Searches for new physics in Upsilon decays

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Presented at
Rencontres de Moriond EW 2010
6-13 March 2010
La Thuile, Italy

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On behalf of the BABAR Collaboration

Overview

Direct searches for Higgs bosons and dark matter candidates at a B factory:

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

Presentation by Elisa Guido:

- Lepton universality and lepton flavour violation in Υ decays

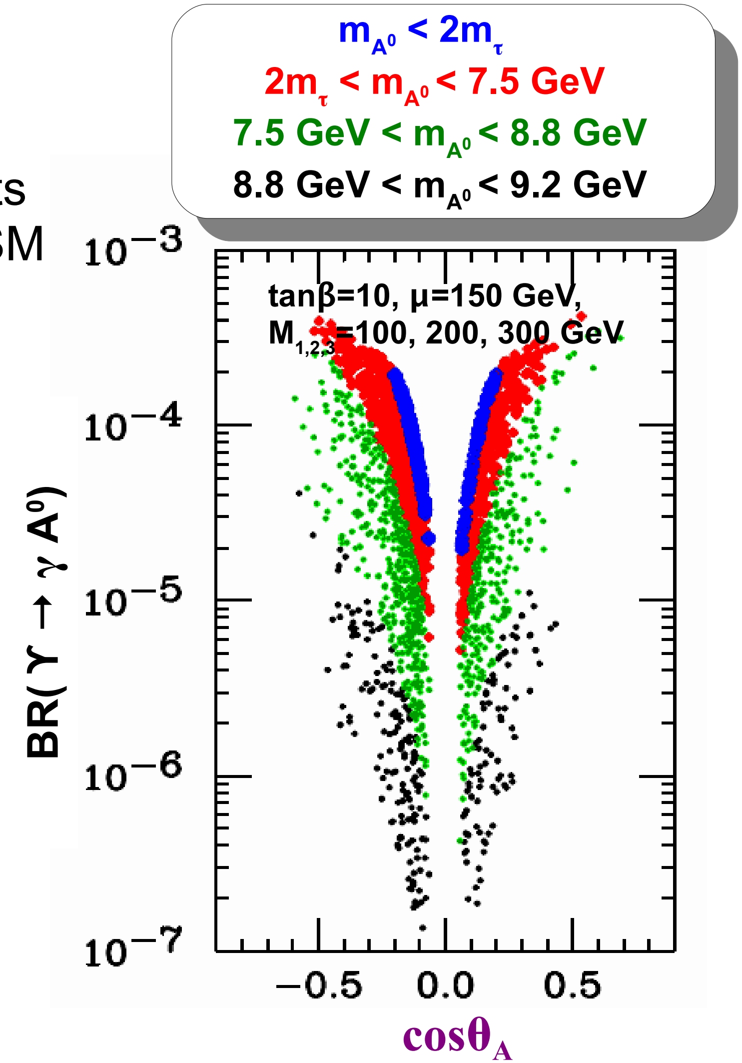
Physics Motivation

- Light CP-odd Higgs bosons arise in many beyond SM scenarios
  - NMSSM: adding singlet Higgs field to MSSM results in an additional CP-odd Higgs that mixes with MSSM CP-odd Higgs

$$A^0 \equiv a_1 = \cos\theta_A \, a_{MSSM} + \sin\theta_A \, a_{singlet}$$

  - for $m_{A^0} < 2m_B$ the lightest CP-even Higgs (h^0) can evade LEP bounds by $h^0 \to A^0 A^0$
- Generic dark matter models can be constructed by postulating dark matter candidate χ^0 and scalar (or vector) boson U ($m_U \sim 2m_\chi$) to mediate s-channel annihilation
  - U boson couples to Standard Model particles via mixing with bosons

PRD 72:103508 (2005)

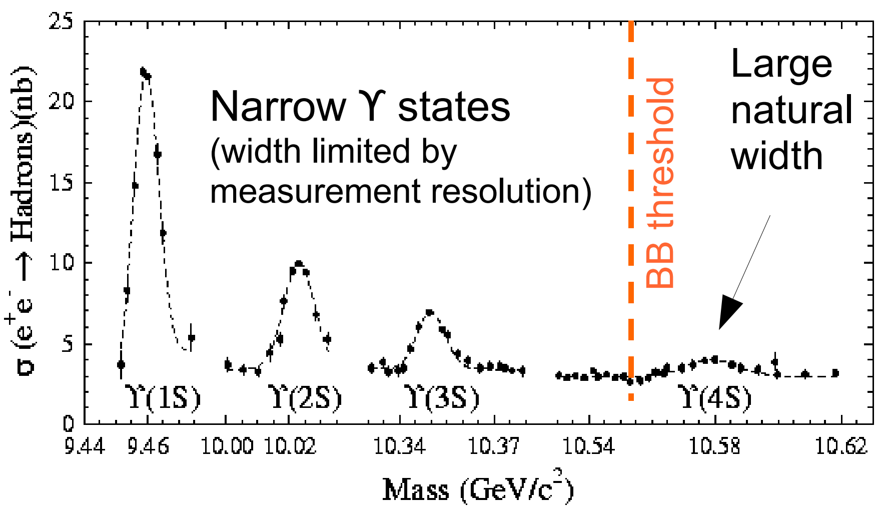


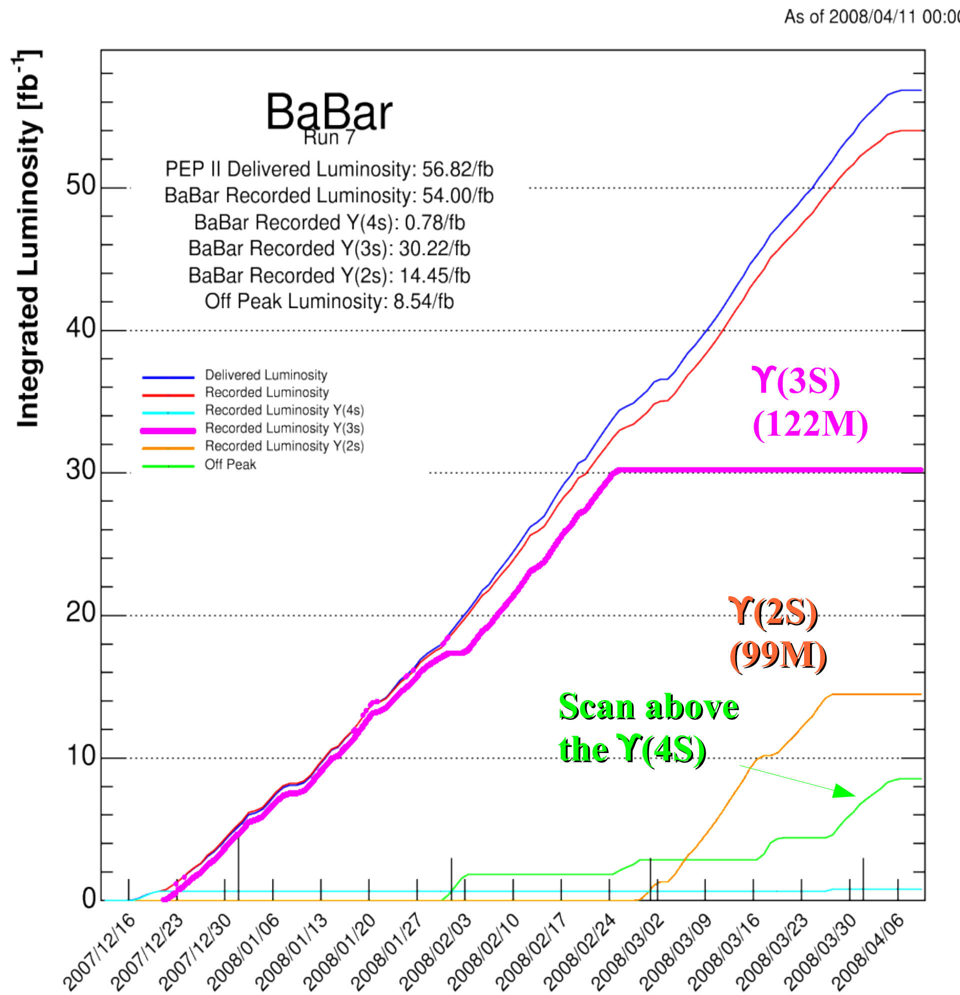
PRL 95:041801 (2005);
PRD 76:051105 (2007)

- Either scenario can produce substantial enhancements in narrow Upsilon branching fractions

BABAR data samples

- BaBar data sets:
  - 122×10^6 $\Upsilon(3S)$ decays
  - 99×10^6 $\Upsilon(2S)$ decays
  - "offpeak" samples of $1.4 fb^{-1}$ and $2.4 fb^{-1}$ collected ~30 MeV below the $\Upsilon(2S)$ and $\Upsilon(3S)$
  - $79 fb^{-1}$ "continuum background" samples of $\Upsilon(4S)$ with similar detector conditions

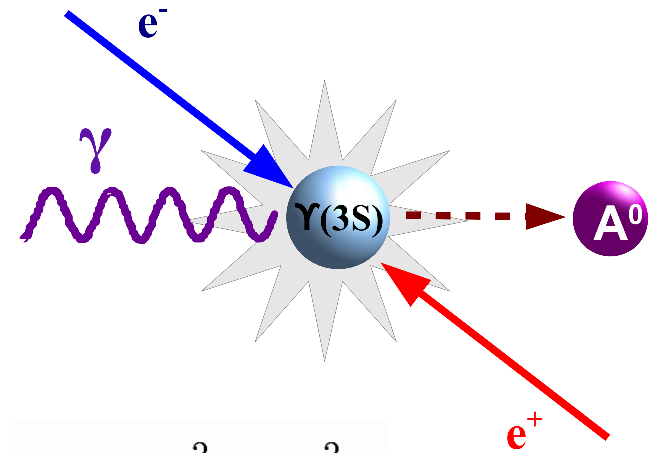




- Trigger requirements modified for narrow ϒ data taking

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

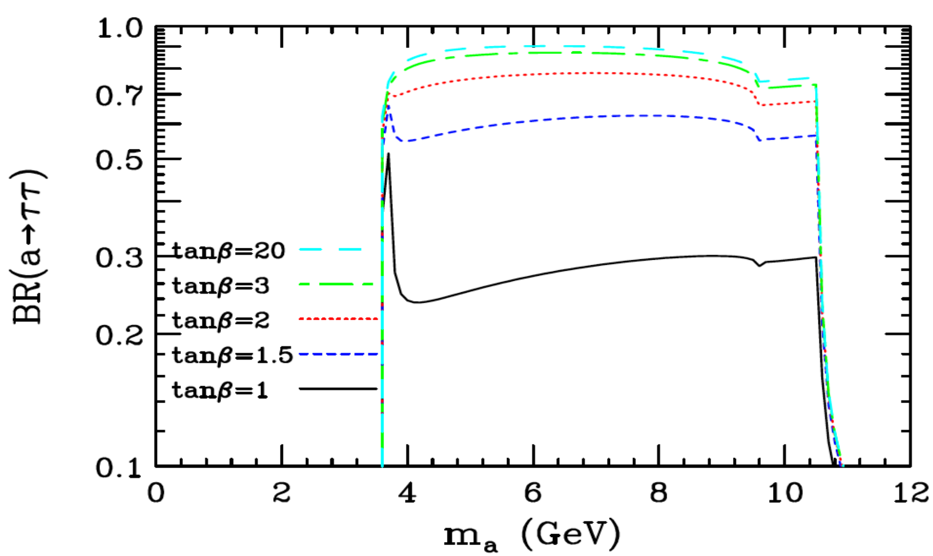
A^0 can be produced in 2-body radiative decays of narrow Υ states

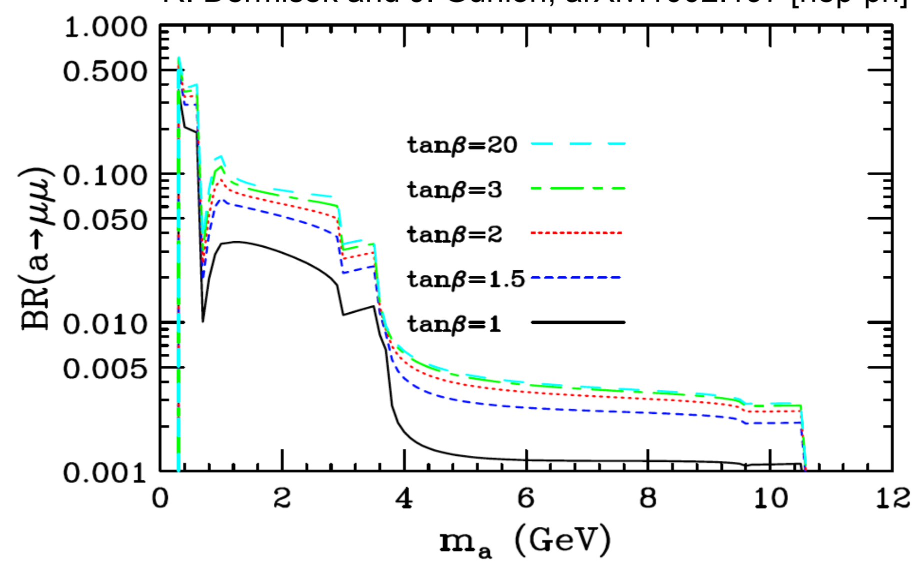


- $A^0 \rightarrow \tau^+\tau^-$ typically dominant for $m_{A^0} > 2m_\tau$
- $A^0 \rightarrow \mu^+\mu^-$ can be significant below $\tau^+\tau^-$ threshold
- Possibly also large branching fraction to neutralino pairs (i.e. invisible)

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

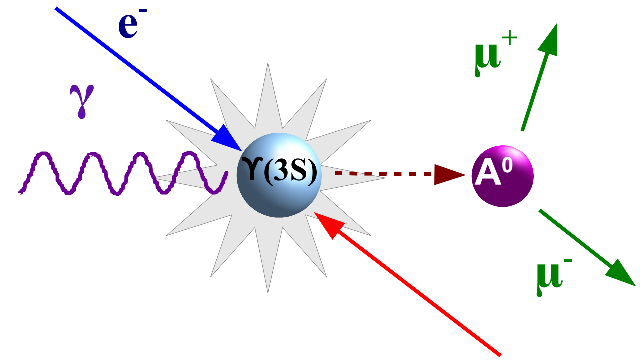
R. Dermisek and J. Gunion, arXiv:1002.197 [hep-ph]

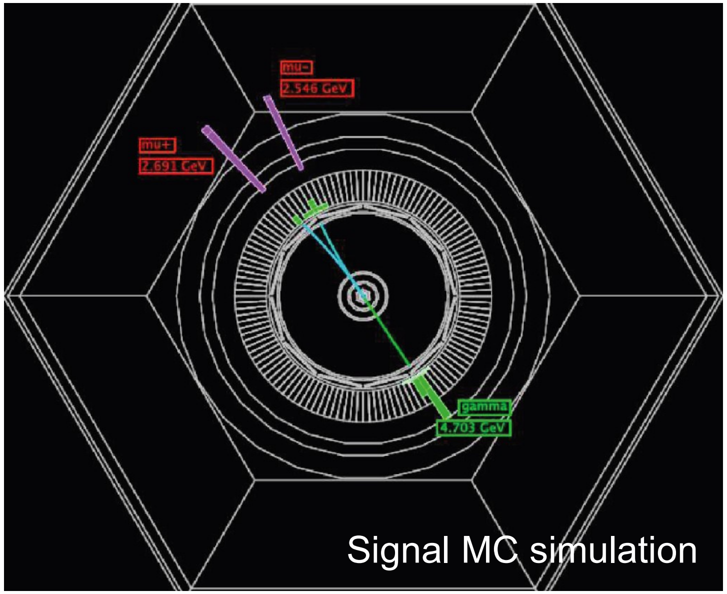




$\Upsilon(2S, 3S) \rightarrow \gamma A^0$, $A^0 \rightarrow \mu^+\mu^-$ PRL 103, 081803 (2009)

- Search for fully reconstructed $\Upsilon(2S, 3S)$ final state with $\mu^+\mu^-$ mass resonance
  - require exactly two oppositely charged tracks, which for a vertex, and at least one of which is identified as a muon
  - require a single photon with E_γ > 200 MeV (lower energy photons permitted)
  - additional colinearity criteria applied to γ/A^0 and γ/μ combinations to suppress dominant background from "continuum" $e^+e^- \rightarrow \gamma\mu^+\mu^-$
- Kinematic fit of $\gamma\mu^+\mu^-$ system, including beam energy and primary vertex constraints





$\Upsilon(2S, 3S) \rightarrow \gamma A^0$, $A^0 \rightarrow \mu^+\mu^-$ PRL 103, 081803 (2009)

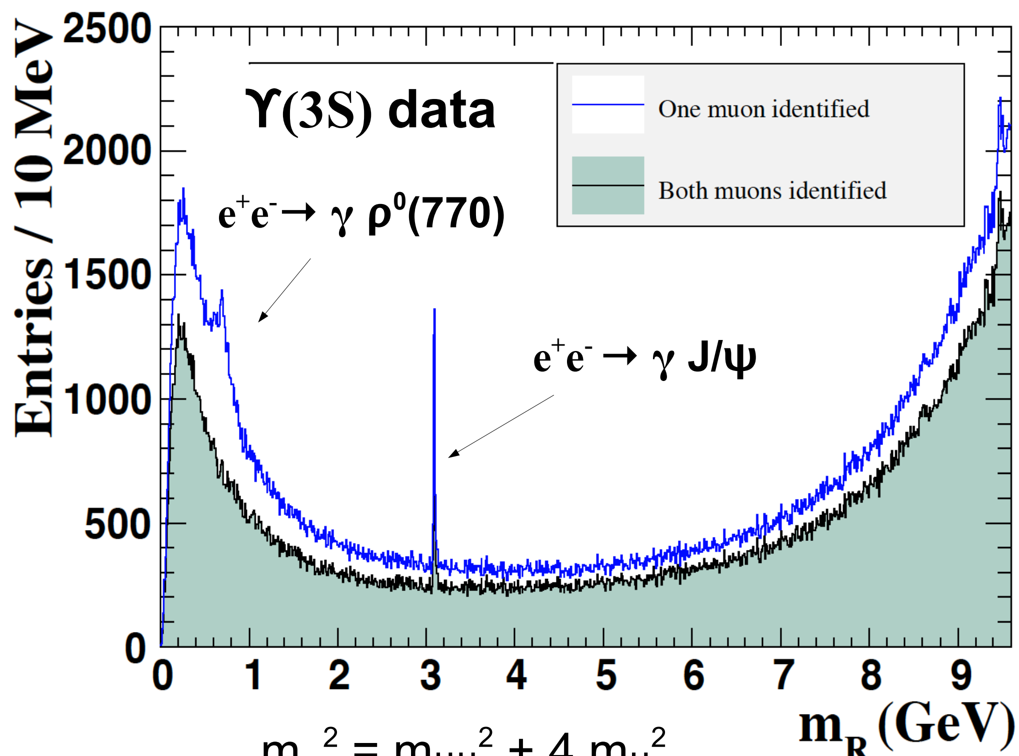
Scan the $\mu^+\mu^-$ invariant mass spectrum for evidence of a A^0 peak

- continuum and known resonances ρ^0, ϕ, J/ψ, $\psi(2S)$, $\Upsilon(1S)$ included in background parameterization
- signal shape from MC, with width varying as a function of m_{A^0}

- fit sliding 300 MeV window in 2-5 MeV steps

  i.e. <1σ of signal A^0 mass resolution

- J/ψ, $\psi(2S)$ regions explicitly excluded from search
- 1951 points in total



$m_R^2 = m_{\mu\mu}^2 + 4\, m_\mu^2$

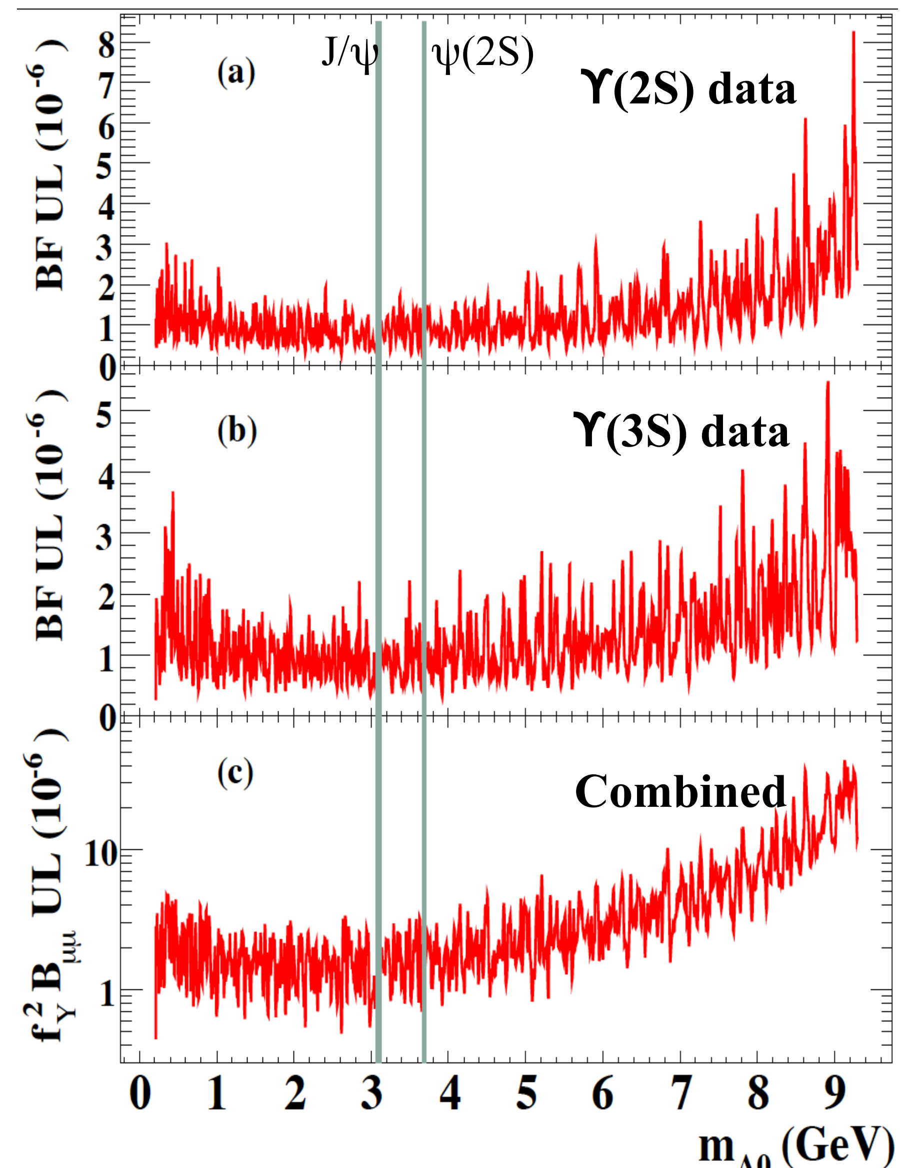
$\Upsilon(2S, 3S) \to \gamma A^0$, $A^0 \to \mu^+\mu^-$ PRL 103, 081803 (2009)

Scan range $0.212 \le m_{A^0} \le 9.3$ GeV for evidence of A^0

- Most significant positive fluctuations is 2.8σ (3.1σ) in $\Upsilon(3S)$ ($\Upsilon(2S)$) sample
  - consistent with expected statistical fluctuations given number of independent trials
- No signal observed at $m_{A^0} \sim 214$ MeV (HyperCP)

Effective Yukawa coupling of A^0 to bound state b-quark

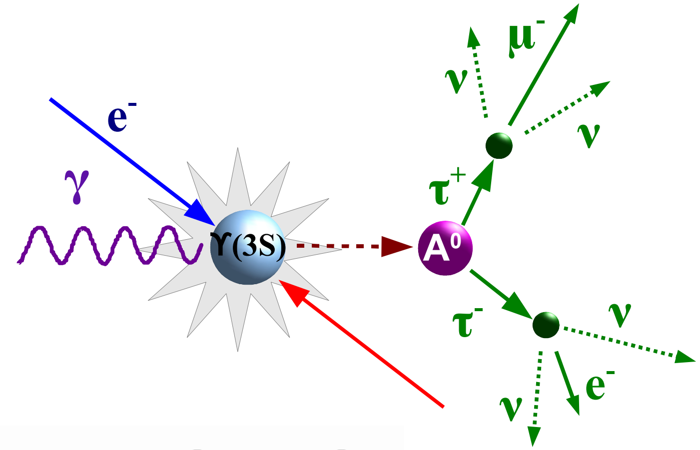
$$\frac{\mathcal{B}(\Upsilon(nS) \to \gamma A^0)}{\mathcal{B}(\Upsilon(nS) \to l^+ l^-)} = \frac{f_\Upsilon^2}{2\pi\alpha}\left(1 - \frac{m_{A^0}^2}{m_{\Upsilon(nS)}^2}\right)$$



$\Upsilon(3S)\rightarrow\gamma A^0,\ A^0\rightarrow\tau^+\tau^-$

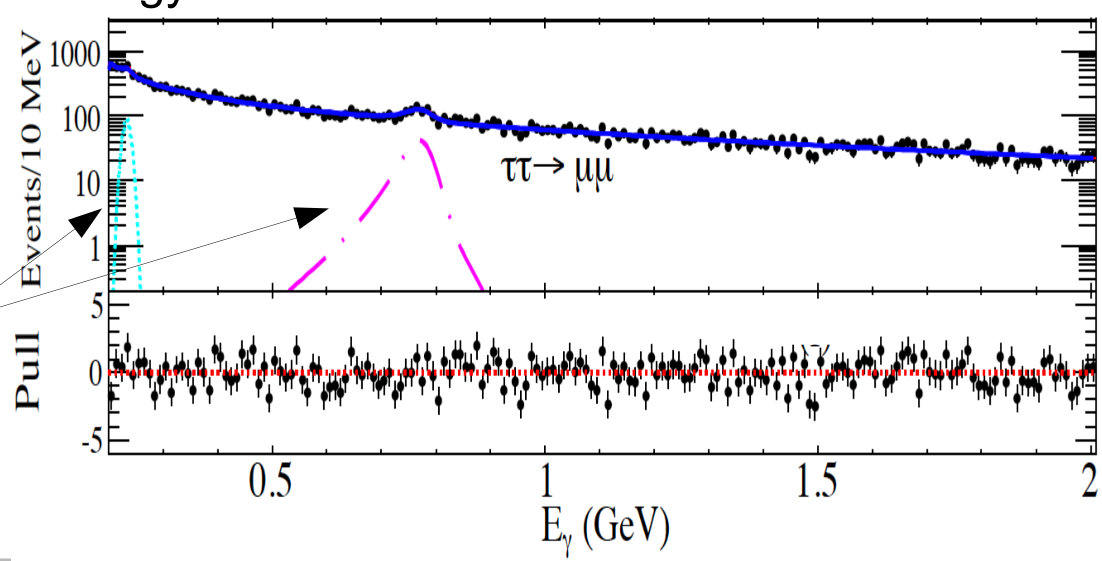
PRL 103, 181801 (2009)

- Search for $A^0\rightarrow\tau^+\tau^-$ in $\tau^+\rightarrow e^+\nu\nu$ and $\tau^+\rightarrow\mu^+\nu\nu$
  - E_γ >100 MeV and exactly two tracks identified as leptons
  - Missing energy in τ decays precludes event kinematic fit; A^0 mass obtained from E_γ and known CM energy
  - Additional background suppression provided by set of 8 kinematic and angular variables, optimized in 5 ranges of photon energy



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

- Background mostly QED $e^+e^-\rightarrow\gamma\,\tau^+\tau^-$ and 2-photon
- peaking contributions from $\Upsilon(3S)\rightarrow\gamma\,\chi_{bJ}(2P)$, $\chi_{bJ}(2P)\rightarrow\gamma\,\Upsilon(nS)$ (n=1,2; J=0,1,2)

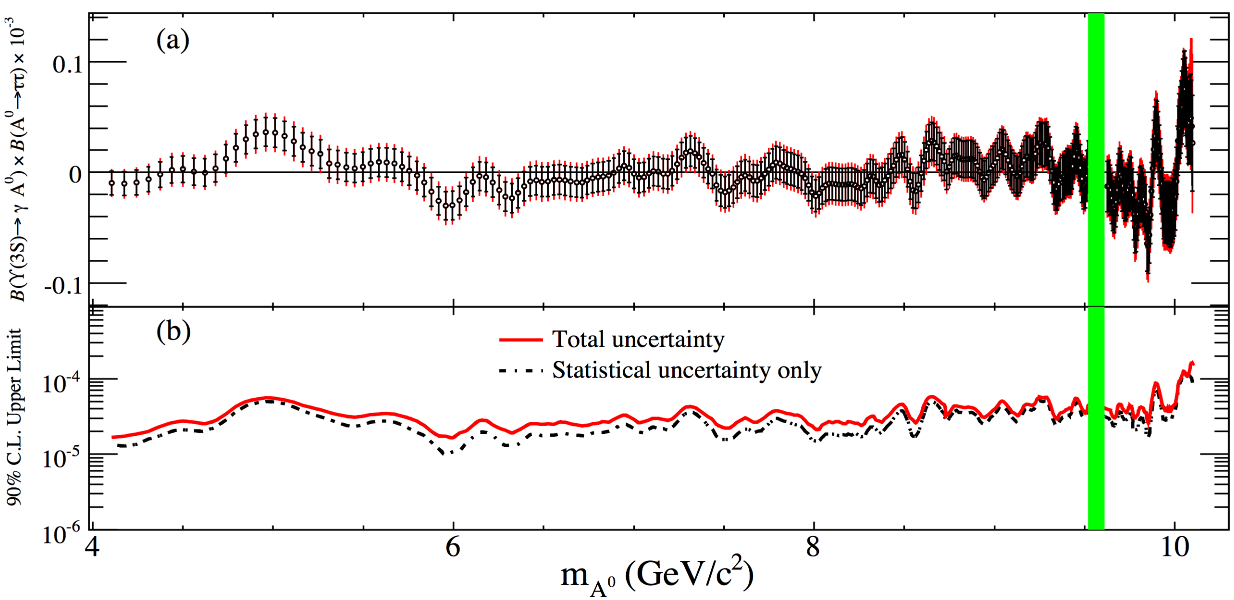


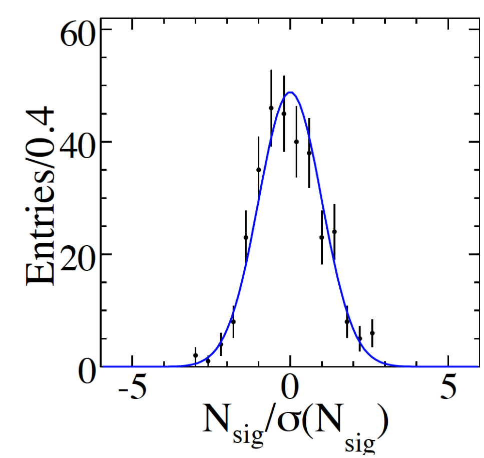
$\Upsilon(3S) \rightarrow \gamma A^0$, $A^0 \rightarrow \tau^+\tau^-$

PRL 103, 181801 (2009)

- Scan for peaks in E_γ spectrum (307 scan points) across range corresponding to $4.03 < m_{A^0} < 10.10\ \mathrm{GeV}/c^2$
  - signal represented as peaking distribution of known width (varying with E_γ)
  - simultaneous fit to γee and $\gamma\mu\mu$ and $\gamma e\mu$ final states
- Distribution of yield significances consistent with standard normal distribution

$\mathcal{B}(\Upsilon(3S) \rightarrow \gamma A^0) \cdot \mathcal{B}(A^0 \rightarrow \tau^+\tau^-) < (1.5 - 16) \times 10^{-5}$ at 90% C.L.





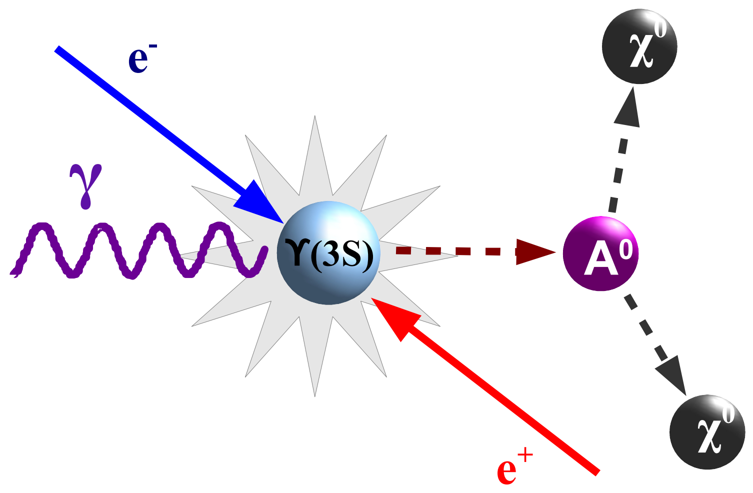
$\Upsilon(3S) \rightarrow \gamma A^0$, $A^0 \rightarrow$ invisible

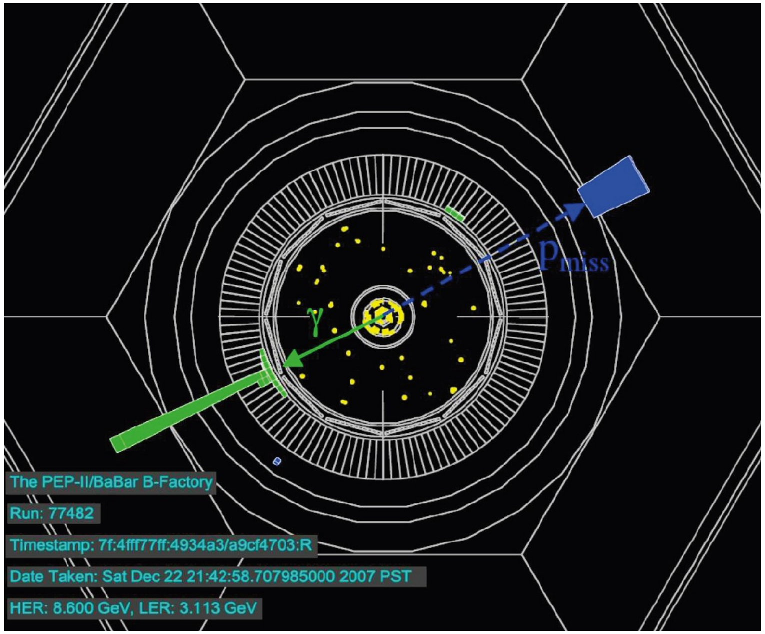
arXiv:0808.0017[hep-ex]
BABAR preliminary

- $A^0 \rightarrow \chi^0 \chi^0$ can be dominant decay mode in some NMSSM scenarios with light neutralino LSP
- Search for mono-energetic peak in single photon spectrum
  - Signal selection based on photon fiducial and quality requirements, and the presence of additional detector activity in the event
  - requires single-photon trigger; data sample naturally split into "low" and "high" E_γ regions with different background composition:

    $e^+e^- \rightarrow \gamma\gamma$ $\qquad$ $e^+e^- \rightarrow (e^+e^-)\,\gamma$

  - Selection optimized on 10% of final data sample and signal MC samples generated over a broad range of masses





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

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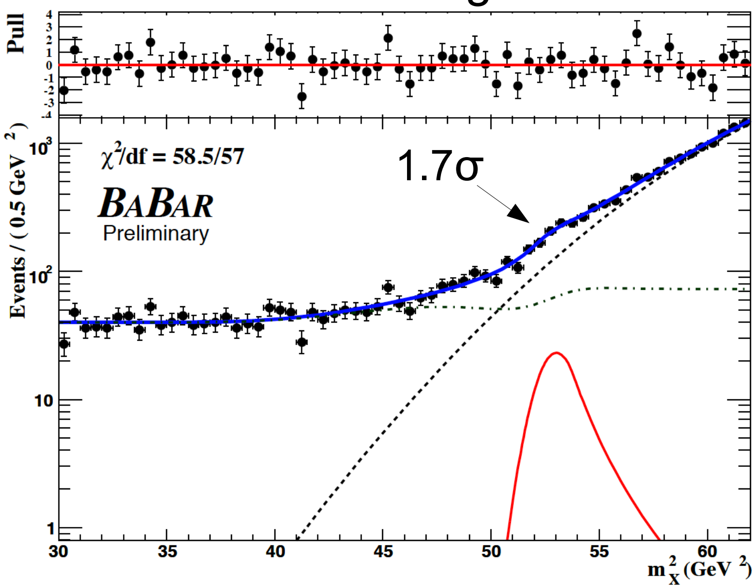
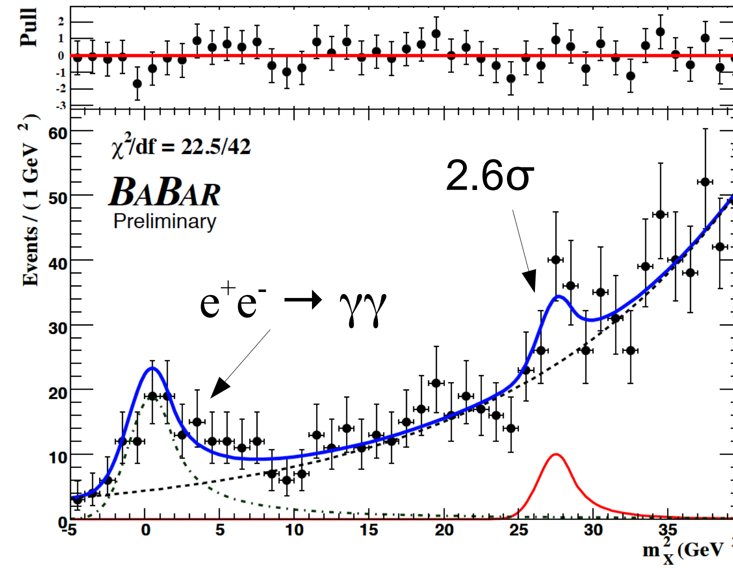
BABAR preliminary

Low mass region

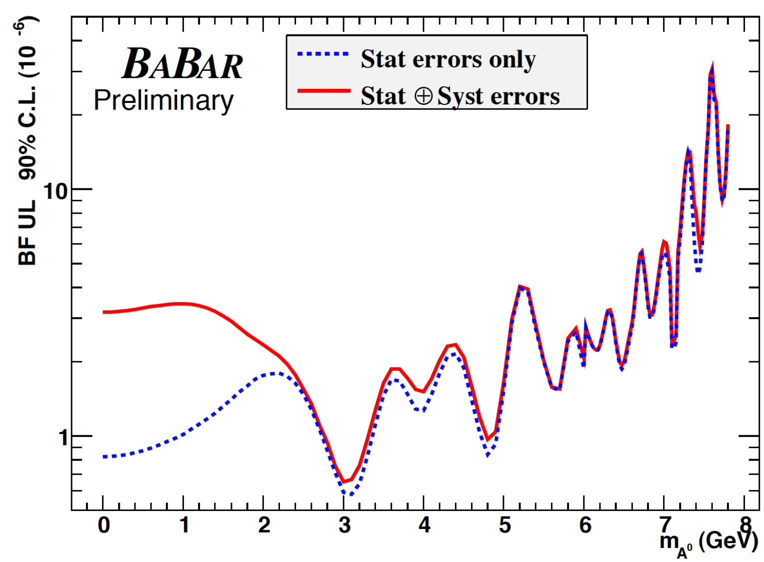


High mass region



- Signal extracted from unbinned maximum likelihood fits to m_X^2 distribution in $\Delta m_X = 0.1\text{GeV}$ steps

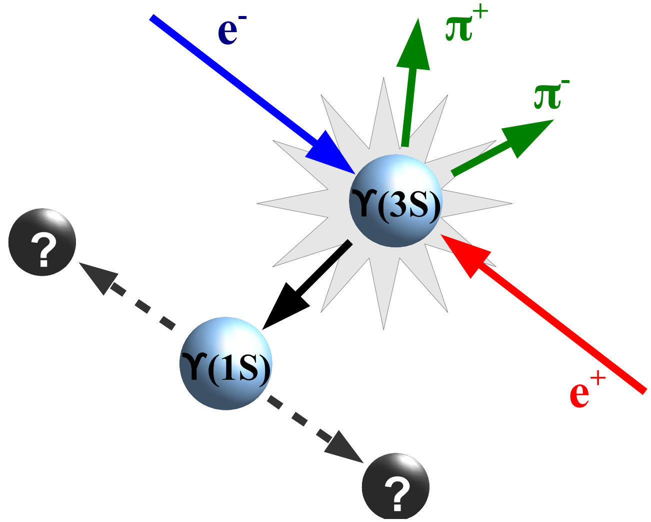
$$B(\Upsilon(3S)\rightarrow\gamma A^0)\cdot B(A^0\rightarrow \text{invisible}) < (0.7 - 31)\times 10^{-6} \text{ at 90\% C.L for } m_{A^0}\leq 7.8\text{ GeV}$$



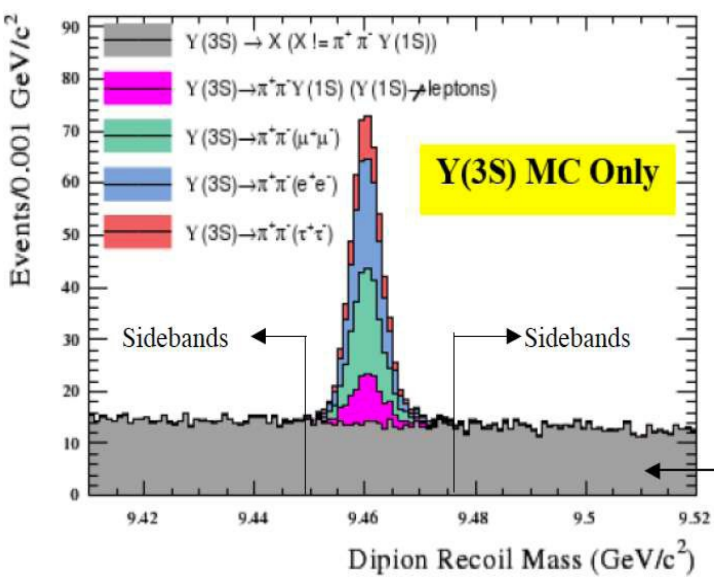
$\Upsilon(1S) \rightarrow$ invisible

PRL 103, 251801 (2009)

- B($\Upsilon(1S) \rightarrow \nu\bar{\nu}$) ~ 1 x 10^{-5} in Standard Model
  - can be enhanced to ~10^{-4} – 10^{-3} by decays into pairs of low mass weakly interacting dark matter candidates
- Identify the $\Upsilon(1S)$ from the $\Upsilon(3S) \rightarrow \pi^+\pi^-\Upsilon(1S)$ transition pions with "recoil" mass consistent with $\Upsilon(1S)$
- Select signal by requiring absence of significant additional activity in the detector
  - peaking background from $\Upsilon(1S)$ decays with undetected (SM) particles passing outside of detector acceptance
  - estimated from MC and validated against "near invisible" control samples



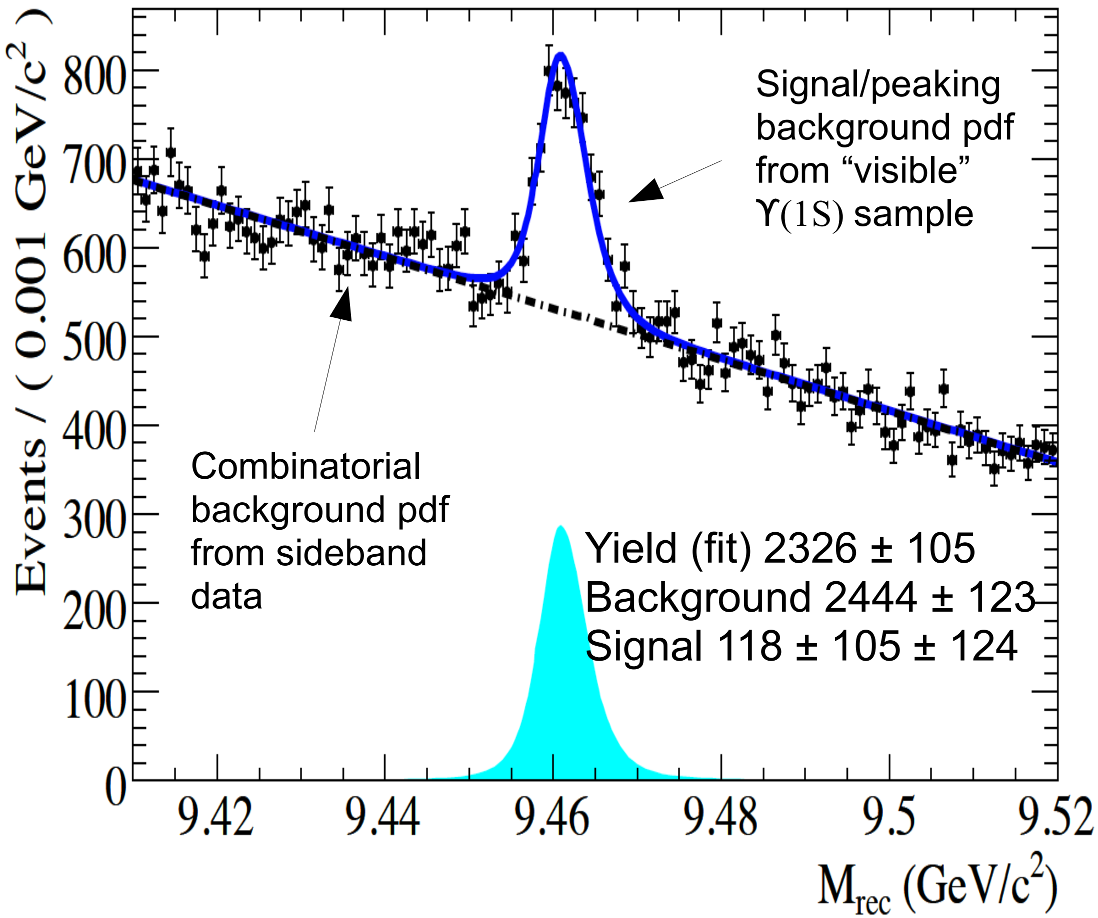
$$M_{\text{rec}}^2 = s + M_{\pi\pi}^2 - 2\sqrt{s}E_{\pi\pi}^*$$



$\Upsilon(1S) \rightarrow$ invisible

PRL 103, 251801 (2009)

- Multivariate classifier used to suppress substantial non-peaking background
  - trained on sideband data and signal MC; optimized to minimize background statistical error
- Large "visible" $\Upsilon(1S)$ sample validates MC signal and background models, and overall $\Upsilon(1S)$ yield



$B(\Upsilon(1S)\rightarrow$invisible$) = (-1.6 \pm 1.4(\text{stat}) \pm 1.6(\text{syst})) \times 10^{-4}$
$< 3.0 \times 10^{-4}$ at 90% C.L.

  - order of magnitude improvement over previous limits

Summary

- Constraints on light Higgs bosons in the mass region below ~10 GeV/c^2

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

  PRL 103, 081803 (2009)

  $\Upsilon(3S) \rightarrow \gamma A^0, \;\; A^0 \rightarrow \tau^+\tau^-$

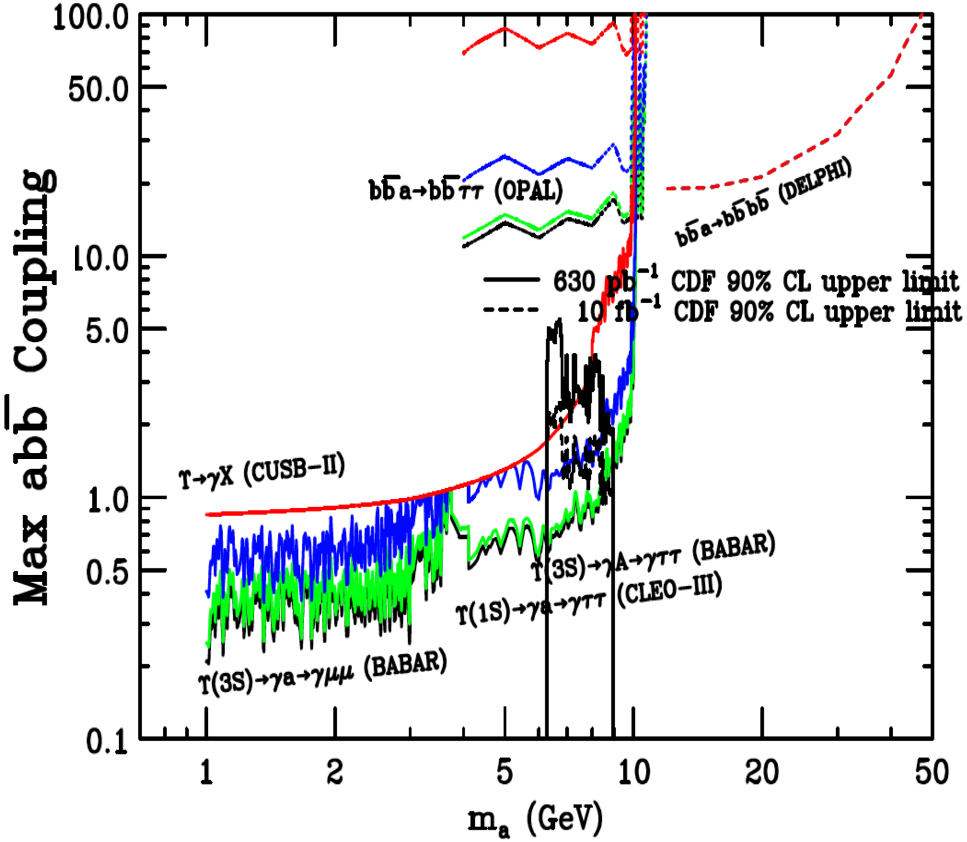
  PRL 103, 181801 (2009)

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

  arXiv:0808.0017[hep-ex]
  BABAR preliminary

  can be interpreted in context of NMSSM and similar models

R. Dermisek and J. Gunion, arXiv:1002.197 [hep-ph]



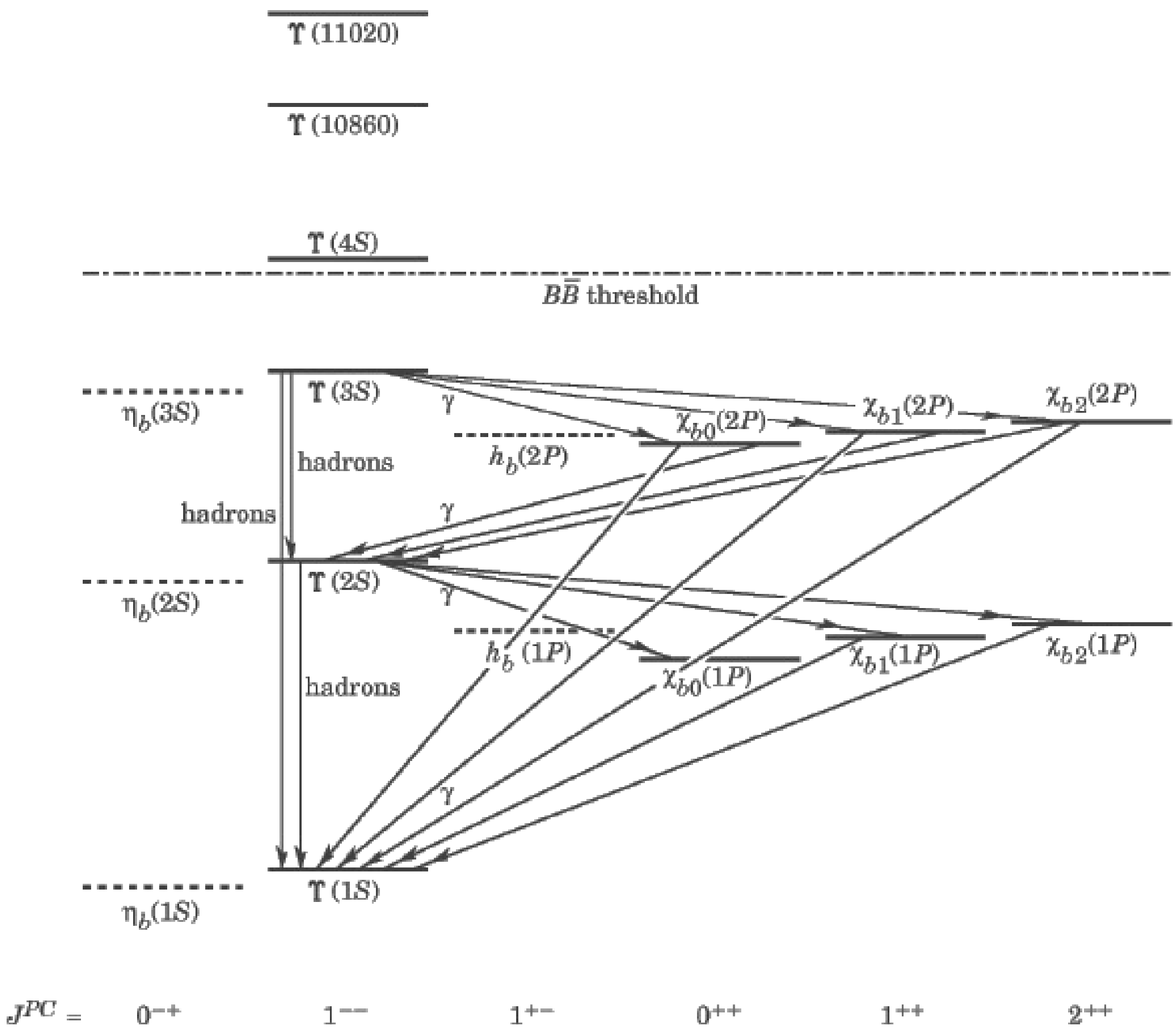
- Dark Matter search:

  $\Upsilon(3S) \rightarrow \pi^+\pi^- \Upsilon(1S), \;\; \Upsilon(1S) \rightarrow$ **invisible**

  $B(\Upsilon(1S) \rightarrow \text{invisible}) < 3.0 \times 10^{-4}$ (90% CL) PRL 103, 251801 (2009)

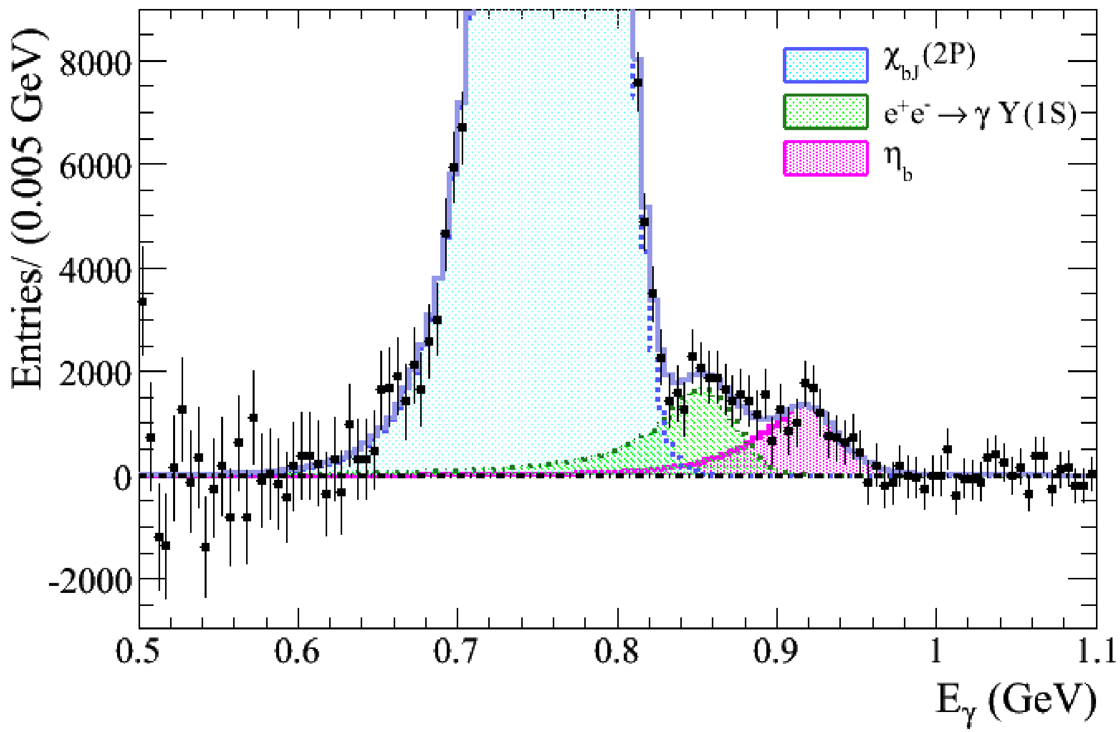
Backups

Bottomonium spectroscopy



η_b observation

PRL 101, 071801 (2008)



Fitted signal yield:

19200 ± 2000 (stat.)
± 2100 (syst.)

Branching Fraction:

$(4.8 \pm 0.5 \pm 1.2) \times 10^{-4}$

Fitted Mean: $E_\gamma = 921.2^{+2.1}_{-2.8} \pm 2.4\,\text{MeV}$

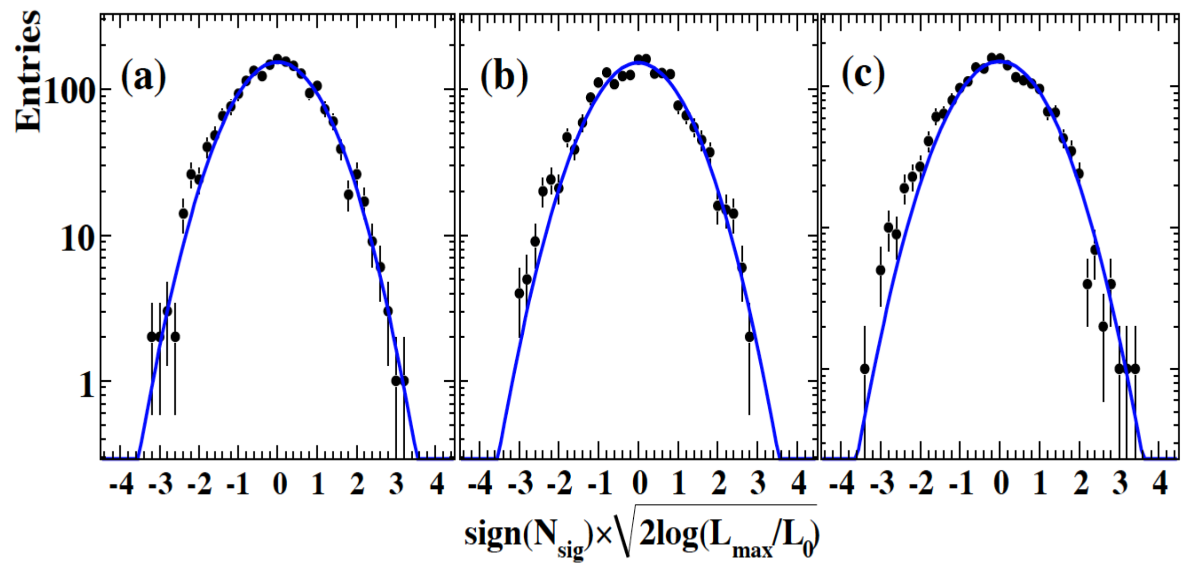
Mass: $9388.9^{+3.1}_{-2.3} \pm 2.7\,\text{MeV}/c^2$

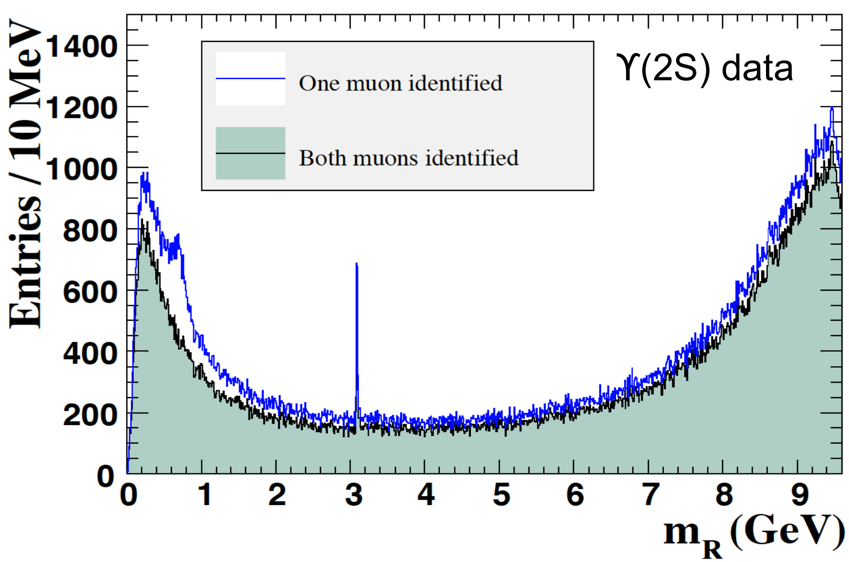
Hyperfine Splitting: $71.4^{+2.3}_{-3.1} \pm 2.7\,\text{MeV}/c^2$

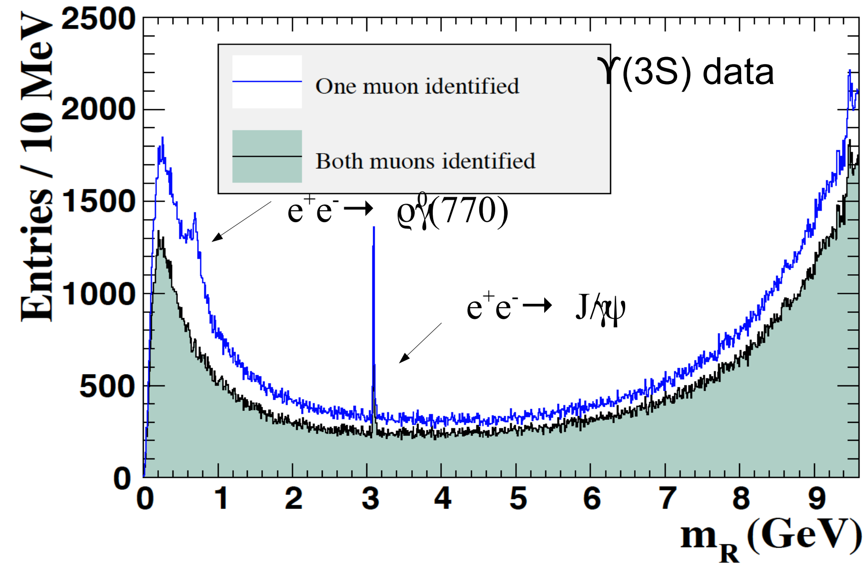
$\Upsilon(2S, 3S) \rightarrow \gamma A^0$, $A^0 \rightarrow \mu^+\mu^-$

PRL 103, 081803 (2009)

- No significant outliers, distribution consistent with statistical fluctuations (standard normal distribution)

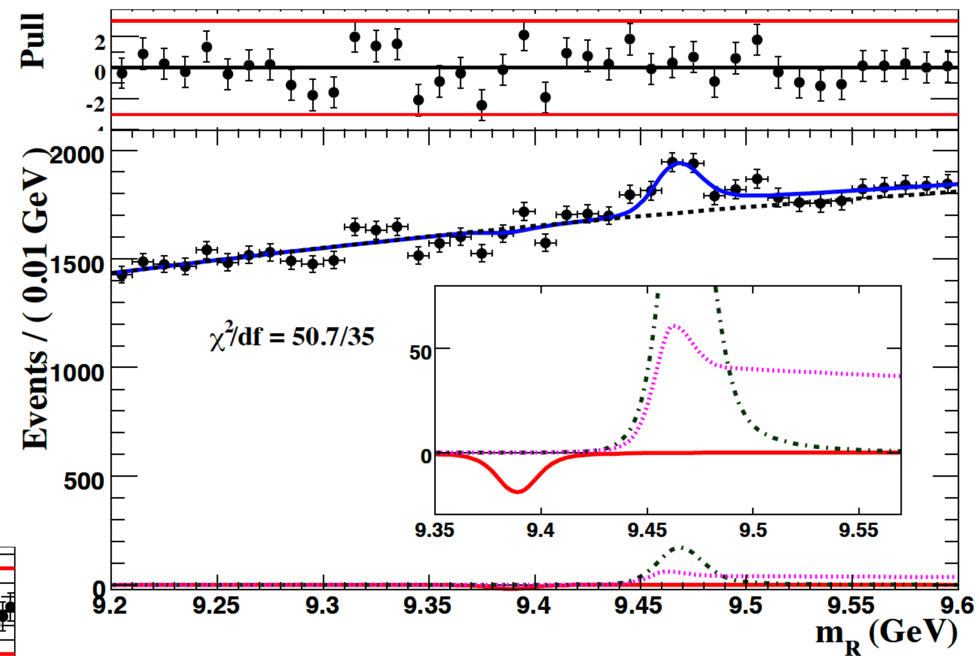


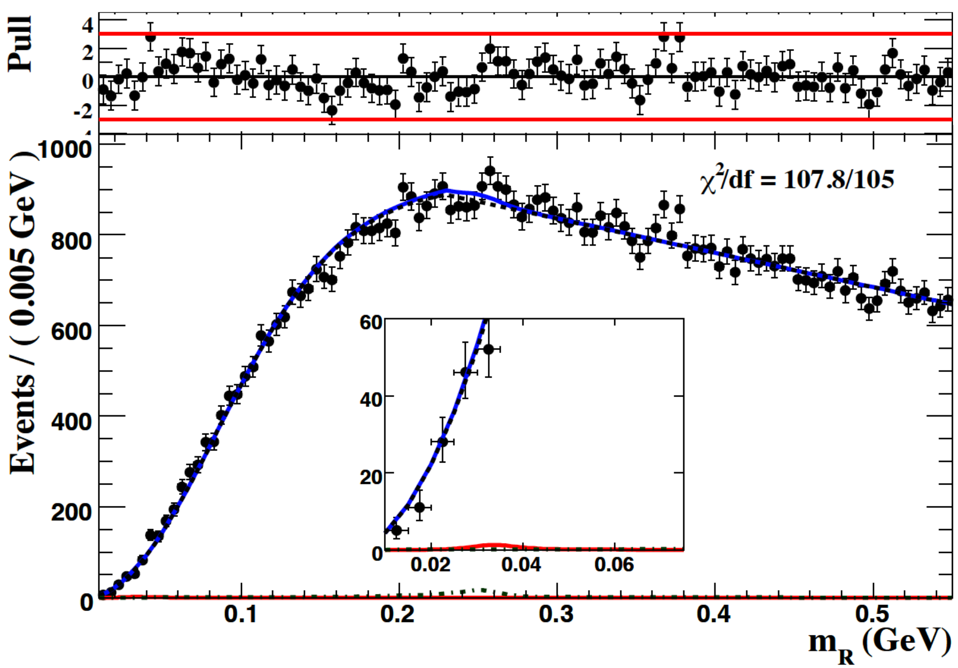




$\Upsilon(2S, 3S) \to \gamma A^0, \ A^0 \to \mu^+\mu^-$

PRL 103, 081803 (2009)





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

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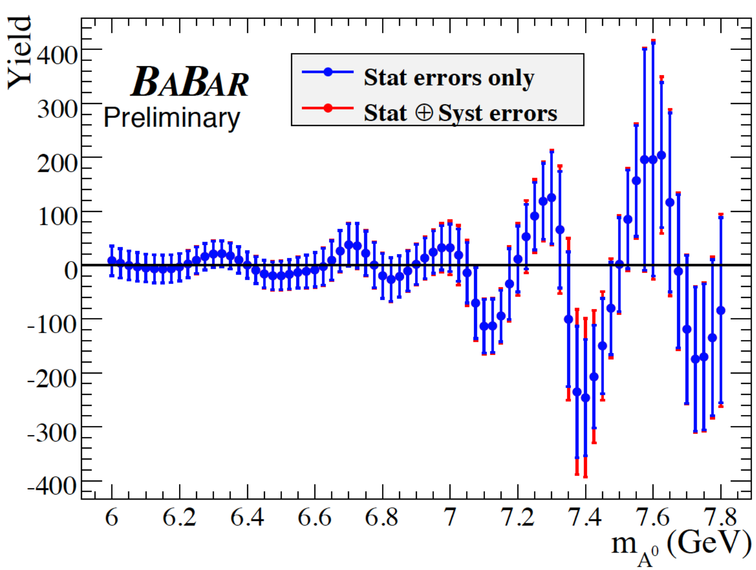


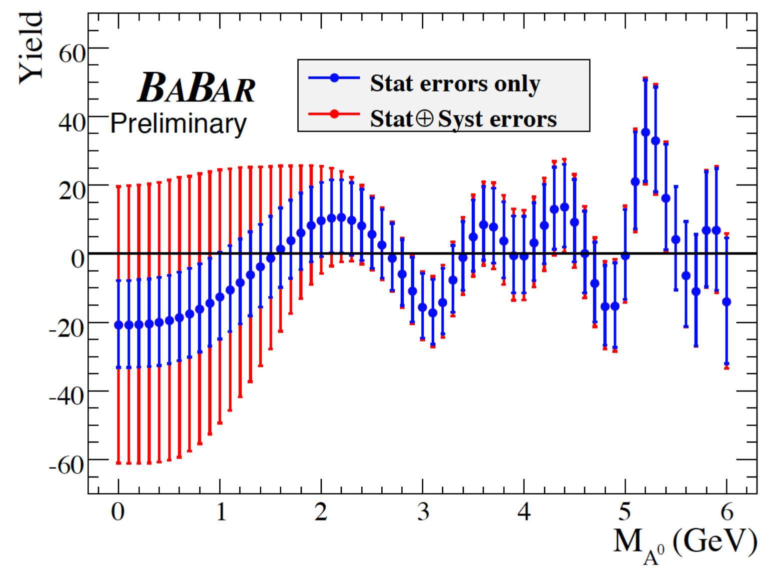
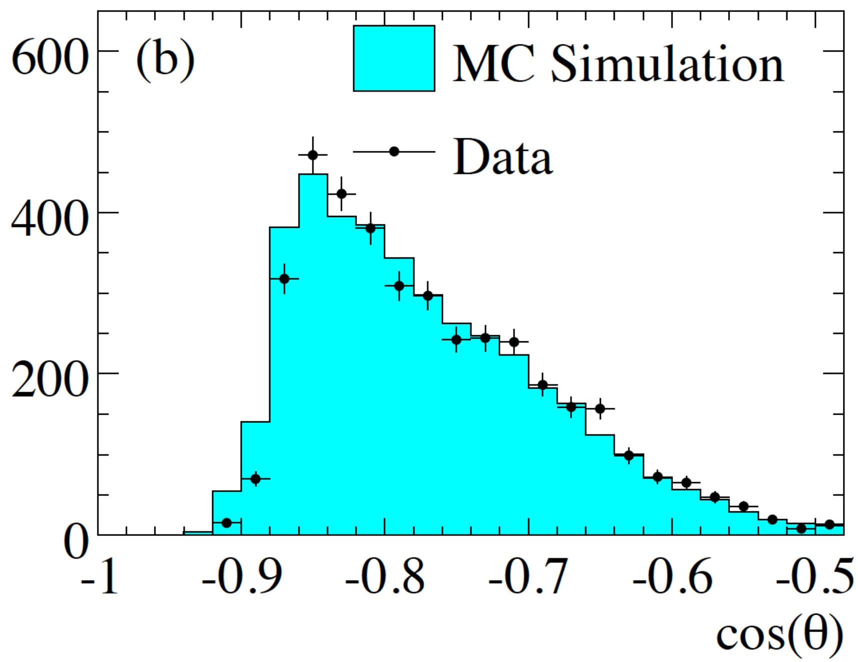


Table 1: Selection criteria for the two regions, low and high energies.

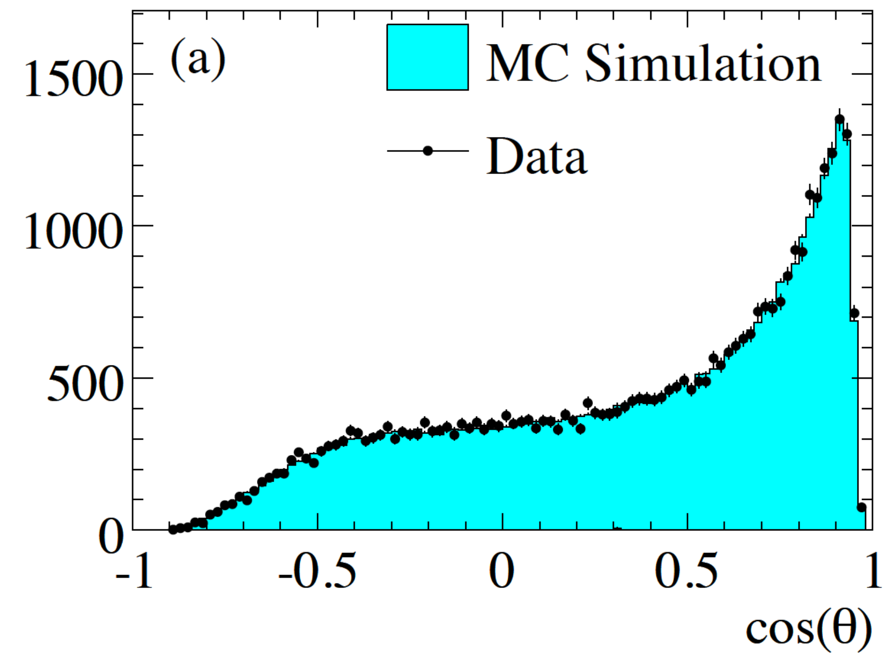
Variable	$3.2 < E^*_\gamma < 5.5$ GeV	$2.2 < E^*_\gamma < 3.7$ GeV
Number of crystals in EMC cluster	$20 < N_{\rm crys} < 48$	$12 < N_{\rm crys} < 36$
LAT shower shape	$0.24 < LAT < 0.51$	$0.15 < LAT < 0.49$
a_{42} shower shape	$a_{42} < 0.07$	$a_{42} < 0.07$
Polar angle acceptance	$-0.31 < \cos\theta^*_\gamma < 0.6$	$-0.46 < \cos\theta^*_\gamma < 0.46$
2nd highest cluster energy (CMS)	$E^*_2 < 0.2$ GeV	$E^*_2 < 0.14$ GeV
Extra photon correlation	$\cos(\phi^*_2 - \phi^*_1) > -0.95$	$\cos(\phi^*_2 - \phi^*_1) > -0.95$
Extra EMC energy (Lab)	$E_{\rm extra} < 0.1$ GeV	$E_{\rm extra} < 0.22$ GeV
IFR veto	$\cos(\Delta\phi^*_{\rm NH}) > -0.9$	$\cos(\Delta\phi^*_{\rm NH}) > -0.95$
IFR fiducial	$\cos(6\phi^*_\gamma) < 0.96$	...

$\Upsilon(1S) \to$ invisible

PRL 103, 251801 (2009)



3 track sample
high p track



Four track sample
(+ high p track)

Scan

- precision scan of the ϒ(4S) – ϒ(6S) region