+\mu^-$, PRL**103**, 081803 (2009)
- ✔ $A^0\to\tau^+\tau^-$, PRL**103**, 181801 (2009)
- ✔ $A^0\to$hadrons, PRL**107**, 221803 (2011)
- ✔ $A^0\to$invisible, arXiv:0808.0017

- ✔ $A^0\to\mu^+\mu^-$, PRD **87**, 031102 (2013)
- ✔ $A^0\to\tau^+\tau^-$, PRD **88**, 071102 (2013)
- ✔ $A^0\to$hadrons, PRD **82**, 0317019R (2013)
- ✔ $A^0\to$invisible (light dark matter), PRL**107**, 021804 (2011)

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

- Select clean data sample with $\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S)$ transitions
  - ☞100M $\Upsilon(2S)$ decays
- Look for one-prong τ decays; identify $\tau^+\tau^-$ with at least one lepton in the final state
  - ❑ 5 decay channels in total: (ee, $\mu\mu$, $e\mu$, $e\pi$, $\mu\pi$)
- Two neural net discriminants: dipion transitions and $A^0\to\tau\tau$ decays
  - ☞Signal efficiency 1-4.5%
- Look for peaks in photon energy spectrum (mass recoiling against photon)

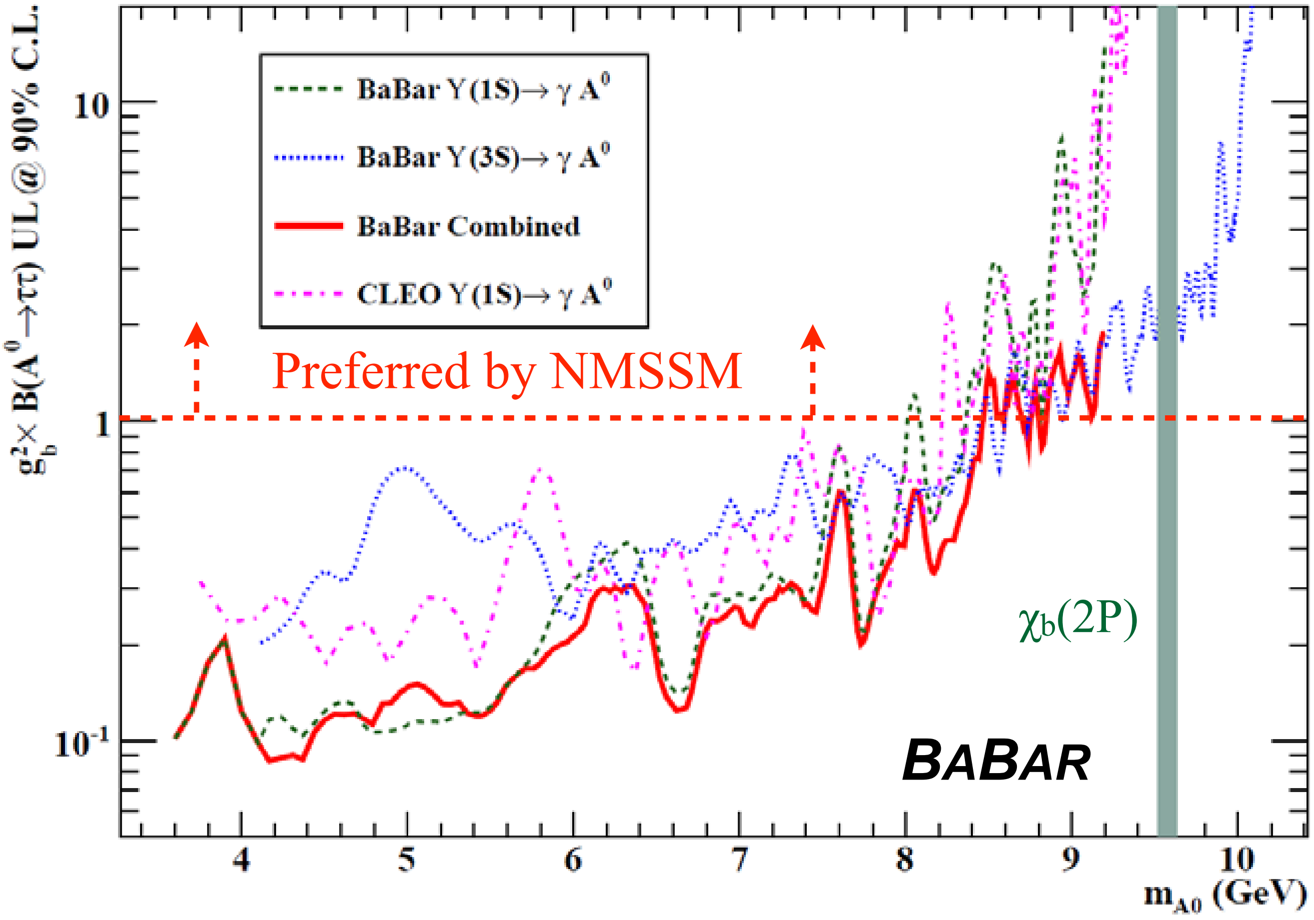


Simulated event $\Upsilon(2S)\to\pi\pi\Upsilon(1S)$, $\Upsilon(1S)\to\gamma A^0$, $A^0\to\tau\tau$, $\tau\tau\to\pi e(+3\nu)$

$\Upsilon(nS)\rightarrow\gamma A^0, A^0\rightarrow\tau^+\tau^-$: Results

Limit A^0 couplings over broad range of mass

PRL103 (2009) 181801
PRD 88 (2013) 071102



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

$$g_b = \tan\beta\cos\theta_A$$

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

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

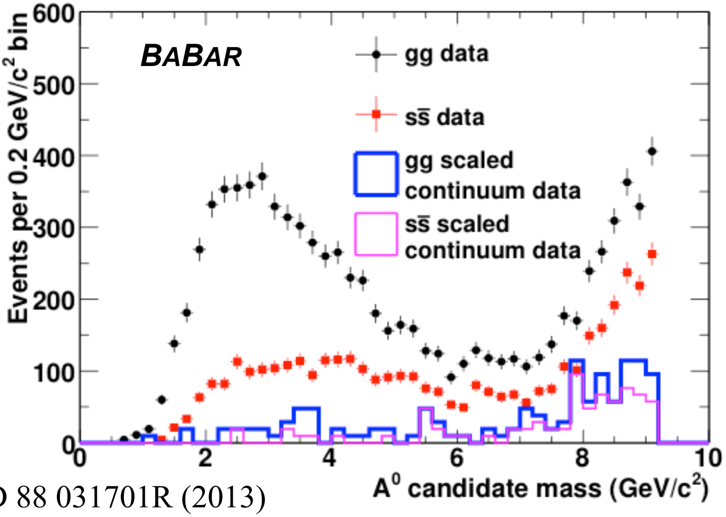
#	Channel	#	Channel
1	$\pi^+\pi^-\pi^0$	14	$K^+K^-\pi^+\pi^-$
2	$\pi^+\pi^-2\pi^0$	15	$K^+K^-\pi^+\pi^-\pi^0$
3	$2\pi^+2\pi^-$	16	$K^\pm K^0_S\pi^\mp\pi^+\pi^-$
4	$2\pi^+2\pi^-\pi^0$	17	$K^+K^-\eta$
5	$\pi^+\pi^-\eta$	18	$K^+K^-2\pi^+2\pi^-$
6	$2\pi^+2\pi^-2\pi^0$	19	$K^\pm K^0_S\pi^\mp\pi^+\pi^-2\pi^0$
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	$K^\pm K^0_S\pi^\mp2\pi^+2\pi^-\pi^0$
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	$p\bar{p}\pi^+\pi^-$

Main background

- Y(1S) → γgg (low masses)
- Y(1S) → ggg (high masses)

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

Large systematic uncertainty from hadronization (~50%)



PRD 88 031701R (2013)

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

PRD 88 (2013) 031701R

Most significant signals

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

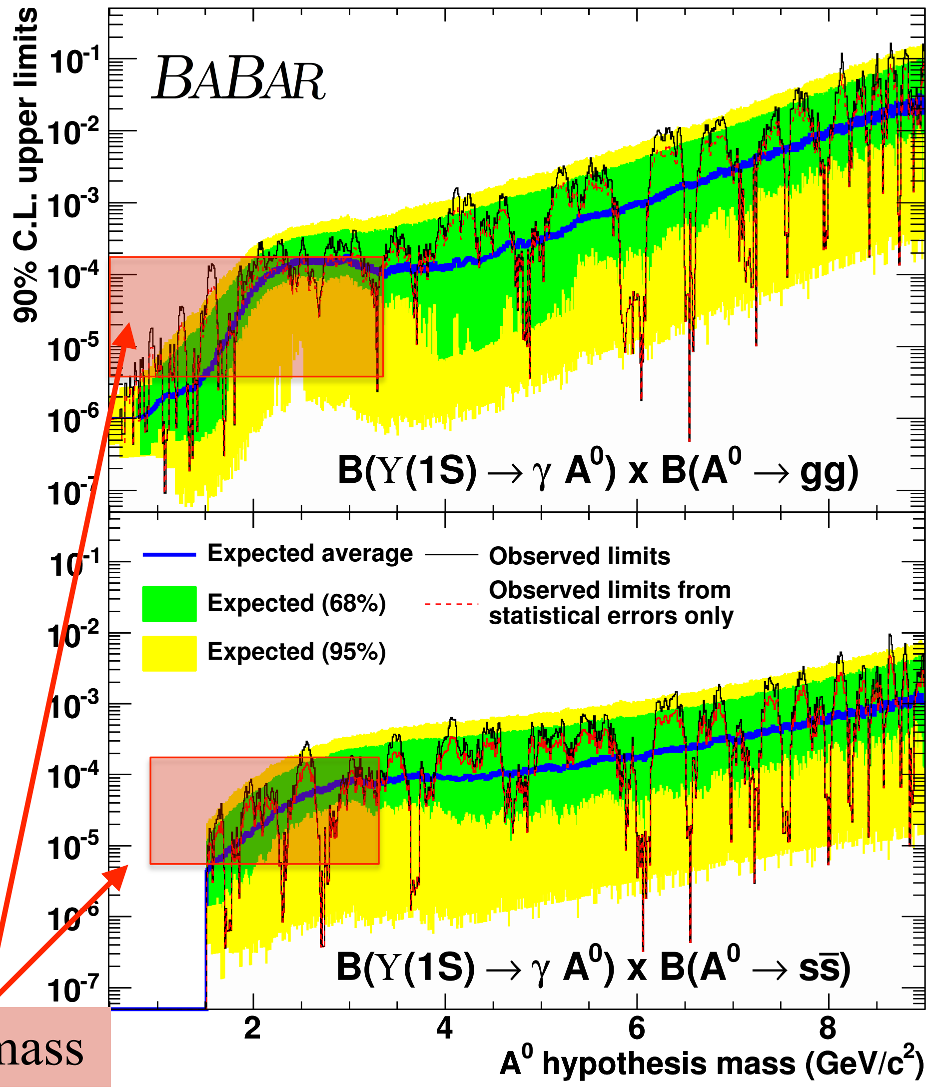
Toy Monte Carlo studies shows that the probability to see a significance as large as the observed one is

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

No significant signal is observed

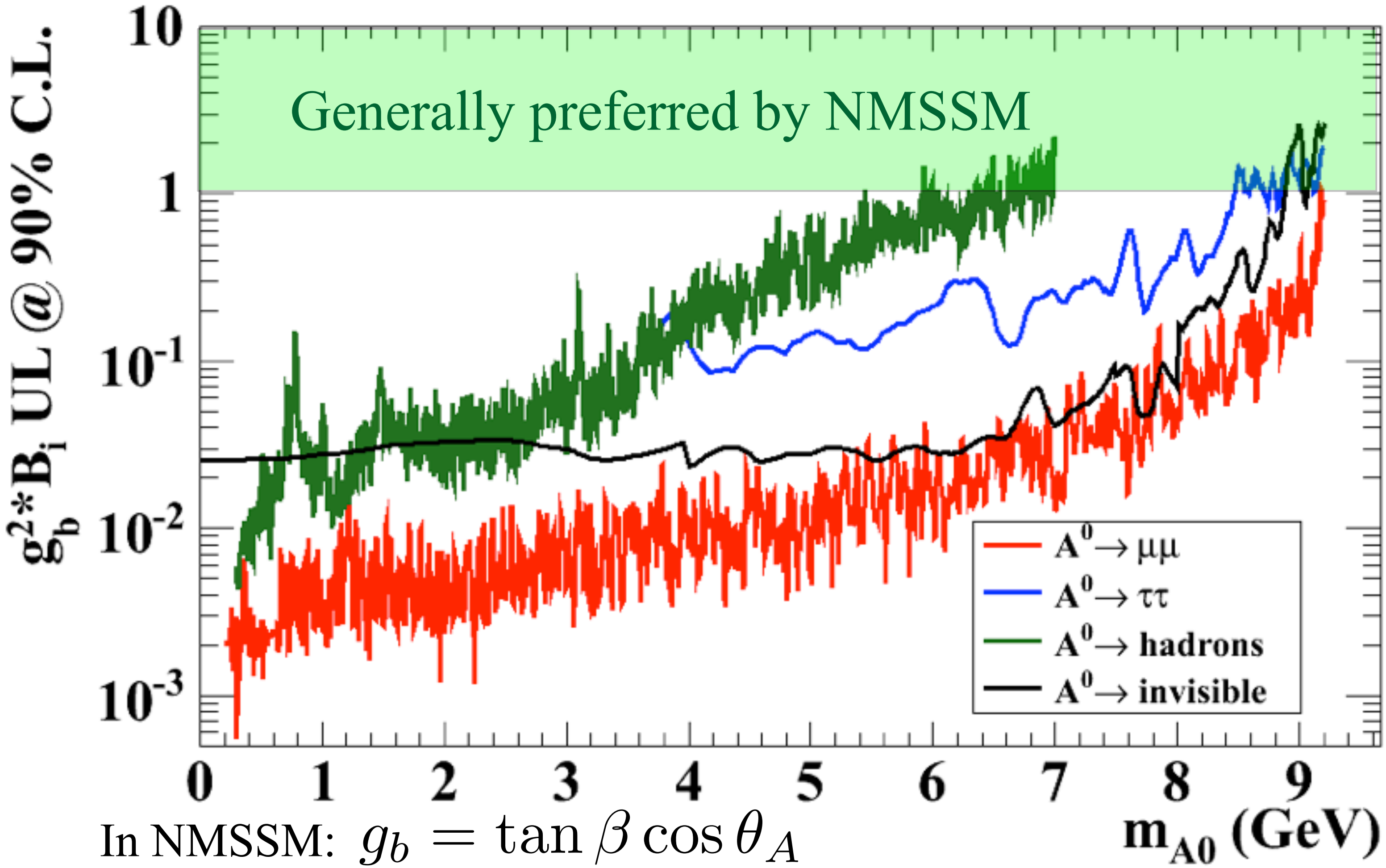
Bayesian upper limits (90% CL) in the range $0.5 \leq m_{A0} \leq 9.0$ GeV

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



NMSSM preferred range excluded at low mass

BaBar Higgs Coupling Limits



In NMSSM: $g_b = \tan\beta\cos\theta_A$

Comprehensive limits on low-mass (NMSSM etc.) Higgs

Also place significant constraints on other models, e.g. axion-like states, dark photons

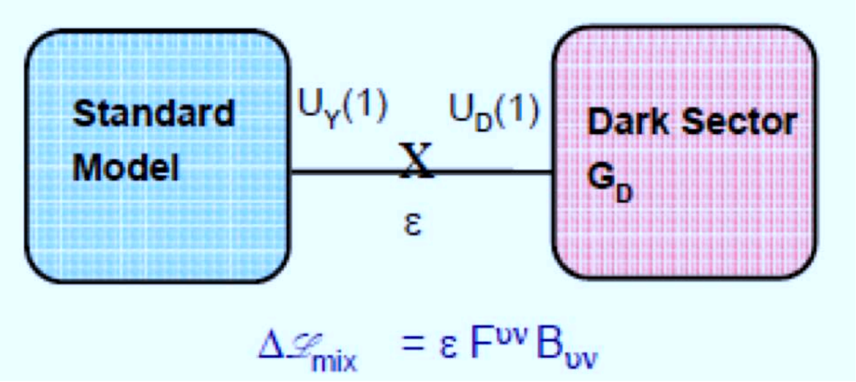
Gauge Bosons in the "Dark Sector"

Dark matter particles in ~TeV range, but new gauge bosons in ~GeV range

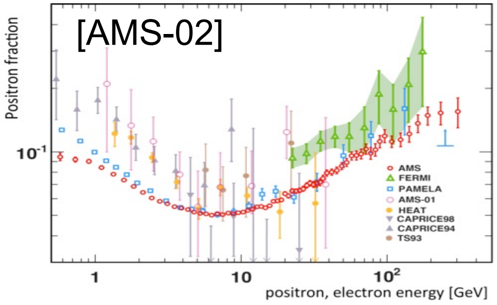
Coupling to leptons due to small mixing between SM and DS

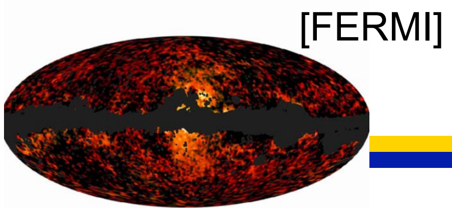
New gauge bosons decay to lepton pairs, anti-proton production forbidden by kinematics or suppressed → explains PAMELA etc features

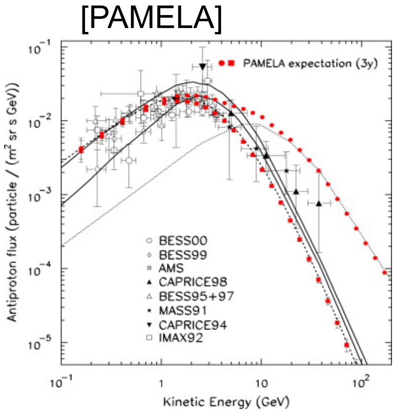
Search for low-mass states in e^+e^- annihilation @ B-Factories

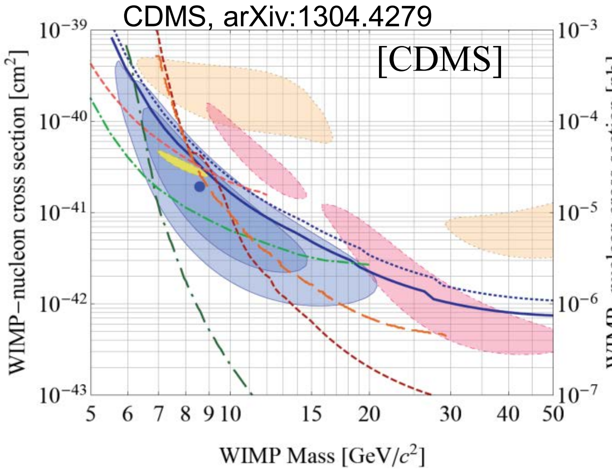


N. Arkani-Hamed et al
PRD 79, 015014 (2009)

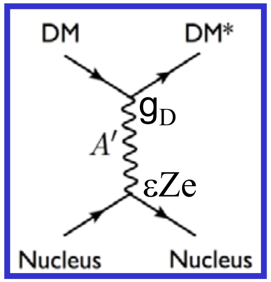








[Slatyer, Schuster&Toro,…]



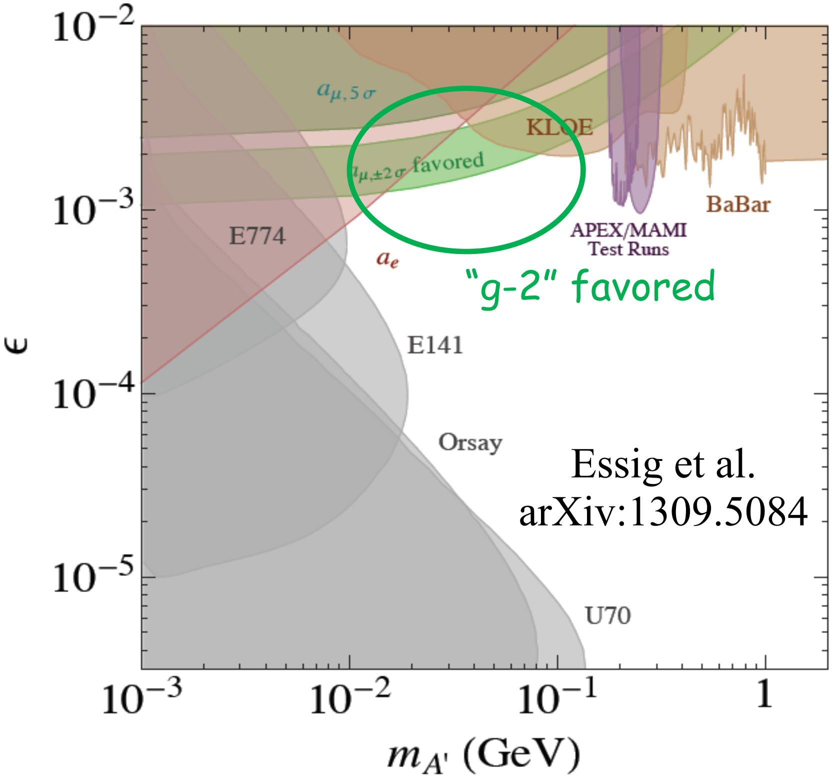
Dark Sector Searches

Coupling to SM particles proportional to $\varepsilon^2\alpha$

Search for direct resonance production in e^+e^- annihilation.

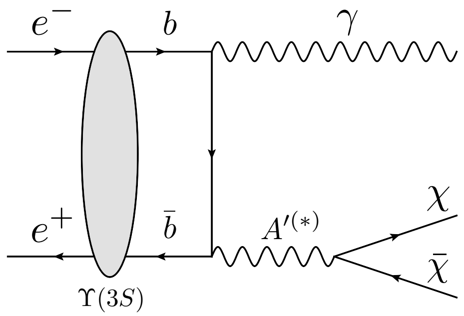
Multi-lepton final states, or radiative processes $e^+e^- \rightarrow \gamma e^+e^-, \gamma\mu^+\mu^-$.

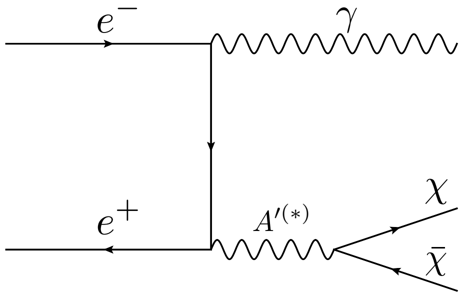
Very large datasets (>500 fb^{-1} in BaBar and ~1000 fb^{-1} in Belle) allows for high-statistics searches



"g-2" favored

Essig et al.
arXiv:1309.5084

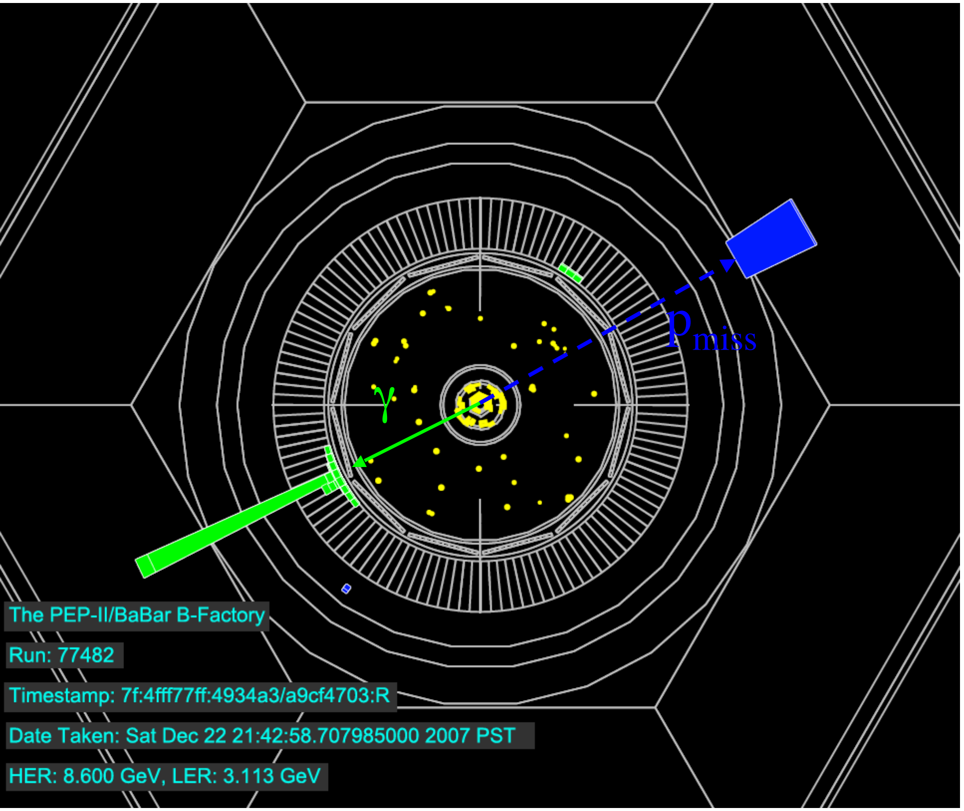




Pospelov;
Bjorken, Essig, Schuster, Toro
Andreas, Niebuhr, Ringwald
Batell, Pospelov, Ritz;
Essig, Harnik, Kaplan, Toro
Blumlein, Brunner;

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

Invisible Dark Photon: $e^+e^-\to\gamma$+invisible

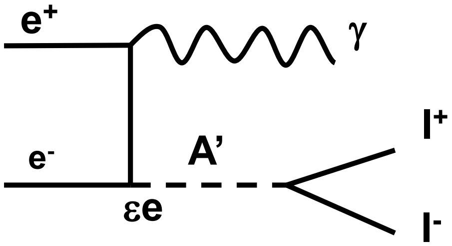


Dominant background from $e^+e^-\to\gamma\gamma$, with one of the photons missing the EM calorimeter. Veto such events by detecting activity in the muon detector (IFR).

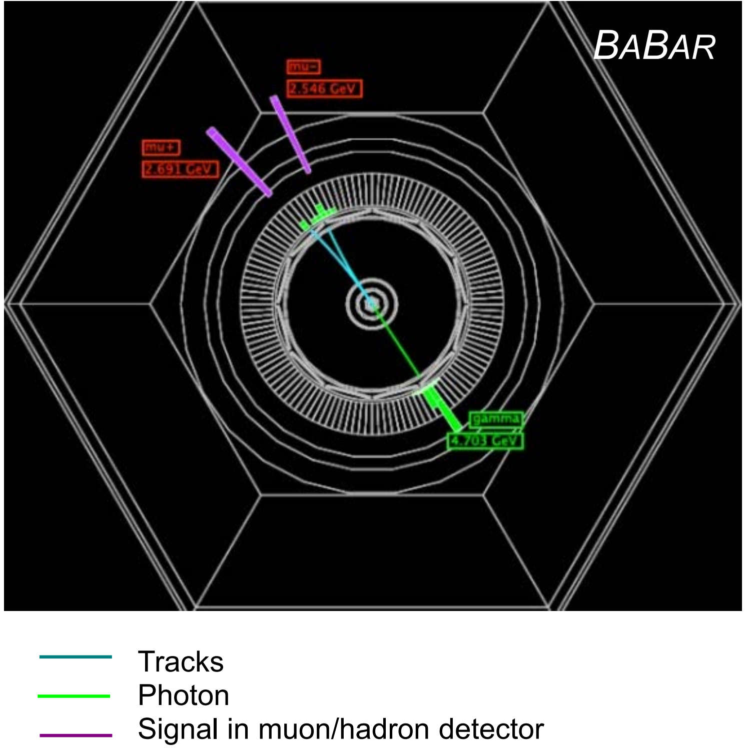
- $\Upsilon(3S)\to\gamma$+invisible (arXiv:0808.0017)
- Require a single photon with $E^*_\gamma>2.2$ GeV
- No charged tracks
- No additional energy in EMC above 100 MeV
- Missing momentum points to EMC
- No activity in IFR aligning with missing momentum
- No signal found: limits on ε of order $O(10^{-3}-10^{-2})$

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

- Dark photon can be produced in $e^+e^-\rightarrow\gamma A', A'\rightarrow e^+e^-, \mu^+\mu^-$
- So far similar search has been done in Υ(3S) and Υ(2S) decays: extend to full dataset NEW ! arXiv:1406.2980
- Measure the cross section for $e^+e^-\rightarrow\gamma A', A' \rightarrow e^+e^-, \mu^+\mu^-$ from 20 MeV to 10.2 GeV
- Look for a narrow peak in invariant mass
- Full BaBar data sample: 514 fb^{-1}

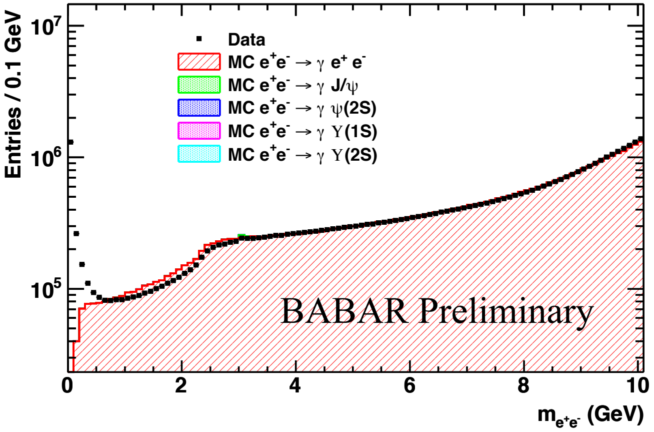


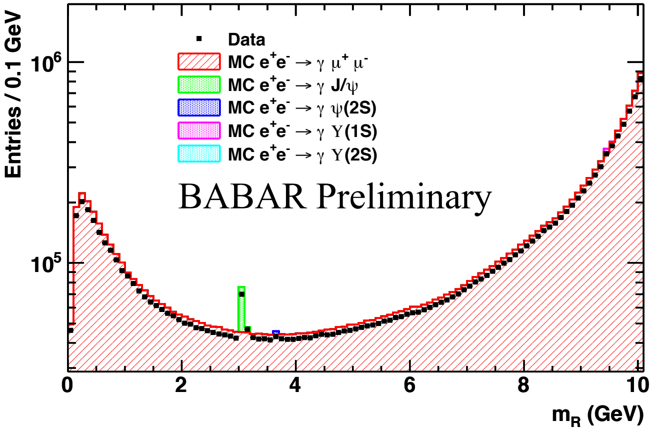
Typical event



Event Selection

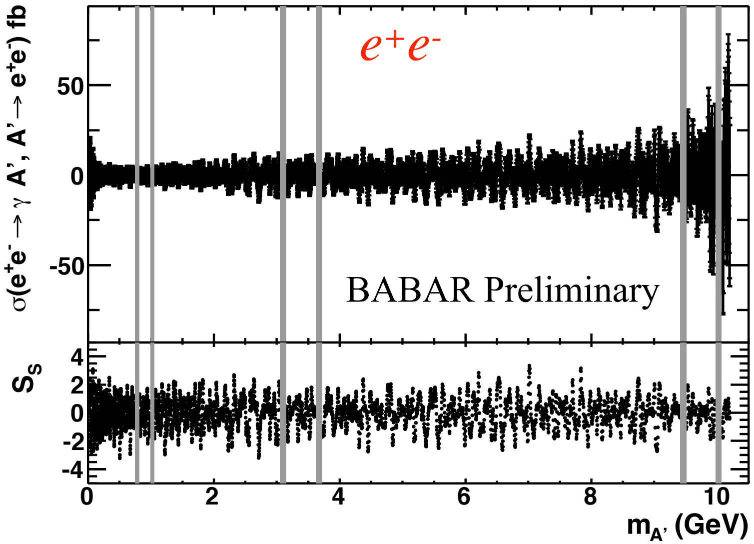
- Clean selection: high energy photon and a pair of oppositely-charged, well-identified e^+e^- or $\mu^+\mu^-$
    - The dielectron channel is tuned to provide the best results for $m_A < 215$ MeV
    - Reject photon conversion events in $A' \rightarrow e^+e^-$ using a multivariate discriminant
    - $A' \rightarrow \mu^+\mu^-$ most sensitive above $m_{A'} > 2m_\mu$
        - ☞ High-efficiency selection; background dominated by QED processes
- No significant excess found: set limit on cross section and dark photon coupling ε

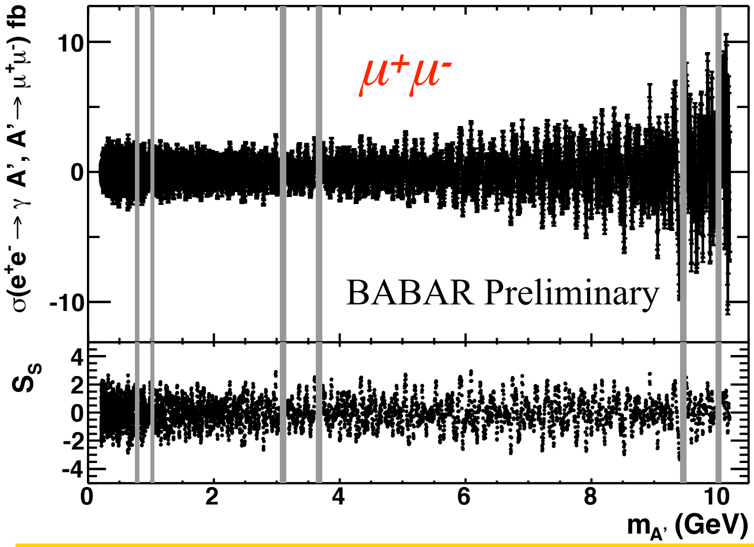


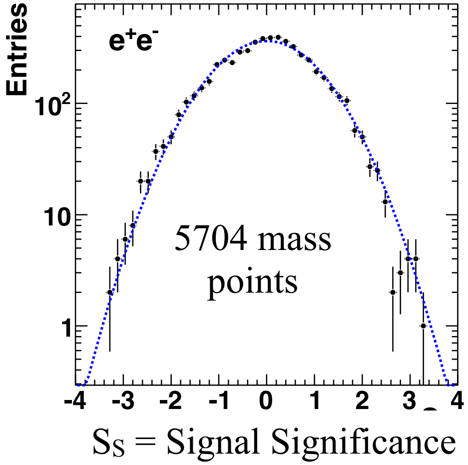


arXiv:1406.2980

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

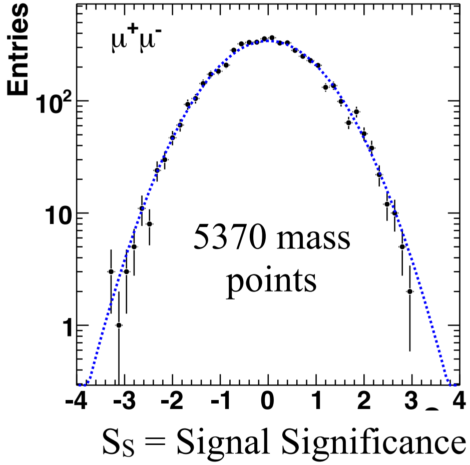






5704 mass points

S_S = Signal Significance



5370 mass points

S_S = Signal Significance

Largest local significances:

3.4σ for electrons @ 7.02 GeV

→ 0.6σ with trial factors

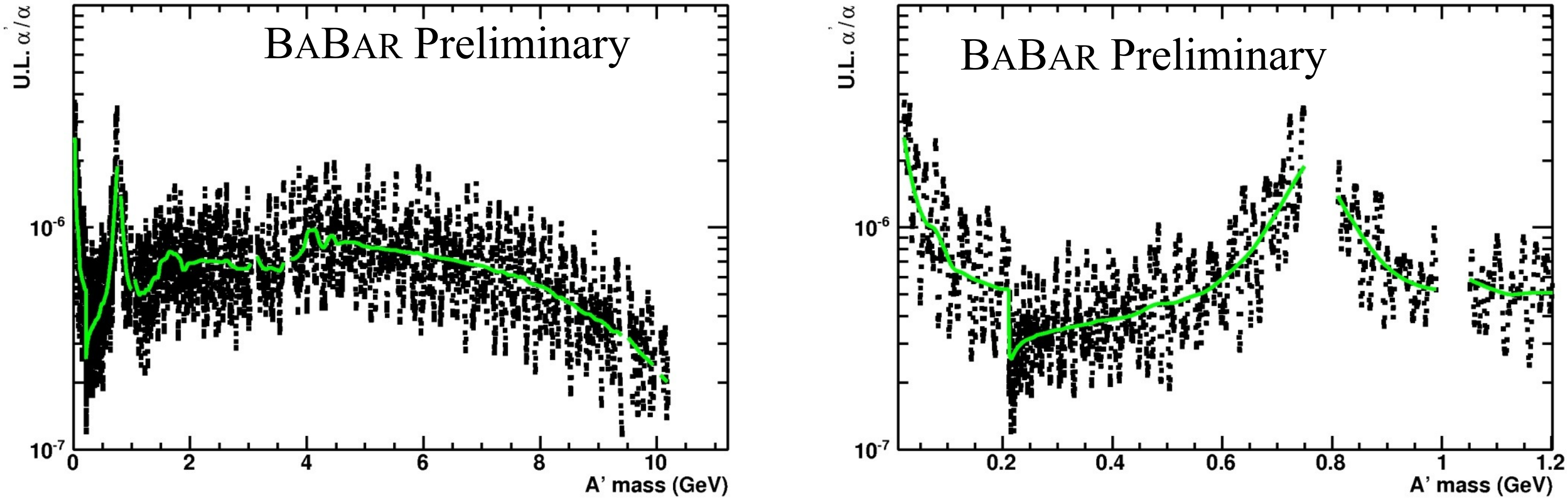
2.9σ for muons @ 6.09 GeV

→ 0.1σ with trial factors

arXiv:1406.2980

Results: Dark Sector Mixing

90% CL upper limits on $\varepsilon^2 = \alpha'/\alpha$

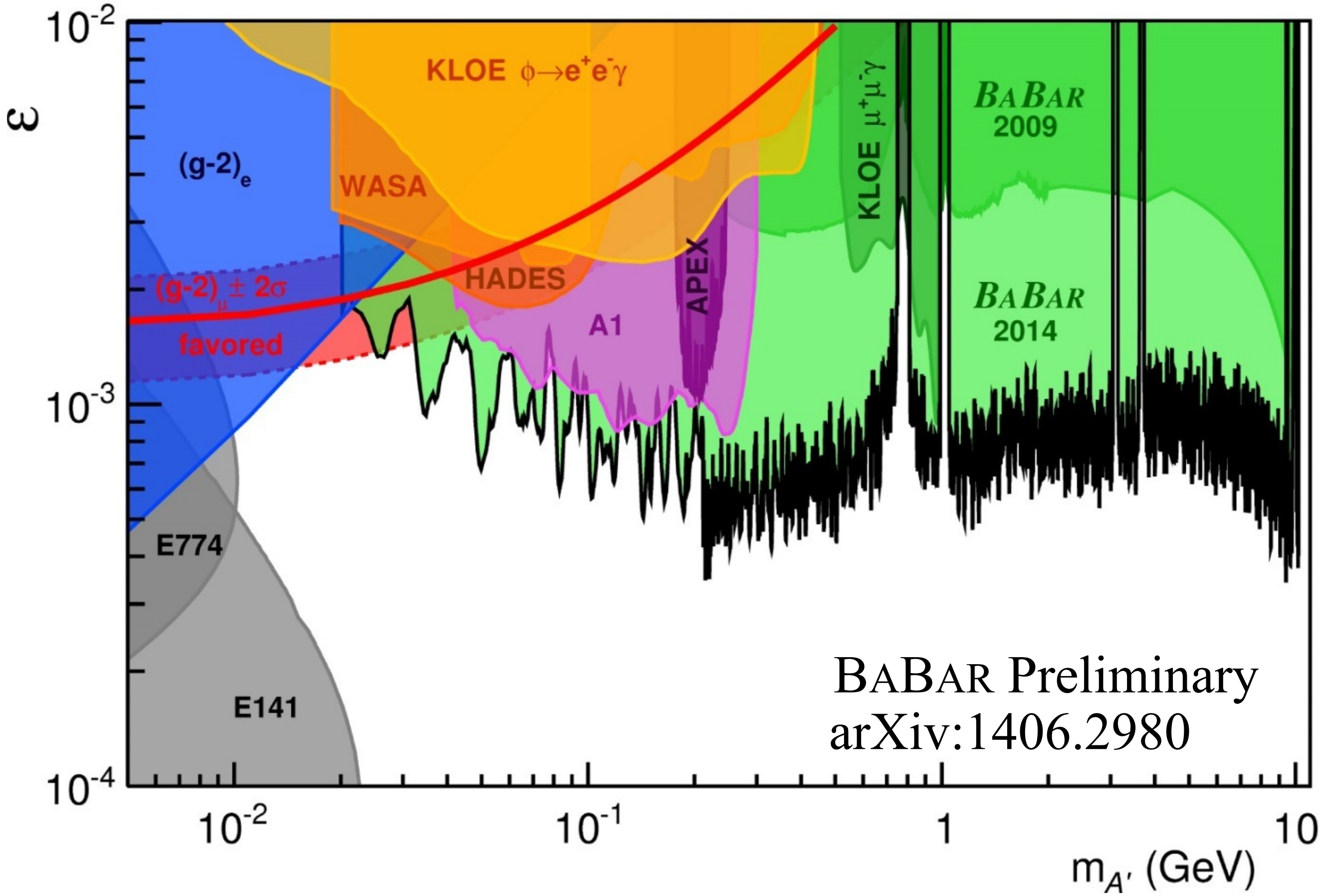


— Moving average to guide the eye

Limits at the level of O(10^{-7} – 10^{-6})

arXiv:1406.2980

Results: Dark Sector Mixing

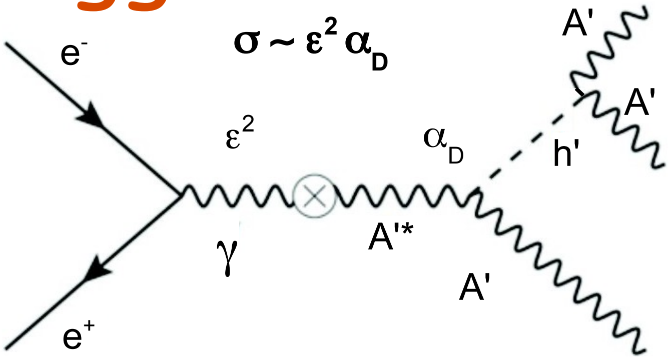


BABAR Preliminary
arXiv:1406.2980

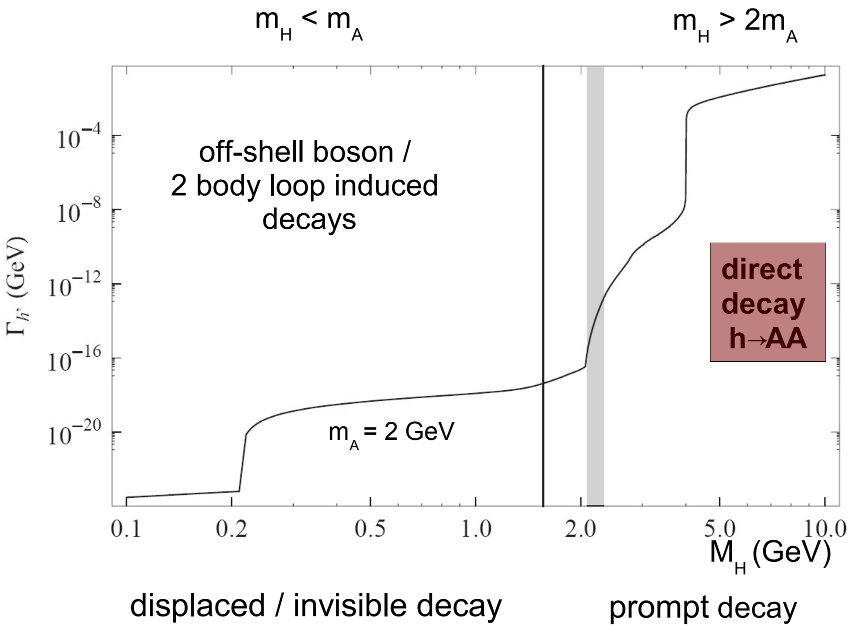
Further exclude the region favored by the muon g-2 anomaly and improve the existing constraints over a wide range of masses.

Search for Dark Higgs

- Extension of the dark sector models: dark Higgs
  - Mass generation in dark sector
  - Mass can be low
  - Detect by Higgs-strahlung process $e^+e^- \longrightarrow$ A'h'
  - Decays to A' pairs
    - ☞ Multi-particle (multi-lepton) final state
    - ☞ Clean detection, virtually no QED background



Higgs decay topology



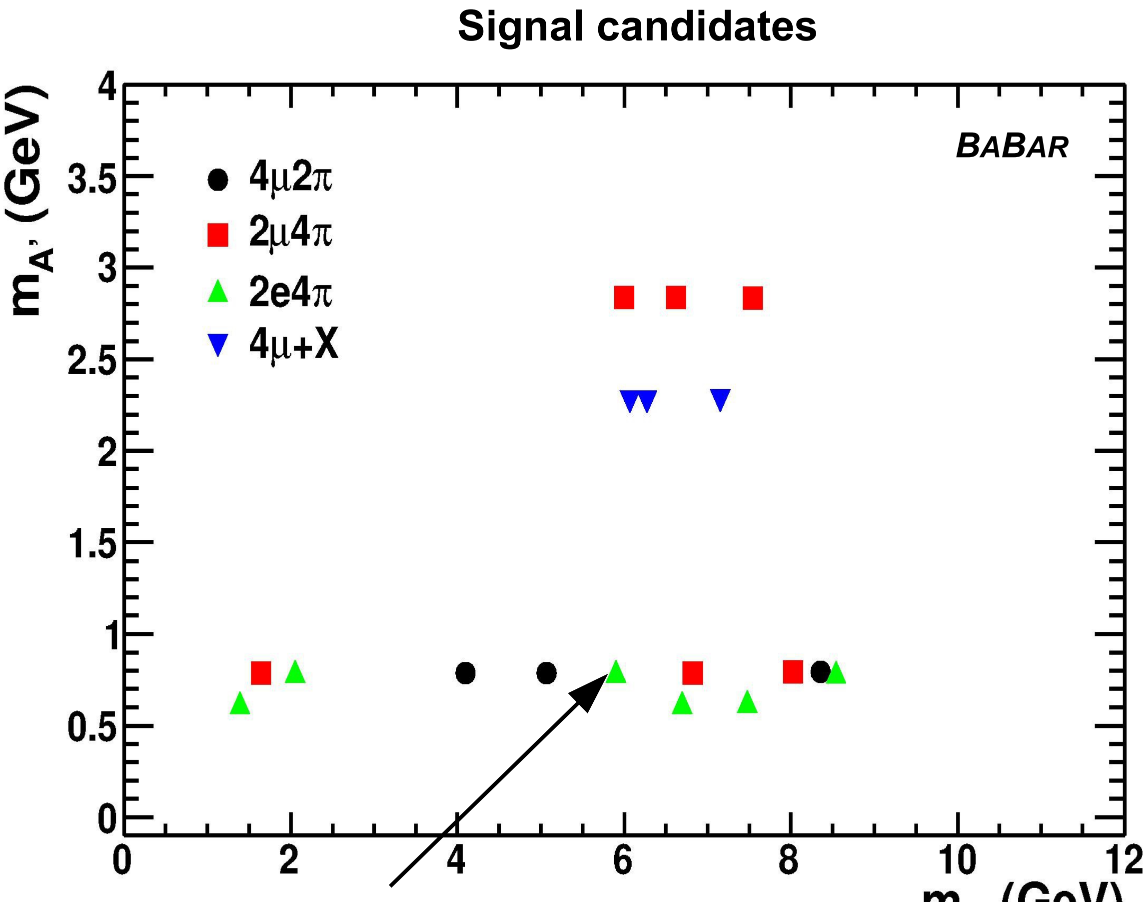
Dark Higgs Search

Focus on direct decay topology: $e^+e^- \rightarrow A'h'$; $h' \rightarrow A'A'$
Look for A' decays to a pair of oppositely-charged tracks, or to invisible final state ($A' \rightarrow e^+e^-$, $\mu^+\mu^-$, $\pi^+\pi^-$, X)

Require same mass for each pair

6 events selected (18 combinations)

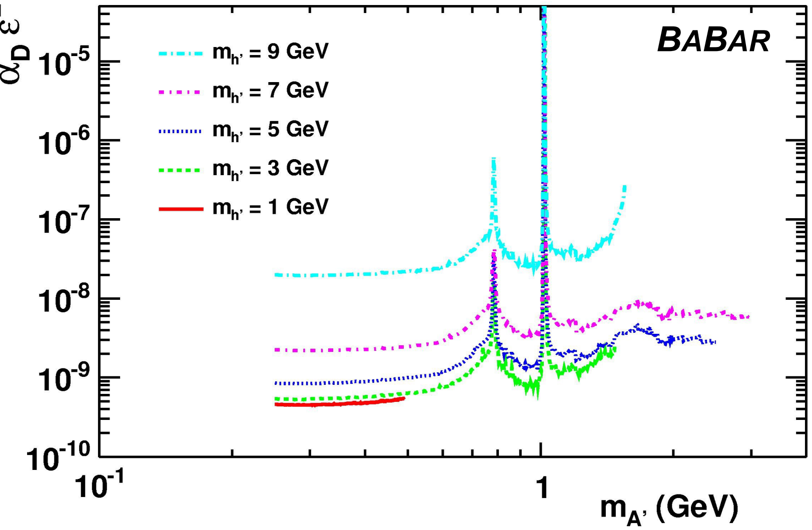
Consistent with background estimates



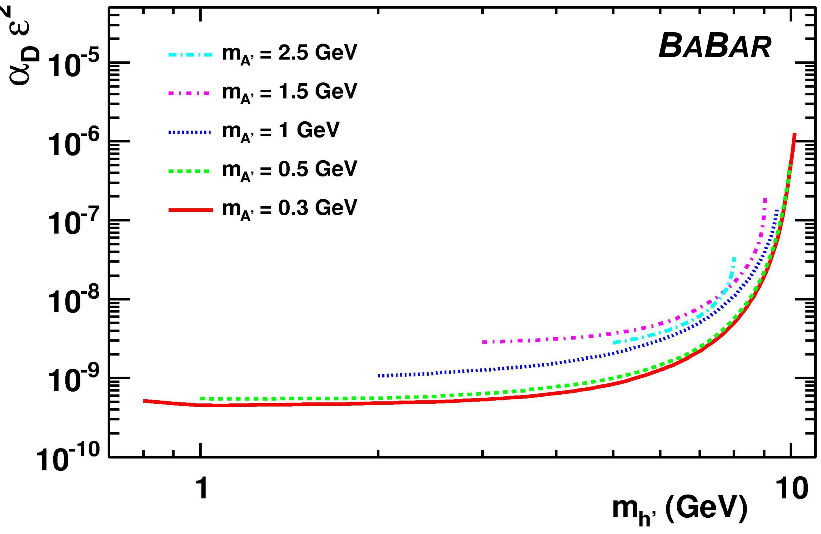
Likely $e^+e^- \rightarrow e^+e^- \rho\rho,\omega\omega$ or $e^+e^- \rightarrow 6\pi^\pm$

Dark Higgs Limits

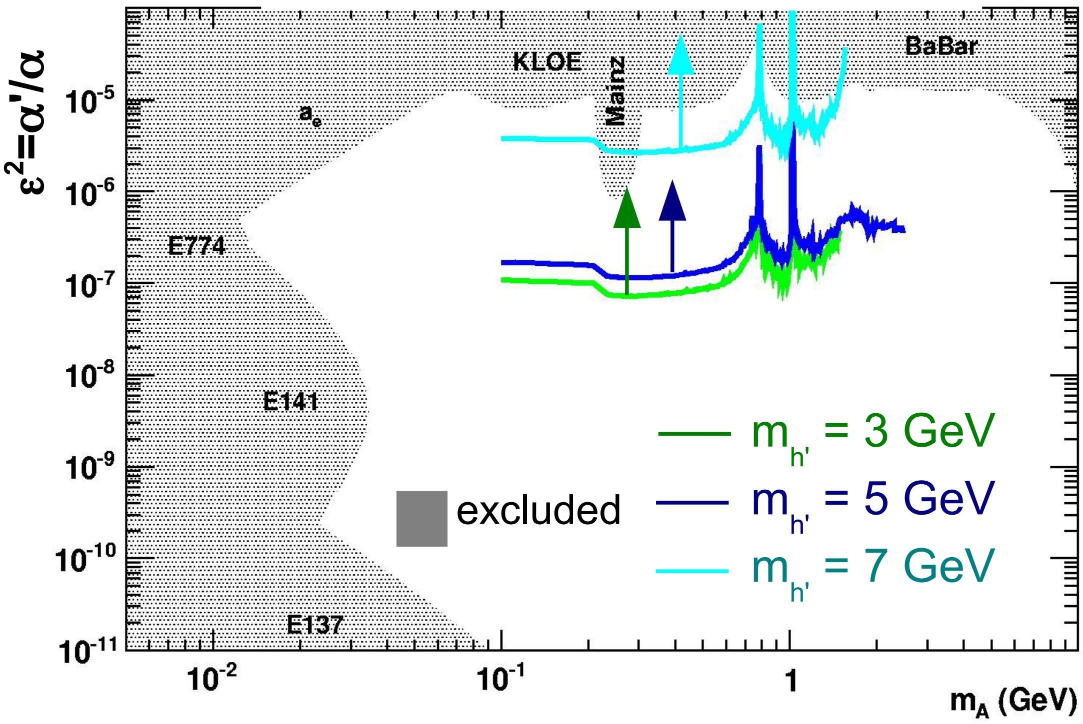
90% CL upper limit on $\alpha_D \varepsilon^2$



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



Limit on $\varepsilon^2=\alpha'/\alpha$ assuming $\alpha_D=\alpha_{em}=1/137$



PRL **108**, 211801 (2012)

Substantial improvement over previous limits. Constrain model space

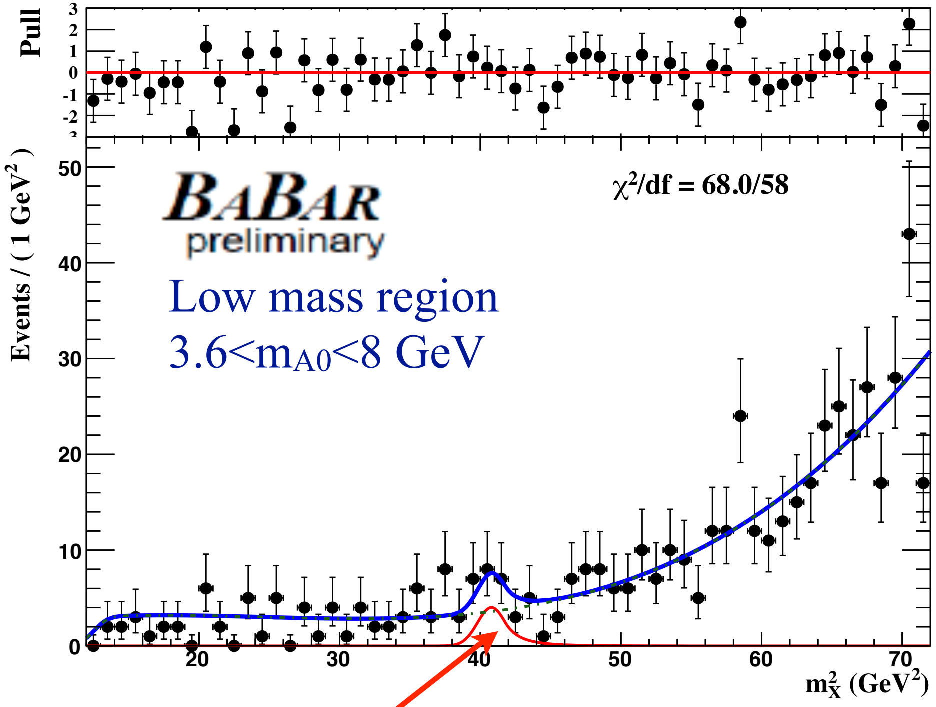
Summary and Outlook

- B Factories provide significant constraints on new physics models with low-mass degrees of freedom
  - ❑ Direct searches: unique sensitivity to low-mass new physics in high-statistics datasets
- Belle-II will increase statistics by ~100
  - ❑ Combined with LHC and direct detection dark matter searches, these measurements will provide unique information on the dynamics and flavor structure of new physics

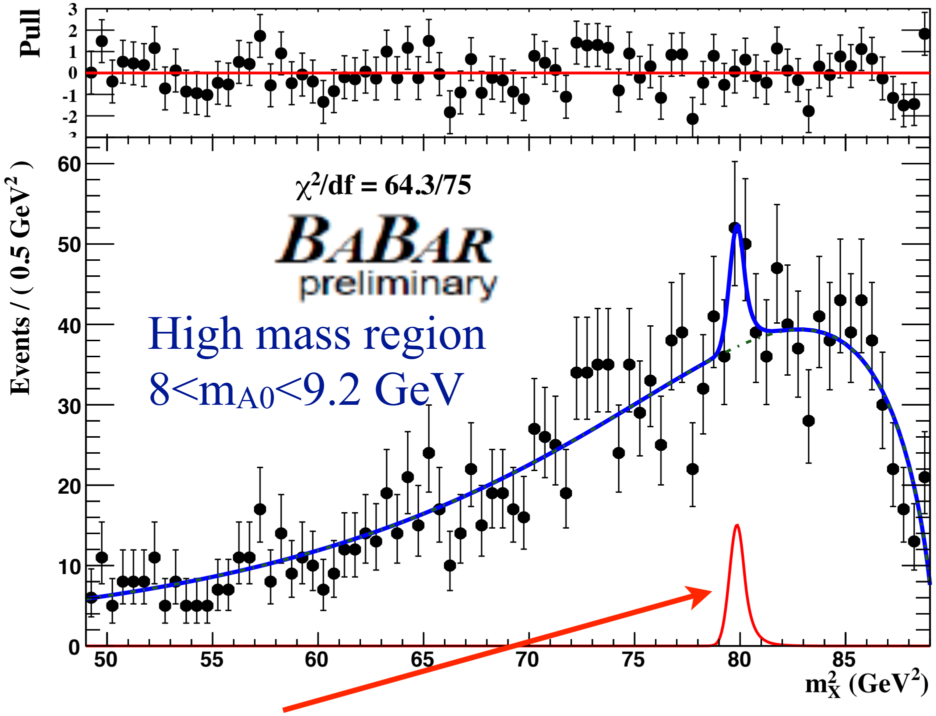
Backup

$\Upsilon(1S)\rightarrow\gamma A^0, A^0\rightarrow\tau^+\tau^-$: ML Fits

ML fits to data distributions: signal peak + smooth background
Look for significant excess of signal events over background as a function of assumed A^0 mass



m_{A0}=6.36 GeV, Local significance=2.7σ

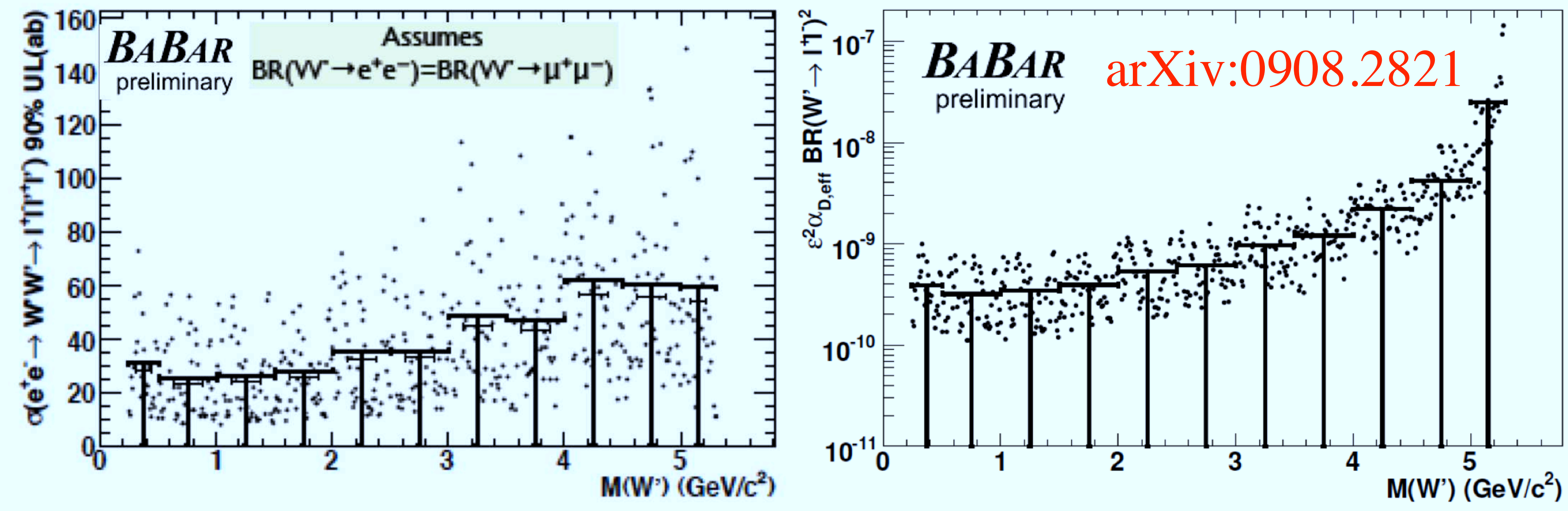


m_{A0}=8.93 GeV, Local significance=3.0σ
Global significance = 1.4σ

Direct Search for Dark Sector

Look for $e^+e^- \to l^+l^-l^+l^-$ final states (4e, 2e2μ,4μ) as a function of two-lepton mass

Full BaBar dataset (~540 fb^{-1})

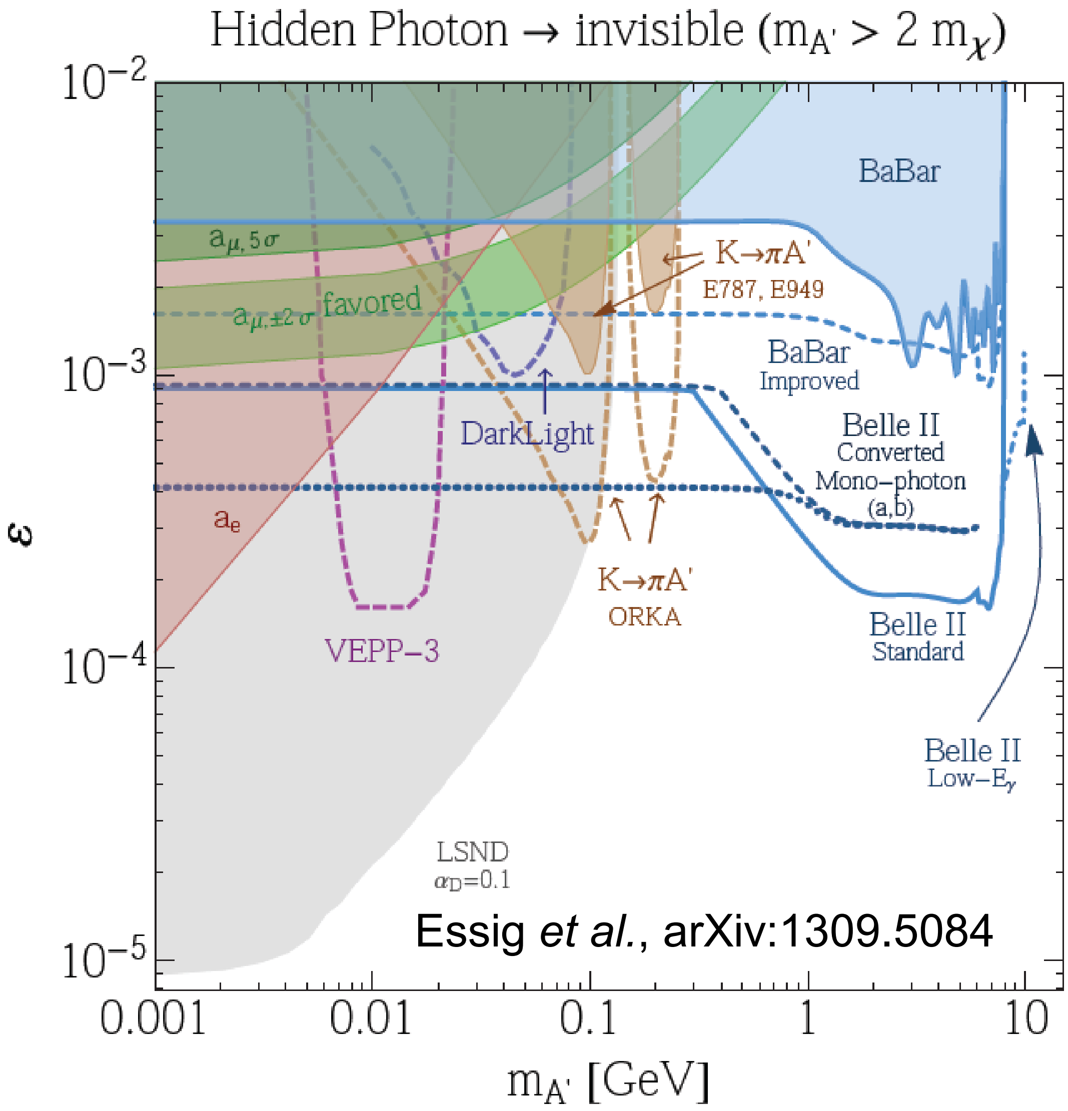


arXiv:0908.2821

$$\sigma(e^+e^- \to W'W' \to l^+l^-l'^+l'^-) < (25 - 60)\,\mathrm{ab}$$

Some of the smallest cross section ULs measured @ B-Factories

Invisible Dark Photon: $e^+e^- \to \gamma$+invisible



Essig *et al.*, arXiv:1309.5084