Low-mass Dark Sector at BaBar and Preliminary Studies at BESIII

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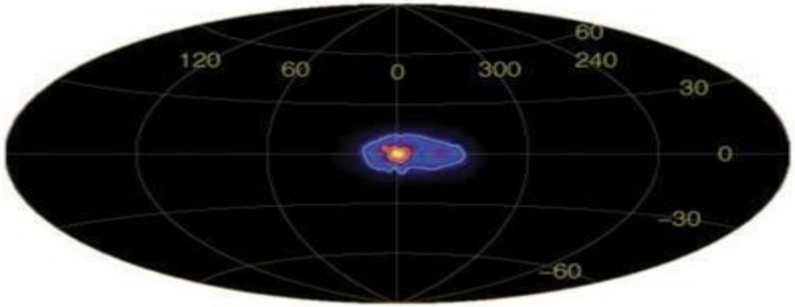
Outline

- ✓ Motivation
- ✓ Dark boson searches at BaBar
- ✓ Probing dark forces at BESIII
- ✓ Summary and future prospects

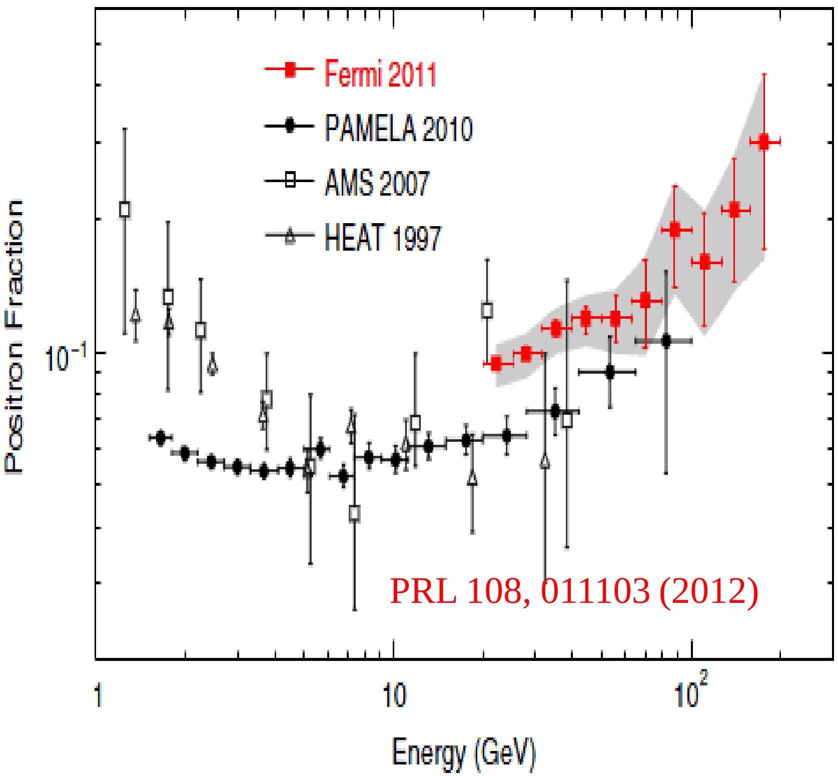
Motivation

- Many extensions of Standard Model (SM) predict light week-interacting degrees of freedom.
  - Motivated by astrophysical observations and theoretical prejudice.
  - 511 keV gamma ray excess from galactic center (INTEGRAL).



ESA/Integral/MPE (G. Weidenspointner et al.)

  - Positron excess in cosmic ray from PAMELA.
  - Hints of low-mass direct dark-matter (DM) detection (DAMA, CoGent, CRESST)



❖ Typical models: low-mass gauge bosons and/or scalars (Higgs).

Motivation

Examples:

- Models with low-mass dark Higgs and gauge bosons.
  - E.g. "Dark-sector".
- Next-to-Minimal Supersymmetric Standard Model (NMSSM) with a light CP-odd Higgs boson.
  - Solves fine tuning of Minimal Supersymmtric Standard Model (MSSM).
  - CP-odd Higgs, A^0, below 2mb is not constrained by LEP.
  - Large BR fraction for $\Upsilon \to \gamma A^0$ possible.
  - Also contains a total of five neutral fermionic states ($\chi^0_{1,2,3,4,5}$), which are light supersymmetric particles (LSP), and viable candidates of dark matter.
- Accessible at e^+e^-/pp collider experiments.

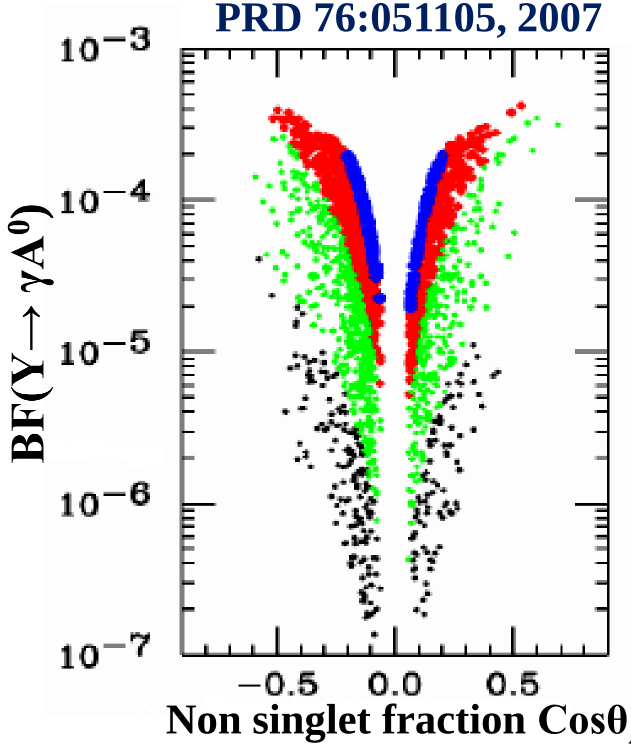
$m_{A^0} < 2m_\tau$

$2m_\tau < m_{A^0} < 7.5$ GeV/c^2

7.5 GeV < m_{A^0} < 8.8 GeV/c^2

8.8 GeV/c^2 < m_{A^0} < 9.2 GeV/c^2

R. Dermisek et. al, PRD 76:051105, 2007



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

Non-singlet

Singlet

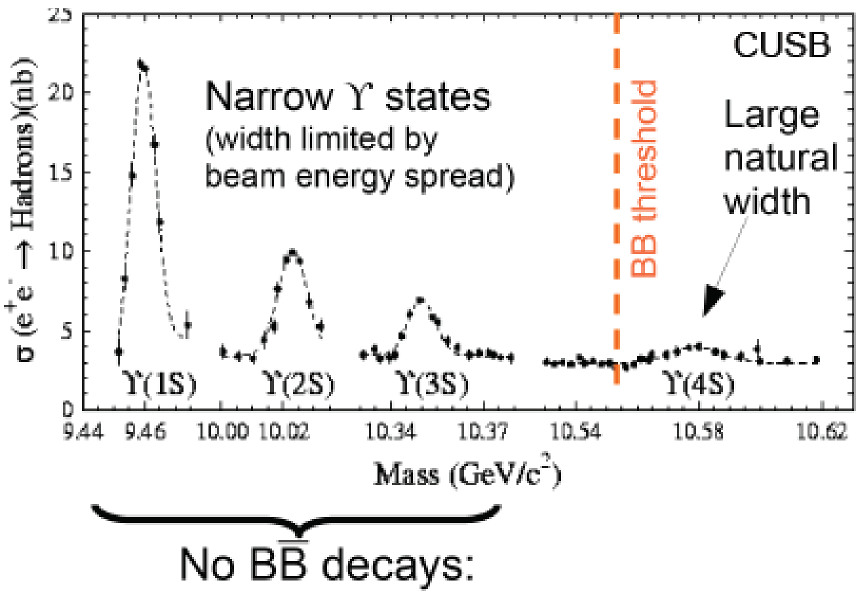
BaBar Experiment

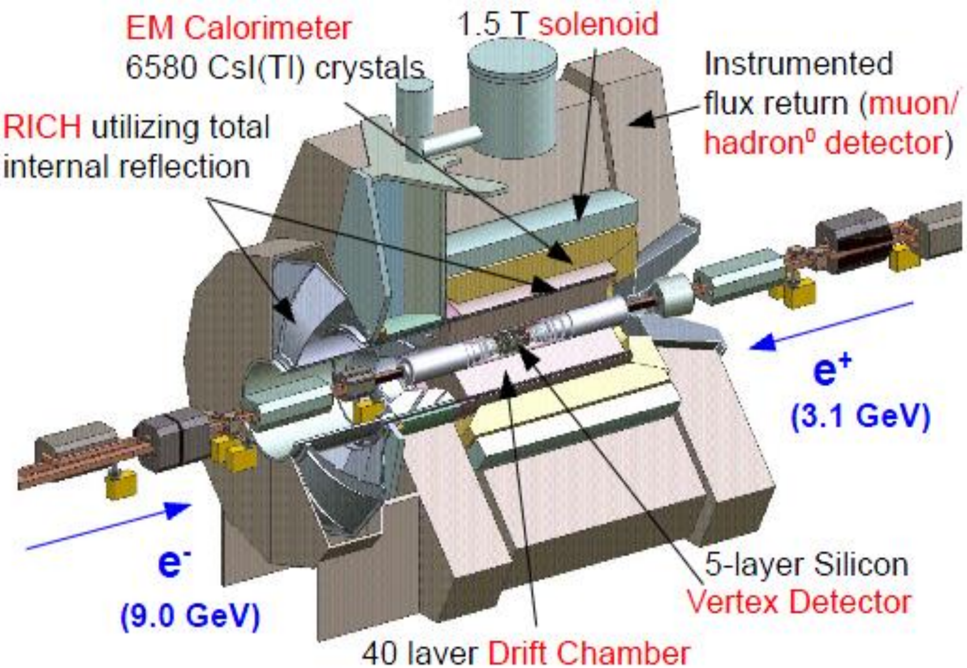
~121 million Υ(3S) (10×Belle, 25×CLEO)

~ 98 million Υ(2S) (10×CLEO)

Used for light Higgs searches

~ 521 fb^{-1} (Υ(2S), Υ(3S) and Υ(4S), both on and off peak) was used in Dark Higgs analysis.





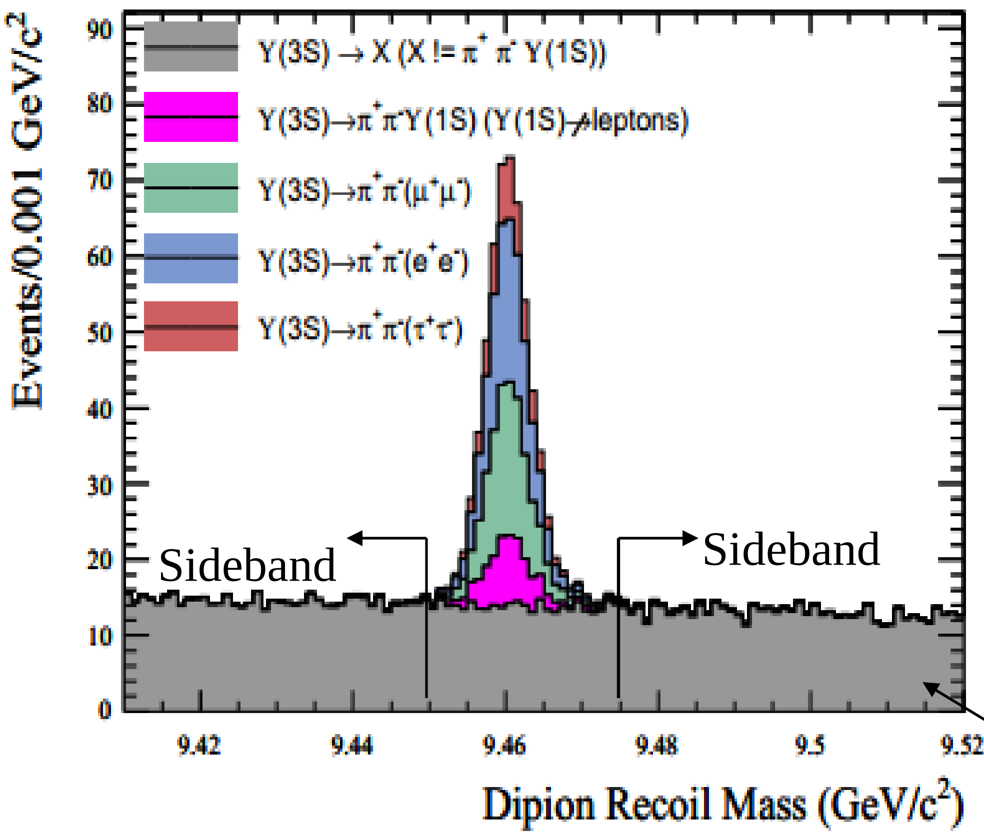
Clean environment for new physics searches.

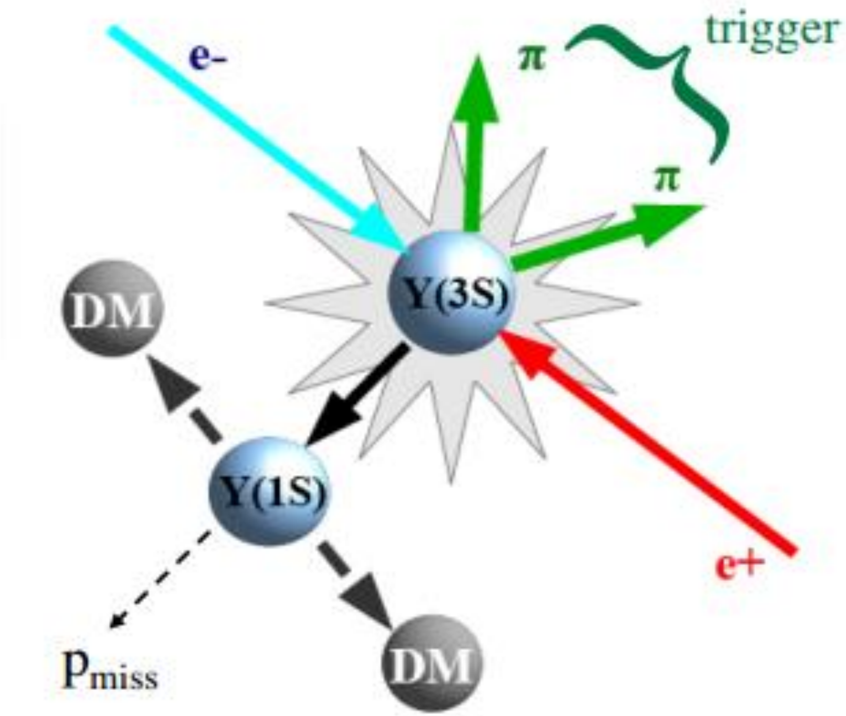
Searches for Dark Matter Production

- **Generic Model**: Dark-matter invisible particle χ with $m_\chi < m_\Upsilon/2$.
  - Plus a new scalar (A^0) or vector (A') particle mediate s-channel annihilation.
    - On-shell: $m_\chi < m_{A^0}/2 < m_\Upsilon/2$: resonant decays of Υ.
    - Off-shell: $m_\chi < m_\Upsilon/2 < m_{A^0}/2$: non-resonant decays.
  - Signatures and predicted rates:
    - Invisible decays of Υ with BF >> BF($\Upsilon\to\nu\nu$).
      - ✓ BF($\Upsilon\to\chi\chi$) ~ $(4.0 - 20.0)\times10^{-4}$ [PRD 72, 103508 (2005)]
    - Radiative decays $\Upsilon\to\gamma$+invisible
      - ✓ BF($\Upsilon\to\gamma\chi\chi$) ~ 10^{-5}-10^{-4} [PRD 80, 115019 (2009)]

Υ(1S)→invisible: Analysis Strategy

Clean sample of Υ(1S) is selected by tagging the pion pair from $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(1S)$ transition.





$$m^2_{recoil} = s + m^2_{\pi^+\pi^-} - 2E_{\pi^+\pi^-}\sqrt{s}$$

Additional non-peaking backgrounds from $e^+e^-\to\gamma\gamma^*\to e^+e^-\pi^+\pi^-$ not included.

Υ(1S)→invisible: Signal Extraction

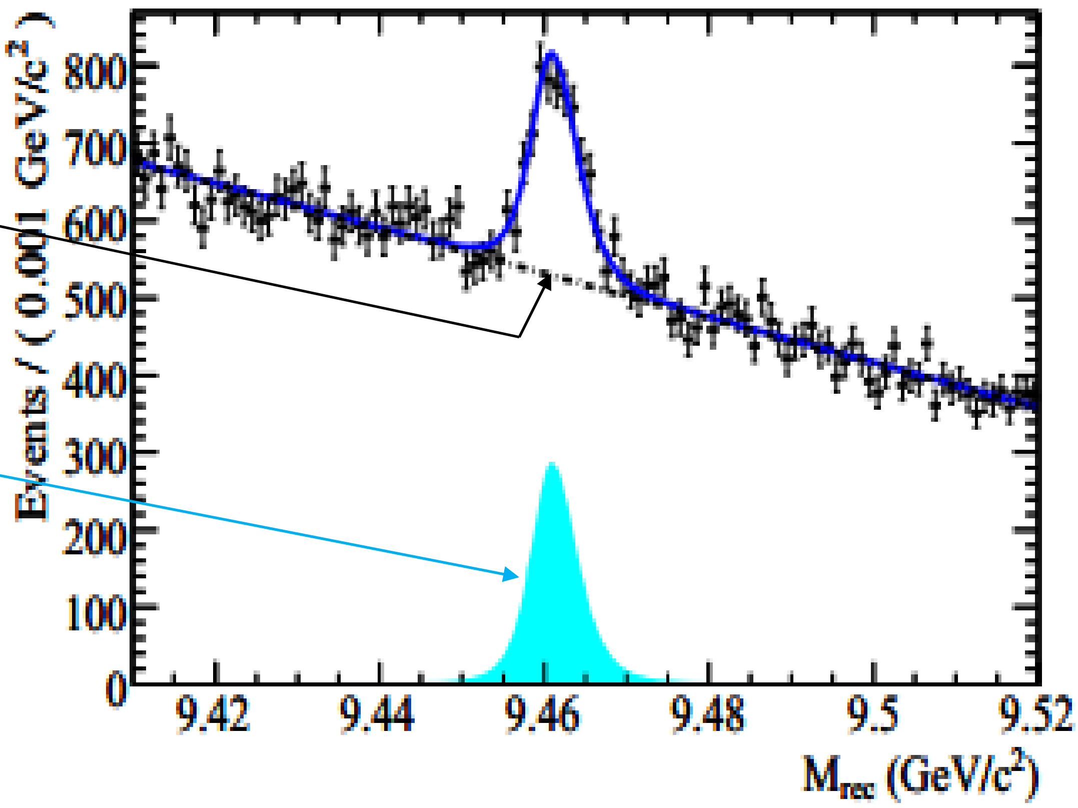
Maximum likelihood fit to 2-track "invisible" sample

Non-peaking background:

- ✓ Float all parameters and yield.

Peaking background:

- ✓ Fix shape, float yield contains peaking background and signal



BF(Υ(1S)→invisible) = (-1.6±1.4 (stat)±1.6 (syst))×10^{-4}

BF(Υ(1S)→invisible) = 3.0×10^{-4} @ 90% CL [BaBar PRL **103**, 251801 (2009)]

BF(Υ(1S)→invisible) = 2.5×10^{-4} @ 90% CL [Belle PRL 98, 132001 (2007)]

Y(1S)→γ+invisible

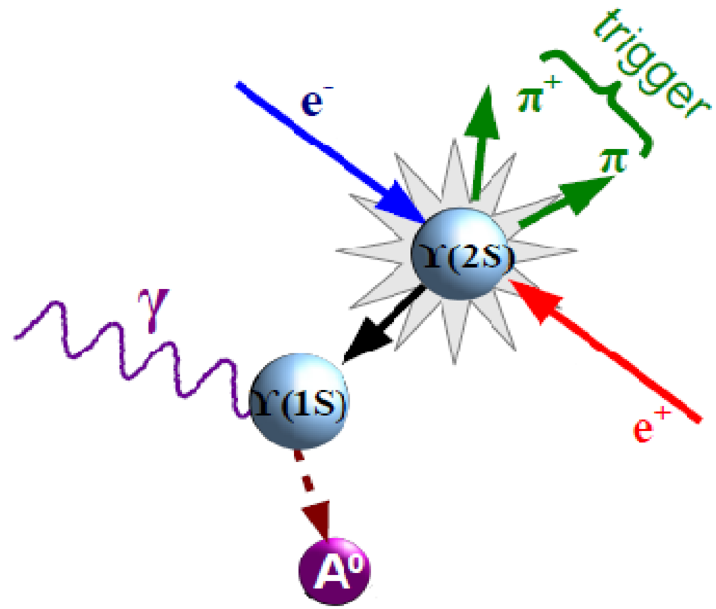
- Perform a search for $Y(2S)\to\pi^+\pi^- Y(1S)$, $Y(1S)\to\gamma$+invisible
- Resonant (invisible = Higgs) or non-resonant (invisible = $\chi\chi$, e.g. light dark matter)
- Select the event of interest by two low-momentum from $Y(2S)\to\pi^+\pi^- Y(1S)$ transition, a single energetic photon, and large missing energy.

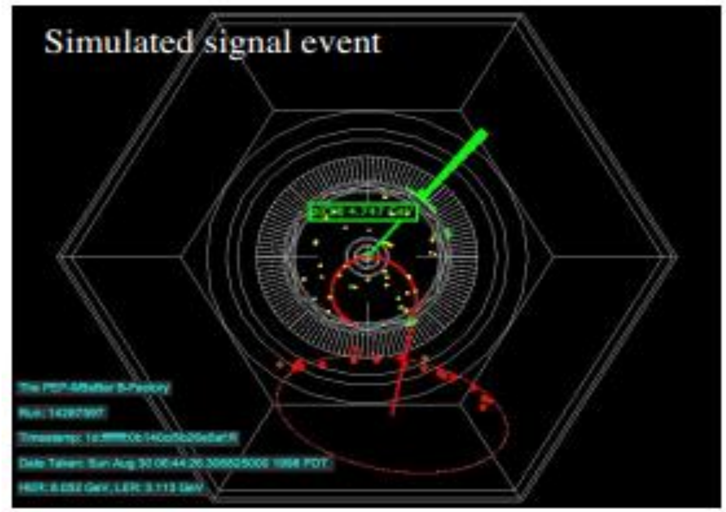
Two key kinematic variables: di-pion recoil-mass and missing mass.

$$M^2_{\mathrm{recoil}} = M^2_{\Upsilon(2S)} + m^2_{\pi\pi} - 2M_{\Upsilon(2S)}E^*_{\pi\pi}$$

$$M_X^2 = (\mathcal{P}_{e^+e^-} - \mathcal{P}_{\pi\pi} - \mathcal{P}_{\gamma})^2$$

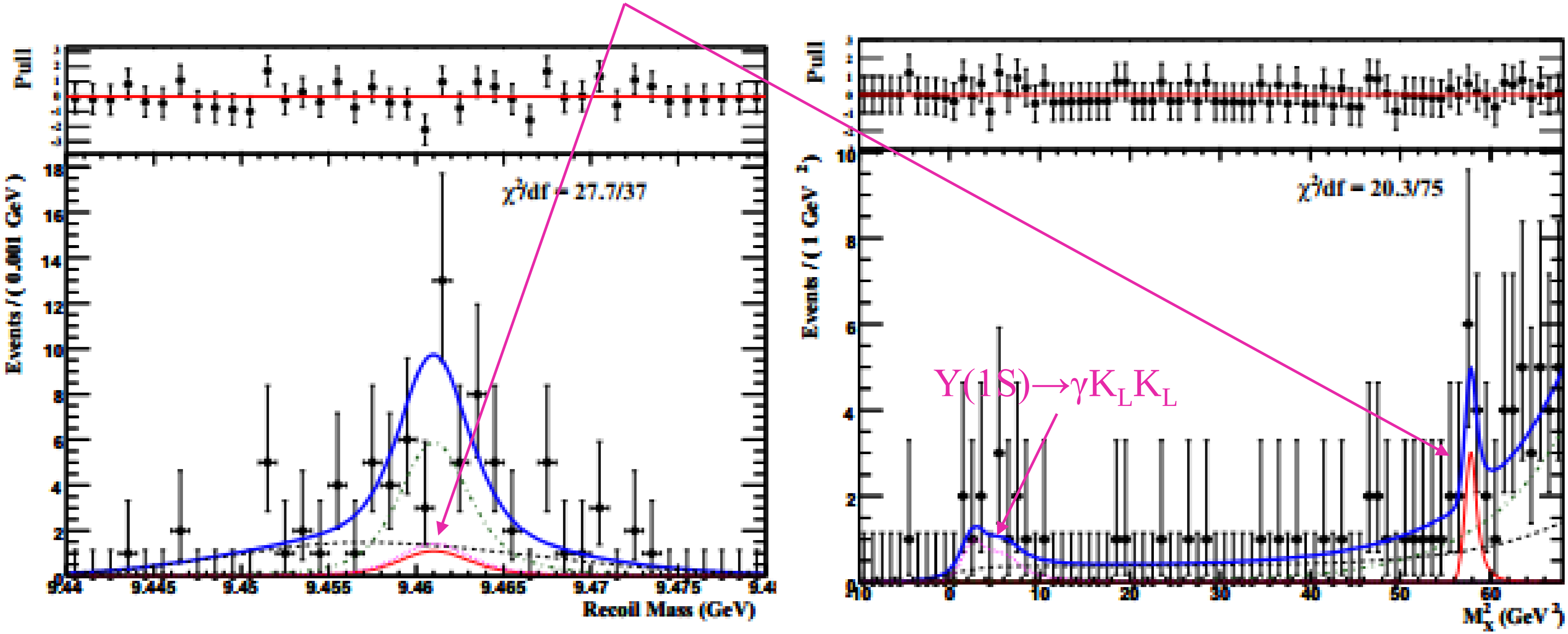
Search for excess of events over background as a function of missing mass.





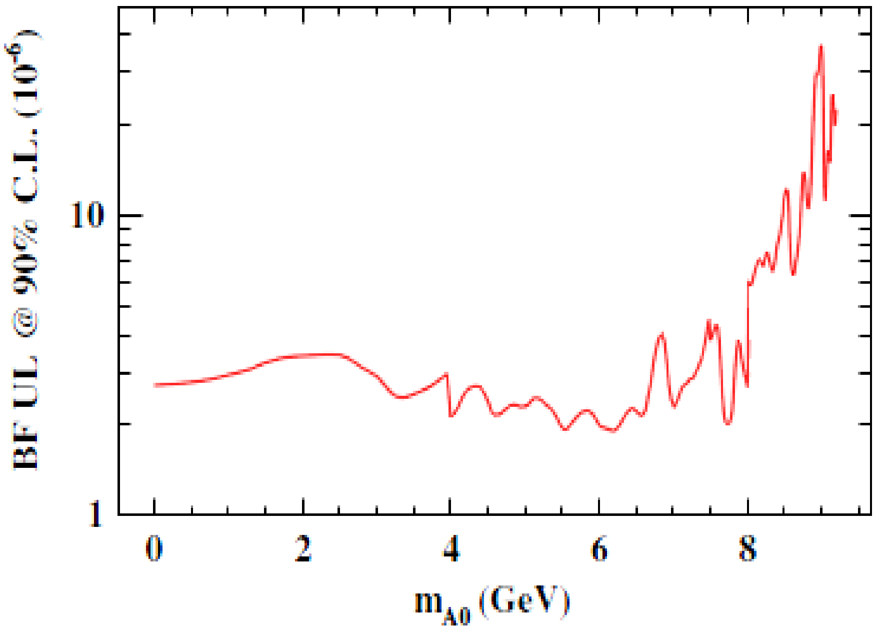
Υ(1S)→γ+invisible

Most significant peak in missing mass at Higgs mass = 7.58 GeV/c^2 (2.0σ significance).

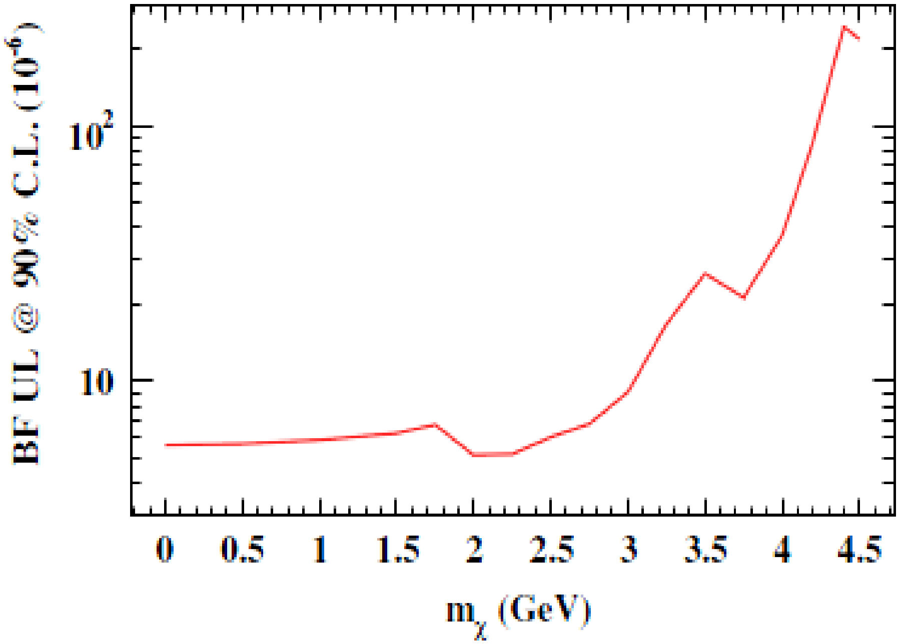


- 30% probability to observe a peak of this significance anywhere in the MA0 < 9.2 GeV range [PRL 107, 021804 (2011)].

Y(1S)⟶γ+invisible Limits



Resonant Y(1S)→γA^0 search



Non-resonant Y(1S)→γχχ search

✓$\mathcal{B}$(Y(1S) →γA^0) × $\mathcal{B}$(A^0→invisible < (1.9 – 37) × 10^{-6} for $0 \le m_{A^0} \le 9.2$ GeV/c^2 @ 90% CL.

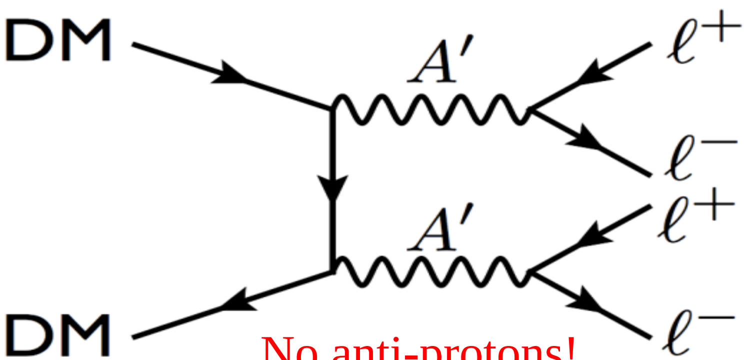
✓ $\mathcal{B}(\Upsilon(1S) \to \gamma\chi\overline{\chi})$< (0.5 – 24) × 10^{-5} for $0 \le m_\chi \le 4.5$ GeV/c^2.

- Best limits on radiative decays of ϒ(1S) to invisible final states **[PRL 107, 021804 (2011)].**

Gauge bosons in the "Dark Sector"

➢ New Models introduce new dark force carriers (e.g. dark-photon A') with light hidden sectors.

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



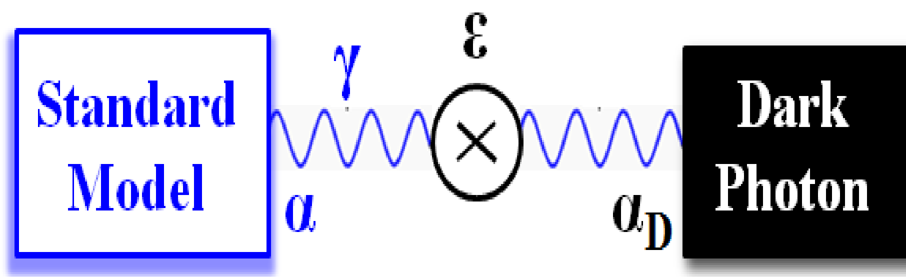
No anti-protons!

$m_{DM} \sim$ TeV $\quad$ MeV $\lesssim m_{A'} \lesssim$ GeV

❖ Produces high-energy (~100 GeV) cosmic-ray electrons and positrons.

❖ Could explain cosmic ray excesses (PAMELA/ATIC features).

❖ Interaction with SM via kinetic mixing with mixing strength (ε).



$$\Delta\mathcal{L} = \epsilon F^{\mu\nu} F^{D}_{\mu\nu}.$$

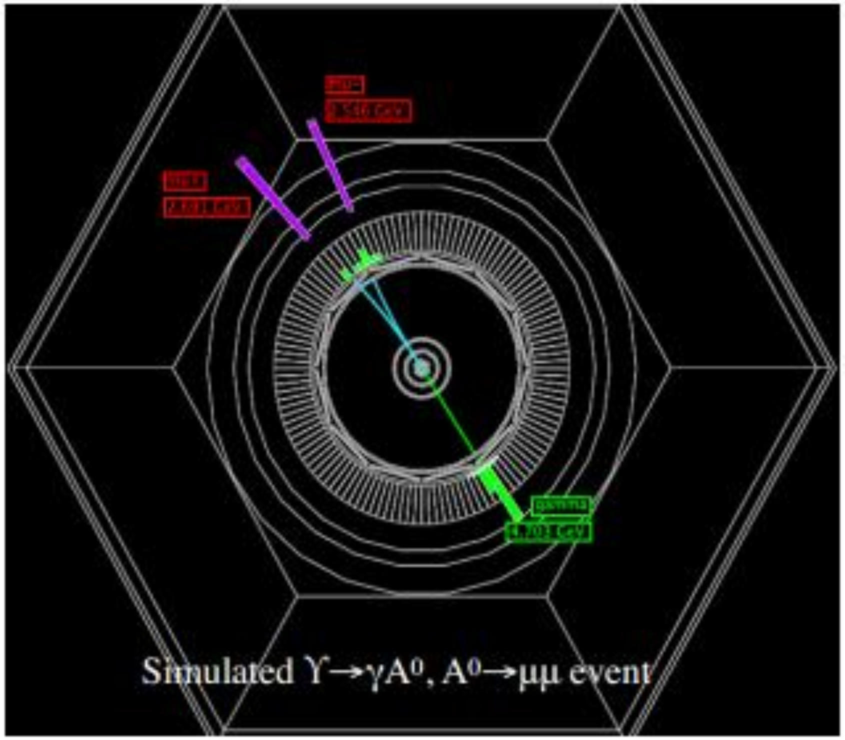
ε = hypercharge mixing strength.

❖ Kinematic mixing generates non-zero coupling of SM fermions to A':

$\alpha_D = \alpha\varepsilon$

B. Batell, et al, PRD79, 115008 (2009);
R. Essig, et al, PRD80 015003 (2009)

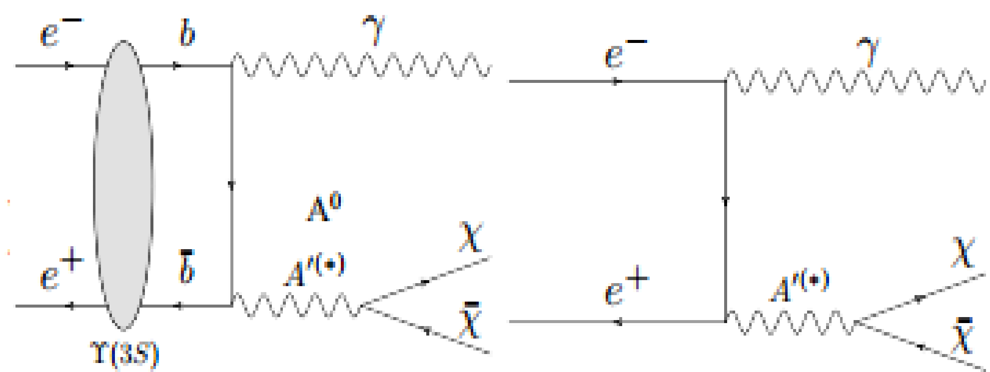
Higgs Searches: $e^+e^- \to \Upsilon(2S,3S) \to \gamma A^0$



- (Pseudo)scalar $A^0 \to \mu^+\mu^-$, $\tau^+\tau^-$, hadrons.
- Partially or fully-reconstructed final state with ≥ 2 charged tracks and a single energetic photon.

Look for A^0 signal as a narrow peak in photon energy spectrum or A^0 invariant mass.

Also can be interpreted as search for a vector dark gauge boson ("dark photon") $e^+e^- \to \gamma A'$.



Diagrams courtesy to R. Essig et al.

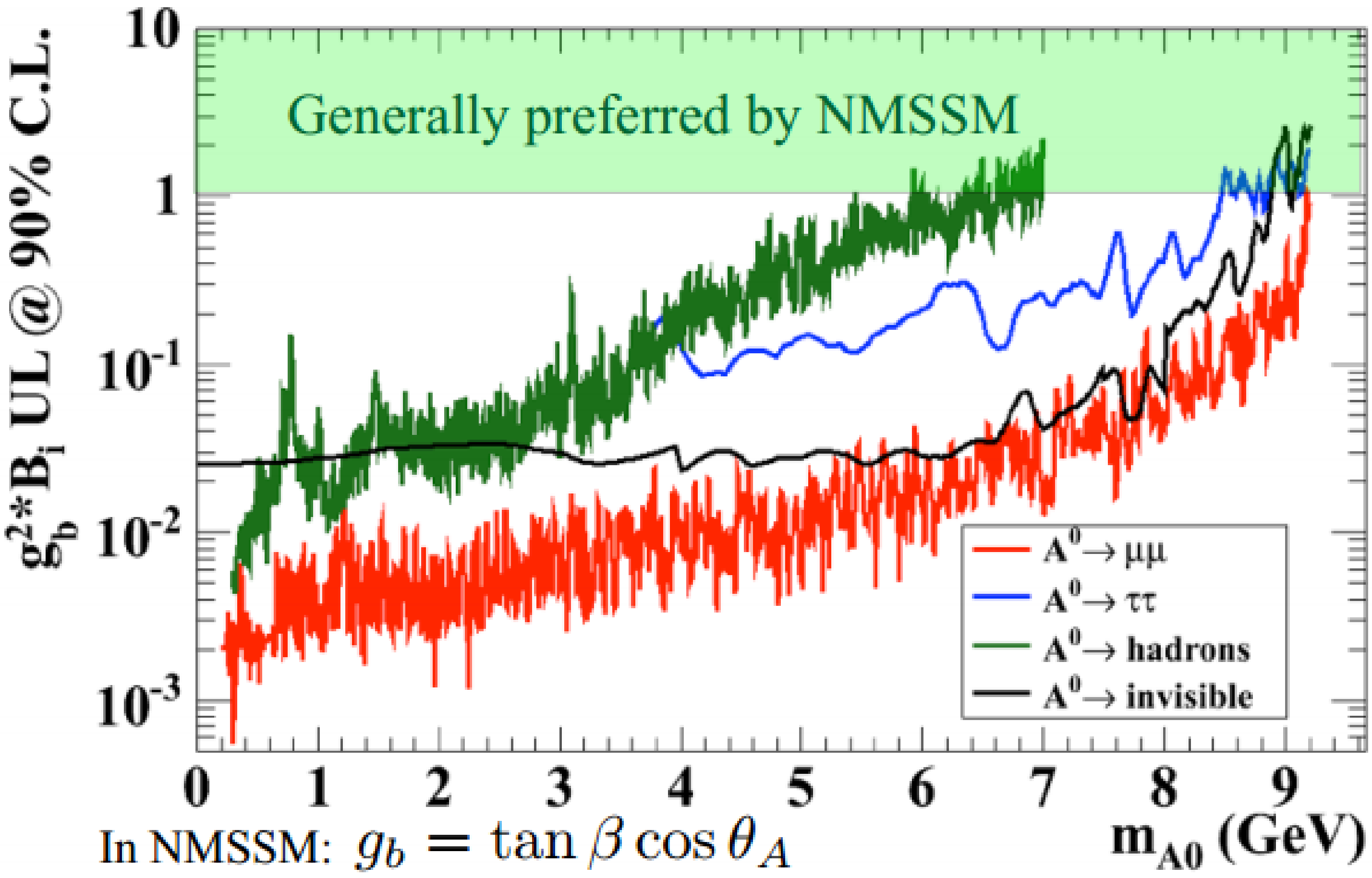
✓$A^0 \to \mu^+\mu^-$, **PRL 103, 081803 (2009)**

✓$A^0 \to \tau^+\tau^-$, **PRL 103, 081801 (2009)**

✓ $A^0 \to$ hadrons, **PRL 107, 221803 (2011)**

✓$A^0 \to$ invisible, **arXiv:0808.0017 [hep-ex]**

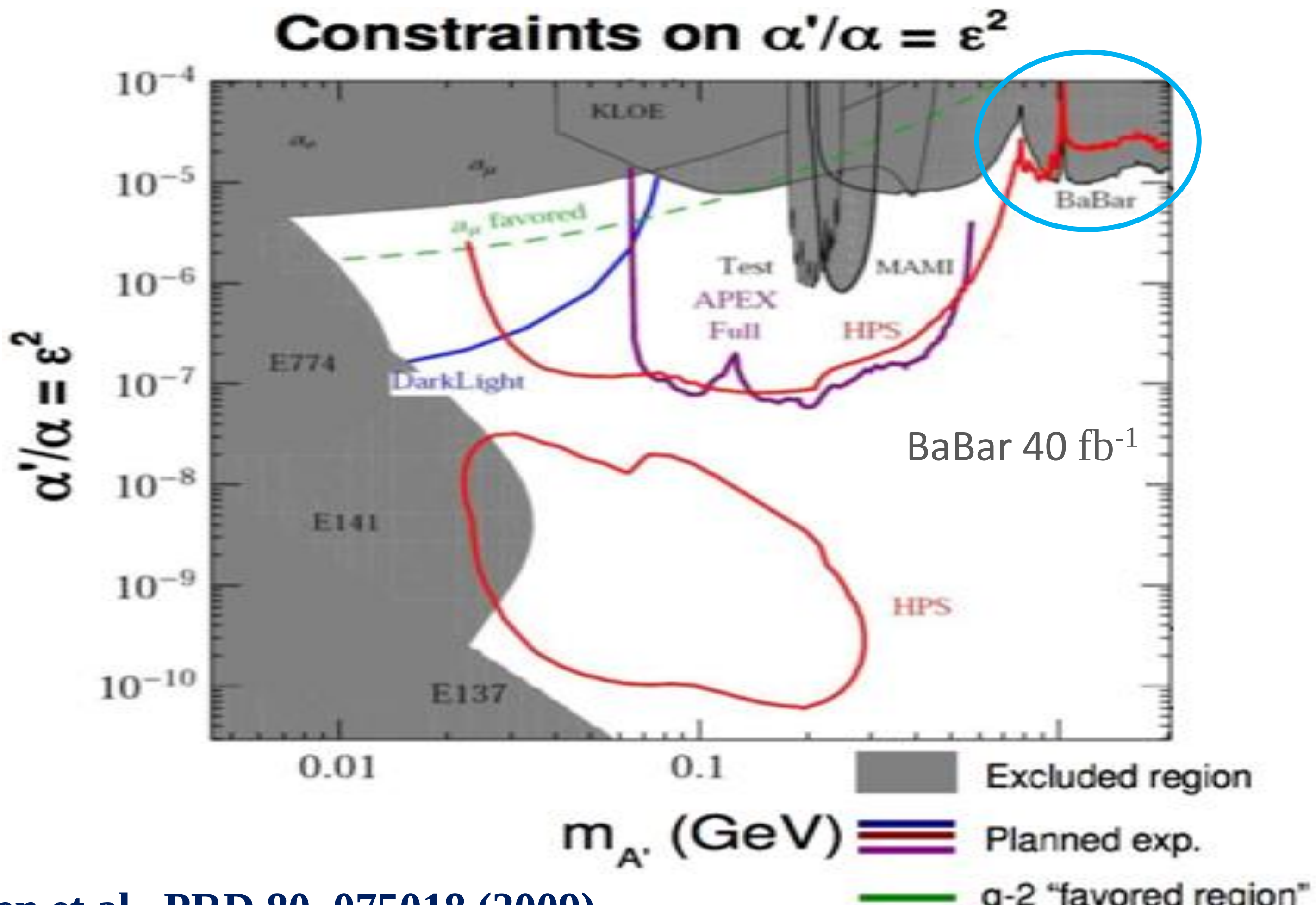
BaBar Higgs Coupling Limits



- Comprehensive limits on the low-mass (NMSSM etc.) Higgs.
- Also place significant constraints on other models, e.g. axion-like states and dark-photons.

Dark Photon Limits

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



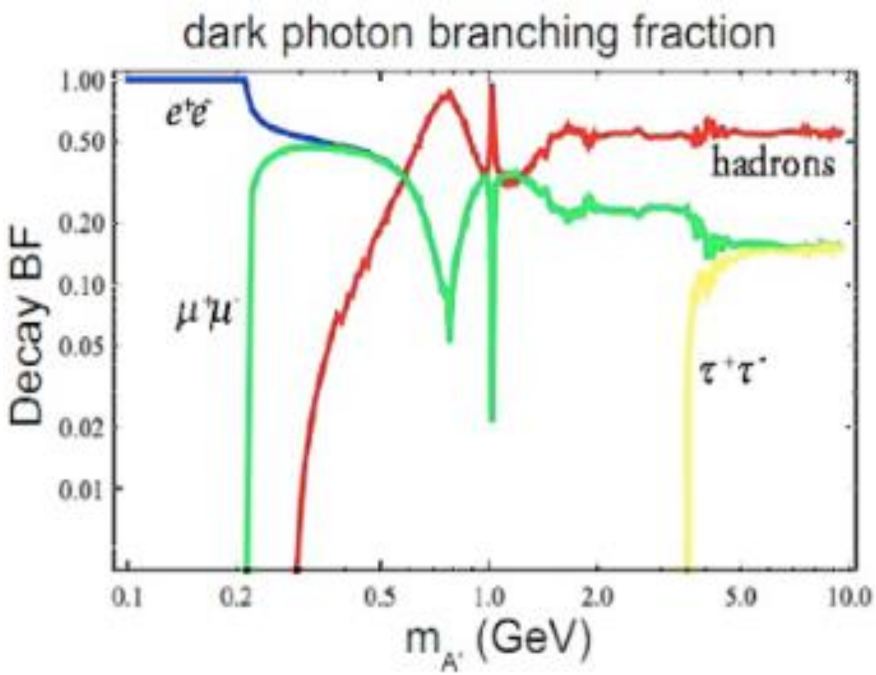
J. Bjorken et al., PRD 80, 075018 (2009)

Search for a dark Higgs boson h'

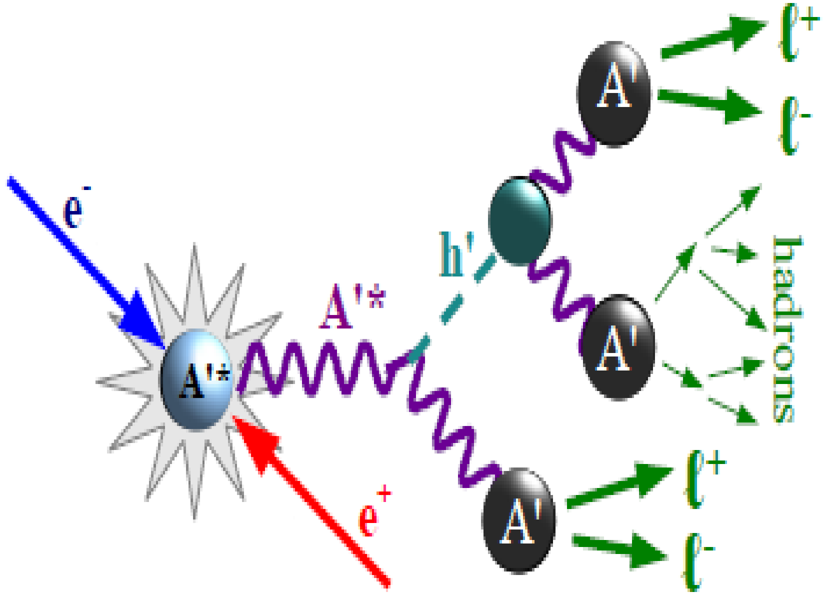
- Minimal gauge group: Abelian U(1) broken by dark-Higgs h'.

  B. Batell et al., PRD 79, 115008 (2009)

- Higgs-strahlung process $e^+e^- \to A'^* \to h'A'$, $h' \to A'A'$ is suppressed only by ε^2.



PRD 79, 115008 (2009)



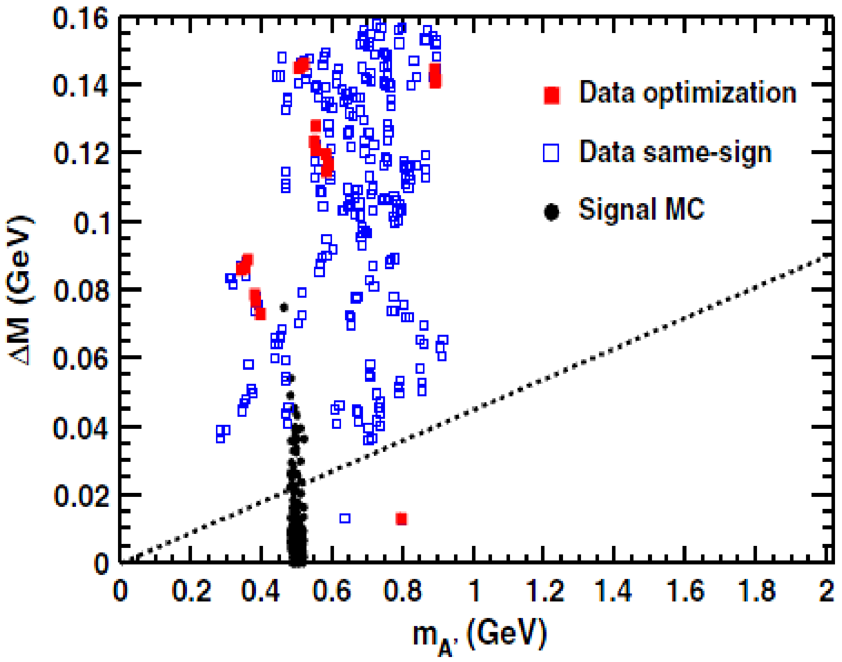
- Accessible final states depend on mass of A'.

- Search for $A' \to e^+e^-$, $\mu^+\mu^-$, $\pi^+\pi^-$ combinations.

Search for a dark Higgs boson h'

➢ Event Selection criteria:

- Exclusive mode:
  - Fully reconstructed all 3 dark photons: $A' \to e^+e^-, \mu^+\mu^-, \pi^+\pi^-$.
  - 6 tracks with an invariant mass to be greater than 95% of the e^+e^- CM energy.
  - The largest mass difference between dark photon candidates, ΔM, must be less than 10 – 240 MeV/c^2, depending on final states and the dark photon masses.



- Inclusive modes (only for $m_{A'} > 1.2$ GeV/c^2):
  - $A_1' \to e^+e^-, \mu^+\mu^-, A_2' \to \mu^+\mu^-$

    $A_3' \to X\ \ \ell^+\ell^-$ or $\pi^+\pi^-$. ($X \neq \ell^+\ell^-$ or $\pi^+\pi^-$).
  - four or more charged tracks.
  - Reconstruct four momentum:

    $P_3 = P_{ee} – P_1 – P_2$.

- Use a PID algorithm for $A' = \ell^+\ell^-$ or $\pi^+\pi^-$.
- Cosine of helicity angle of $A' \to e^+e^-$ < 0.9

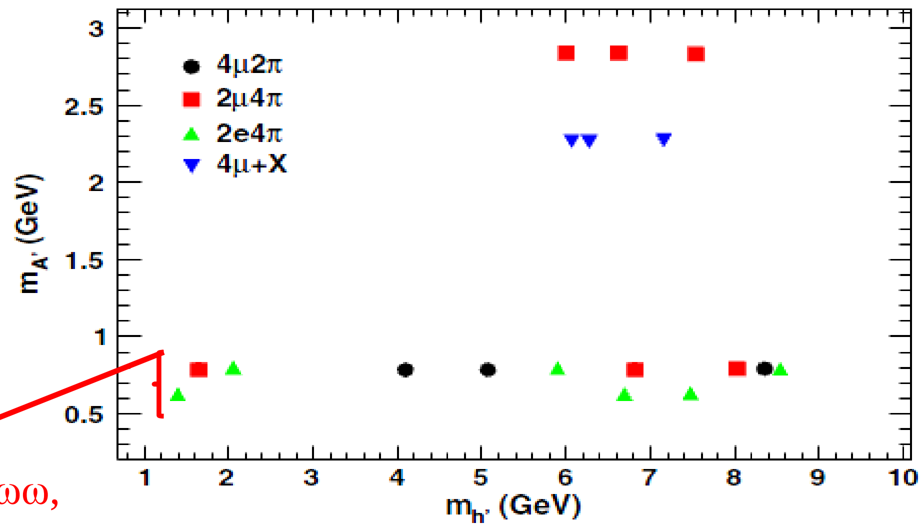
Search for a dark Higgs boson h'

➢Perform a search for dark Higgs (h') in the range of $0.8 < m_{h'} < 10.0$ GeV/c^2 and $0.23 < m_{A'} < 3.0$ GeV/c^2 with the constraint $m_{h'} > 2m_{A'}$.

Results:

➢A total of 6 events are observed using 516 fb^{-1} of Y(2S,3S,4S) datasets in the following candidates:

$1\times4\mu2\pi$	
$2\times2\mu4\pi$	Most likely from
$1\times2e4\pi$	$e^+e^-\to(e^+e^-)\rho\rho$, $(e^+e^-)\omega\omega$,
$2\times2\mu X$	or 6π final states.

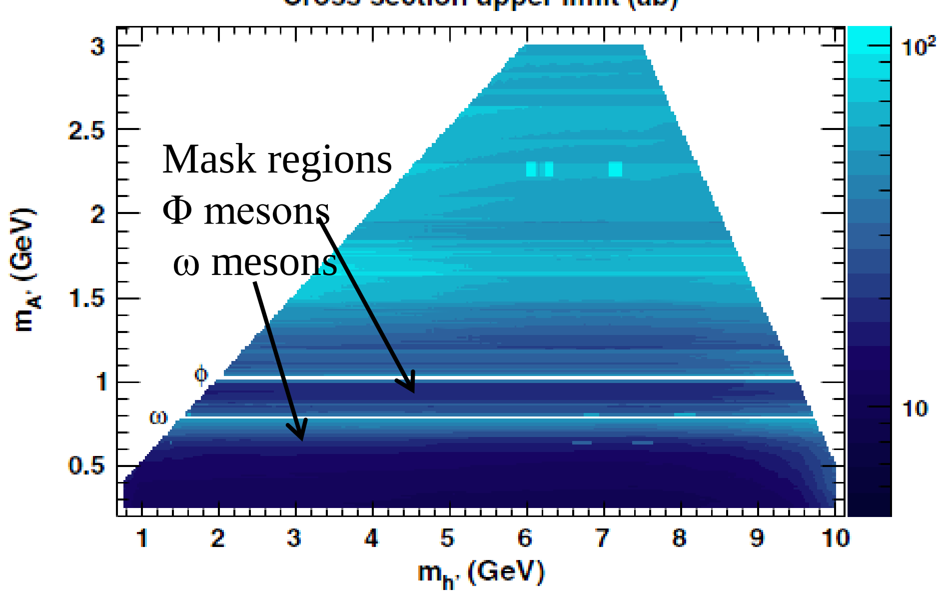


➢ No events are observed in 6 leptons search.

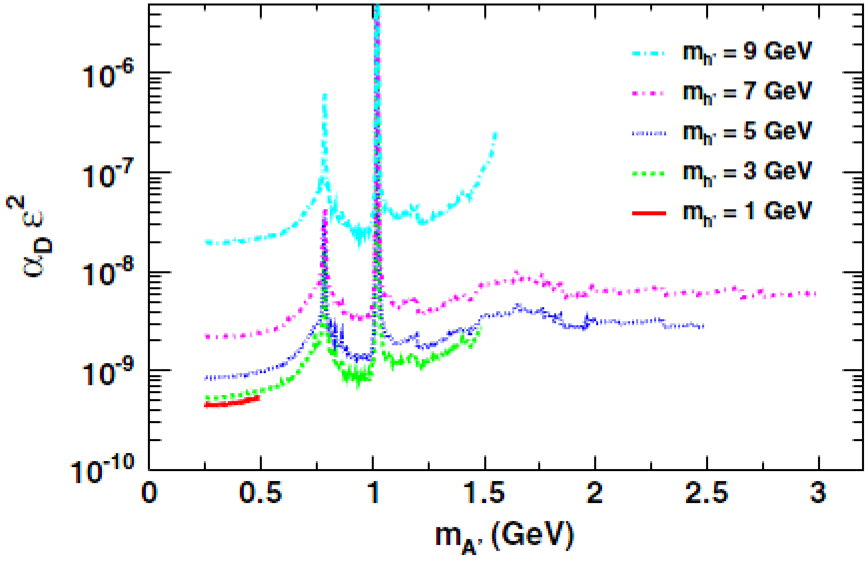
➢ Largest systematic uncertainty (1 – 8%) is due to signal selection efficiency interpolation between the simulated mass points.

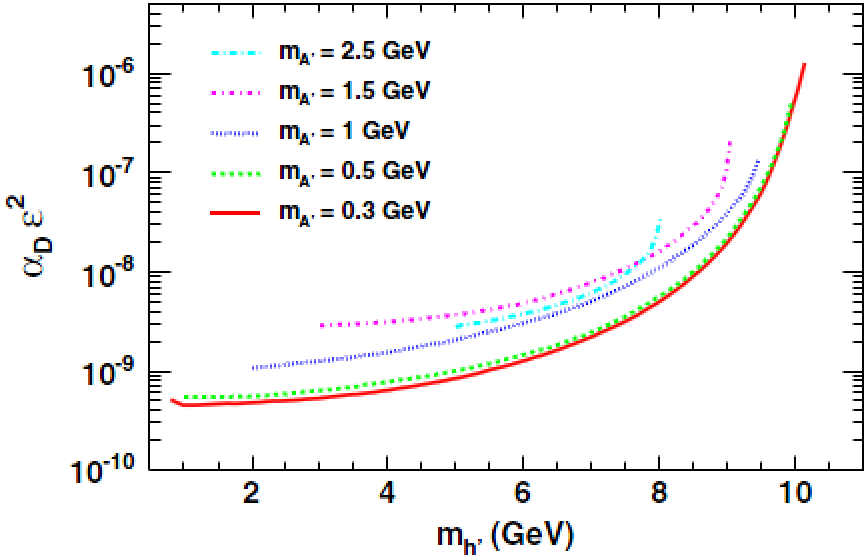
➢ 90% CL Bayesian upper limit on the $e^+e^-\to A'h'$, $h'\to A'A'$ cross-section is computed using a uniform prior.

$\sigma(e^+e^-\to A'h', h'\to A'A') < 10 – 100$ ab.



Search for a dark Higgs boson h'





$\alpha_D\varepsilon^2$ < few × 10^{-10} at 90% CL

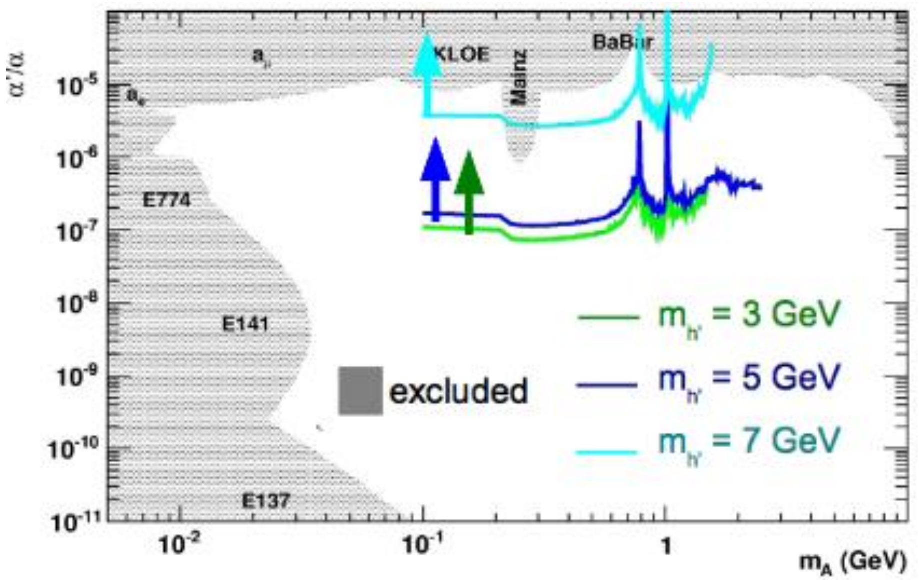
$$\alpha_D = g_D^2 / 4\pi$$

g_D = dark sector coupling constant

ε = mixing strength

Phys. Rev. Lett. 108, 211801 (2012)

Limits on $\varepsilon^2 = \alpha'/\alpha$ assuming $\alpha_D = \alpha$ for various Higgs mass

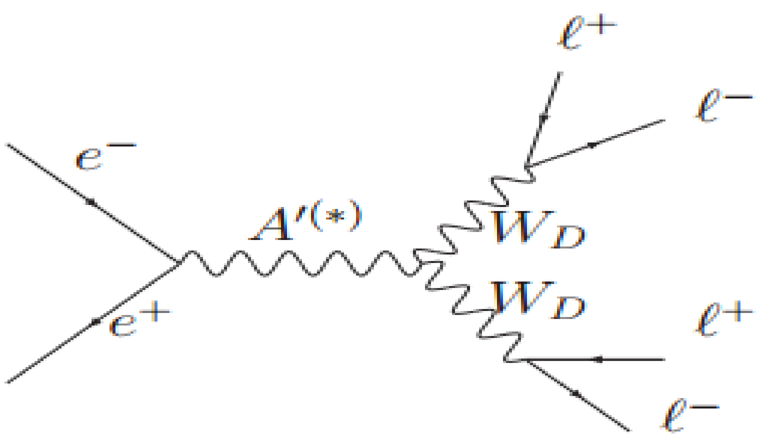


Assuming $\alpha_D=\alpha$, limits on ε are [10^{-3}, 10^{-4}], about 10 times better than previous measurement.

Non-Abelian dark sector

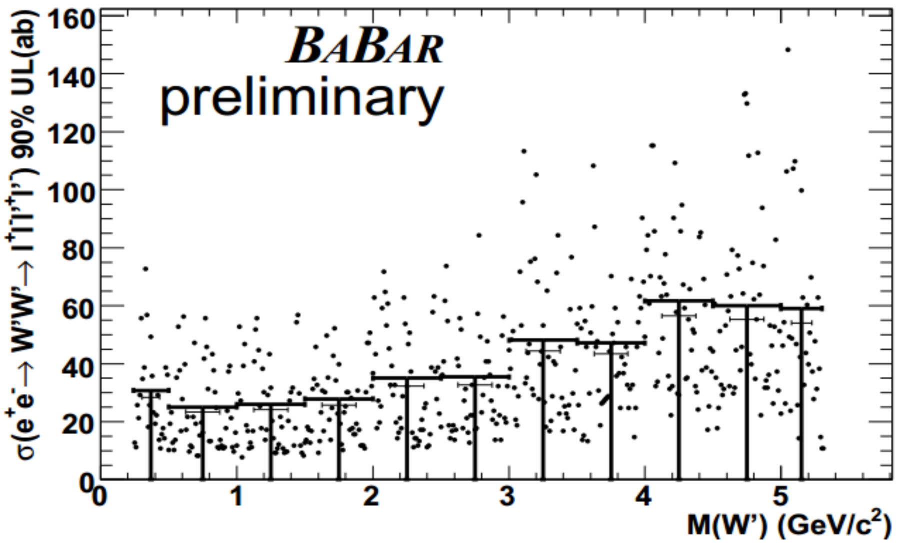
- The simplest extension to a non-abelian case is SU(2)×U(1), which has four bosons: A', W_D, W_D', W_D''.

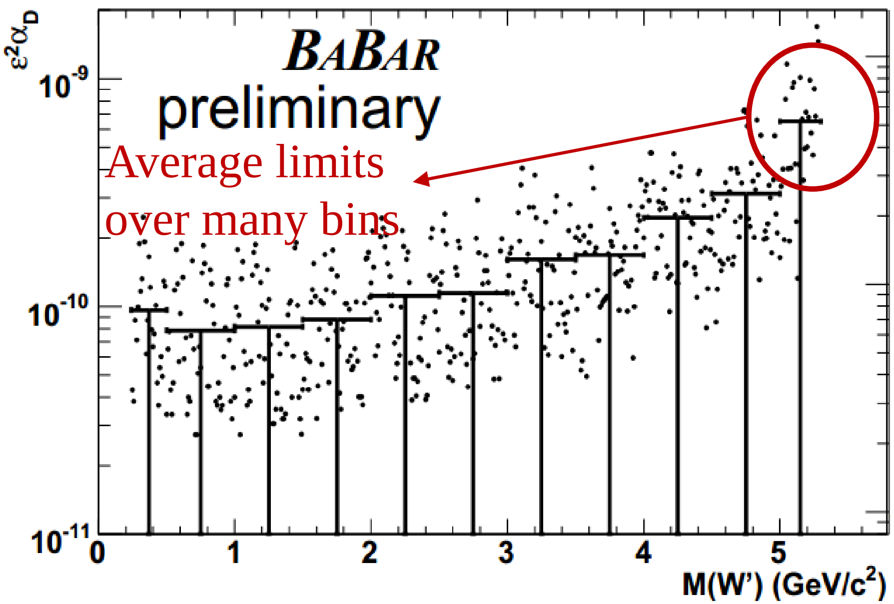
Essig et al., Phys. Rev. D 80, 015003 (2009)



arXiv:0908.2821 [hep-ex]

- Signature: $e^+e^- \to W_D W_D \to (l^+l^-)(l^+l^-)$, ($l$= e, μ)
- Search for two di-leptonic resonances with equal mass.
- Used full BaBar data-sets (~540 fb^{-1}).





Probing dark forces at BESIII

➢Hai-Bo Li et al. [Phys. Lett. B 686, 249 - 253 (2010)], P.F. Yin et al. [Phys. Lett. B 679, 362 (2009)] and Shou-hua Zhu [PRD 75, 115004 (2007)] have done a phenomenological study to search for a GeV scale vector boson at BESIII/BEPCII.

➢ Both the A′ boson and the h′ can be produced at BESIII, if their masses are less than Charmonium states.

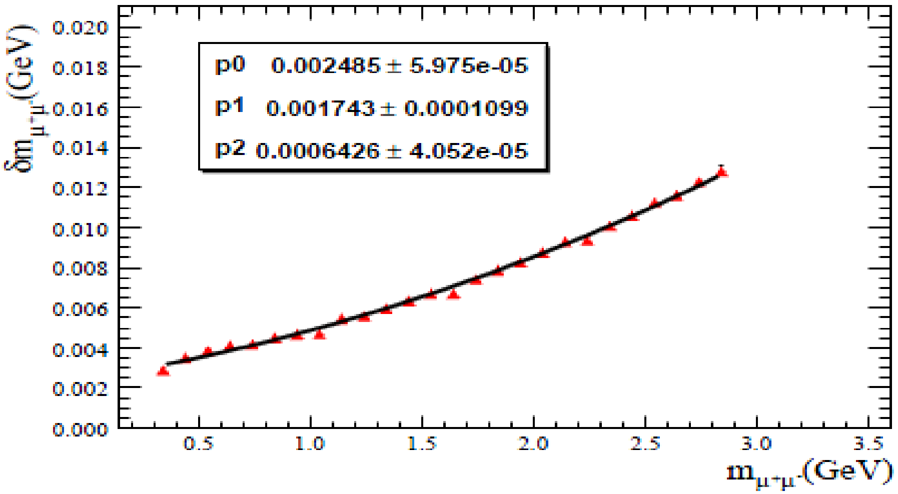
• **$e^+e^- \to \gamma A'$ events:**

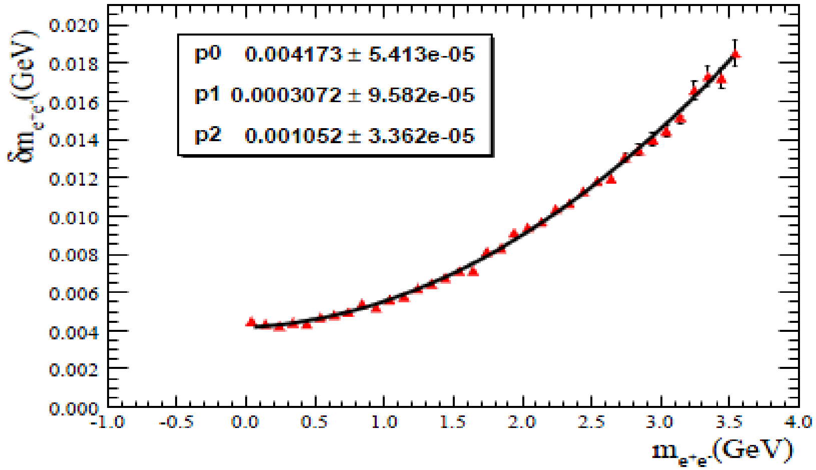
Mass resolution of A′ (here A′ = U)

$$\delta m(\mu^+\mu^-) = \left(2.5 + 1.7\left(\frac{m_U}{1.0\mathrm{GeV}}\right) + 0.6\left(\frac{m_U}{1.0\mathrm{GeV}}\right)^2\right)\ (\mathrm{MeV}),$$

$$\delta m(e^+e^-) = \left(4.1 + 0.3\left(\frac{m_U}{1.0\mathrm{GeV}}\right) + 1.1\left(\frac{m_U}{1.0\mathrm{GeV}}\right)^2\right)\ (\mathrm{MeV}).$$

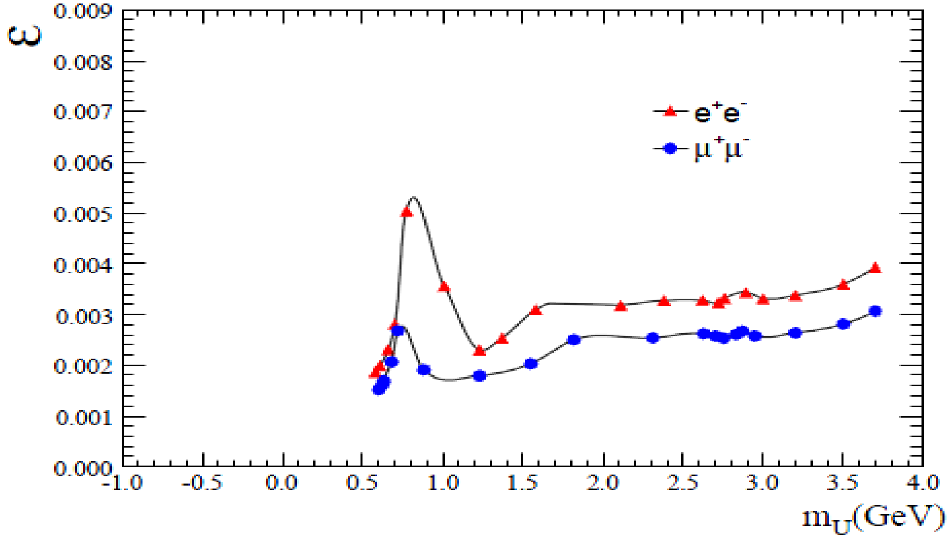
[Phys. Lett. B 686, 249 - 253 (2010)]



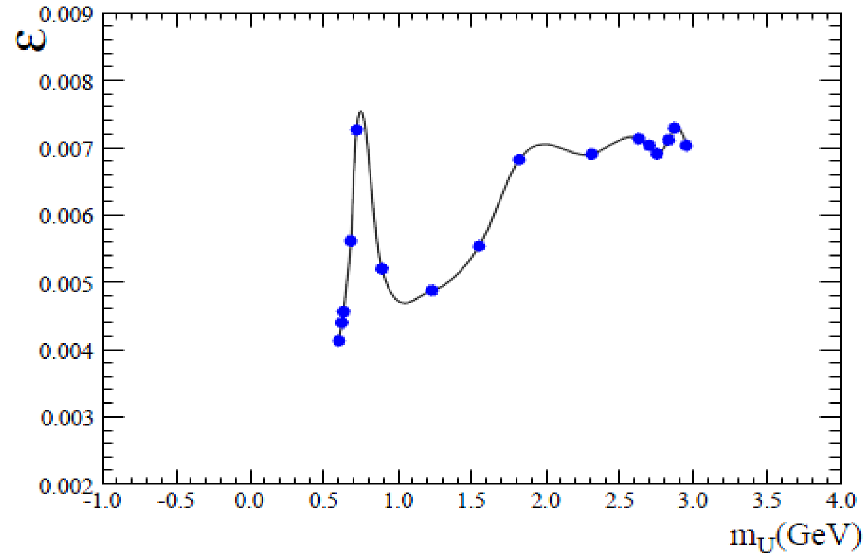


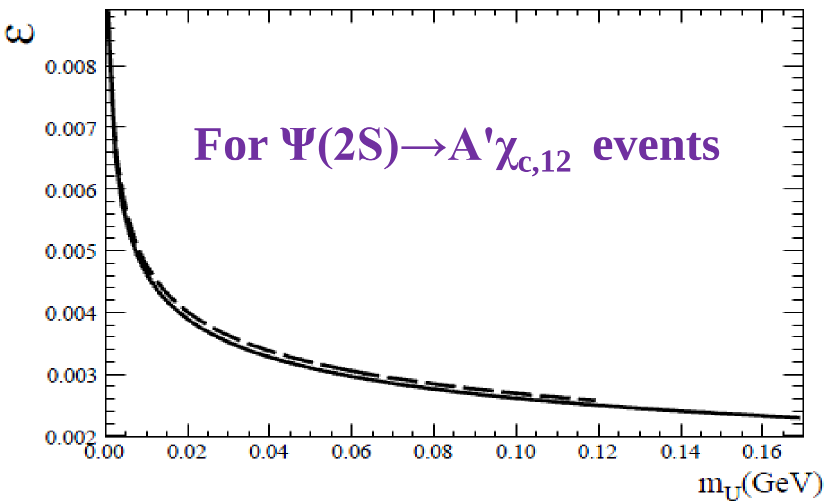
Probing dark forces at BESIII

- For $e^+e^- \rightarrow \gamma A'$ events



- For $J/\Psi \rightarrow A' l^+ l^-$ events





- $\chi_{c,12}$ can be reconstructed in the $\chi_{c,12} \rightarrow \gamma J/\Psi$, $J/\Psi \rightarrow l^+ l^-$ decays.

- The dominant background is $\Psi(2S) \rightarrow \gamma^* \chi_{c,12} \rightarrow e^+e^- \chi_{c,12}$.

[Phys. Lett. B 686, 249 - 253 (2010)]

Summary & Future Prospects

- Dark forces open a new window for new physics beyond the SM.

- In particular, light gauge bosons in hidden sector and low-mass Higgs bosons are well motivated by theory, astrophysics, and particle physics measurements.

- No evidence for light Higgs or dark bosons productions are found

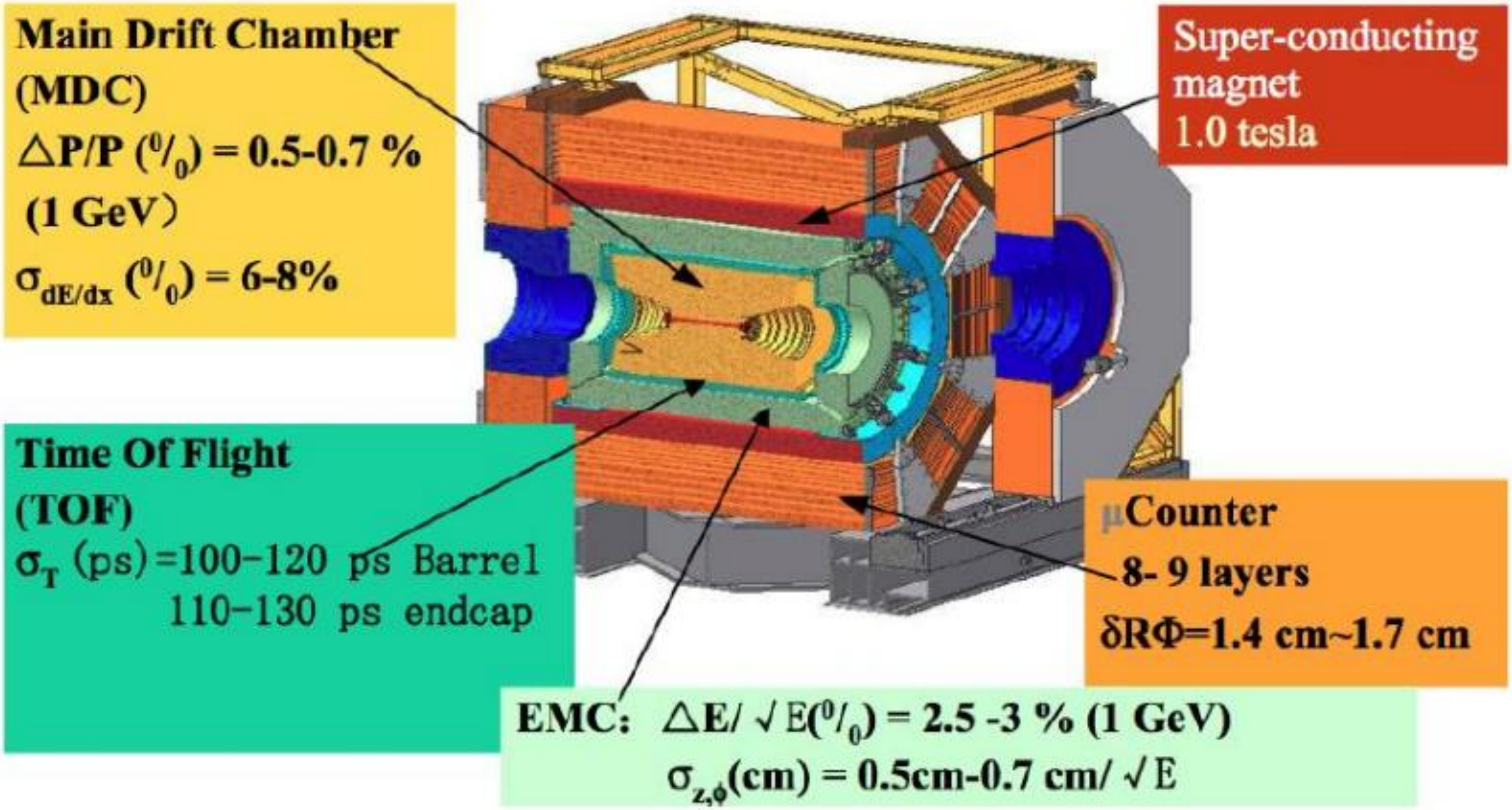
  • Upper limits have been set with improvements over the previous measurements.

  • Excluded a large portion of the parameter space of the new physics models such as NMSSM, axion-like states, dark-bosons etc.

- Future high statistics flavor physics, including BESIII, experiments can achieve better sensitivity for these new physics searches.

Back up Slide

BESIII Experiment



Search for light Higgs boson

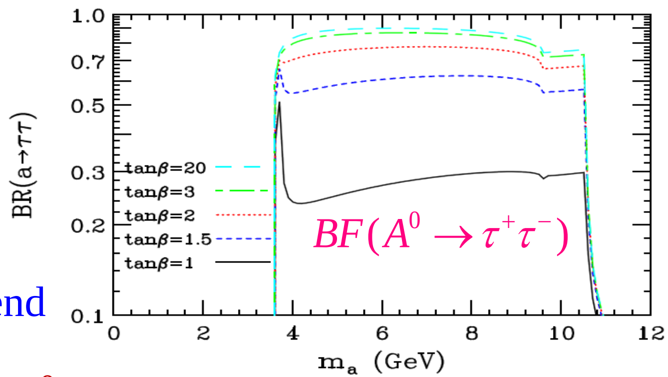
- Coupling of fermions and the CP-odd Higgs A^0 in the NMSSM:

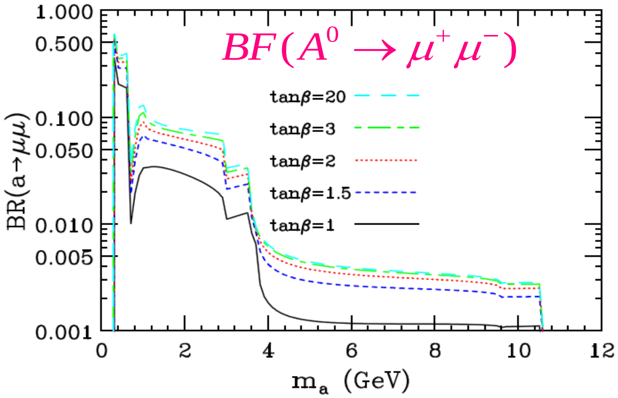
$$L_{\rm int}^{f\bar{f}} = -\cos\theta_A \tan\beta \frac{m_f}{v} A^0 \bar{d}(i\gamma_5)d, \quad d = d, s, b, e, \mu, \tau$$

$$L_{\rm int}^{f\bar{f}} = -\cos\theta_A \cot\beta \frac{m_f}{v} A^0 \bar{u}(i\gamma_5)u, \quad u = u, c, t, \nu_e, \nu_\mu, \nu_\tau$$

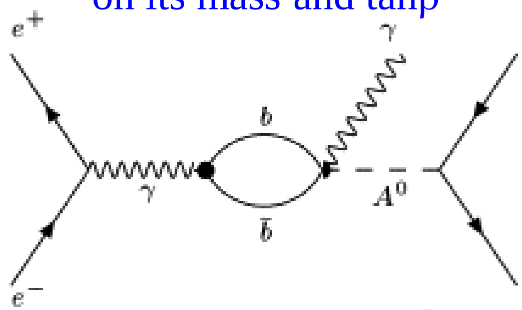
$$\tan\beta = \frac{v_u}{v_d}$$

E. Fullana et. al, Phys. Lett. B 653, 67 (2007)



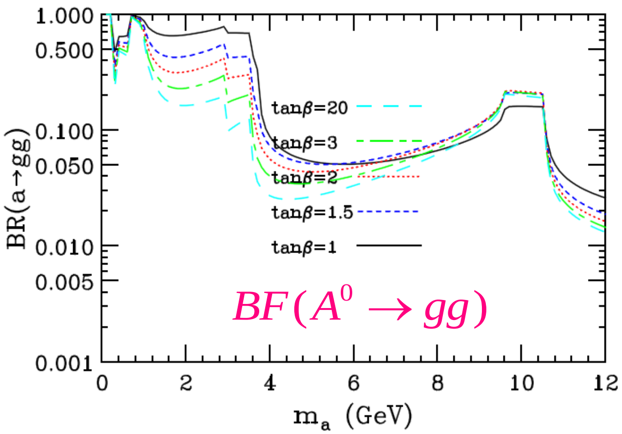


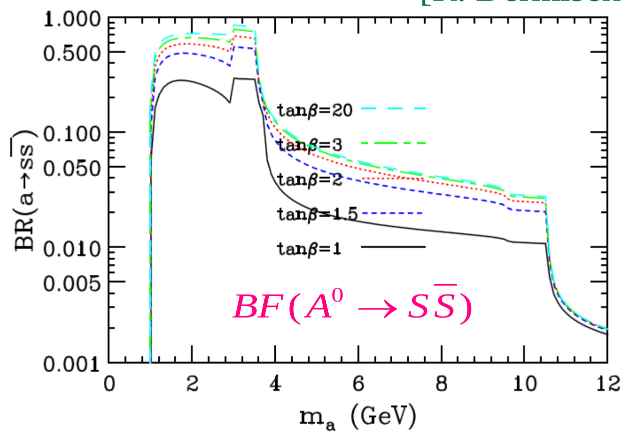
- Decay patterns of the A^0 depend on its mass and tanβ

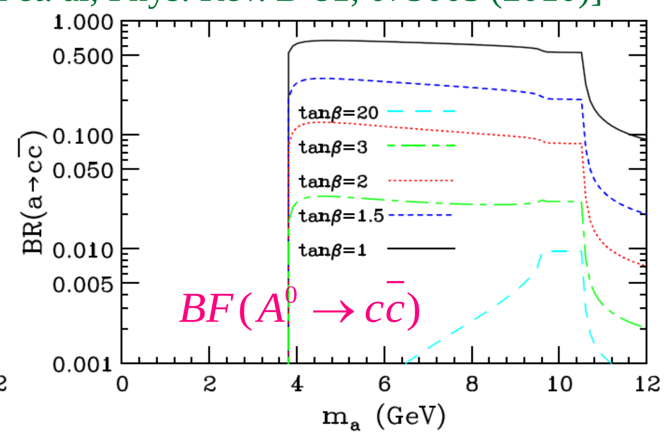


$A^0 \to$ hadrons
$A^0 \to$ invisible
$A^0 \to \tau^+\tau^-$
$A^0 \to \mu^+\mu^-$
A0 → neutralinos if $m_{A^0} > 2m_{\chi^0}$

[R. Dermisek et. al, Phys. Rev. D 81, 075003 (2010)]





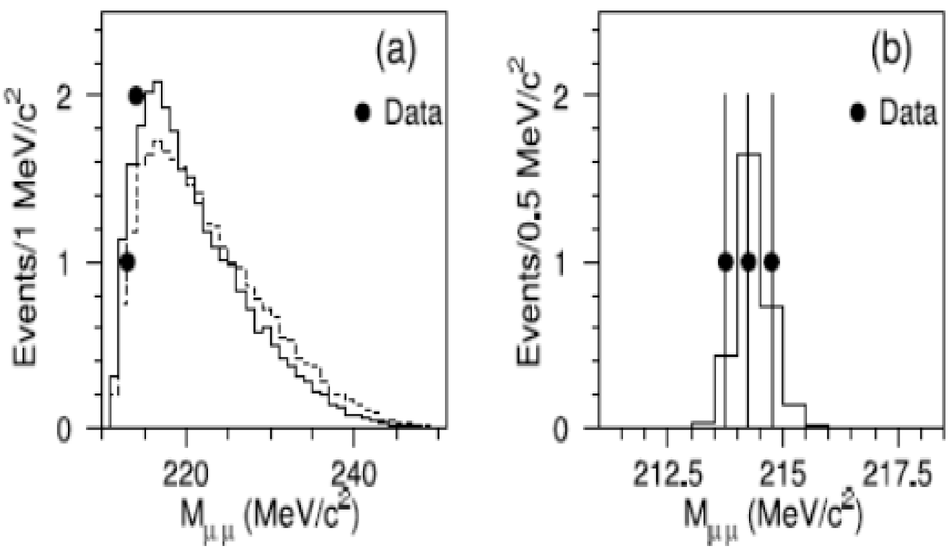


Search for light Higgs boson

➢ HyperCP Anomaly

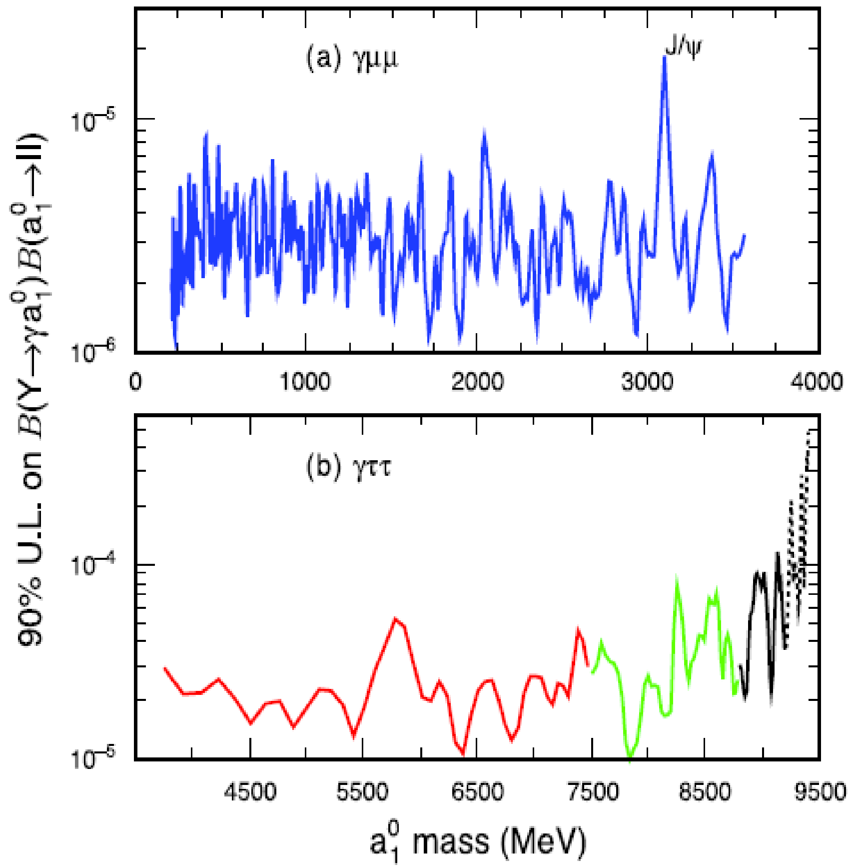
• Observed three anomalous events in $\Sigma \to p\mu^+\mu^-$ near threshold ($m_{\mu\mu}$ = 214 MeV), which were interpreted as CP-odd light Higgs boson.

[PRL 94, 021801 (2005)]



• If light CP-odd Higgs boson, could be produced in $\Upsilon \to \gamma A^0$.

➢ CLEO collaboration

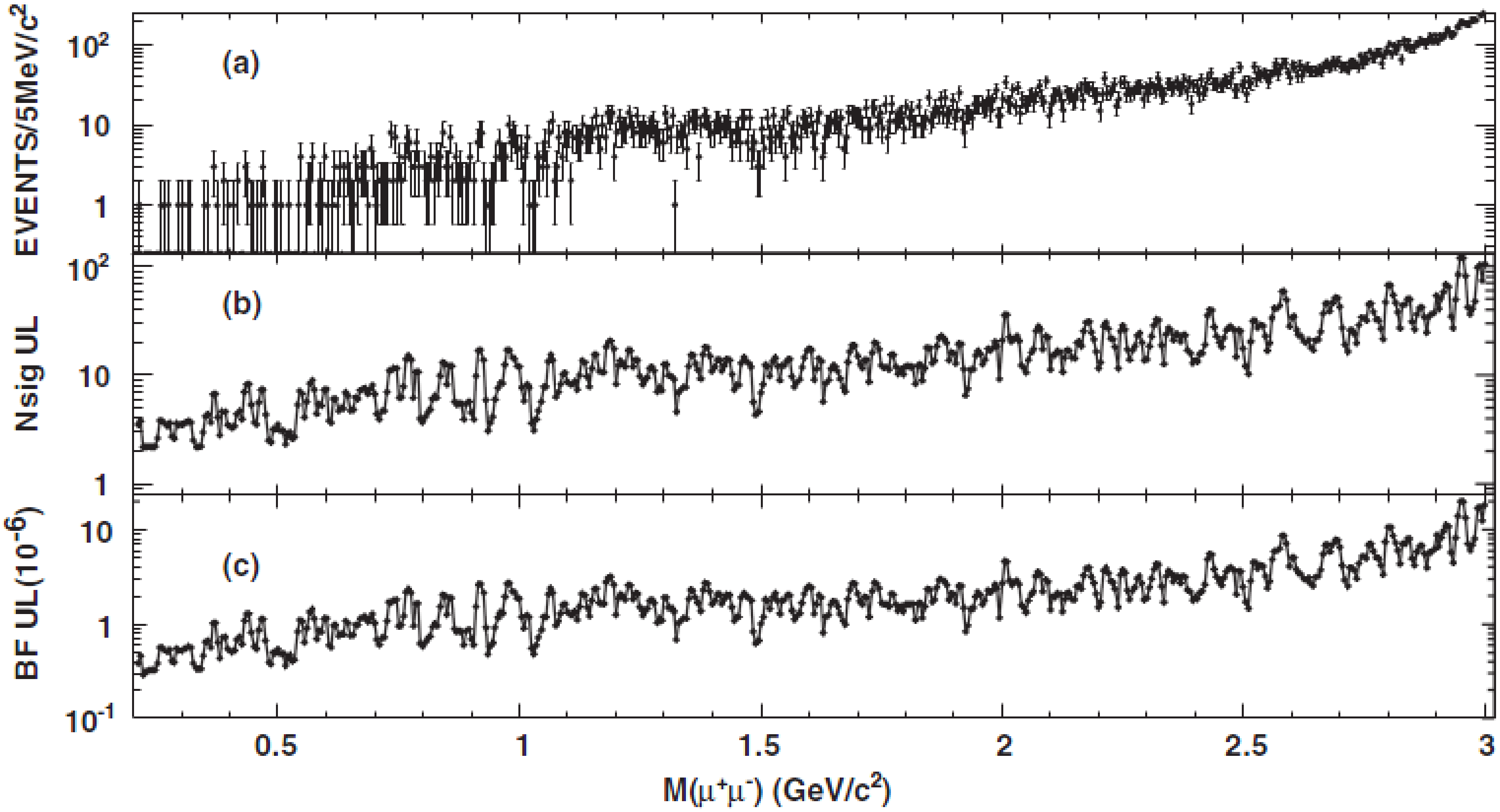


PRL**101, 151802 (2008)**

Search for light Higgs boson

BESIII collaboration

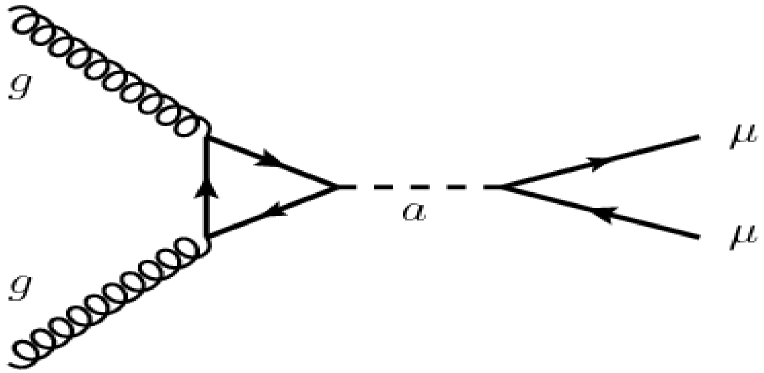
$\psi(2S) \rightarrow \pi^+\pi^- J/\psi$, $J/\psi \rightarrow \gamma A^0$, $A^0 \rightarrow \mu^+\mu^-$

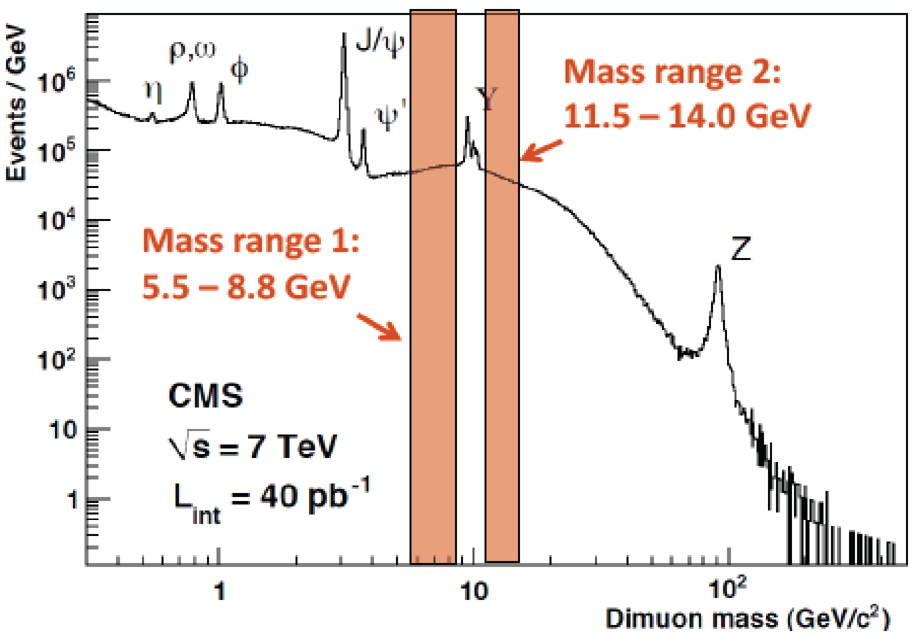


PRD 85, **092012** (2012).

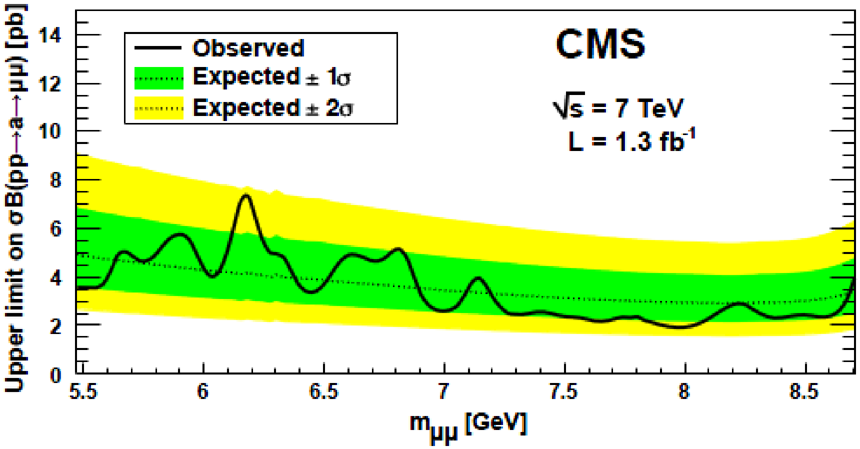
Search for light Higgs boson

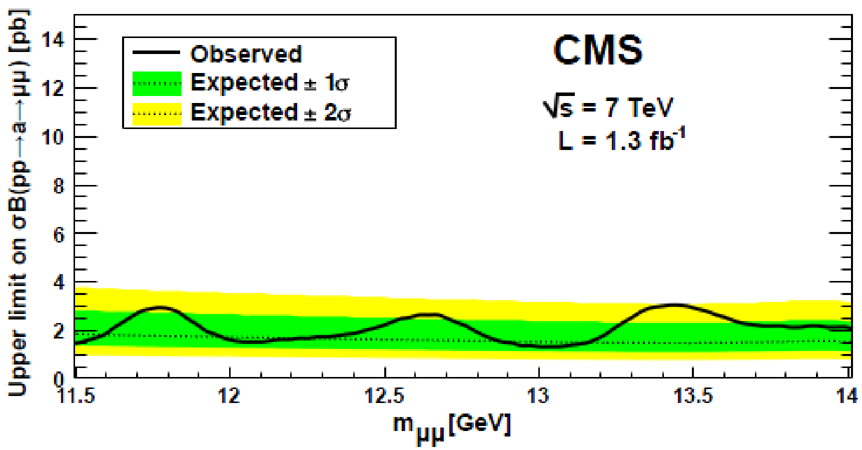
Light CP-odd Higgs boson at CMS experiment





CMS Collaboration, PRL 109, 121801 (2012)

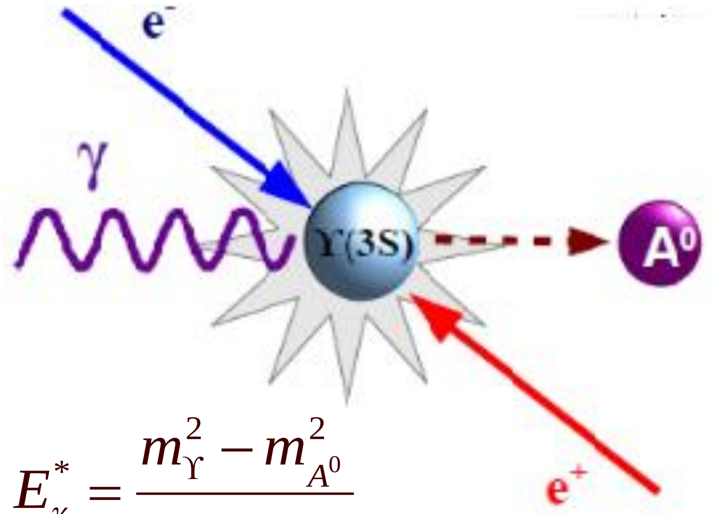




Searches of light Higgs at BaBar

➢ Radiative decays of Υ(2S,3S).

➢Search for monochromatic photon in the recoil mass spectrum.



$$E_\gamma^* = \frac{m_\Upsilon^2 - m_{A^0}^2}{2m_\Upsilon}$$

✓**$A^0 \to \mu^+\mu^-$, PRL 103, 081803 (2009)**

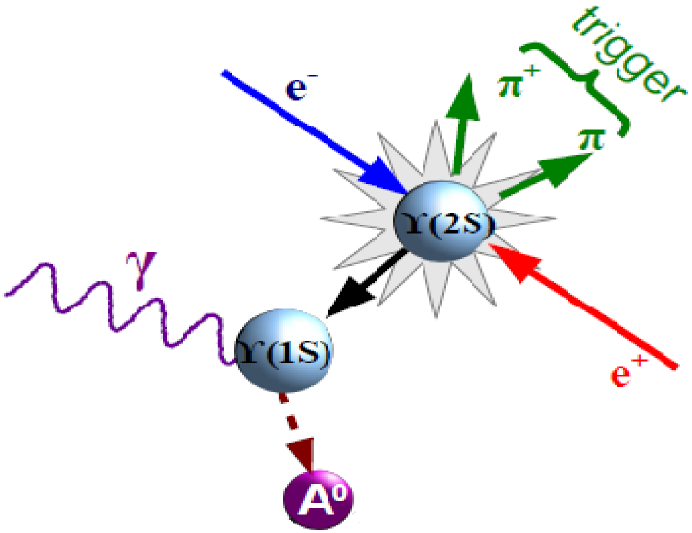
✓**$A^0 \to \tau^+\tau^-$, PRL 103, 081801 (2009)**

✓ **$A^0 \to$hadrons, PRL 107, 221803 (2011)**

✓**$A^0 \to$invisible, arXiv:0808.0017 [hep-ex]**

➢ Radiative decays of Υ(1S).

➢Υ(1S) sample is selected by tagging the pion pair in the Υ(2S,3S)→$\pi^+\pi^-$Υ(1S) transitions.



✓**$A^0 \to$invisible (light dark matter), PRL 107, 021804 (2011)**

✓**$A^0 \to \tau^+\tau^-$, PRD 88, 071102 (R) (2013)**

✓**$A^0 \to \mu^+\mu^-$, PRD 87, 031102 (R) (2013)**

✓**$A^0 \to$gg or $s\bar{s}$ PRD 88, 031701 (R) (2013)**

Searches of light Higgs at BaBar

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

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

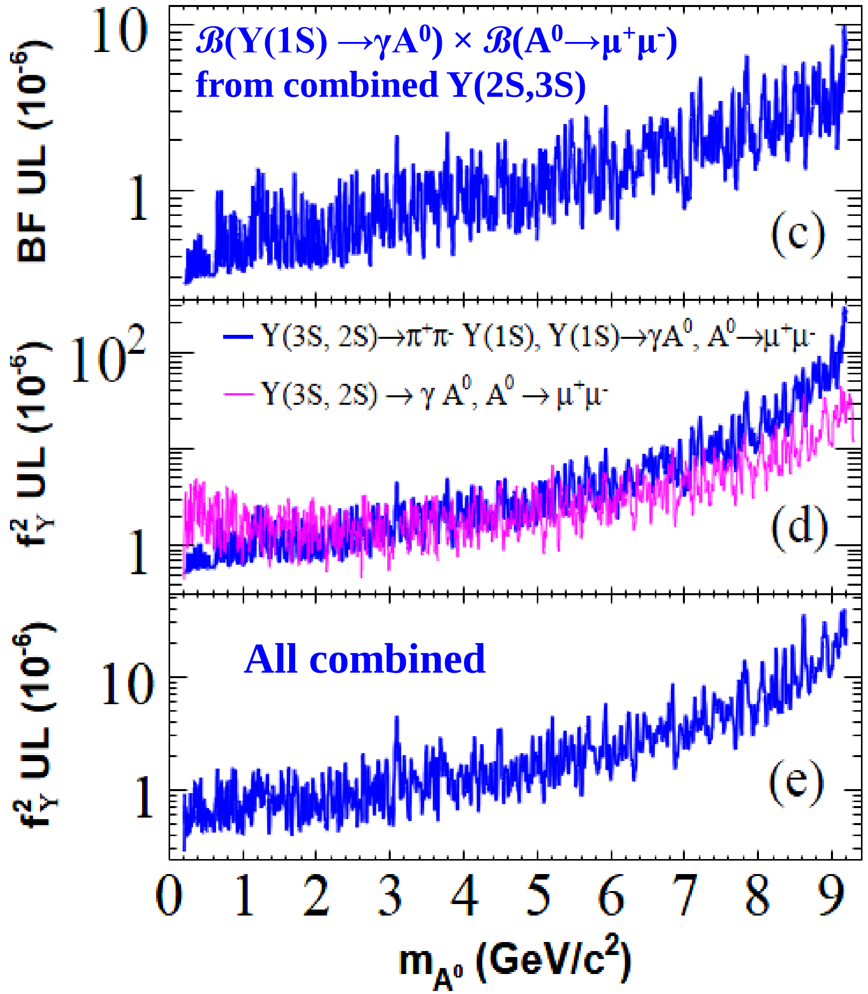
Effective Yukawa coupling of b-quarks to the A^0.

✓ $\mathcal{B}(\Upsilon(1S) \to \gamma A^0) \times \mathcal{B}(A^0 \to \mu^+\mu^-) < (0.28 - 9.7) \times 10^{-6}$ for $0.212 \le m_{A^0} \le 9.2$ GeV/c² @ 90% CL.

✓ 2-3 times improvement over previous BaBar limit [PRL 103, 081803 (2009)] for $m_{A^0} \le 1.2$ GeV/c².

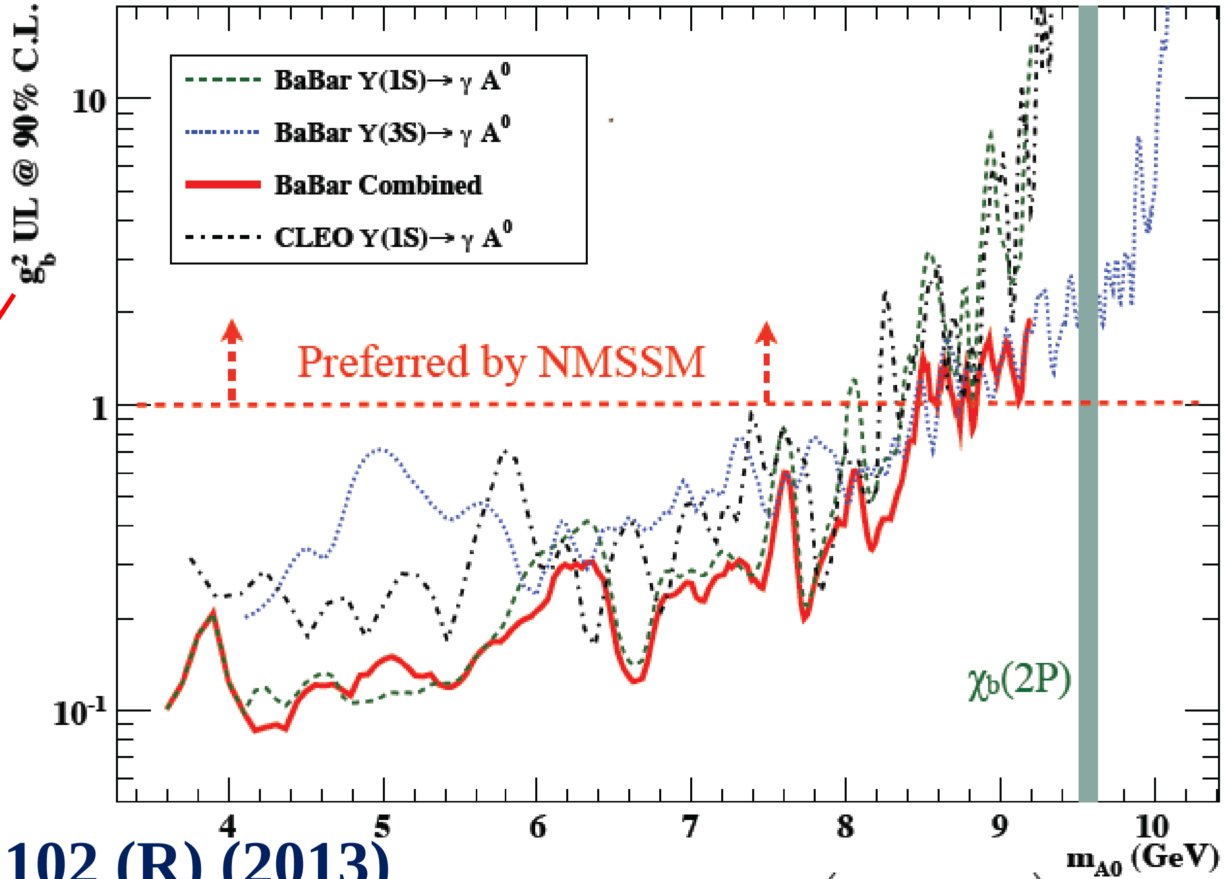
✓ $f_\Upsilon^2 \times \mathcal{B}(A^0 \to \mu^+\mu^-) < (0.29 - 40) \times 10^{-6}$ for GeV/c².

PRD 87, 031102 (R) (2013)



Searches of light Higgs at BaBar

Results: $A^0 \to \tau^+\tau^-$



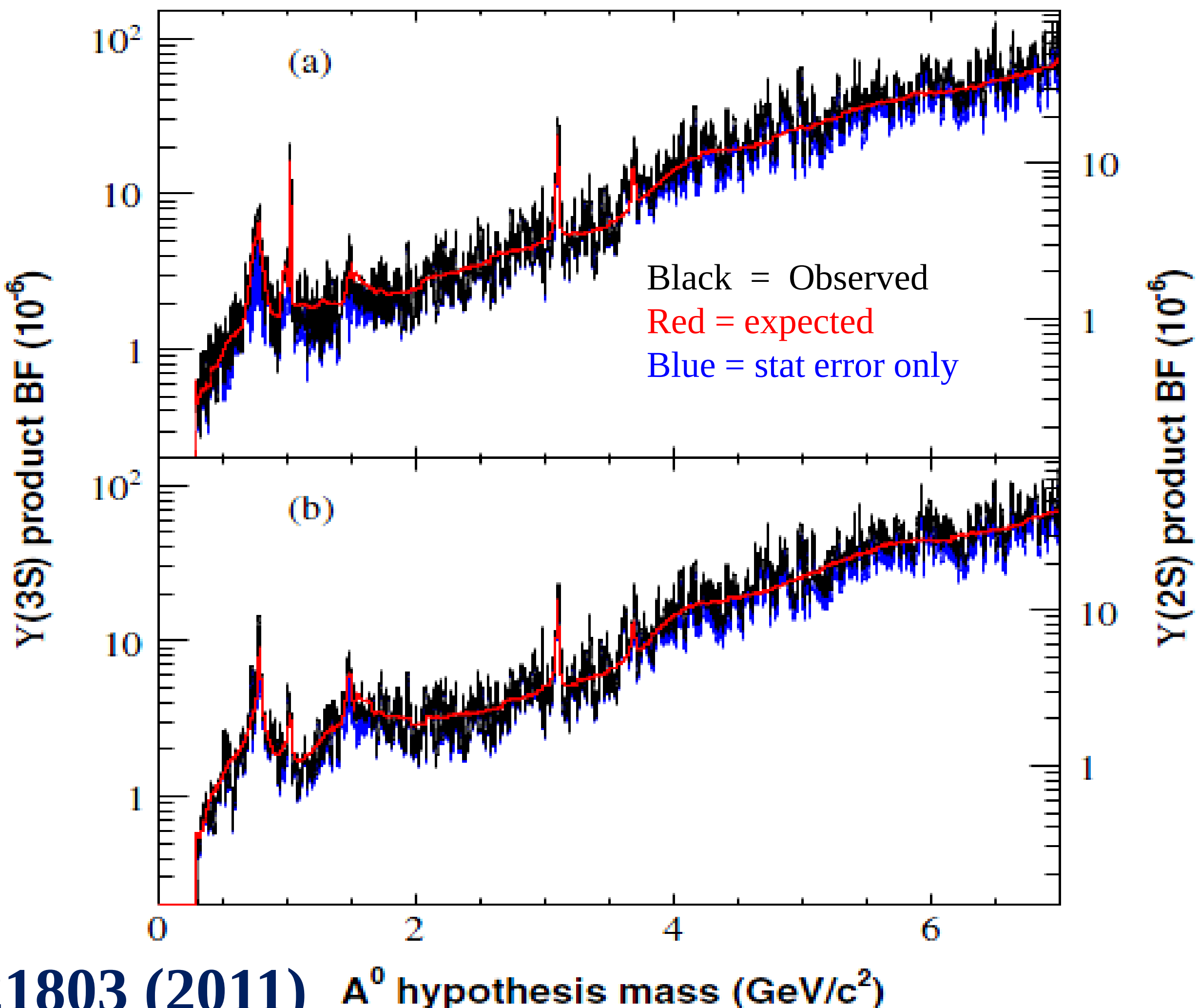
Yukawa coupling of b-quark to the A^0 ($\equiv \cos\theta_A \tan\beta$).

PRD 88, 071102 (R) (2013)

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

Searches of light Higgs at BaBar

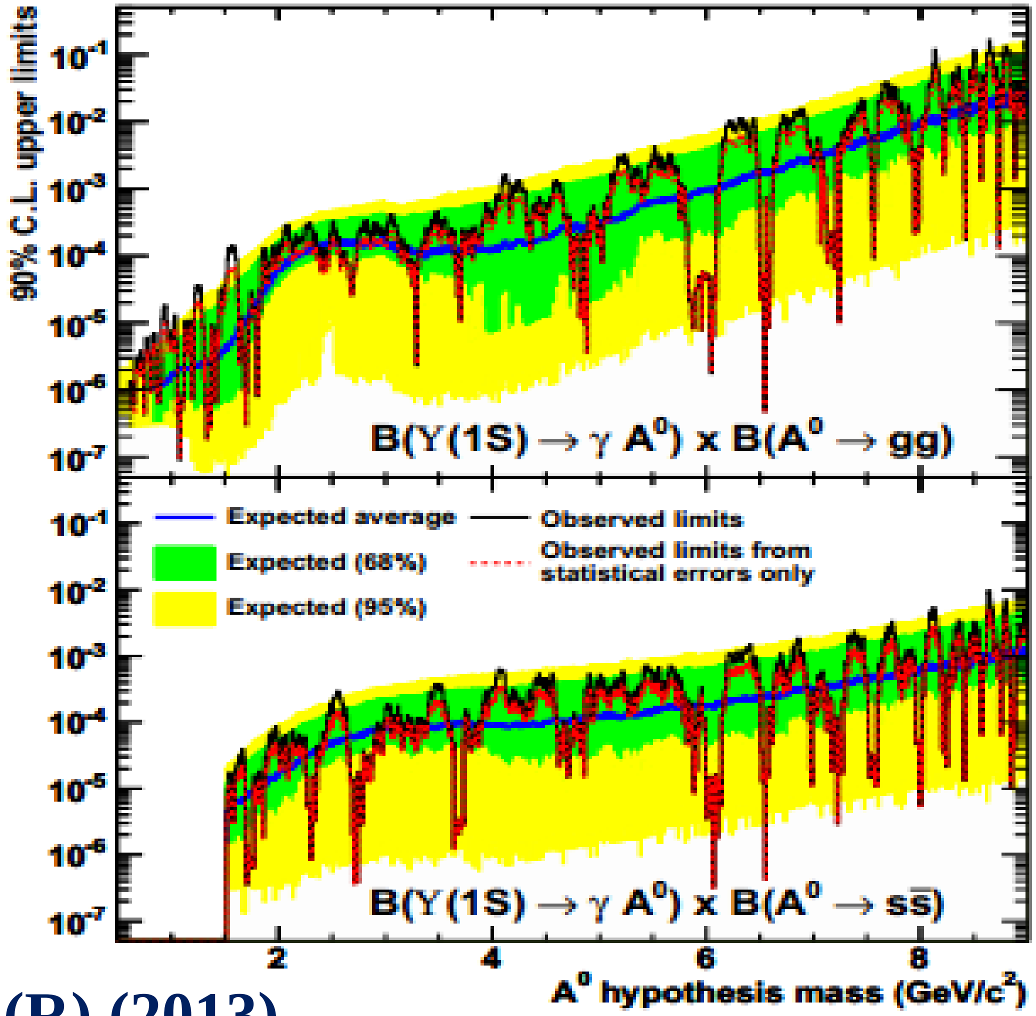
Results: $A^0 \rightarrow$ hadrons



PRL 107, 221803 (2011)

Searches of light Higgs at BaBar

Results: $A^0 \to gg$ or $s\bar{s}$



PRD 88, 031701 (R) (2013)