DIS2013 – Marseilles, France – April 23th 2013

Light Higgs and Dark Photon Searches at *BABAR*

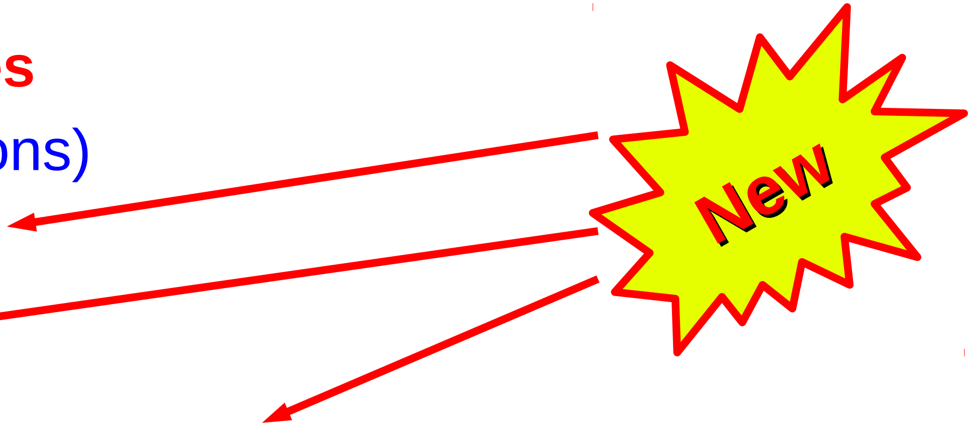
XXI International Workshop on Deep-Inelastic Scattering and Related Subjects

Alejandro Pérez
INFN – Sezione di Pisa
On behalf of the BABAR Collaboration

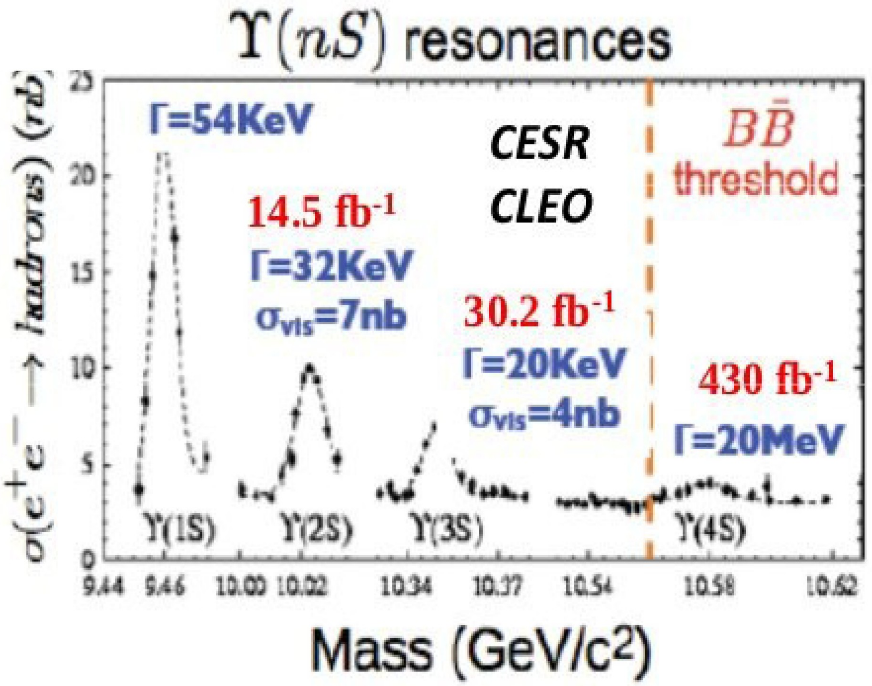
Outline

- The *BABAR* dataset

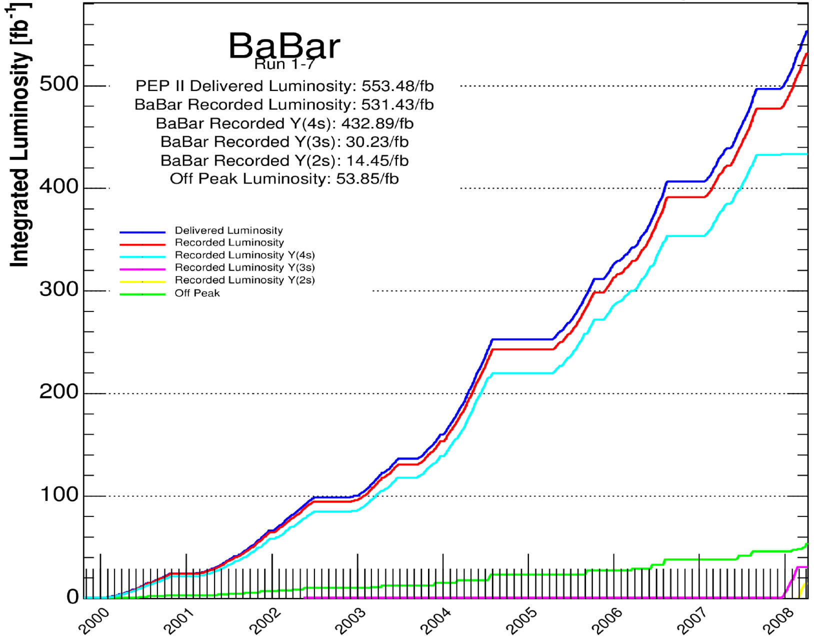
- Some highlights
  - **Light Higgs Boson searches**
    - $\Upsilon(2S,3S) \rightarrow \gamma A^0 (\rightarrow \text{hadrons})$
    - $\Upsilon(1S) \rightarrow \gamma A^0 (\rightarrow \tau^+\tau^-)$
    - $\Upsilon(1S) \rightarrow \gamma A^0 (\rightarrow \mu^+\mu^-)$
  - **Dark Higgs searches**
    - $e^+e^- \rightarrow A'h'(\rightarrow A'A');\ A' \rightarrow e^+e^-,\ A' \rightarrow \mu^+\mu^-,\ A' \rightarrow \pi^+\pi^-$



***BABAR* dataset**



7 Runs over the course of 9 years



Run7: data at Υ(2S) and Υ(3S)

- Experiment was able to rapidly adapt trigger for new experimental environment: low-multiplicity and low-energy-photons

Total data sample ~531 fb^{-1}

- 471x10^{6} Υ(4S) decays
- 120x10^{6} Υ(3S) decays
- 98x10^{6} Υ(2S) decays
- 18x10^{6} Υ(1S) from $\Upsilon(2S)\rightarrow\pi^{+}\pi^{-}\Upsilon(1S)$

Light Higgs Searches

Motivation

- MSSM model introduces 2 Higgs doublets: h, H (CP-even light and heavy), A (CP-odd), $H^{\pm}$ (charged partners)
- Next to MSSM (NMSSM) includes the possibility of a light Higgs boson to solve EW fine tuning: one CP-odd and one CP-even Higgs and one neutralino
- Mixing can produce light CP-odd Higgs $A^0 = A_{MSSM} \cos(\theta_A) + A_{singlet} \sin(\theta_A)$
- If $m_{A0} < 2m_b$, models not excluded by LEP
- Radiative decays $\Upsilon(nS) \to \gamma A^0$ (n = 1,2,3) offer an ideal environment to search for light Higgs:
  - Fully reconstructed: $A^0 \to \mu^+\mu^-$
  - Partially reconstructed: $A^0 \to \tau^+\tau^-$, $q\bar{q}$

Can have large BR!

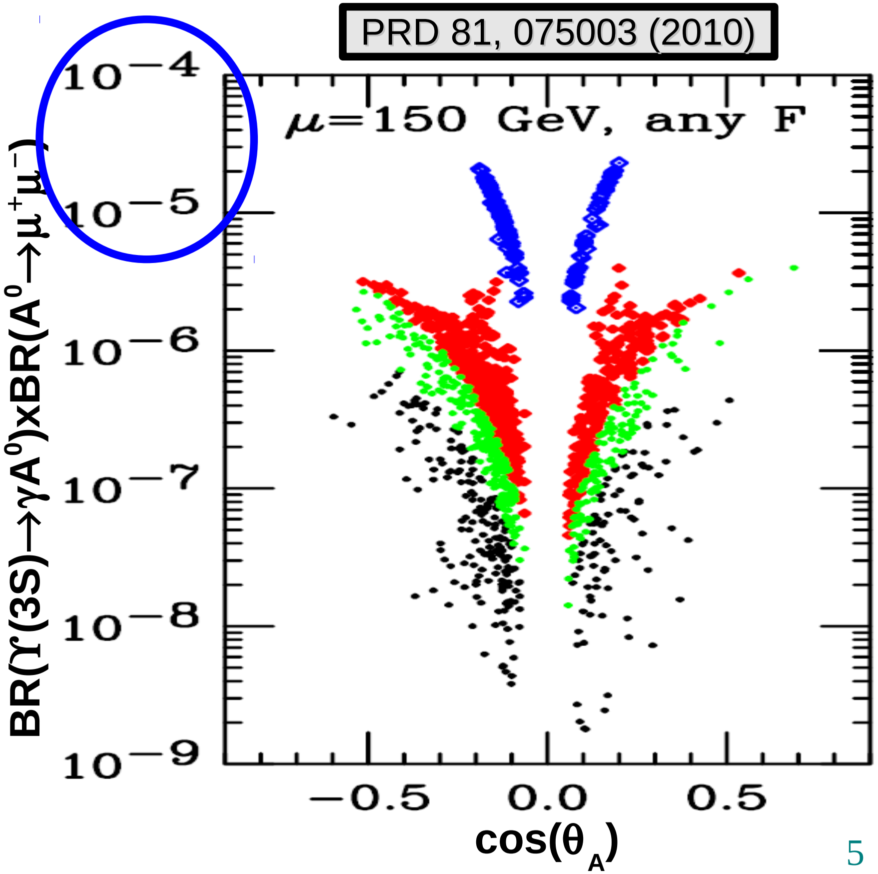
$0 < m_{A0} < 2m_\tau$

$2m_\tau < m_{A0} < 7.5$ GeV/c^2

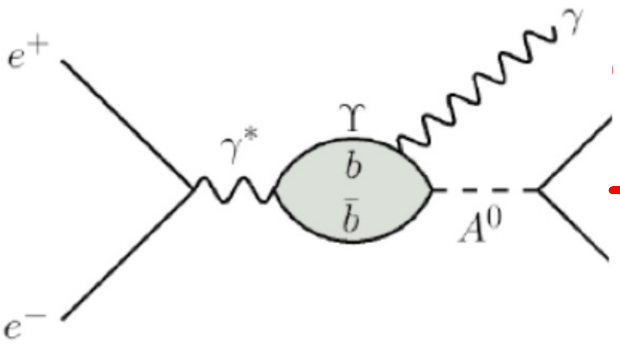
$7.5 < m_{A0} < 8.8$ GeV/c^2

$8.8 < m_{A0} < 9.2$ GeV/c^2

PRD 81, 075003 (2010)



Motivation



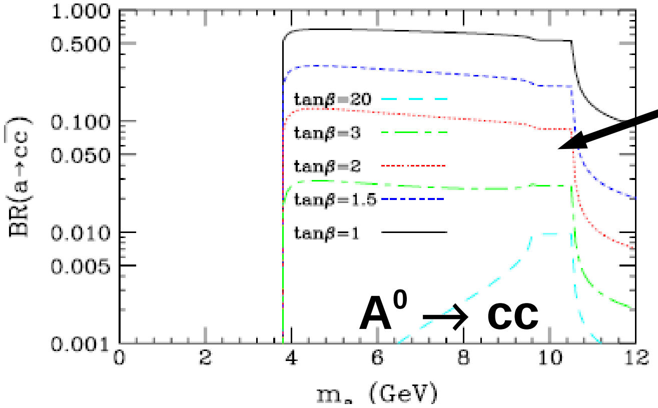
A^0 decay products depend on $m(A^0)$ and $\tan\beta$

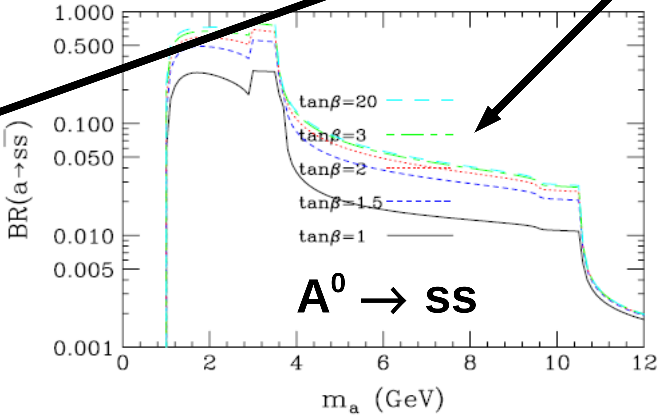
- $A^0 \to$ invisible
- $A^0 \to \tau^+\tau^-$
- $A^0 \to \mu^+\mu^-$
- $A^0 \to$ hadrons

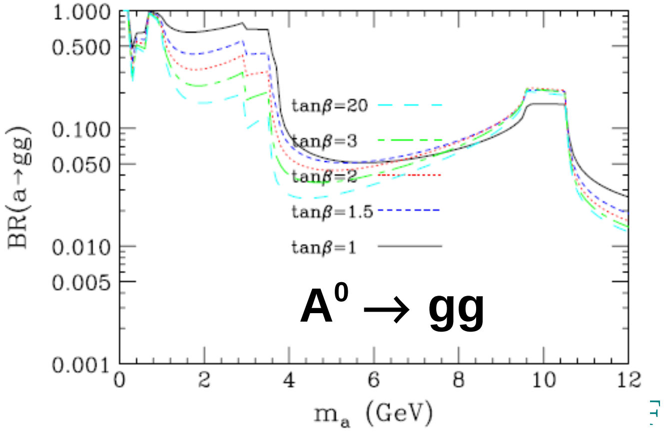
$B(A^0 \to f\bar{f}) \propto m_f^2/\tan^2\beta$ up-type fermions

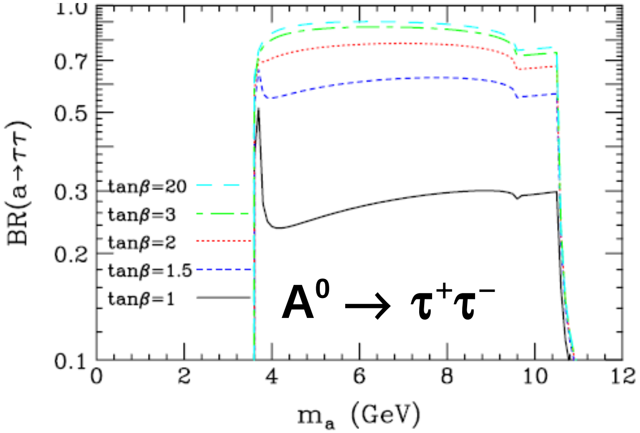
$B(A^0 \to f\bar{f}) \propto m_f^2\tan^2\beta$ down-type fermions

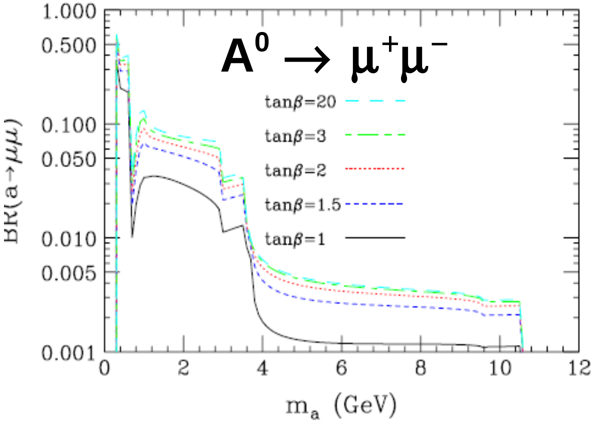
PRD 81, 075003 (2010)







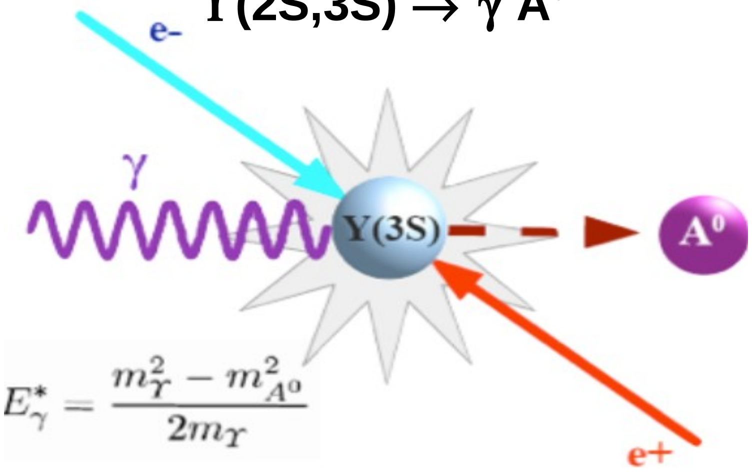




Light Higgs Searches at BaBar

$\Upsilon(2S)$ and $\Upsilon(3S)$ radiative decays

$\Upsilon(2S,3S) \rightarrow \gamma\ A^0$



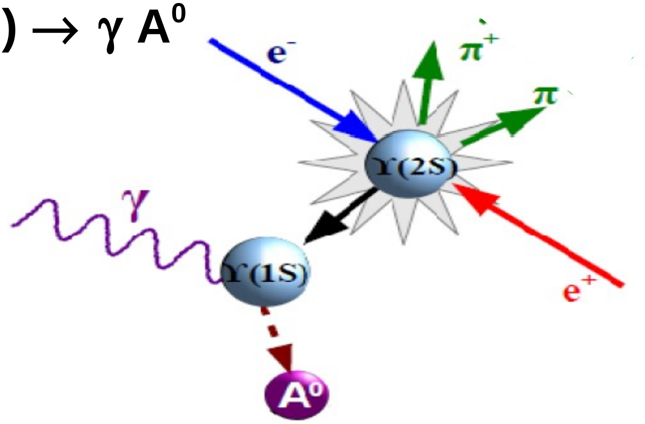
$$E^*_\gamma = \frac{m^2_\Upsilon - m^2_{A^0}}{2m_\Upsilon}$$

- Search for monochromatic photon in the recoil mass spectrum
- **$A^0 \rightarrow \mu^+\mu^-$** PRL 103, 081803 (2009)
- **$A^0 \rightarrow \tau^+\tau^-$** PRL 103, 181801 (2009)
- **$A^0 \rightarrow$ had** PRL 107, 221803 (2011)

This Talk

$\Upsilon(1S)$ radiative decays

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



- $\Upsilon(1S)$ sample by tagging the $\pi^+\pi^-$ in $\Upsilon(2S,3S) \rightarrow \pi^+\pi^-\Upsilon(1S)$ transitions
- Reduce backgrounds using missing mass & Di-pion recoil mass

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

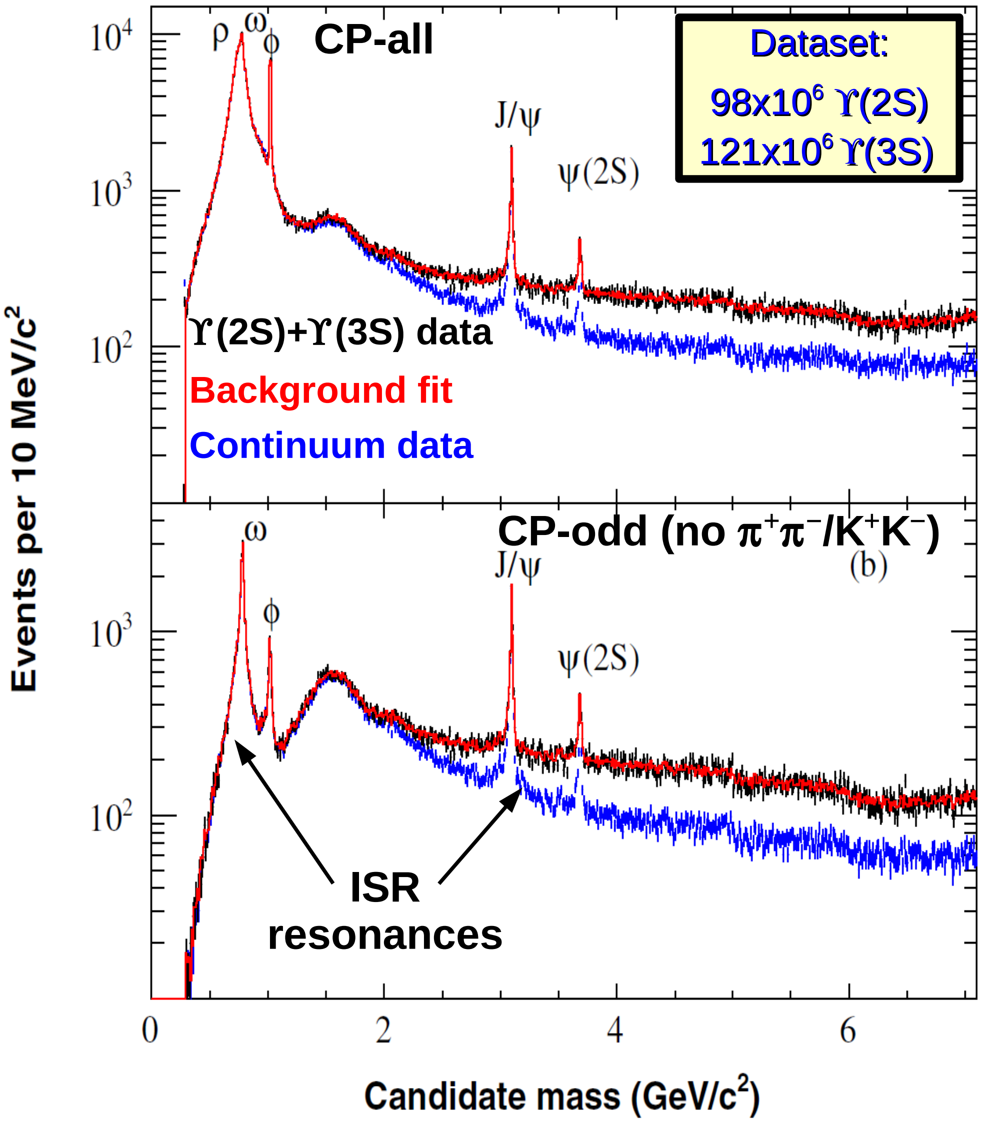
$$m^2_X = (P_{e^+e^-} - P_{\pi\pi} - P_\gamma)^2$$ (Missing mass)

- **$A^0 \rightarrow$ invisible (light dark matter)** PRL 107, 021804 (2011)
- **$A^0 \rightarrow \mu^+\mu^-$** PRD 87, 031102 (2013)
- **$A^0 \rightarrow \tau^+\tau^-$** arXiv: 1210.5669 (preliminary)

$\Upsilon(2S,3S) \rightarrow \gamma A^0$, $A^0 \rightarrow$ hadrons

Phys. Rev. Lett. 107, 221803 (2011)

- First broad-band search for hadronic A^0 decays
- Reconstruct the decay chain (beam-energy-constraint to improve m(A^0) resolution: 3 - 26MeV/c^2)
    - Photon with > 2.5 (2.2) GeV in 3S (2S) data, π^0-veto
    - at least two tracks in A^0 candidate decay
- Reject Bhabha & di-μ with PID
- Two parallel analyses:
    - CP-odd (only CP-odd final states)
    - CP-all (all final states)
- Fit and scan (many points) A^0 mass spectrum including several background components:
    - Continuum
    - Non-resonant Y decays (spline)
    - Resonant Y decays (5-16 resonances)



$\Upsilon(2S,3S) \to \gamma A^0$, $A^0 \to$ hadrons

Phys. Rev. Lett. 107, 221803 (2011)

Dataset:
98×10^6 $\Upsilon(2S)$
121×10^6 $\Upsilon(3S)$

Results:

- Most significant signals ($N_{sig}/\sigma(N_{sig})$):
  - CP-all: 2.9σ at 3.107 GeV/c^2
  - CP-odd: 3.1σ at 4.727 GeV/c^2

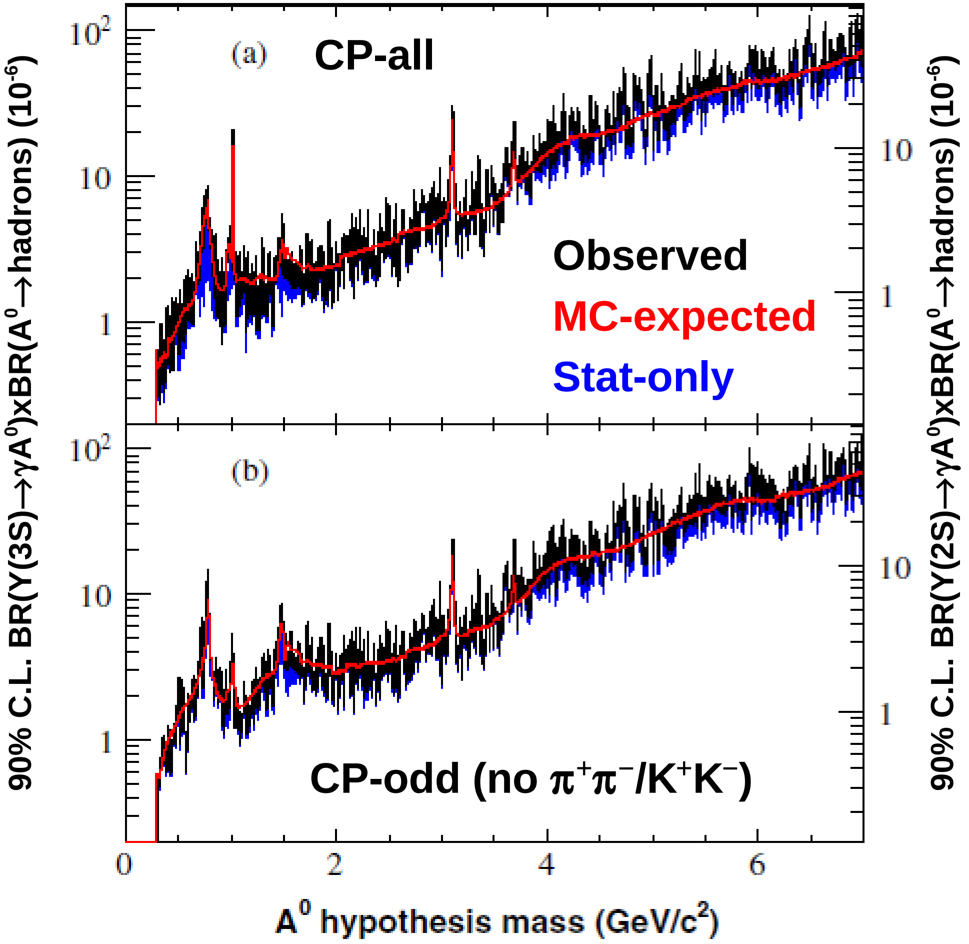
  (Probabilities of 33% and 62%)

⇒ No evidence of A^0 production is found in the $\Upsilon(2S,3S)$ data.

- 90% upper limits are calculated on $B(\Upsilon(2S)\to\gamma A^0)\times B(A^0\to\text{hadrons})$ and $B(\Upsilon(3S)\to\gamma A^0)\times B(A^0\to\text{hadrons})$ assuming the same matrix element for both 2S and 3S decays

$B(\Upsilon(2S,3S)\to\gamma A^0)\times B(A^0\to\text{hadrons})$ UL is $(0.1 – 8.0)\times10^{-5}$ @ 90% C.L. for $0.3 < m(A^0) < 7.0$ GeV/c^2

Product of BR UL vs A^0 mass



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

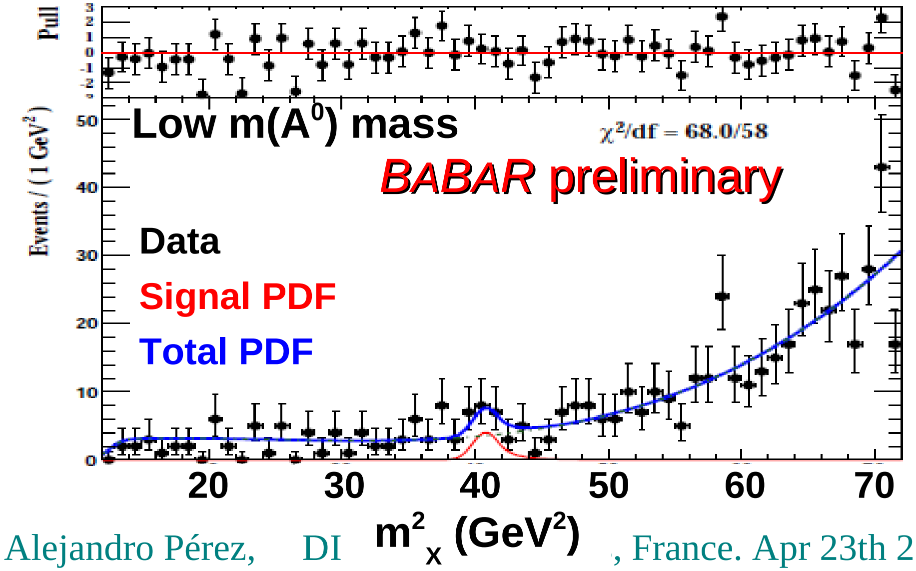
ArXiv: 1210.5669
BABAR preliminary

Dataset:
98×10^6 $\Upsilon(2S)$

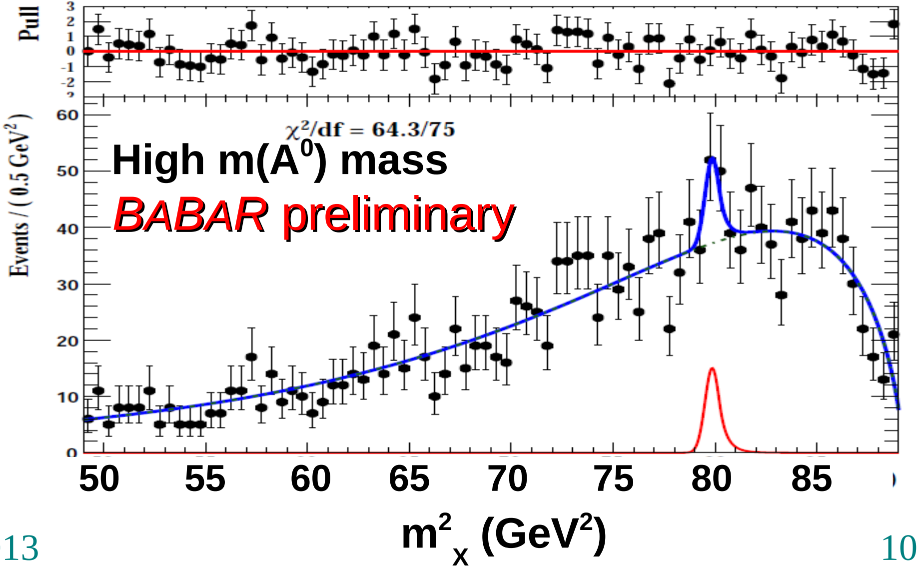
- Mono-chromatic photon in $\Upsilon(1S)$ rest frame
- $\tau^\pm$ pairs from $\tau \to \mu\nu\nu$, $\tau \to e\nu\nu$, $\tau \to \pi\nu$
- Fit and scan (many points) for narrow peak on photon recoil mass in $\Upsilon(1S)$ system (A^0 mass resolution 18-32 MeV/c^2)
- Two mass regions: low and high (different optimizations)
- Fit largest upward fluctuation: 2.7σ (3.0σ) @ 6.36 (8.93) GeV/c^2 for low-(high-) mass
- Pseudo-experiments: 7.5% have 3.0σ fluctuation ⇒ no significant signal found

$$m_X^2 = (P_{e^+e^-} - P_{\pi\pi} - P_\gamma)^2$$

Largest upward fluctuation: low-mass



Largest upward fluctuation: high-mass

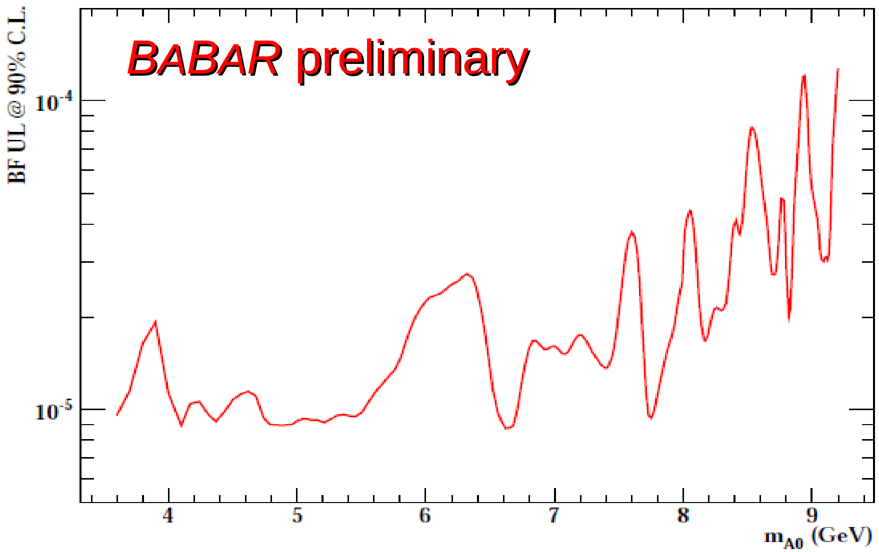


$\Upsilon(1S) \to \gamma A^0, A^0 \to \tau^+\tau^-$

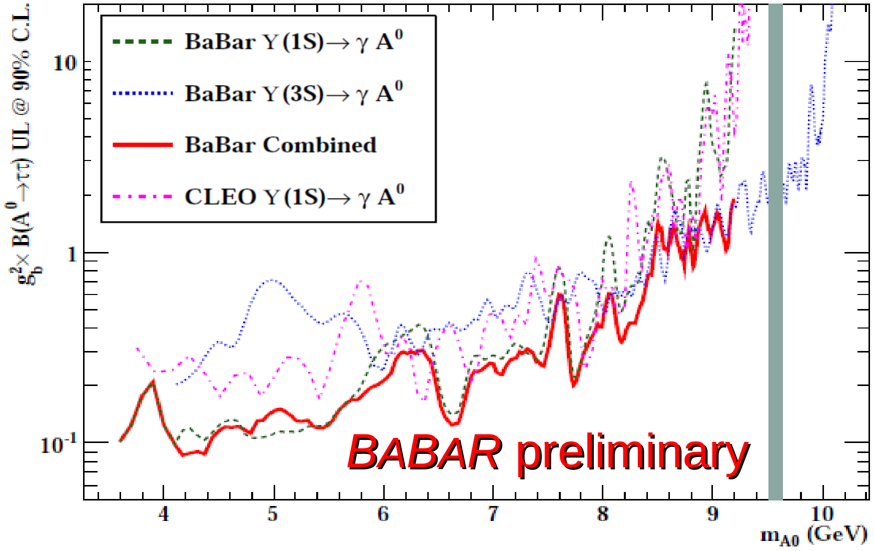
ArXiv: 1210.5669
BABAR preliminary

Dataset:
98×10^6 $\Upsilon(2S)$

Product of BR UL @ 90% vs m(A^0)



g^2_bxBR($A^0\to\tau^+\tau^-$) UL @ 90% vs m(A^0)



$B(\Upsilon(1S)\to\gamma A^0)\times B(A^0\to\tau^+\tau^-)$
UL is $(0.9 - 13)\times10^{-5}$ @ 90% C.L.
for $3.6 < m(A^0) < 9.2$ GeV/c^2

- Set constraint on g^2_bxBR($A^0\to\tau^+\tau^-$) using Yukawa coupling of b-quark to A^0

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

and combine with previous BaBar result $\Upsilon(3S)\to\gamma A^0$; $A^0\to\tau^+\tau^-$

g^2_bxB($A^0\to\tau^+\tau^-$)
UL is (0.09 – 1.9) @ 90% C.L.
for m(A^0) < 9.2 GeV/c^2

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

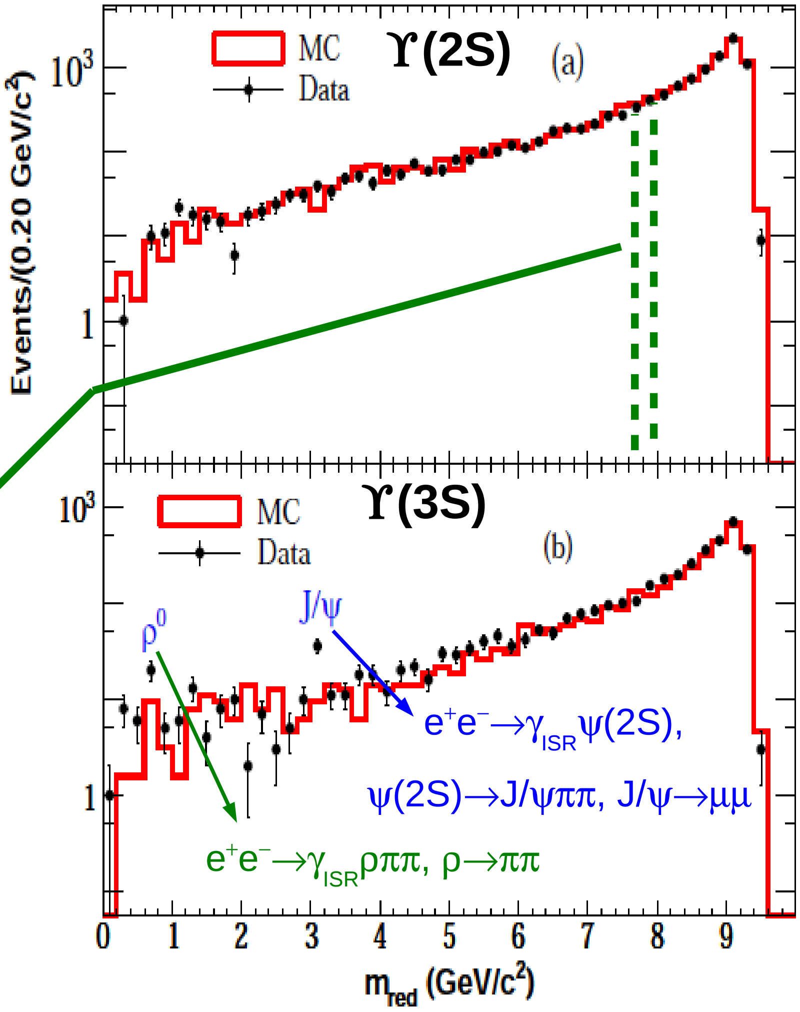
Phys. Rev. D
87, 031102 (2013)

Dataset:
92.8×10^6 $\Upsilon(2S)$
116.8×10^6 $\Upsilon(3S)$

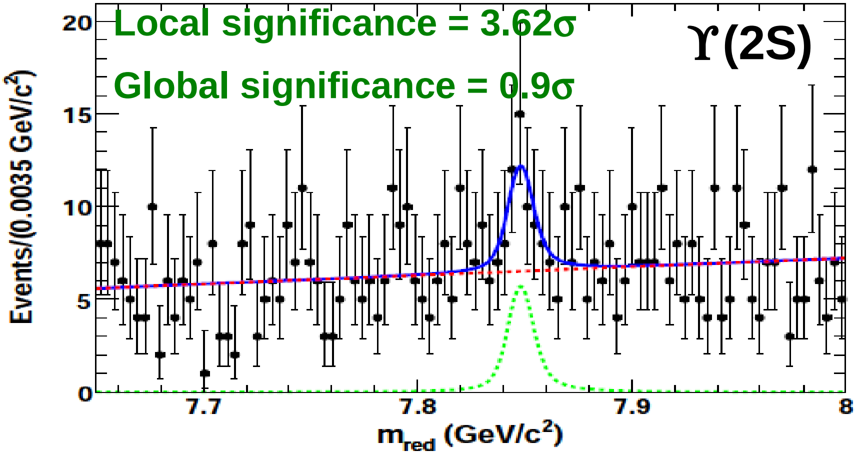
- Use four charged tracks and a single photon with $E^*_\gamma > 0.2$GeV
- Muon ID for at least one μ candidate
- Beam-energy-constraint improves the A^0 mass resolution (2-9 MeV/c^2)
- Dominant background: $\Upsilon(2S,3S) \to \pi^+\pi\Upsilon(1S)$; $\Upsilon(1S) \to (\gamma)\mu^+\mu^-$ non-resonant
- Fit and scan (many points) for a narrow peak to the reduced di-μ mass
- **No evidence for A^0 production is found**

reduced di-μ mass

$$m_{\rm red} = \sqrt{m^2_{\mu^+\mu^-} - 4m^2_{\mu}}$$



Largest upward fluctuation

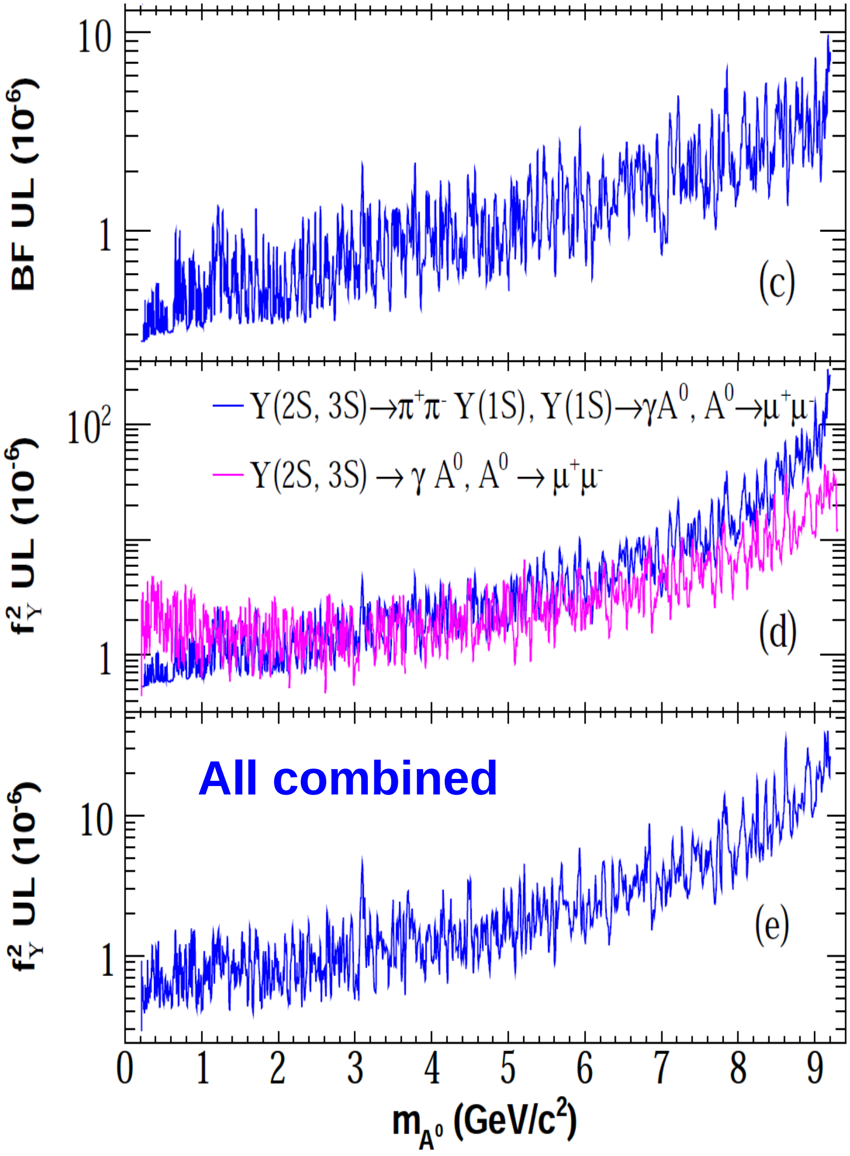


$\Upsilon(1S) \to \gamma A^0, A^0 \to \mu^+\mu^-$

Phys. Rev. D 87, 031102 (2013)

Dataset:
92.8×10^6 $\Upsilon(2S)$
116.8×10^6 $\Upsilon(3S)$

Product of BR UL @ 90% vs m(A^0)



$B(\Upsilon(1S)\to\gamma A^0)\times B(A^0\to\mu^+\mu^-)$
UL is $(0.28 – 9.7)\times10^{-6}$ @ 90% C.L.
for $0.212 < m(A^0) < 9.2$ GeV/c^2

- Set constrain on $f^2_\Upsilon \times BR(A^0\to\mu^+\mu^-)$ using

Effective Yukawa coupling of b-quark to A^0

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

and combine with previous BaBar result $\Upsilon(2S,3S)\to\gamma A^0$; $A^0\to\mu^+\mu^-$

$f^2_{b\Upsilon}\times B(A^0\to\mu^+\mu^-)$
UL is $(0.29 – 40)\times10^{-6}$ @ 90% C.L.
for $m(A^0) < 9.2$ GeV/c^2

Some exclusions based on BaBar results

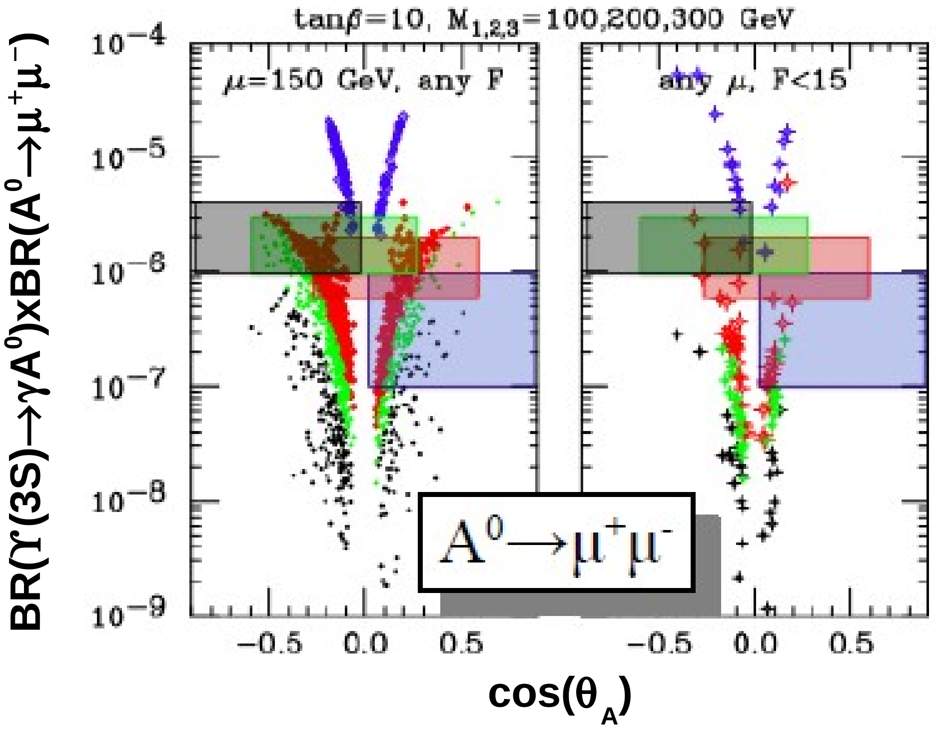
- Boxes: BaBar maximum to minimum exclusions (we exclude the regions above the boxes)
- Additional constraints with Υ(1S) radiative decays

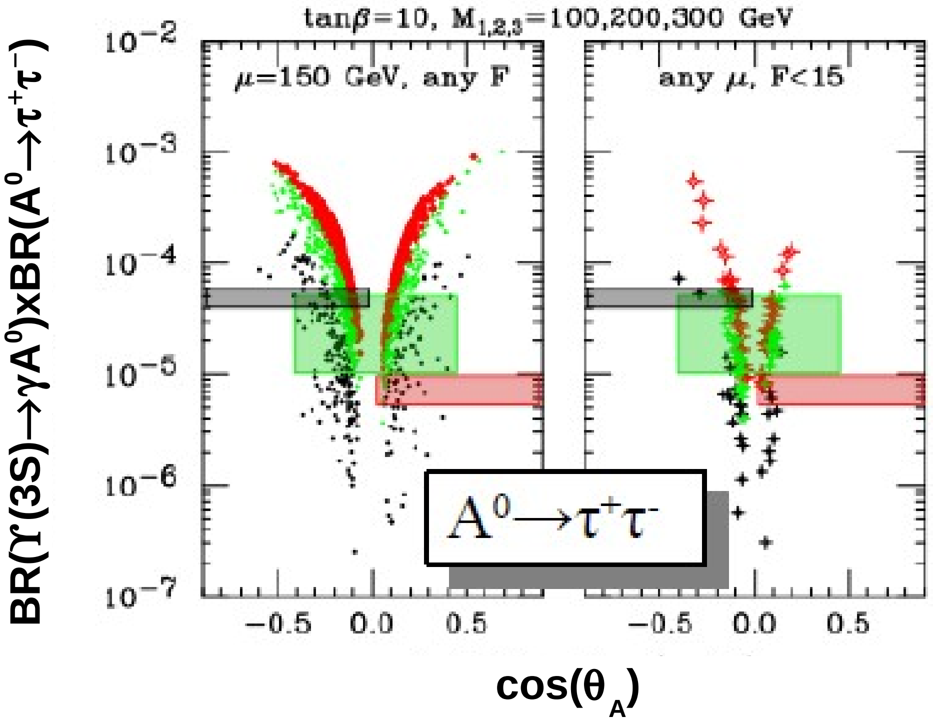
$0 < m_{A0} < 2m_\tau$

$2m_\tau < m_{A0} < 7.5$ GeV/c^2

$7.5 < m_{A0} < 8.8$ GeV/c^2

$8.8 < m_{A0} < 9.2$ GeV/c^2

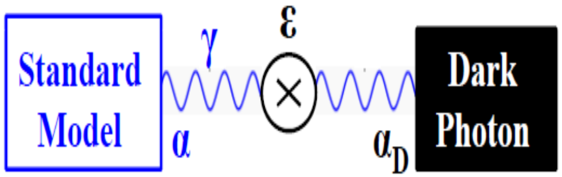




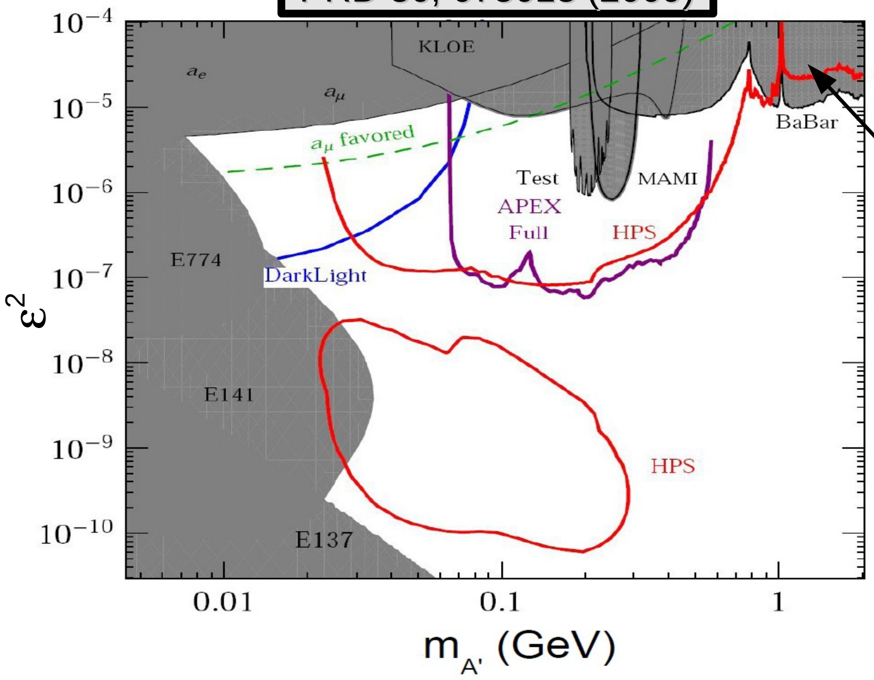
Dark Higgs Searches

Motivation

- Evidence for dark matter is now overwhelming: 511 keV γ–ray excess (INTEGRAL), e^+ excess (PAMELA, ATIC, FERMI, HESS, AMS)
- New models introduce hidden dark sector with $U(1)_{DARK}$ gauge group
- **O(TeV) dark matter → O(GeV) dark photon (A') → SM fermions** (lepton pairs, protons kinematically forbidden)
- Coupling to SM particles via kinetic mixing term $\varepsilon F^{\mu\nu} B_{\mu\nu}$
- A' **coupling to SM fermions** is characterized by $\alpha_D \varepsilon^2$



PRD 80, 075018 (2009)



- A dark photon can be readily produced in $e^+e^- \rightarrow \gamma A' (\rightarrow l^+l^-/q\bar{q})$.
- Limits on $e^+e^- \rightarrow \Upsilon (2S,3S) \rightarrow \gamma \mu^+ \mu^-$ can be reinterpreted as limits on dark photon production
- A' obtains mass via Higgs mechanism, adding a dark Higgs boson (h') to the theory

▨ Excluded region

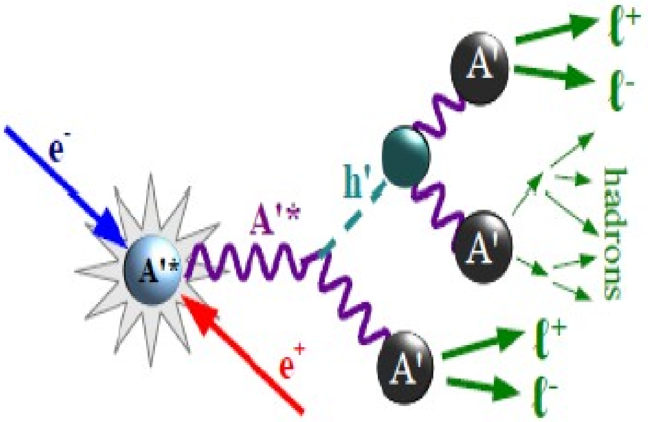
▬ Planned experiments

▬ g-2 "favored region"

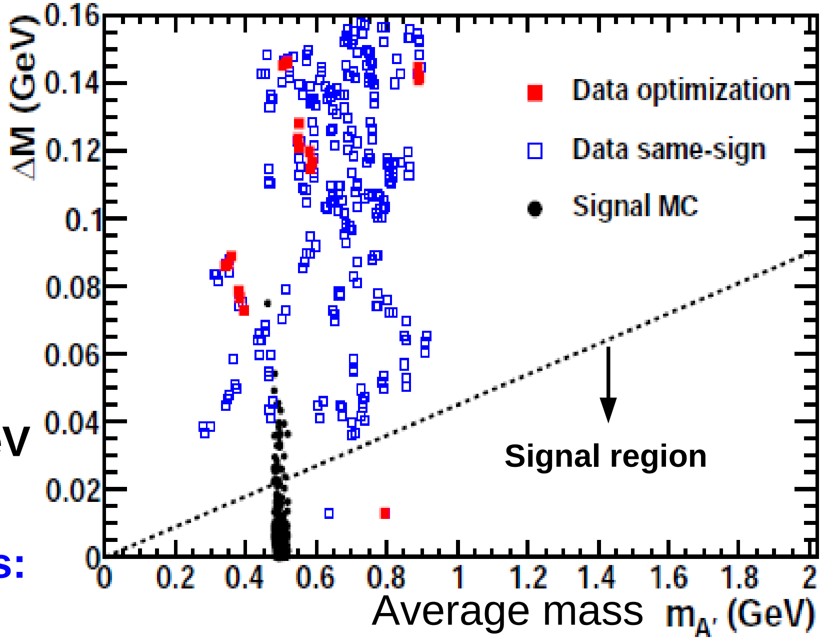
Dark Higgs boson h' search

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

- Search for the "Higgs-strahlung" process
  $e^+e^- \rightarrow A'^* \rightarrow h'\,A',\ h' \rightarrow A'A'$
- Selection using full dataset Υ(4S,3S,2S) of $516 fb^{-1}$
  - Exclusive: fully reconstructed 3 dark photons
    - $A' \rightarrow e^+e^-, \mu^+\mu^-, \pi^+\pi^-$ (using PID);
    - All tracks total invariant mass > $0.95\sqrt{s}$
  - Partial reconstruction: 2A' decaying to leptons and 1A' to hadrons.
    - 4μ + X or $2\mu 2e$ + X
    - 4-momentum of 3rd A' $p_3 = p_{ee} - p_1 - p_2$
  - Require the 3 A' candidates to have similar masses (ΔM = Largest mass difference)



2e4π final state



Signal MC: m(h') = 3GeV, m(A') = 0.5GeV

10% of data used for optimization

Same sign data for background studies: $(e^+e^-)(\mu^+\mu^+)(\mu^-\mu^-)$ and $(e^+e^+)(\mu^-\mu^-)$+X

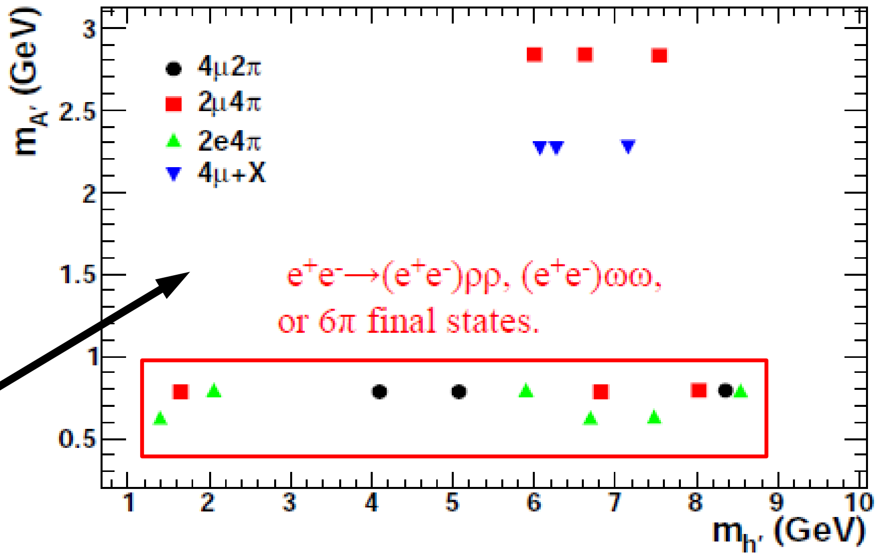
Dark Higgs boson h' search

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

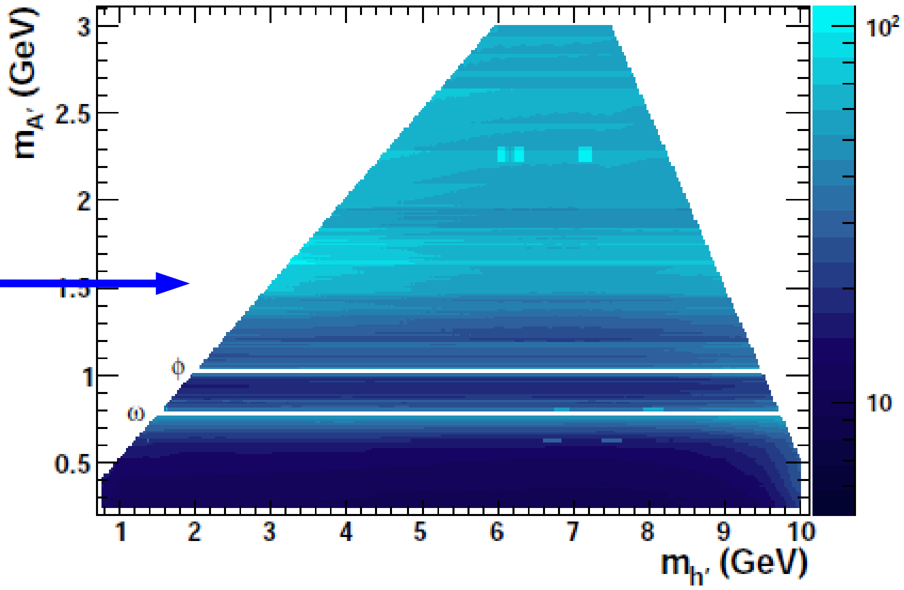
Results:

- Perform dark Higgs searches in range $0.8 < m_{h'} < 10.0$ GeV/c^2 and $0.23 < m_{A'} < 3.0$ GeV/c^2 with $m_{h'} > 2m_{A'}$
- Six events are selected from the full BaBar dataset: 1x4μ2π, 2x2μ4π, 1x2e4π, 2x2μX
- No events in the 6 leptons final state
- Three entries for each event

  ⇒ 3 possible assignment of h'→A'A'
- 90% C.L. Bayesian UL on x-section computed with uniform prior



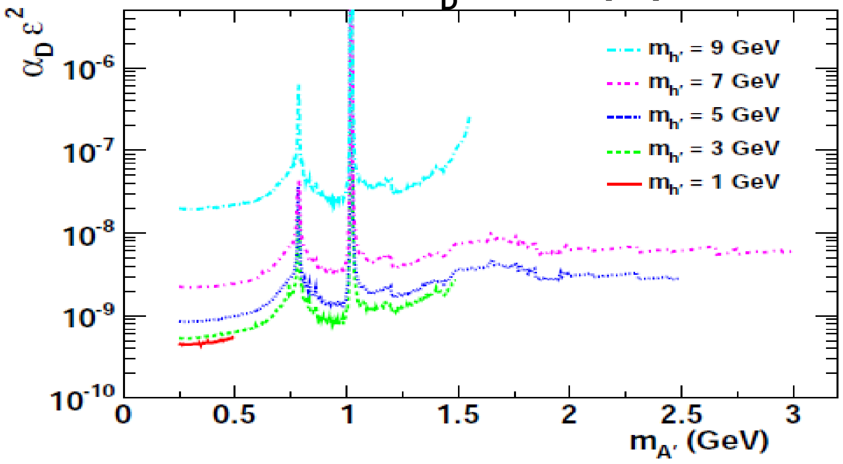
Cross section upper limit (ab)



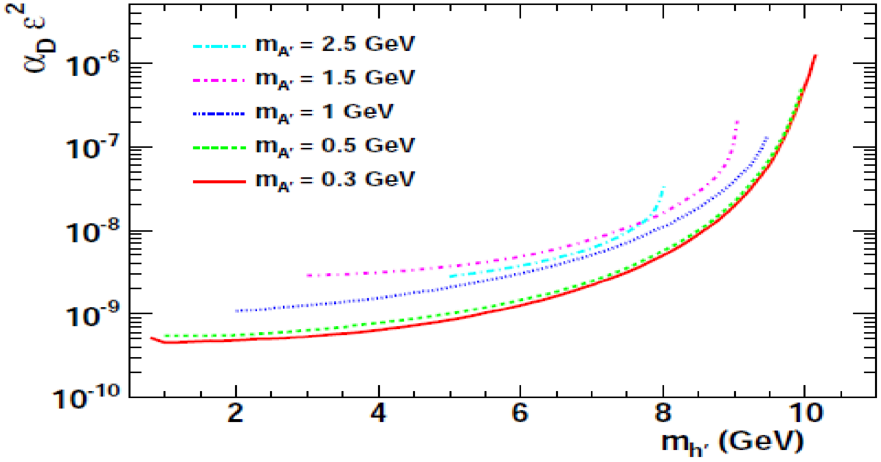
Dark Higgs boson h' search

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

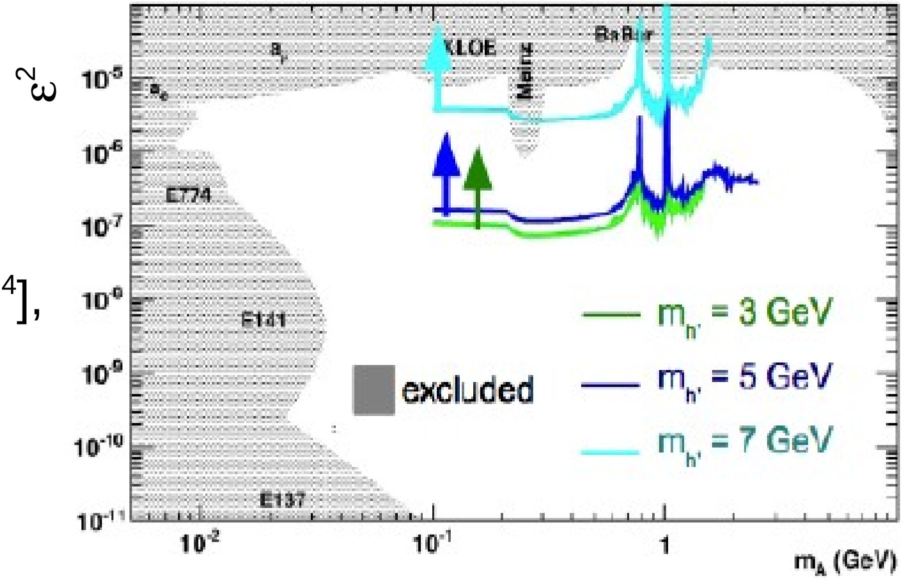
UL on $\alpha_D \varepsilon^2$ vs m(A')



UL on $\alpha_D \varepsilon^2$ vs m(h')



Limit on ε^2 assuming $\alpha_D = \alpha$



- $\alpha_D \varepsilon^2$ < few x 10^{-10} @ 90% C.L.
- $\alpha_D = g^2_D/4\pi$, g_D = dark sector coupling constant, ε = mixing strength
- Assuming $\alpha_D = \alpha$, limits on ε are [10^{-3} , 10^{-4}], about 10x better than previous measurement

Conclusions

- *BABAR* last data collected in 2008, but collaboration still very active
- *BABAR* continues to produce interesting and competitive results

- Light Higgs favoured by NMSSM
  - Comprehensive searches using a variety of channels:

    $BR(\Upsilon(2S,3S)\rightarrow\gamma A^0(\rightarrow \text{hadrons})) < (0.1 - 8.0)\times10^{-5}$ @ 90% C.L.

    $BR(\Upsilon(1S)\rightarrow\gamma A^0(\rightarrow\mu^+\mu^-)) < (0.28 - 9.7)\times10^{-6}$ @ 90% C.L.

    $BR(\Upsilon(1S)\rightarrow\gamma A^0(\rightarrow\tau^+\tau^-)) < (0.9 - 13.0)\times10^{-5}$ @ 90% C.L.

    New results
  - **(Better constraints than CLEO)**
  - Significant constraint NMSSM parameter space!
- Dark Higgs suggested by dark sector models
  - Search $e^+e^-\rightarrow A'^*\rightarrow A'h'(\rightarrow A'A')$:

    $\alpha_D\varepsilon^2 <$ few $\times10^{-10}$ @ 90% C.L. If $\alpha_D = \alpha$, constraint on ε^2 10x better than previous measurements

- Ongoing analyses in progress!

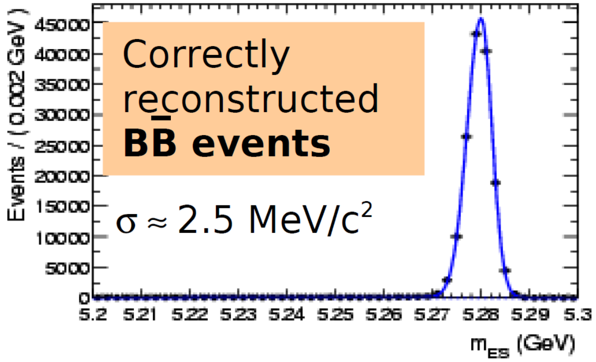
Backup

Experimental Issues

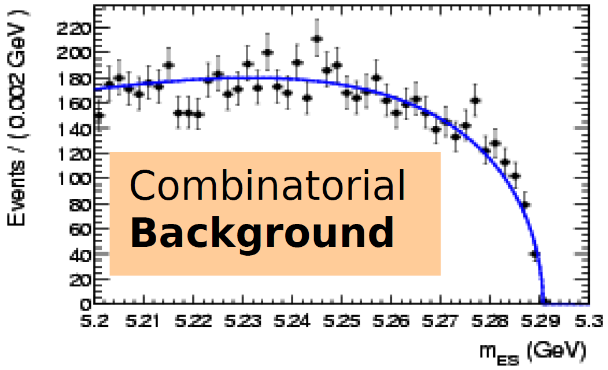
- Small S/B ratio, mostly continuum ($e^+e^- \rightarrow q\bar{q}$, $q \neq b$) background.
- Use kinematical and event-shape variables to discriminate:

Beam-energy substituted mass

$$m_{ES} = \sqrt{E^{*\,2}_{beam} - p^{*\,2}_{B}}$$

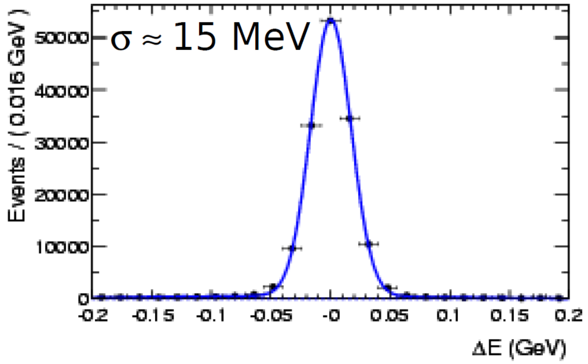

Correctly reconstructed **$B\bar{B}$ events**

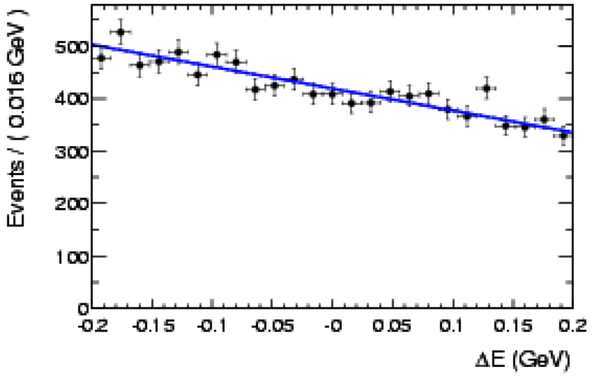
$\sigma \approx 2.5$ MeV/c^2


Combinatorial **Background**

Energy difference

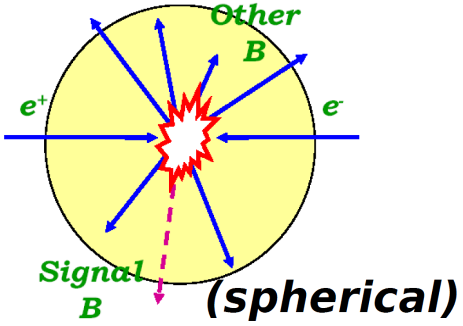
$$\Delta E = E^*_B - E^*_{beam}$$


$\sigma \approx 15$ MeV

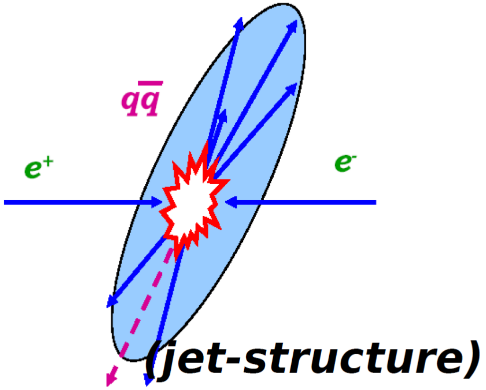


Event topology

(multivariate methods)

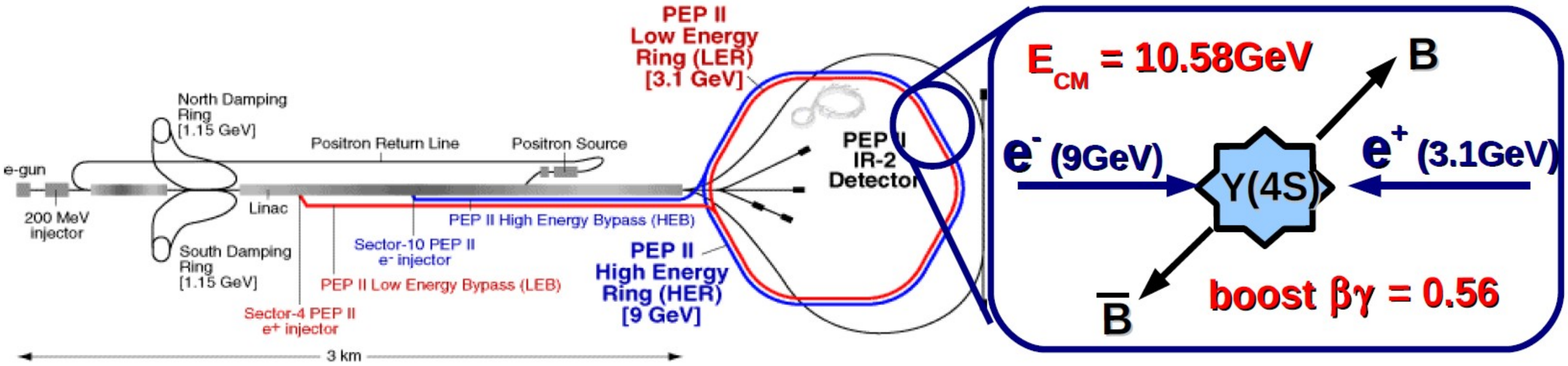


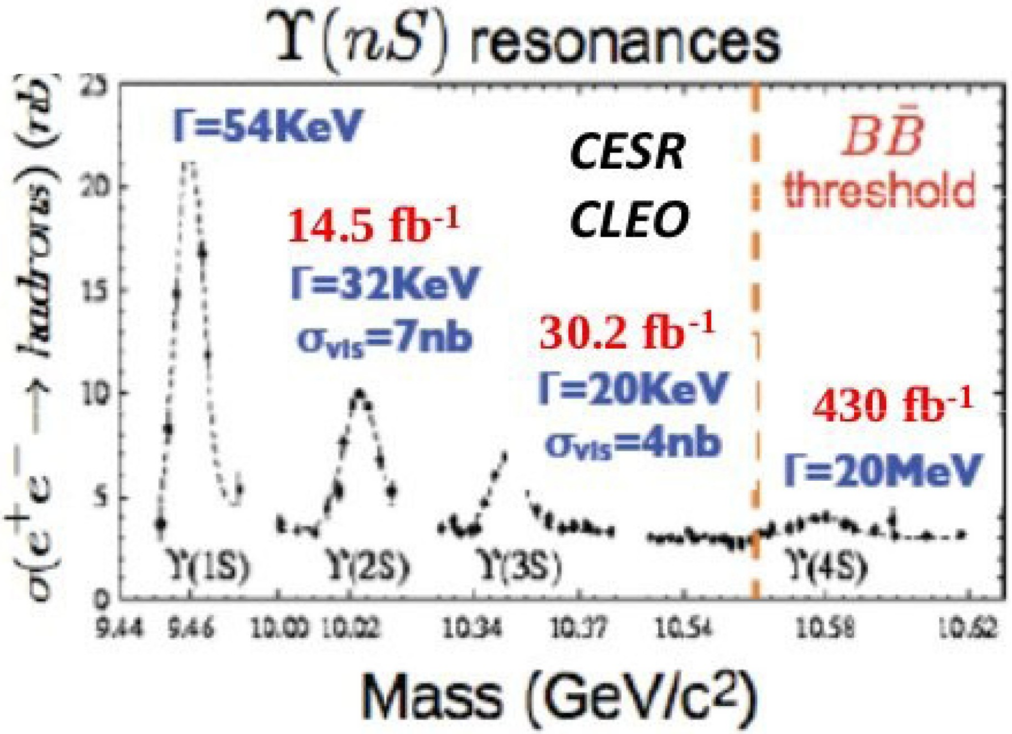
(spherical)

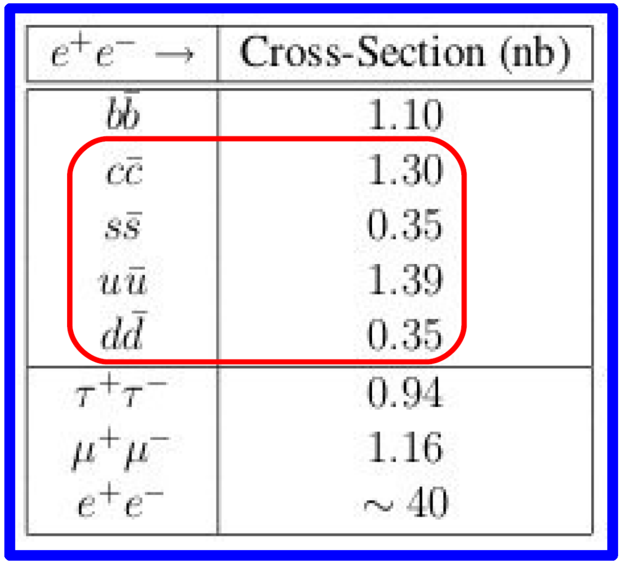


(jet-structure)

PEP-II: a B factory at SLAC





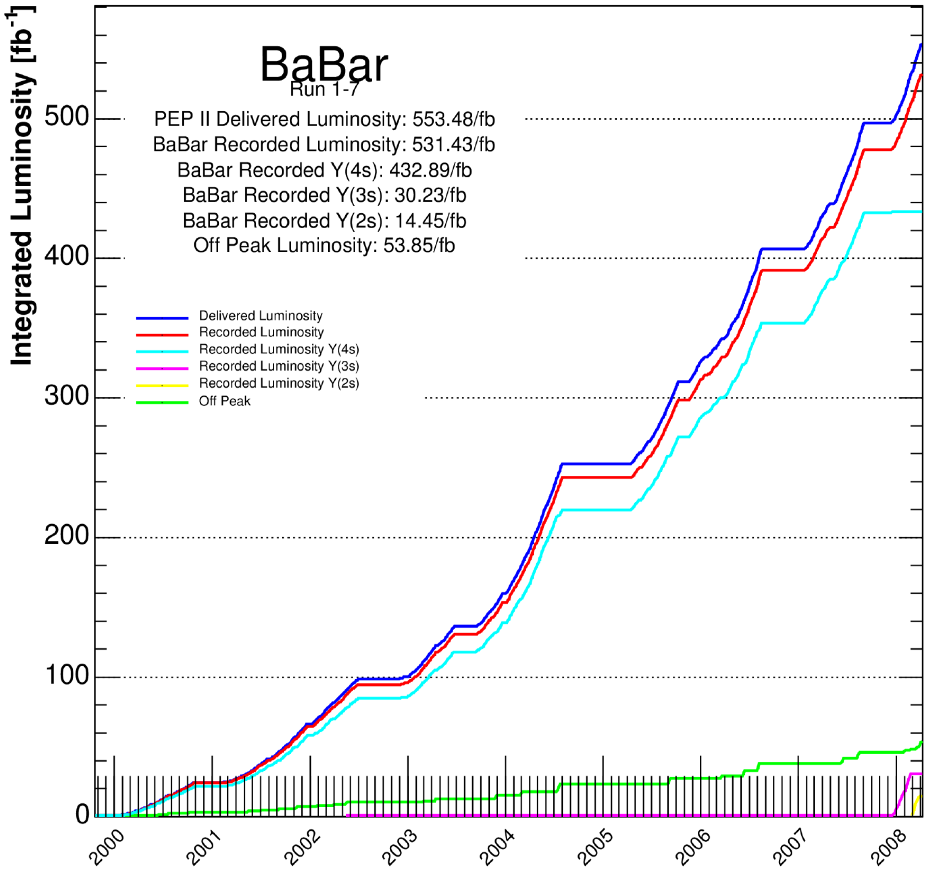


$e^+e^- \to$	Cross-Section (nb)
$b\bar{b}$	1.10
$c\bar{c}$	1.30
$s\bar{s}$	0.35
$u\bar{u}$	1.39
$d\bar{d}$	0.35
$\tau^+\tau^-$	0.94
$\mu^+\mu^-$	1.16
e^+e^-	~ 40

Important background for many analyses $e^+e^- \to q\bar{q}$ (q = u,d,s,c)

BABAR Physics

7 Runs over the course of 9 years



Over 500 submitted/published papers:

- CPV, CKM angles: α, β, γ
- Semi-Leptonic B decays: $|V_{ub}|$, $|V_{cb}|$
- B – B mixing: $|V_{td}|$
- D – D mixing
- Precision measurements, rare decays of B, charm hadrons, τ
- Spectroscopy, discovery of new states
- QCD
- Limits on new physics (NP)

30 publications in 2012

~471×10^6 $B\bar{B}$ (0.5 × Belle)

~690×10^6 $c\bar{c}$

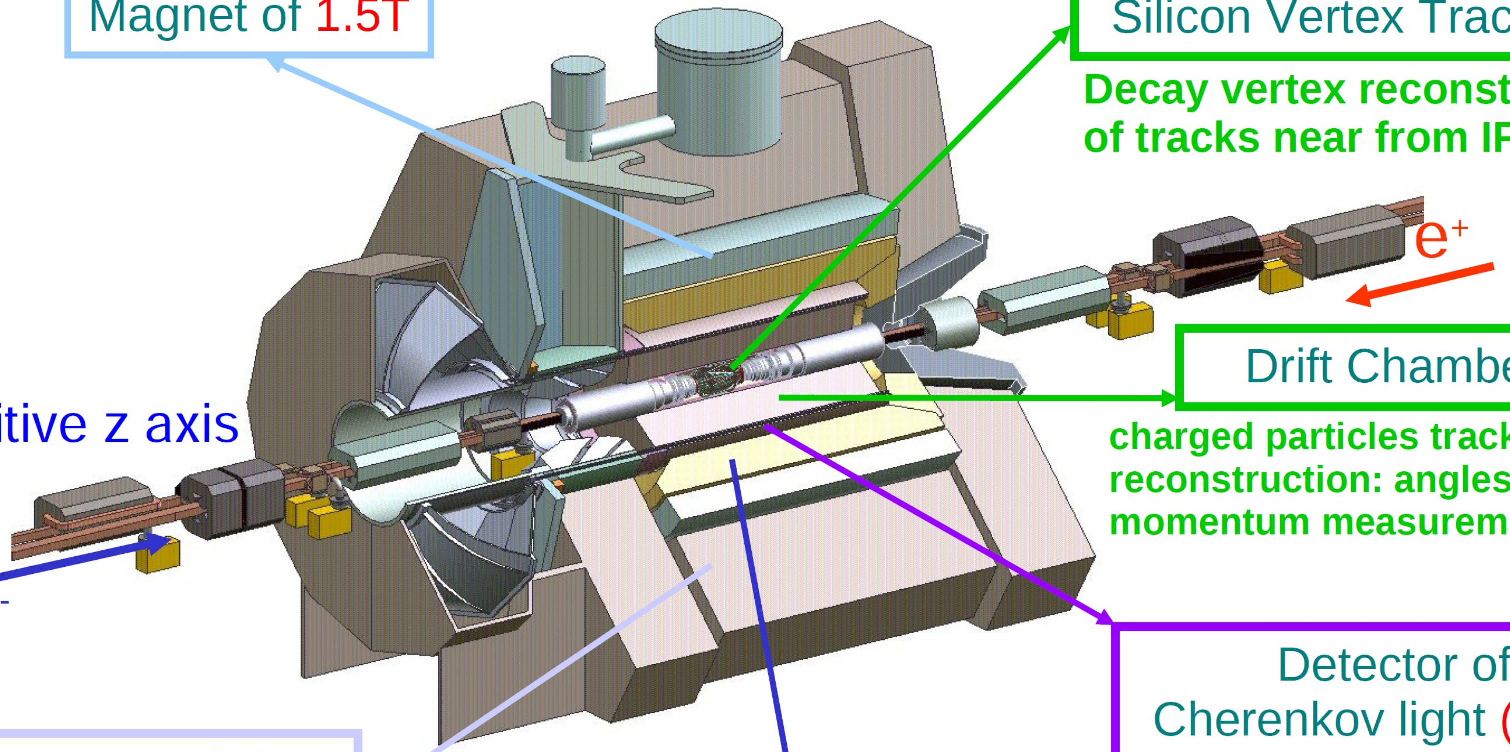
~500×10^6 $\tau^+\tau^-$

~1.2×10^8 Υ(3S) (7 × Belle+CLEO)

~1.0×10^8 Υ(2S) (10 × CLEO)

~1.8×10^7 Υ(1S) (from $\Upsilon(2S)\rightarrow\pi^+\pi^-\Upsilon(1S)$)

BABAR Detector



Magnet of 1.5T

Silicon Vertex Tracker (SVT)

Decay vertex reconstruction of tracks near from IP

Drift Chamber (DCH)

charged particles tracks deviation reconstruction: angles and momentum measurements.

Detector of Cherenkov light (DIRC)

Charged particles ID

K/π separation >2.5σ until 4GeV/c^2

Intrumented flux return (IFR)

$\mu^{+/-}$ Identification

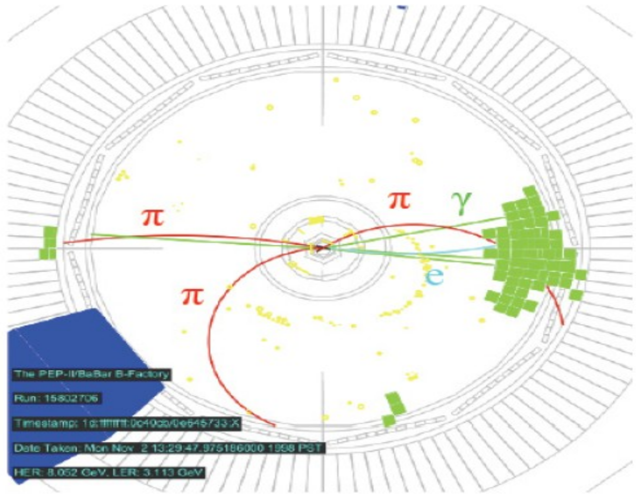
Electromagnetic calorimeter (EMC)

Detection of γ, e^- identification and $\pi^0 \to \gamma\gamma$ reconstruction, Measurements of Energy

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

ArXiv: 1210.5669
BABAR preliminary

Dataset:
$98\mathrm{x}10^6\ \Upsilon(2S)$

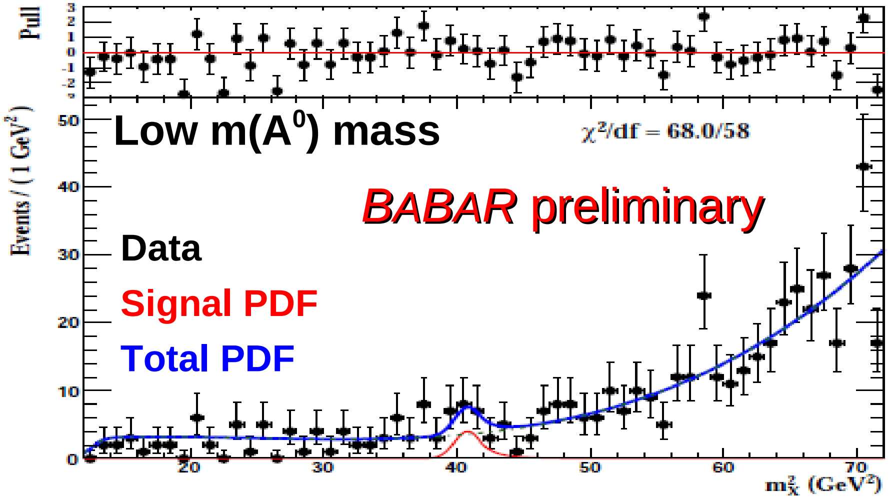


Simulated event $\Upsilon(2S) \rightarrow \pi\pi\Upsilon(1S)$, $\Upsilon(1S) \rightarrow \gamma A^0$, $A^0 \rightarrow \tau\tau$, $\tau\tau \rightarrow \pi e(+3\nu)$

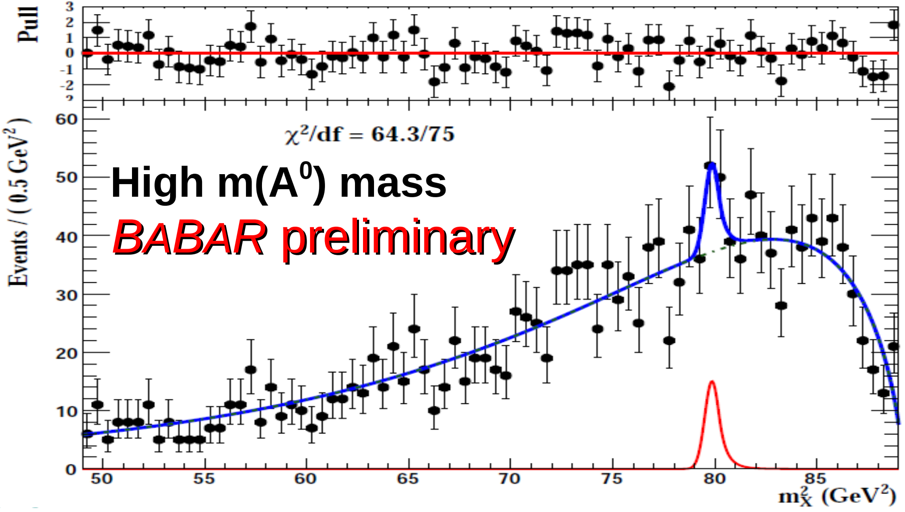
- Mono-chromatic photon
- $\tau^\pm$ pairs from $\tau \rightarrow \mu\nu\nu$, $\tau \rightarrow e\nu\nu$, $\tau \rightarrow \pi\nu$
- Fit and scan for a narrow peak to the photon recoil mass in the $\Upsilon(1S)$ system
- Two mass regions: low and high (different optimizations)
- Fit largest upward fluctuation:
  - 2.7σ (3.0σ) @ 6.36 (8.93) GeV/c^2 for low-(high-) mass
- Pseudo-experiments: 7.5% have 3.0σ fluctuation

$\Rightarrow$ no significant signal found

Largest upward fluctuation: low-mass



Largest upward fluctuation: high-mass



Some exclusions based on BaBar results

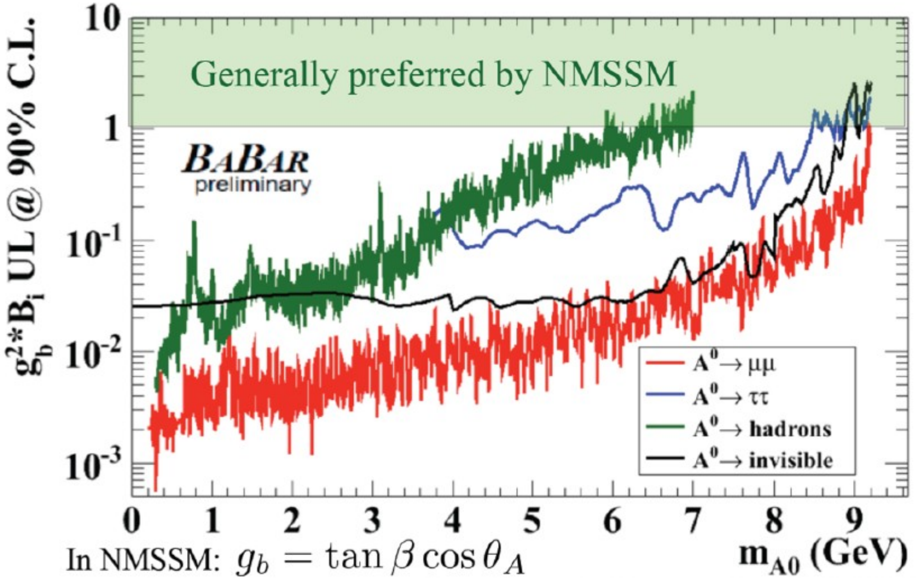
- Upper limits on light Higgs coupling times BR from several BaBar searches
- Boxes: BaBar maximum to minimum exclusions (we exclude the regions above the boxes)

$0 < m_{A0} < 2m_\tau$

$2m_\tau < m_{A0} < 7.5$ GeV/c^2

$7.5 < m_{A0} < 8.8$ GeV/c^2

$8.8 < m_{A0} < 9.2$ GeV/c^2



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