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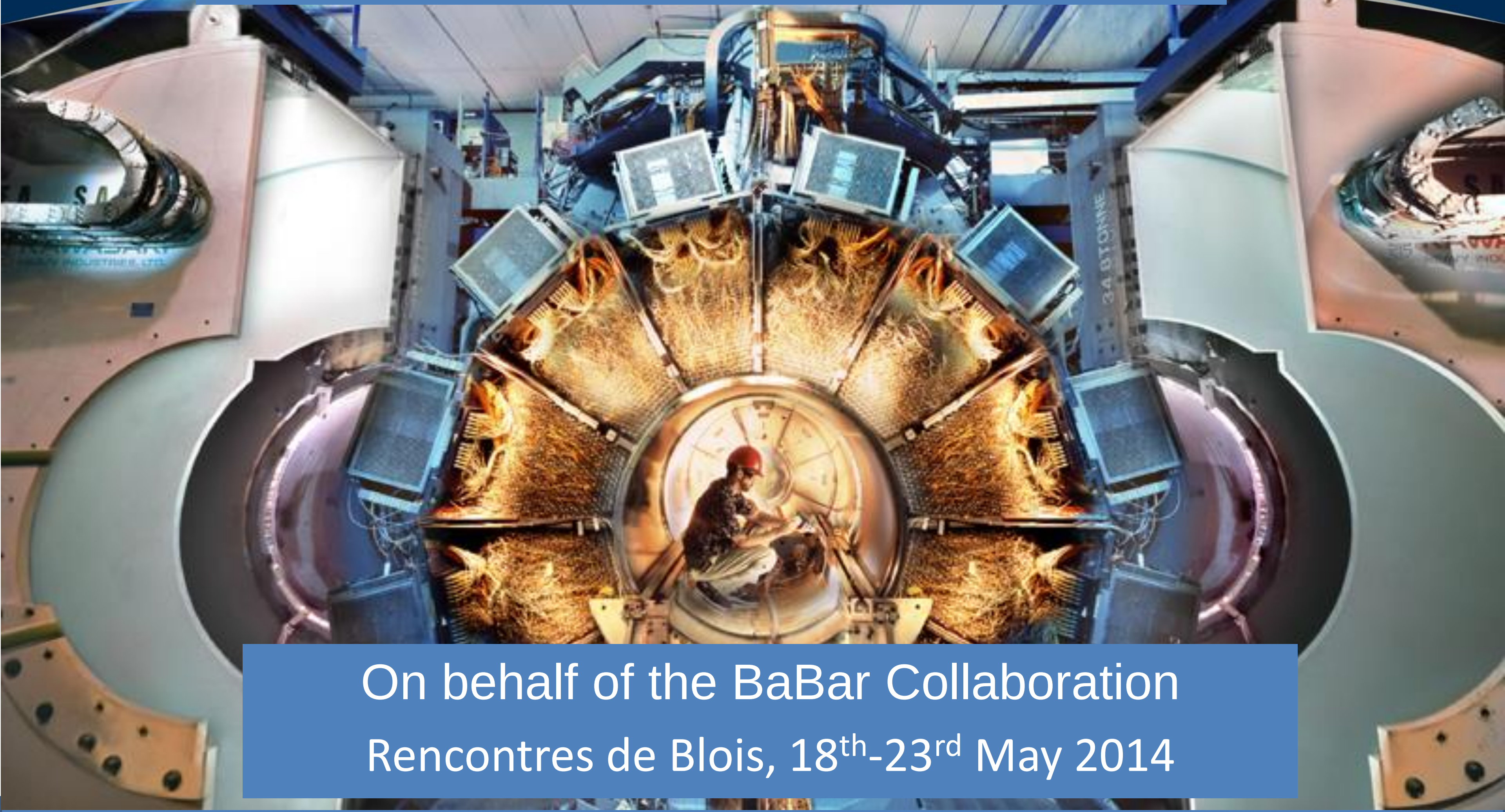
Searches for light CP-odd Higgs



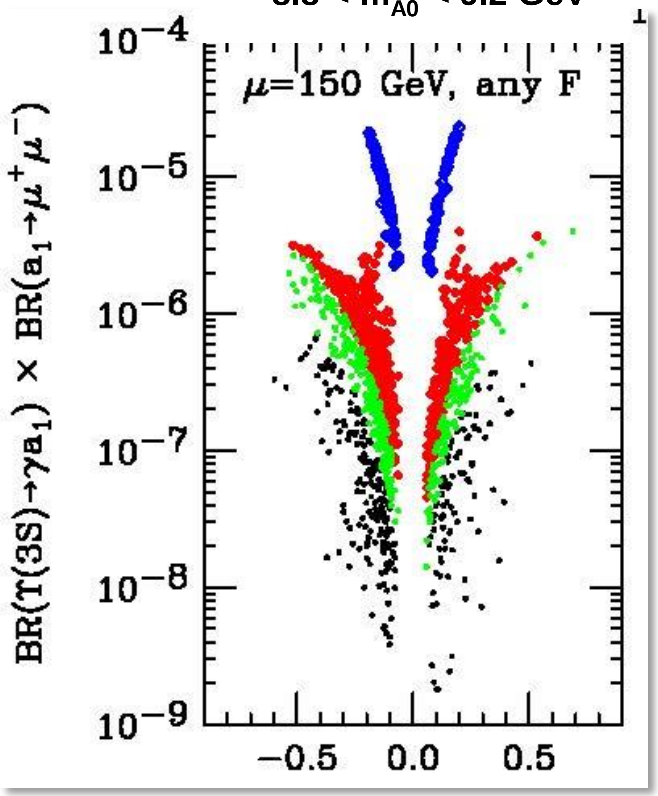
On behalf of the BaBar Collaboration

Rencontres de Blois, 18th-23rd May 2014

Light CP-odd Higgs

- Light CP-odd Higgs A^0 appear in many models e.g. NMSSM.
- In NMSSM coupling to *b* quark depends on $\cos\theta_A$ (CP-odd Higgs doublet/singlet fraction), $\tan\beta$ (ratio of vev of doublet giving mass to up/down-like quarks), and mass of A^0.
  - CP-odd Higgs can be light
  - Important to look at many decay possibilities.
- If A^0 mass < $2m_b$ not detectable at LEP but may be detectable through $\Upsilon(nS)\rightarrow\gamma A^0$ (n=1,2,3).

- $2m_\mu < m_{A0} < 2m_\tau$
- $2m_\tau < m_{A0} < 7.5$ GeV
- $7.5 < m_{A0} < 8.8$ GeV
- $8.8 < m_{A0} < 9.2$ GeV

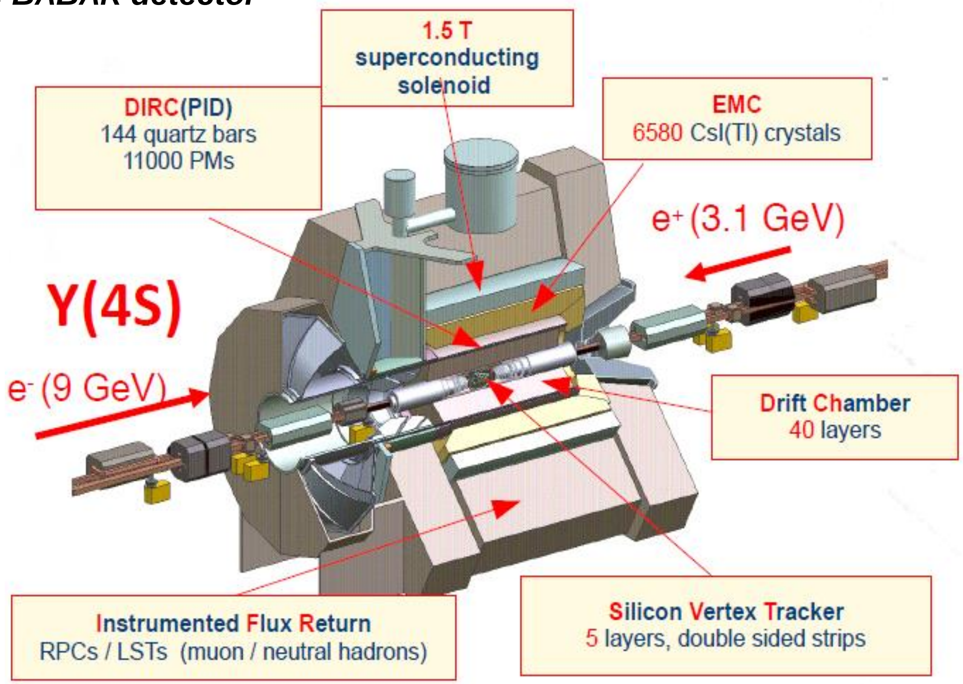


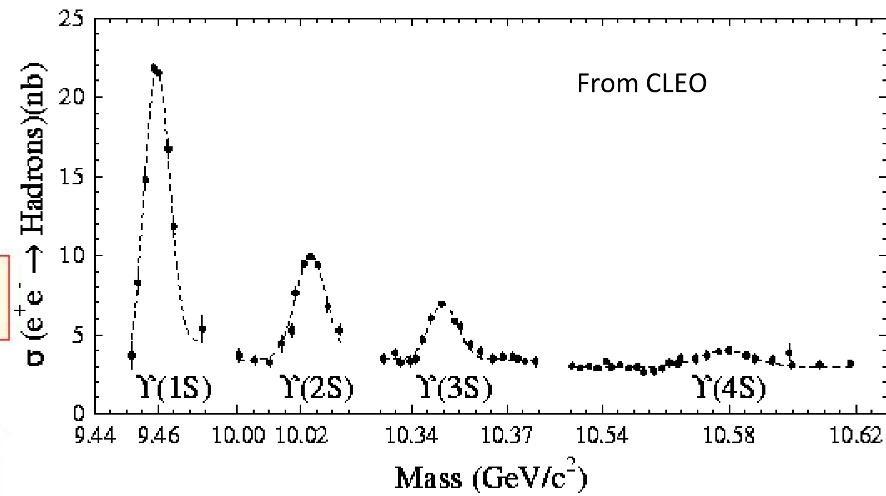
$\cos\theta_A$

Dermisek & Gunion PRD 81, 075003 (2010)

The BaBar detector

The BABAR detector





BABAR data sample contains

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

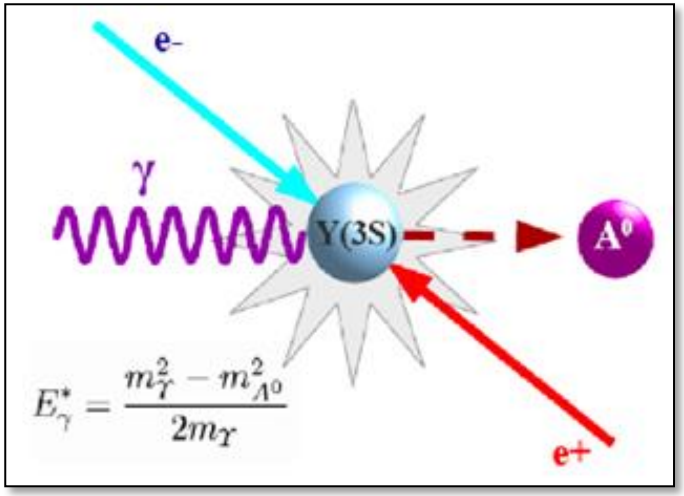
$$B(\Upsilon(2S) \rightarrow \pi^+\pi^-\Upsilon(1S)) = (17.90 \pm 0.06)\%$$

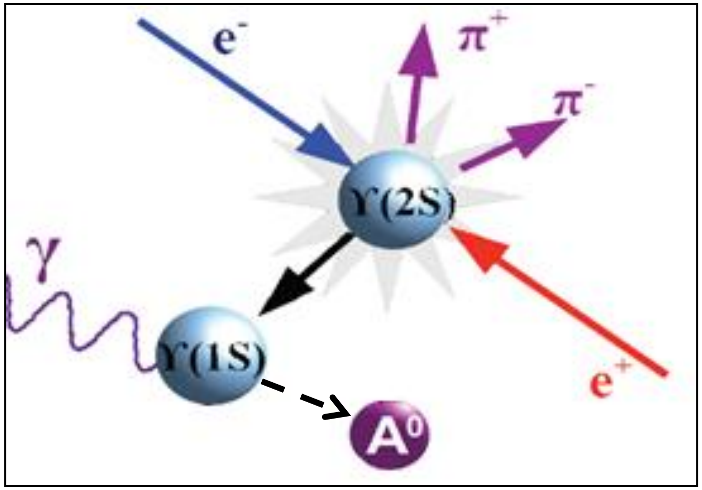
$$B(\Upsilon(3S) \rightarrow \pi^+\pi^-\Upsilon(1S)) = (4.37 \pm 0.08)\%$$

Searches at BaBar

$\Upsilon(3S) \to A_0\gamma$, $A_0 \to$ invisible	arXiv:0808.0017
$\Upsilon(3S) \to A_0\gamma$, $A_0 \to \tau^+\tau^-$	PRL 103, 181801 (2009)
$\Upsilon(2S,3S) \to A_0\gamma$, $A_0 \to \mu^+\mu^-$	PRL 103 081803 (2009)
$\Upsilon(2S,3S) \to A_0\gamma$, $A_0 \to$ hadrons	PRL 107, 221803 (2011)
$\Upsilon(1S) \to A_0\gamma$, $A_0 \to$ invisible	PRL 107 021804 (2011)
$\Upsilon(1S) \to A_0\gamma$, $A_0 \to \mu^+\mu^-$	PRD 87 031102 (2013)
$\Upsilon(1S) \to A_0\gamma$, $A_0 \to \tau^+\tau^-$	PRD 88 071102 (2013)
$\Upsilon(1S) \to A_0\gamma$, $A_0 \to gg$ or $\bar{s}s$	PRD 88 031701 (2013)

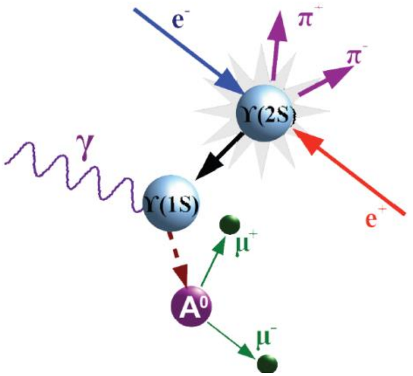
All analyses assume scalar/pseudoscalar A^0 and negligible decay width.





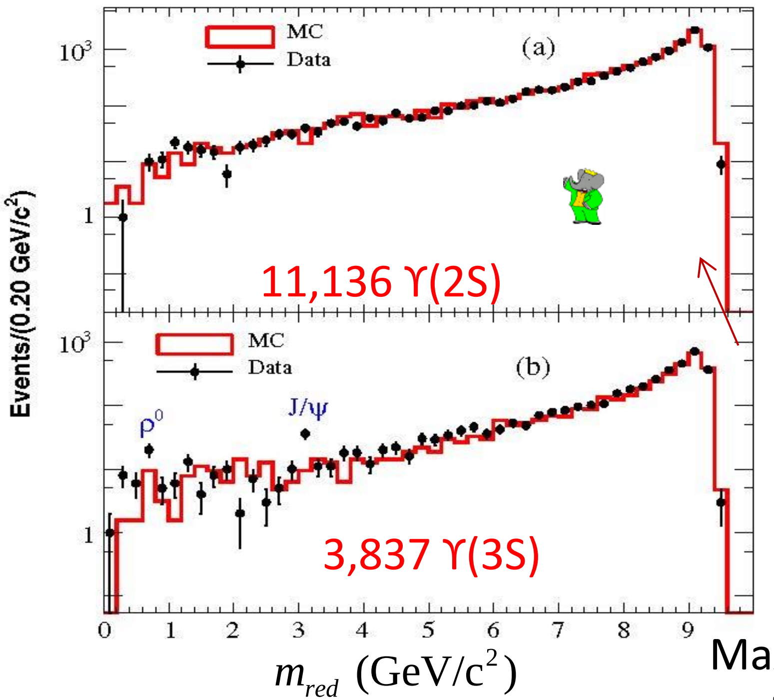
$\Upsilon(2,3S) \rightarrow \pi^+\pi^-\Upsilon(1S)$, $\Upsilon(1S) \rightarrow \gamma A^0$, $A^0 \rightarrow \mu^+\mu^-$

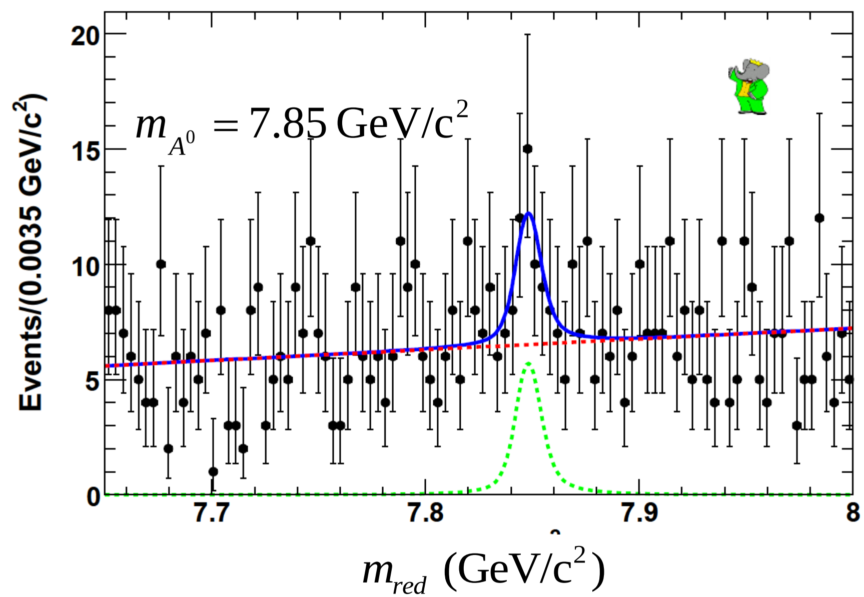
PRD 87, 031102 (2013)



- Identify Υ(1S) from the two pion transition.
- $E_\gamma^* > 200$ MeV + 4 charged tracks; one track identified as muon by Particle Identification (PID) and transverse momentum P_t.
- Random Forest Classifier MVA to reject background.

Reduced mass $m_{red} = \sqrt{m_{\mu\mu}^2 - 4m_\mu^2}$



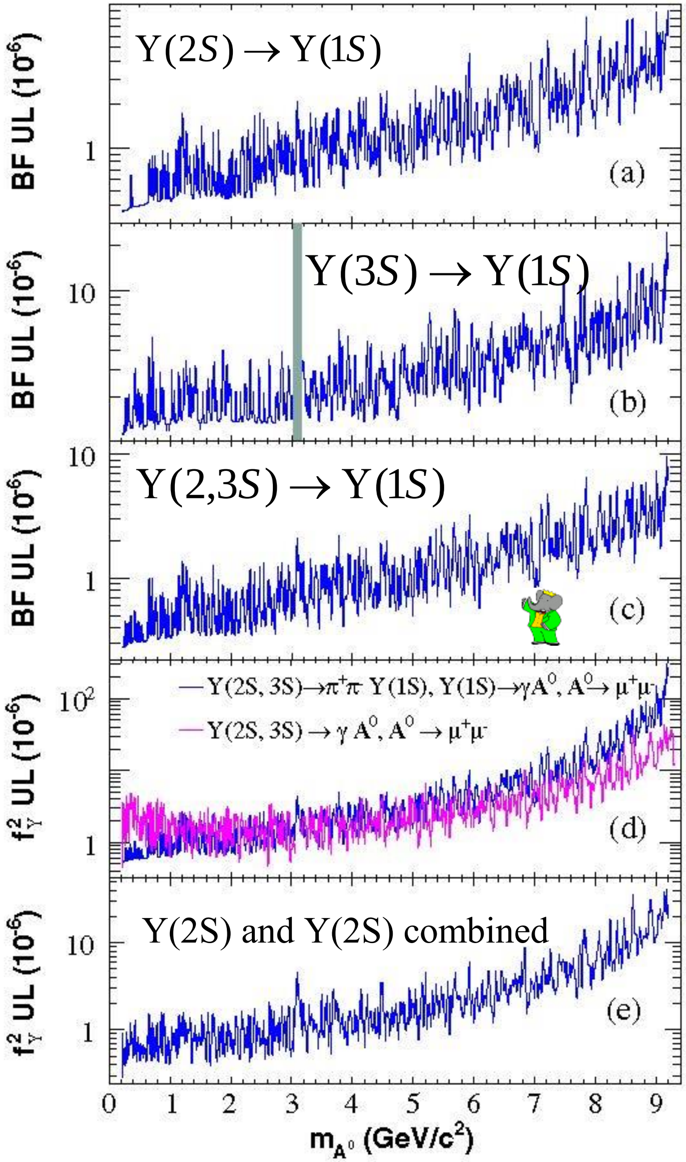


Maximum Likelihood fit scan through m_{red} at 4585 points:

- Background : threshold or Chebyshev function.
- Signal: two Crystal Ball functions.

$\Upsilon(2,3S)\rightarrow\pi^+\pi^-\Upsilon(1S)$, $\Upsilon(1S)\rightarrow\gamma A^0$, $A^0\rightarrow\mu^+\mu^-$

PRD 87, 031102 (2013)
PRL 103, 081803 (2009)



90% CL Upper limits : $(0.28 - 9.7)\times 10^{-6}$ in A^0 mass range $0.212 < m < 9.20$ GeV/c^2.

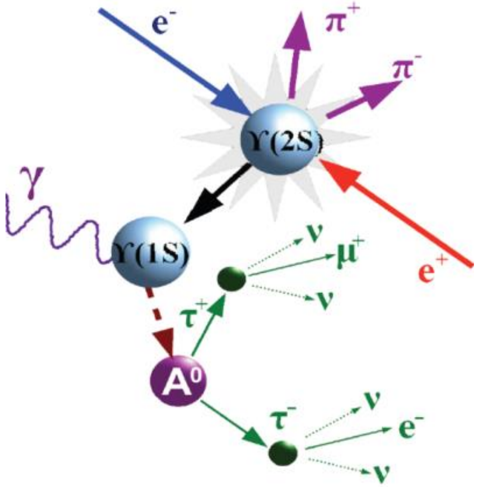
Can place limits on effective Yukawa coupling f_Υ of the *b* quark to the A^0:

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

90% CL Upper Limits (combined with PRL 103, 081803 (2009)):

$$f_\Upsilon^2 \times B(A^0\rightarrow\mu^+\mu^-) < (0.29-40)\times 10^{-6}$$

$\Upsilon(2S)\rightarrow \pi^+\pi^-\Upsilon(1S)$, $\Upsilon(1S)\rightarrow\gamma A^0$, $A^0\rightarrow\tau^+\tau^-$



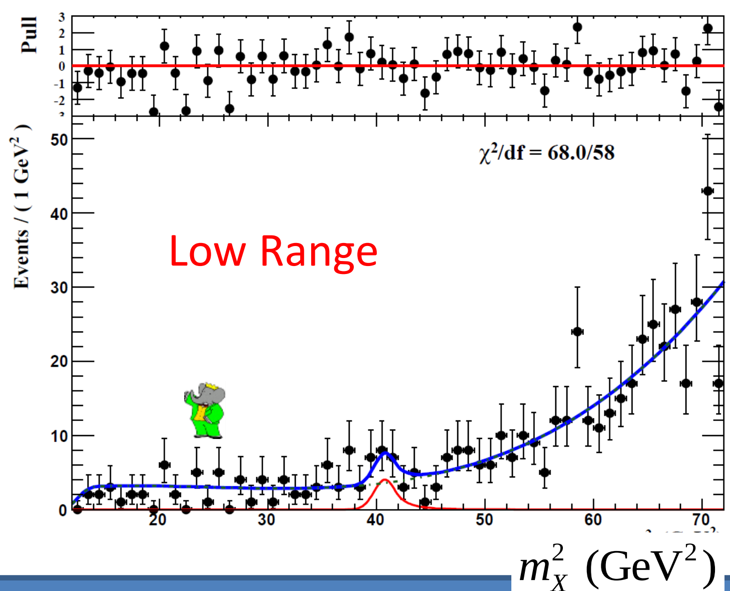
PRD 88, 071102 (2013)

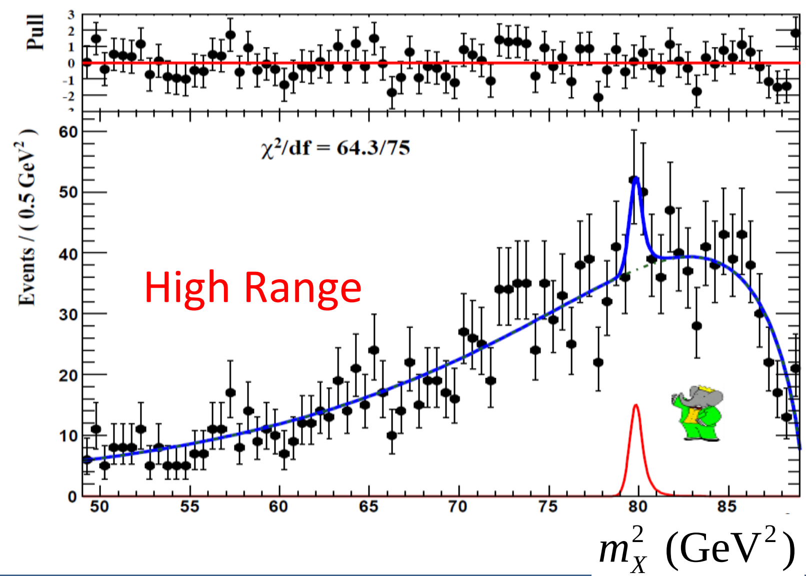
- One-prong decays of τ; at least one decay must be leptonic: ee, eμ, eπ, μμ, μπ.
- Optimize selection in two A^0 mass regions
  - Low: $3.6 < m < 8.0$ GeV/c^2
  - High: $8.0 < m < 9.2$ GeV/c^2
- Separate MVAs for $\Upsilon(2S)\rightarrow\pi^+\pi^-\Upsilon(1S)$ and $\Upsilon(1S)\rightarrow\gamma A^0$
- Mass recoiling against γ in ϒ(1S) frame:

$$m_X^2 = \left(p_{e^+e^-} - p_{\pi\pi} - p_\gamma\right)^2$$

Scan through m_X^2 at 201 points:

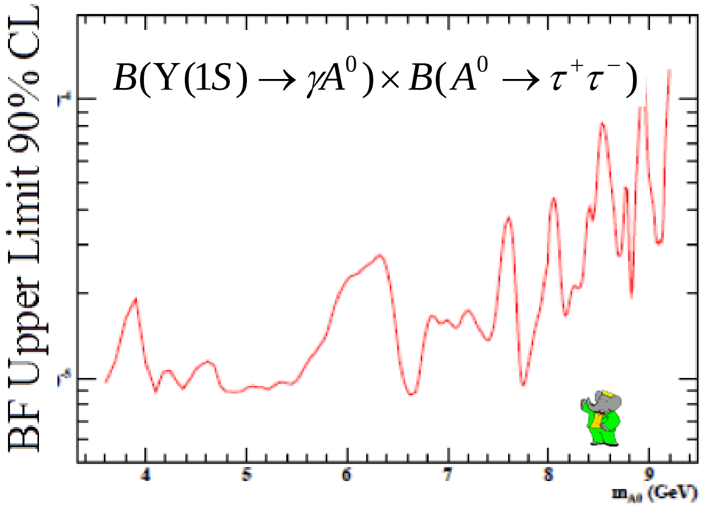
- Background : threshold function. Signal: Crystal Ball function.



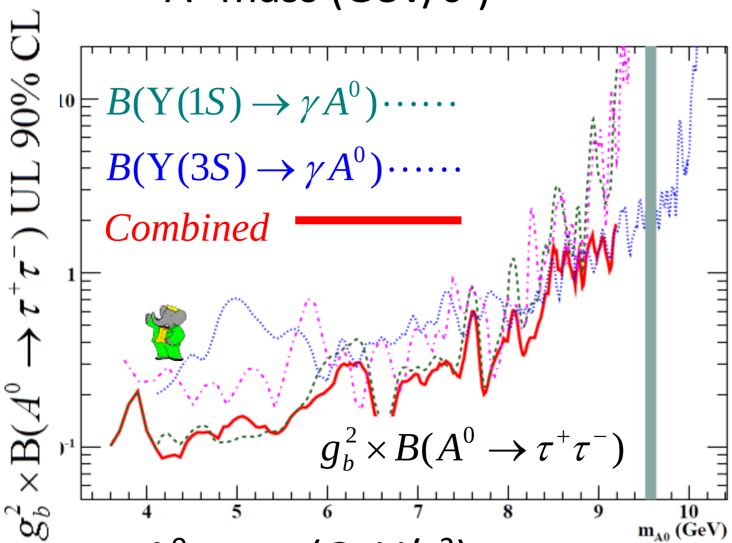


$\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S)$, $\Upsilon(1S)\to\gamma A^0$, $A^0\to\tau^+\tau^-$

PRD 88, 071102 (2013)



A^0 mass (GeV/c^2)



A^0 mass (GeV/c^2)

90% CL Upper limits : $(0.9 - 13)\times 10^{-5}$ in A^0 mass range $3.6 < m < 9.2$ GeV/c^2.

Can place limits on effective Yukawa coupling g^2_b of the *b* quark to the A^0:

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

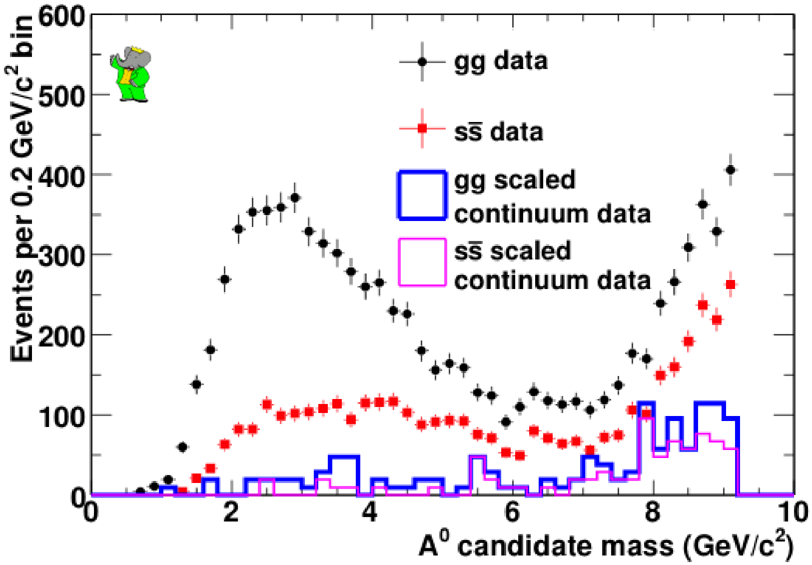
90% CL Upper Limits (combined with ϒ(3S) result from PRL 103, 181801 (2009)):

$$g_b^2\times B(A^0\to\tau^+\tau^-) < (0.09-1.9)\times 10^{-6}$$

$\Upsilon(2S)\rightarrow \pi^+\pi^-\Upsilon(1S)$, $\Upsilon(1S)\rightarrow\gamma A^0$, $A^0\rightarrow gg,\bar{s}s$

PRD 88, 031701 (2013)

Number	Channel	Number	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	$K^+K^0_S\pi^+\pi^+\pi$
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	$K^+K^0_S\pi^+\pi^+\pi\ 2\pi^0$
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	$K^+K^0_S\pi^+2\pi^+2\pi\ \pi^0$
10	$4\pi^+4\pi$	23	$K^+K\ 3\pi^+3\pi$
11	$K^+K\ \pi^0$	24	$2K^+2K$
12	$K^+K^0_S\pi^+$	25	$p\bar{p}\pi^0$
13	$K^+K\ 2\pi^0$	26	$p\bar{p}\pi^+\pi$



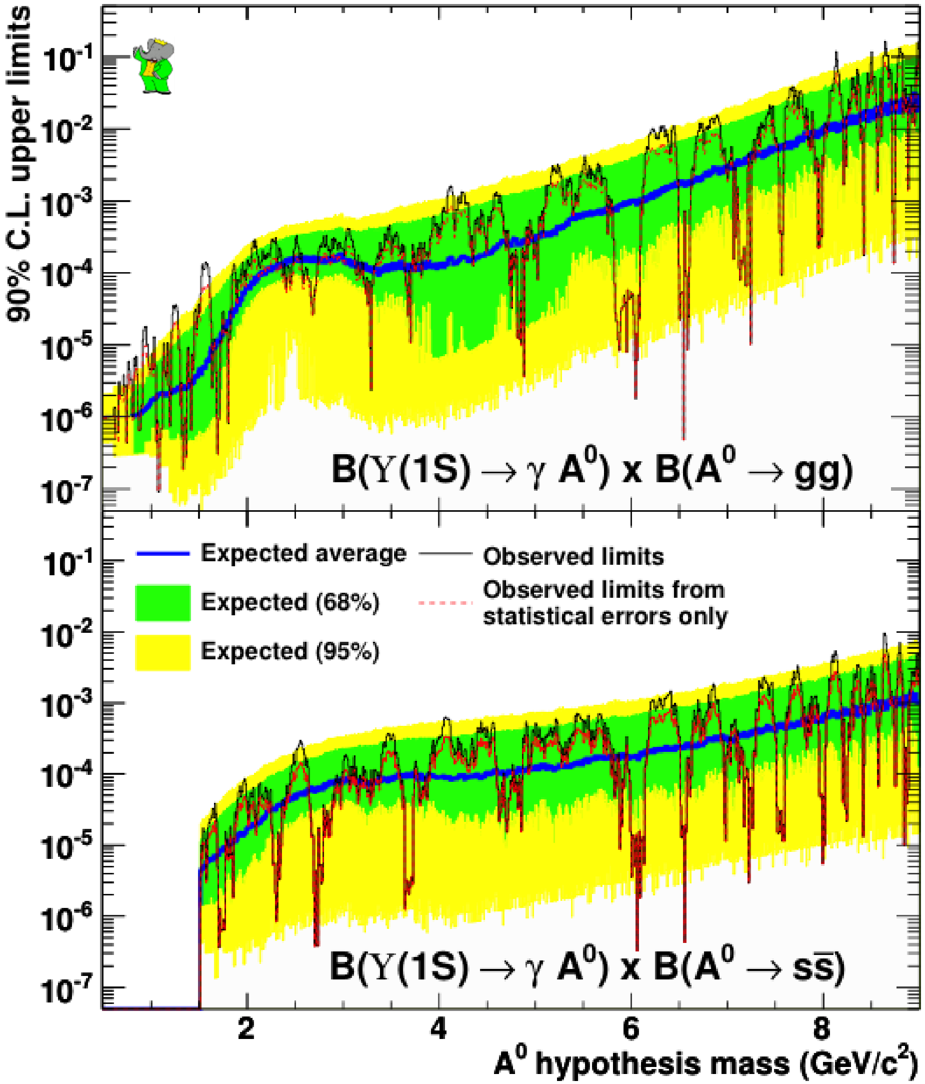
- Events with 2 pions, a radiative photon (E_γ*>200 MeV), and a hadronic system.
- Select events with $9.45 < m_R < 9.47$ GeV/c^2

$$m_R^2 = M_{\Upsilon(2S)}^2 + m_{\pi\pi}^2 - 2M_{\Upsilon(2S)}E_{\pi\pi}^{CM}$$

- Suppress background with an MVA.
- Reconstruct 26 hadronic decays:
  - $\bar{s}s$: 2 or 4 kaons (channels #11-24)
- Form A^0 mass from hadronic system.
- Scan 850 steps through A^0 mass; count events in a mass window centred on A^0 mass hypothesis.
- Large hadronisation uncertainty in MC (~50%). Use data/MC comparison in $\Upsilon(1S)\rightarrow\gamma gg$ for $2 < m_{gg} < 4$ GeV/c^2 to correct.

$\Upsilon(2,3S) \to \pi^+\pi^-\Upsilon(1S)$, $\Upsilon(1S) \to \gamma A^0$, $A^0 \to gg, \bar{s}s$

PRD 88, 031701 (2013)



- Most significant signal
  - gg: 2.7σ at 8.13 GeV/c^2
  - $\bar{s}s$: 2.9σ at 8.63 GeV/c^2
- Statistical fluctuations are consistent with a null-hypothesis
- No evidence for A^0

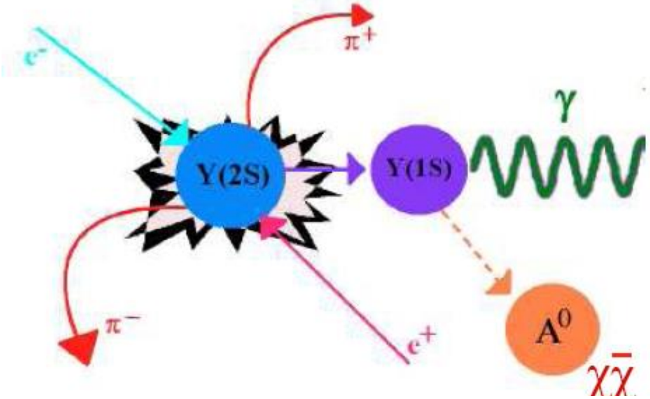
90% CL Upper Limits

$$B(Y(1S) \to \gamma A^0) \times B(A^0 \to gg) < 10^{-6} - 10^{-2}$$

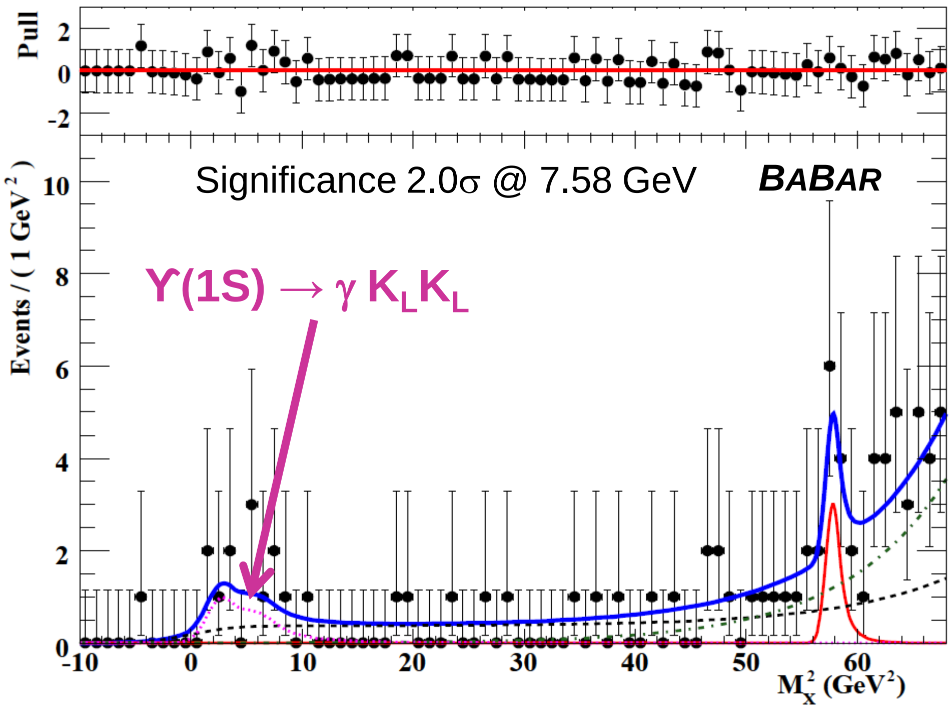
$$B(Y(1S) \to \gamma A^0) \times B(A^0 \to s\bar{s}) < 10^{-5} - 10^{-3}$$

$\Upsilon(2S) \rightarrow \pi^+\pi^-\Upsilon(1S)$, $\Upsilon(1S) \rightarrow \gamma A^0$, $A^0 \rightarrow$ invisible

PRL 107, 021804 (2011)



- Light Higgs A^0 or dark matter pair $\bar{\chi}\chi$
- $\Upsilon(1S) \rightarrow \gamma\nu\bar{\nu}$ branching fraction at least 30 times lower than is detectable at BaBar.
- Tag $\Upsilon(1S)$ as before.
- $E_\gamma^* > 150$ MeV.
- Search for single energetic photon and significant missing energy.



- Scan A^0 mass:
  - 196 points $0<m<8$ GeV/c^2
  - 146 points $7.5<m<9.2$ Gev/c^2
- Scan $\bar{\chi}\chi$ mass
  - 17 points $0<m<4.5$ GeV/c^2
- Use two variables in ML fit
  - m_r^2 and m_X^2

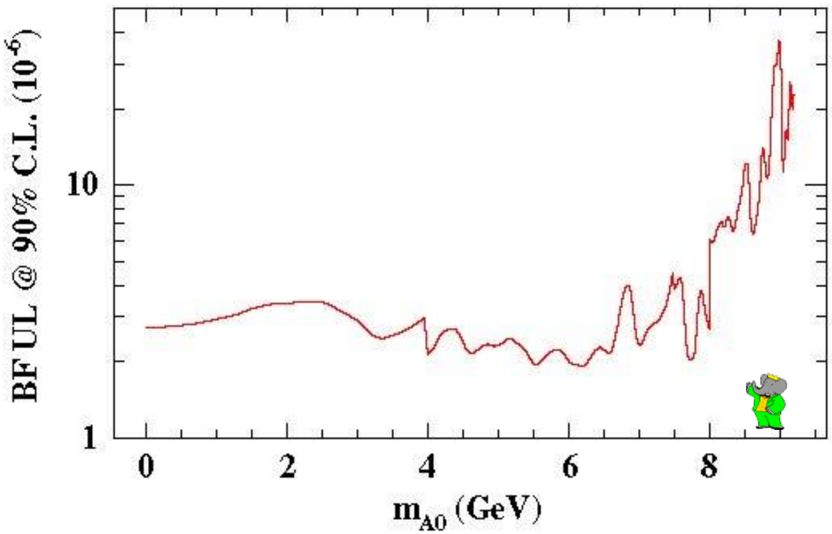
$$m_R^2 = M_{\Upsilon(2S)}^2 + m_{\pi\pi}^2 - 2M_{\Upsilon(2S)}E_{\pi\pi}^{CM}$$

$$m_X^2 = \left(p_{e^+e^-} - p_{\pi\pi} - p_\gamma\right)^2$$

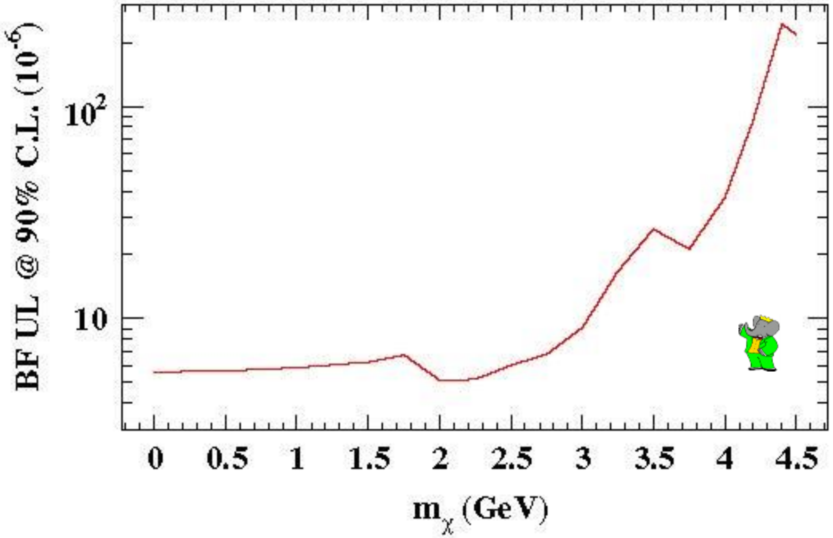
$\Upsilon(2S) \rightarrow \pi^+\pi^-\Upsilon(1S)$, $\Upsilon(1S) \rightarrow \gamma A^0$, $A^0 \rightarrow$ invisible

PRL 107, 021804 (2011)

$B(\Upsilon(1S) \rightarrow \gamma A^0) \times B(A^0 \rightarrow \text{invisible})$



$B(\Upsilon(1S) \rightarrow \gamma\chi\bar{\chi})$



90% CL Upper Limits:

$B(\Upsilon(1S) \rightarrow \gamma A^0) \times B(A^0 \rightarrow \text{invisible}) < (1.9 - 37) \times 10^{-6}$

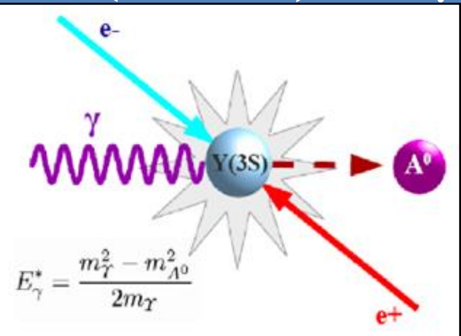
$B(\Upsilon(1S) \rightarrow \gamma\chi\bar{\chi}) < (0.5 - 24) \times 10^{-6}$

Some predictions (e.g. PRD 80, 115019 (2009); PRD 81, 054025 (2010)):

$B(\Upsilon(1S) \rightarrow \gamma A^0) \times B(A^0 \rightarrow \text{invisible}) < (4 - 18) \times 10^{-4}$

$B(\Upsilon(1S) \rightarrow \gamma\chi\bar{\chi}) < (1 - 10) \times 10^{-5}$

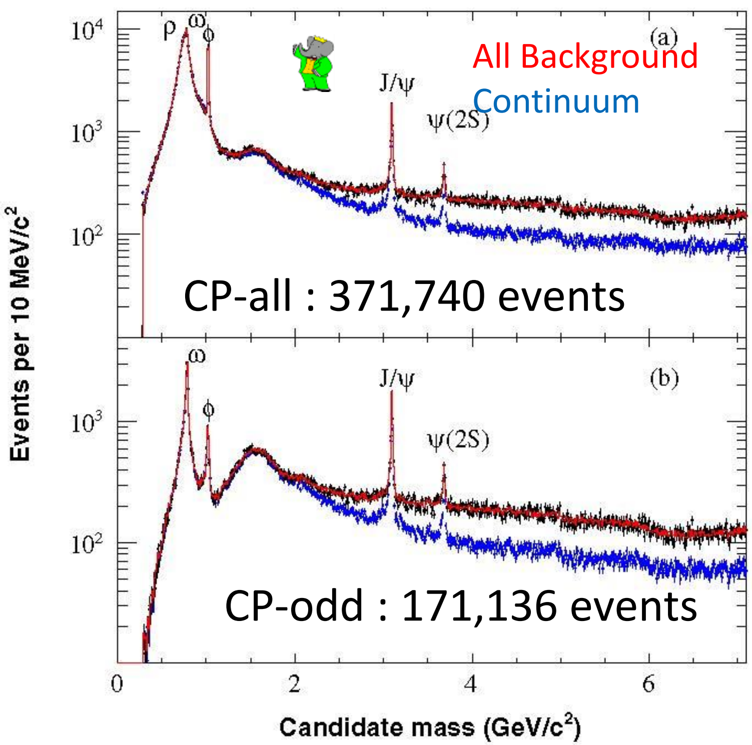
$\Upsilon(2,3S) \rightarrow \gamma A_0$, $A_0 \rightarrow$ hadrons

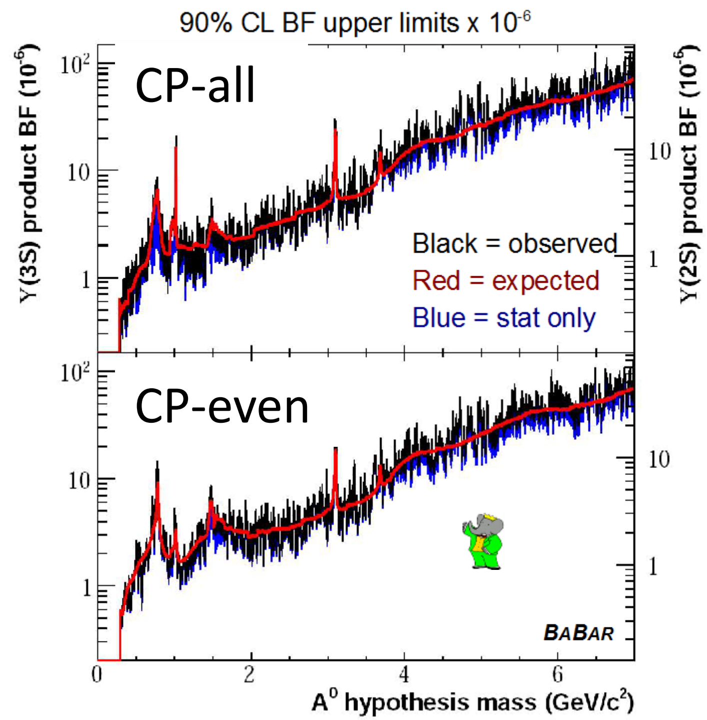


$$E^*_\gamma = \frac{m^2_\Upsilon - m^2_{A^0}}{2m_\Upsilon}$$

PRL 107, 221803 (2011)

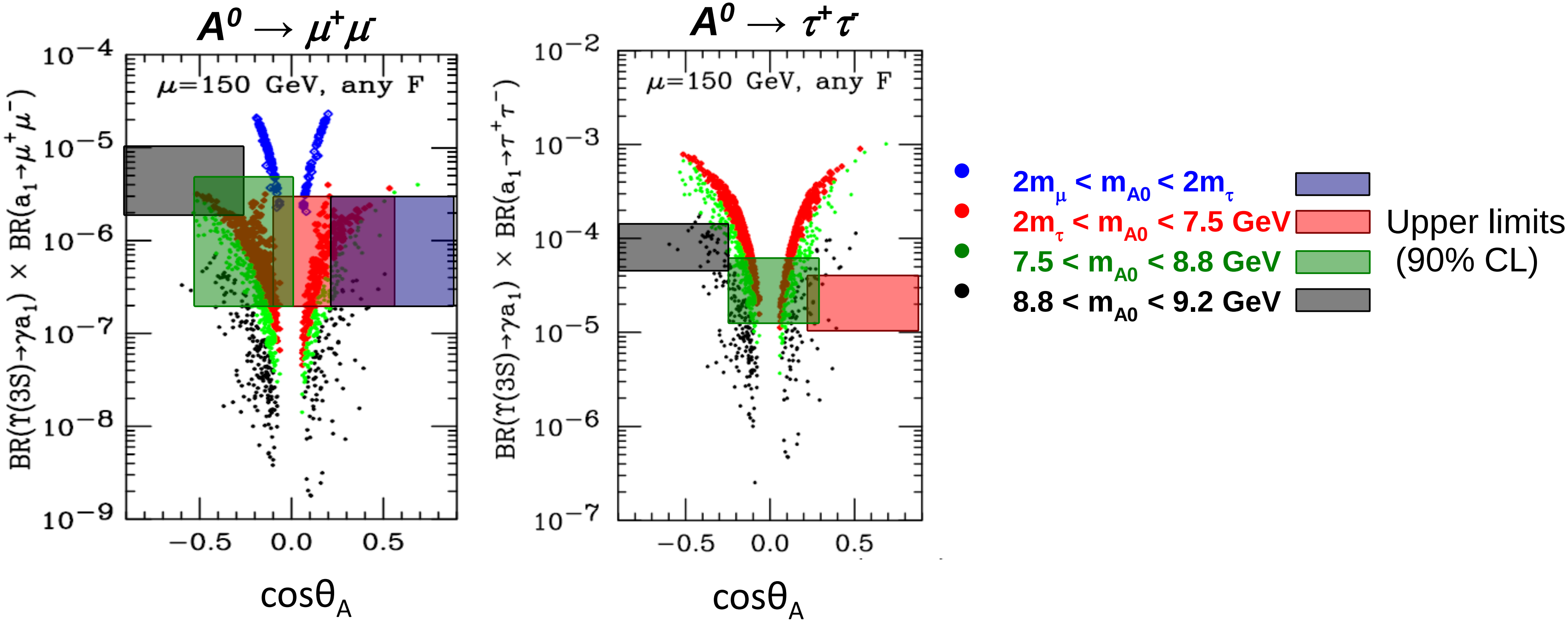
- No Υ(1S) to constrain decay.
- E_γ*> 2.5 GeV for Υ(3S), 2.2 GeV for Υ(2S).
- Consider CP-even ($A^0 \rightarrow KK,\pi\pi$) as well as CP-odd.
- A^0 mass from remaining particles.
- Background fit : 16-knot spline + five Breit Wigner
- Scan 6710 (CP-all) and 6701 (CP-odd) A^0 mass hypotheses





$$B(Y(nS) \rightarrow \gamma A^0) \times B(A^0 \rightarrow \text{hadrons}) < (1-80) \times 10^{-6}$$

Summary



- Searches for $A^0 \to$ hadrons, invisible, $\mu^+\mu^-$, $\tau^+\tau^-$, gg, $\bar{s}s$ have been completed by BaBar.
- Substantial fraction of parameter space up to 7-8 GeV/c^2 excluded.
- New results in preparation: $A_0 \to \bar{c}c$ and $A_0 \to \gamma\gamma$