Searches for Light New Physics with *BABAR*

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(on behalf of the *BABAR* collaboration)

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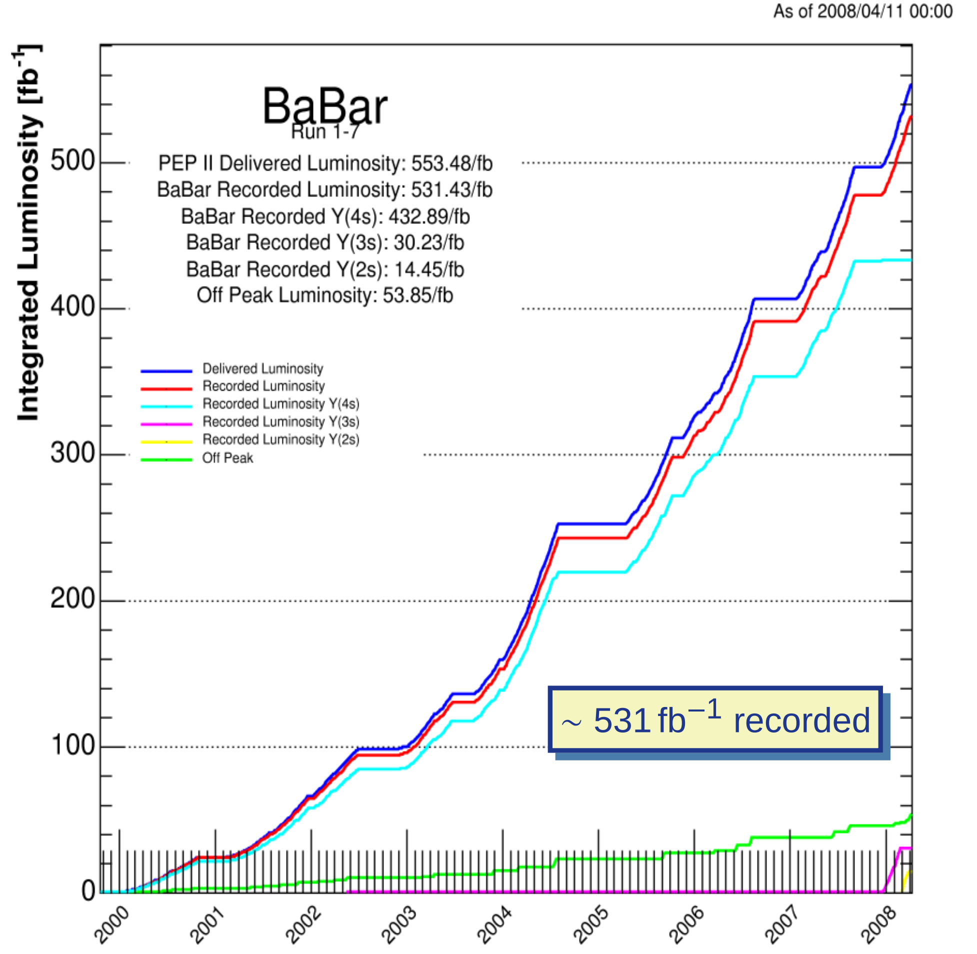
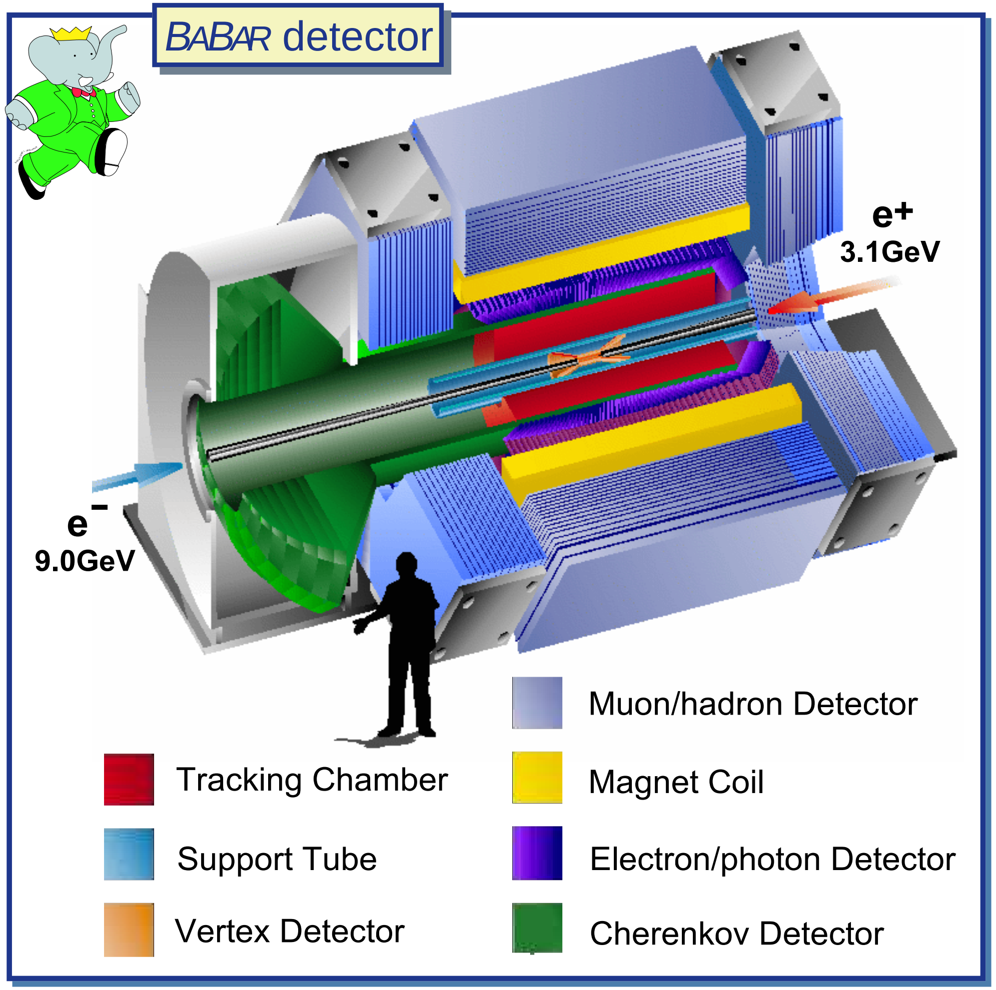
BABAR collected ~ 531 fb^{-1} of e^+e^- collisions around the Υ(4*S*) in 1999–2008





- *BABAR* data sample: **~120M Υ(3*S*)** [10x Belle, 25x CLEO] and **~100M Υ(2*S*)** [12x CLEO]

Why search for light new physics? Light Higgs

NMSSM light CP-odd Higgs a^0

- $\Upsilon(nS) \to \gamma a^0, \quad a^0 \to \ell^+\ell^-, \quad a^0 \to q\bar{q}$
  - Hiller, PRD 70 (2004) 034018,
  - Dermisek/Gunion/McElrath, PRD 76 (2007) 051105
- $\Upsilon(nS) \to \gamma a^0, \quad a^0 \to \chi\bar{\chi}$ (invisible neutralinos)
  - Shrock/Suzuki, PLB 110 (1982) 250

lepton universality violation in $\Upsilon(nS)$ decays e.g. in Type-II Two-Higgs Doublet Model (non-MSSM)

- $\Upsilon(nS) \to \gamma(\text{soft})X^0, \quad X^0 \to \ell^+\ell^-$ with $\tau^+\tau^-$ enhanced over $\mu^+\mu^-$ and e^+e^- by Higgs coupling
- light Higgs mass close to $\Upsilon(nS)$ resonances
- M.A.Sanchis-Lozano, Int. J. Mod. Phys. A19, 2183 (2004)
- E.Fullana and M.A.Sanchis-Lozano, Phys. Lett. B653, 67 (2007)
- F.Domingo et al., JHEP 0901, 061 (2009)

Why search for light new physics? Dark matter, dark sector, dark forces

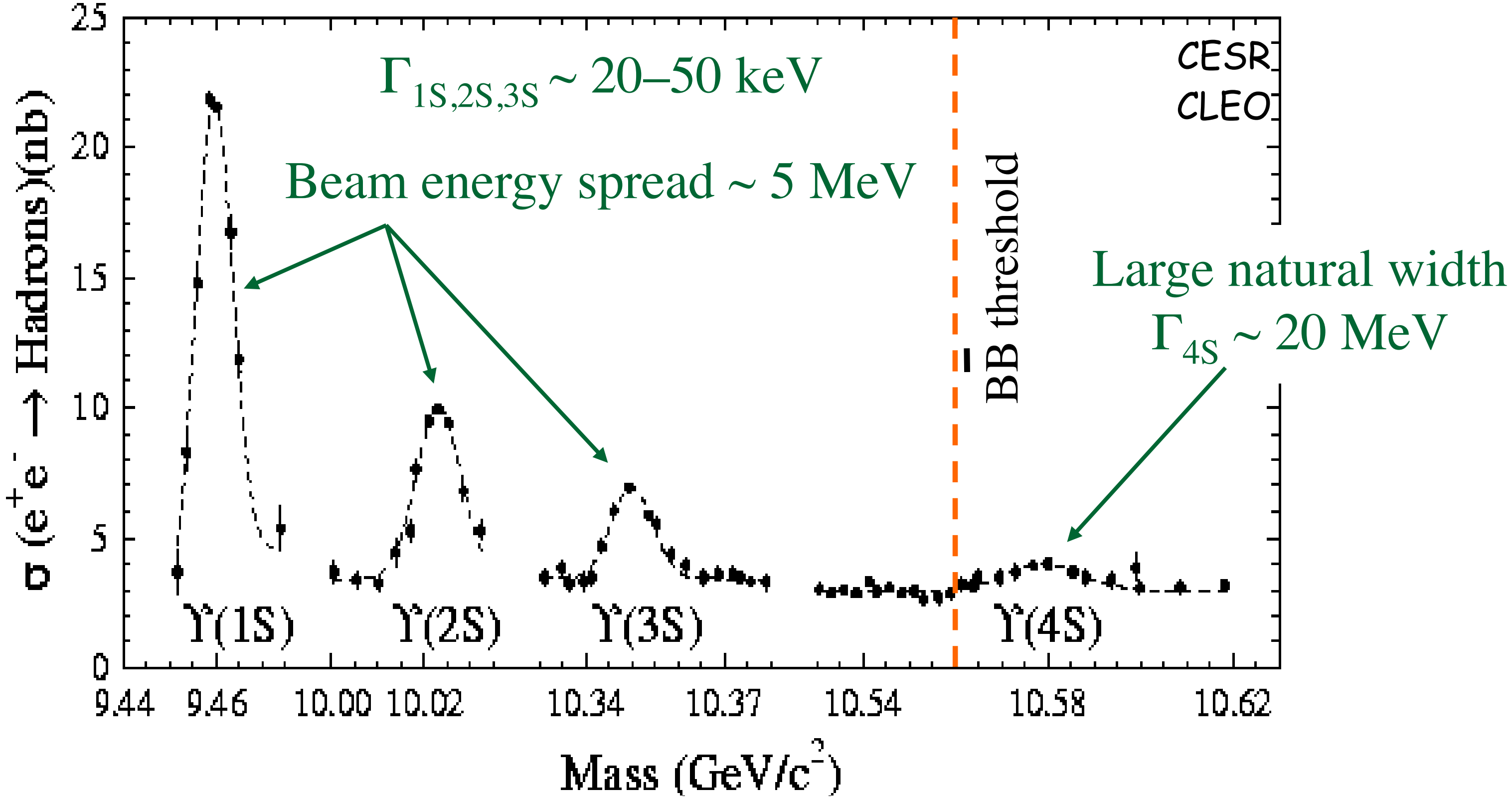
$\Upsilon(nS) \to$ invisible (invisible = $\chi_{\rm dm}\overline{\chi}_{\rm dm}$ dark matter pair via dark photon coupling, BF $\sim 10^{-3}$)

- McElrath, PRD 72 (2005) 103508
- significant enhancement over SM prediction, e.g. $\Upsilon(1S) \to \nu\overline{\nu} \sim 10^{-6}$

Light dark sector particles decaying into leptons

- $e^+e^- \to \gamma A'$, $A' \to \ell^+\ell^-$ (A' dark photon)
  - N. Arkani-Ahmed et al., PRD 79 (2009) 015014
  - Nomura/Thaler, PRD 79 (2009) 075008 (axion-like particle decaying into muons)
- $e^+e^- \to A' \to W'W'$, $W' \to \ell^+\ell^-$ (W' dark-sector secluded gauge boson)
  - N. Arkani-Ahmed et al., PRD 79 (2009) 015014
  - Batell/Pospelov/Ritz, PRD 79 (2009) 115008

Υ(*nS*) resonances



- $e^+e^- \to \gamma^* \to$ Υ(*nS*) New Physics sensitivity much enhanced at narrow resonances
- rare process *X*, typically $\Gamma[\Upsilon(nS) \to X] \approx \Gamma_X$ about the same for all resonances

  → $\mathbf{BF}_{nS,X} = \Gamma_X / \Gamma_{nS,\text{total}} = (\Gamma_{4S,\text{total}} / \Gamma_{nS,\text{total}}) \cdot \mathbf{BF}_{4S,X}$ much larger BF on narrow resonances

Light Higgs Searches

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

BABAR, PRL 103 (2009) 081803

- Event selection
  - photon with $E_\gamma > 0.2$ GeV and two tracks, at least one identified as muon
  - $\mu^+\mu^-\gamma$ system must be compatible with decay of $\Upsilon(2,3S)$ in luminous region
- Major backgrounds
  - $e^+e^- \to \mu^+\mu^-\gamma$ QED radiative di-muons
  - $e^+e^- \to \rho \to \pi^+\pi^-\gamma$ ρ production **specific rejection**
  - $e^+e^- \to \Upsilon(1S)\gamma$ ISR events
  - $e^+e^- \to \Upsilon(2,3S) \to \chi_b(1,2P)\gamma$, $\chi_b(1,2P) \to \Upsilon(1S)\gamma$ **specific rejection**
- Signal efficiency: 25–50% over the searched A^0 mass range (0.212–9.3 GeV)
- Signal yield
  - fit expected **peak** in reduced mass $m = \sqrt{m_{\mu\mu}^2 - 4m_\mu^2}$
  - subtract both continuum background from sidebands and expected peaking backgrounds
  - scan A^0 mass range 0.212–9.3 GeV in 1951 2–5 MeV steps

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

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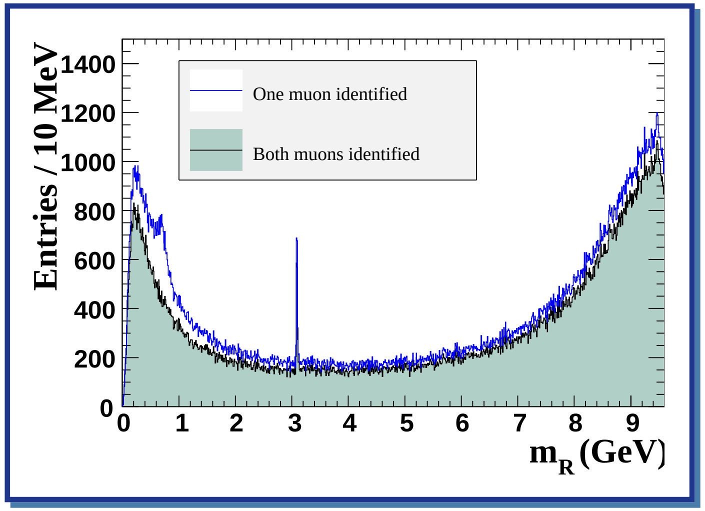
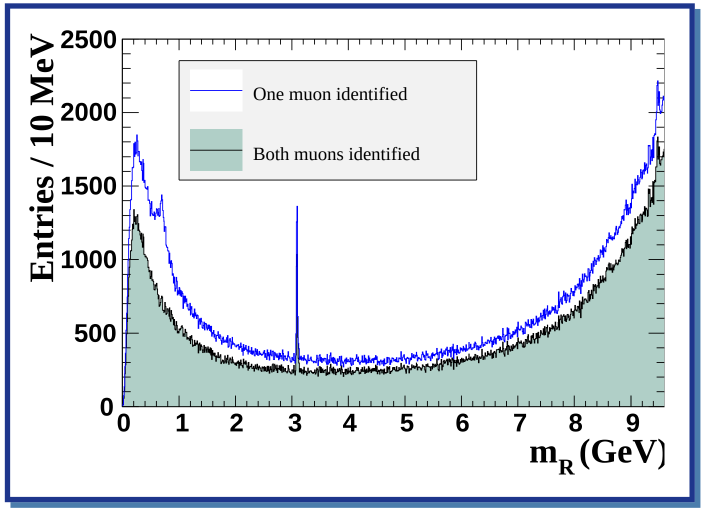
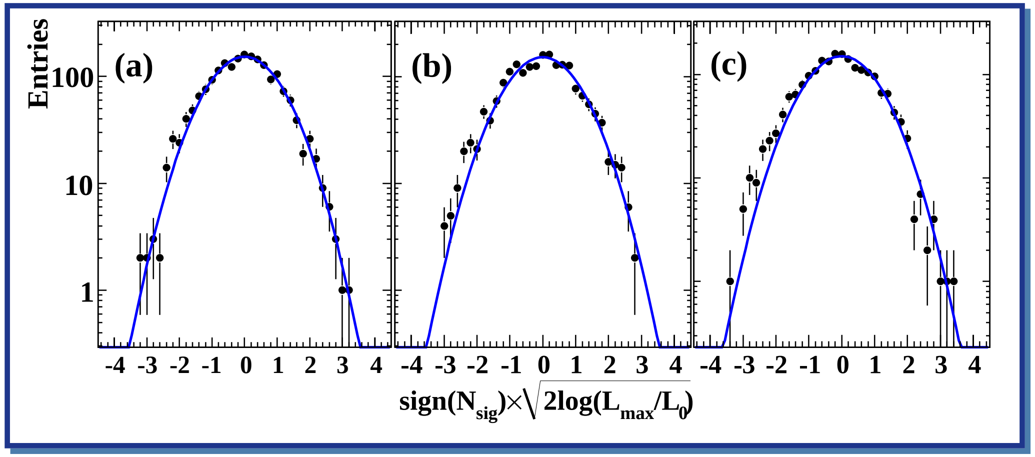
$\Upsilon(2S)$ sample A^0 candidates



$\Upsilon(3S)$ sample A^0 candidates



signal fit yield significance distributed as statistically expected for no signal



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

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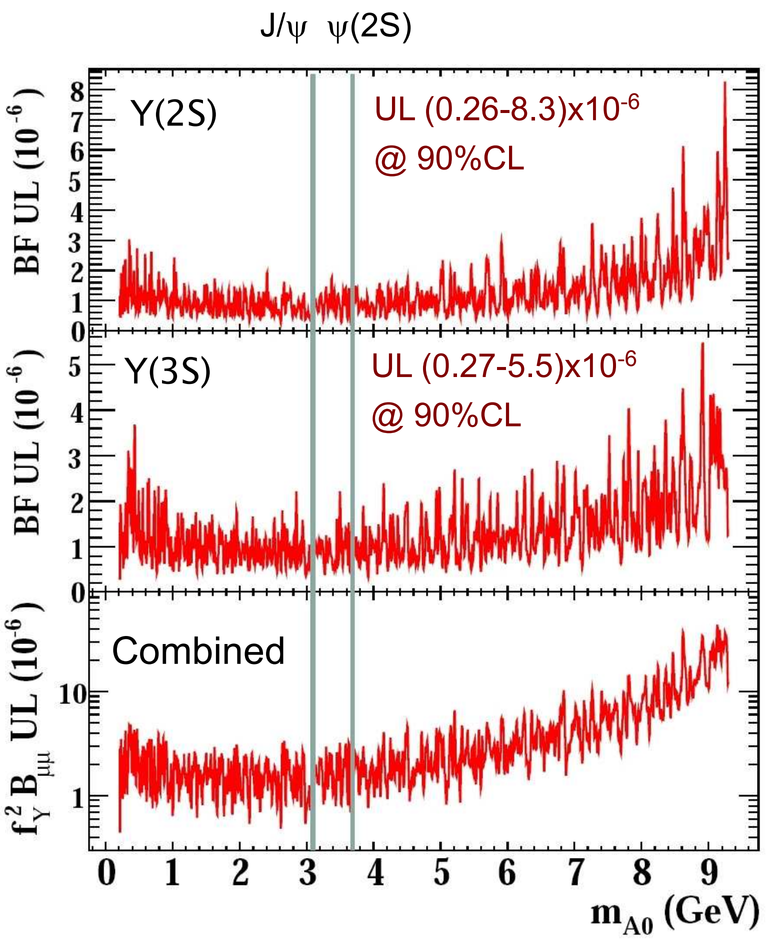
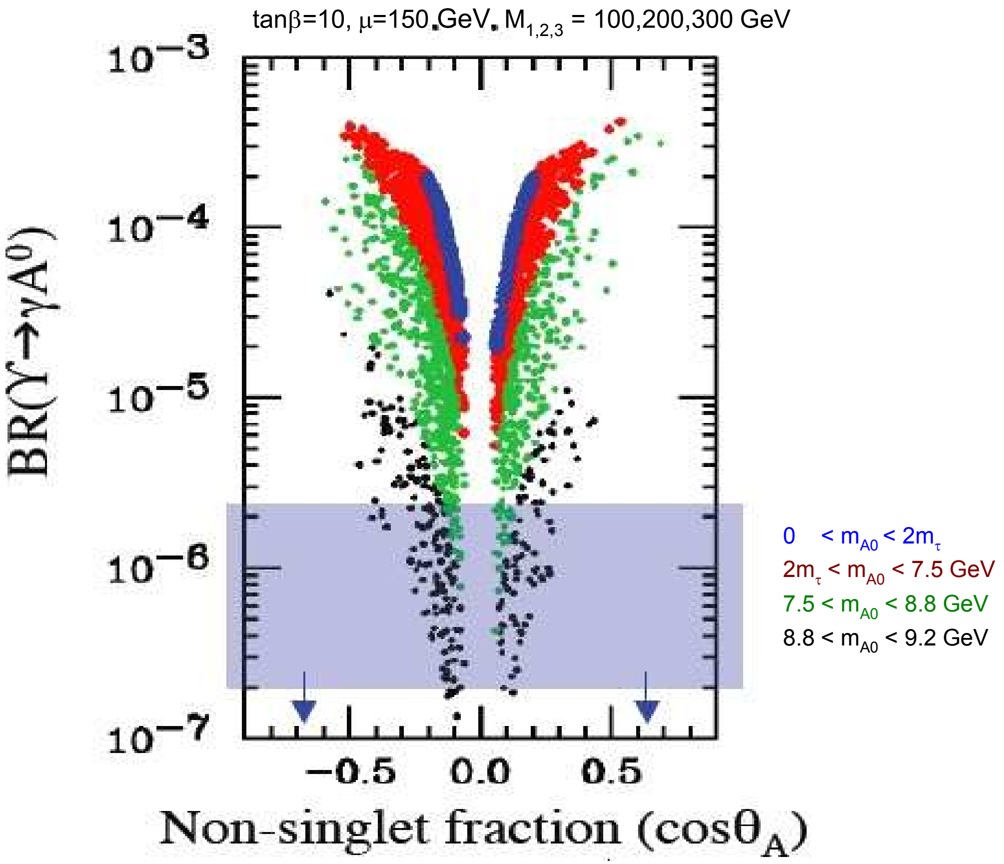




$A^0 = \cos\theta_A A_{MSSM} + \sin\theta_A A_S$

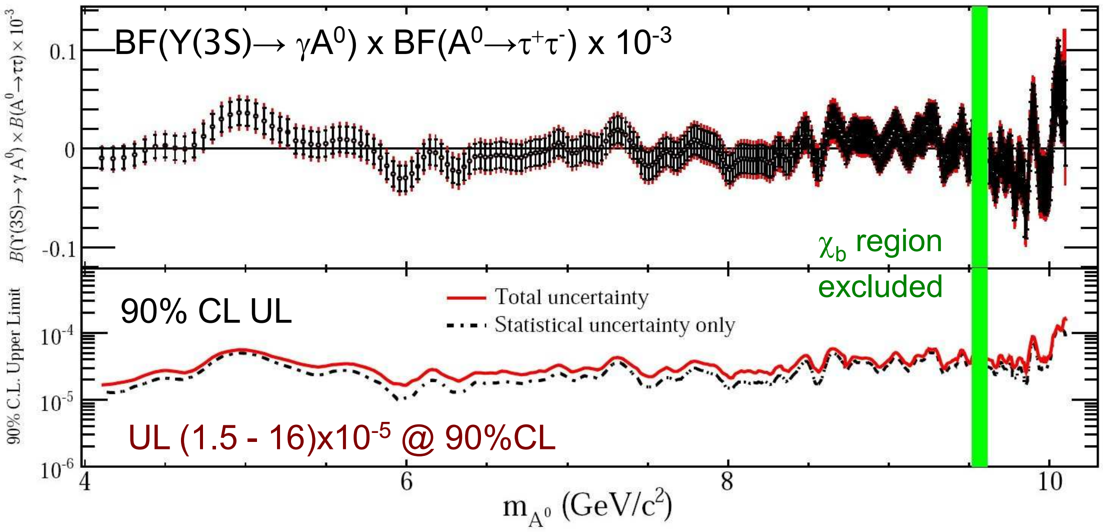
$\Upsilon(3S) \to \gamma A^0, \quad A^0 \to \tau^+\tau^-$

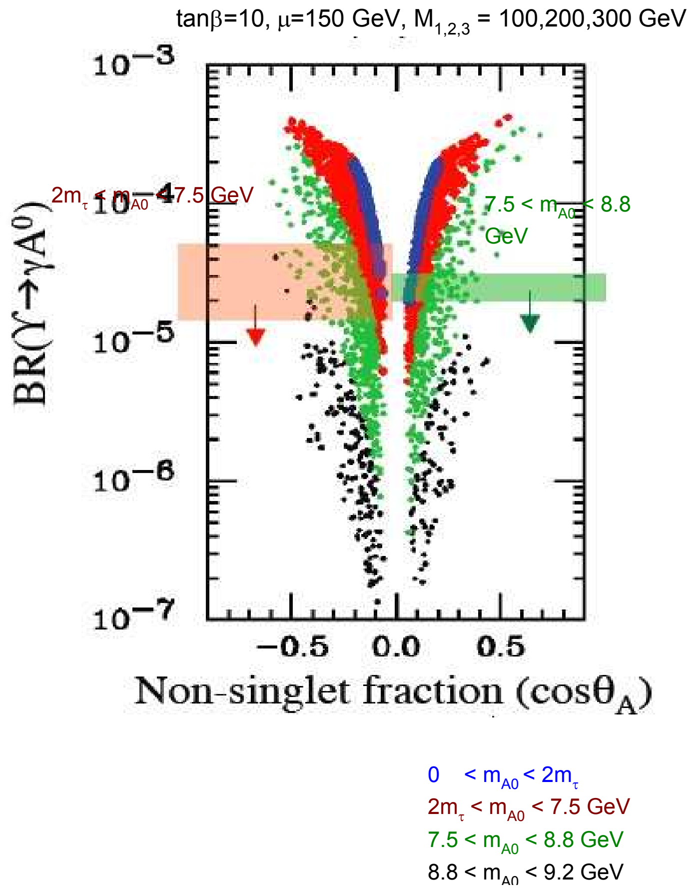
BABAR, PRL 103 (2009) 181801

- Event selection
  - photon with $E_\gamma > 0.1\,\text{GeV}$ and two tracks from 1-prong tau pair decays into $ee, \mu e, \mu\mu$
  - eight discriminating variables: Etot, PT, missing mass/angle, angle photon-lepton plane, angle track-lepton, track-track or track-photon, angle tracks
  - optimization in 5 overlaping regions (reduce discontinuities in efficiency)
- Major backgrounds
  - $e^+e^- \to \tau^+\tau^-\gamma$ QED radiative tau pairs
  - $e^+e^- \to \rho \to \pi^+\pi^-\gamma$ ρ production **specific rejection**
  - $e^+e^- \to 4\,\text{leptons}$ Higher order QED
  - $e^+e^- \to \Upsilon(2,3S) \to \chi_b(1,2P)\gamma, \quad \chi_b(1,2P) \to \Upsilon(1S)\gamma$
- Signal efficiency: 10–26% depending primarily on photon energy
- Signal yield
  - fit expected **peak in photon energy distribution**
  - subtract both continuum background from sidebands and expected peaking backgrounds
  - scan A^0 mass range 4.03–10.10 GeV

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

BABAR, PRL 103 (2009) 181801





Upper limits (90%CL)

$BF(\Upsilon(3S) \to \gamma A^0) \times BF(A^0 \to \tau^+\tau^-) < (1.5 - 16) \times 10^{-5}$

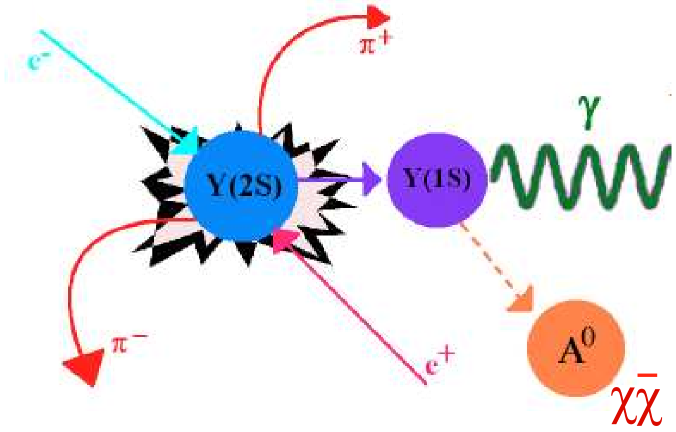
$BF(\eta_b \to \tau^+\tau^-) < 8\%$

$\Upsilon(1S) \rightarrow \gamma$ invisible

Analysis

- Search for $\Upsilon(1S) \rightarrow \gamma$ + invisible in $\Upsilon(2S) \rightarrow \Upsilon(1S)\ \pi\pi$ decays
- Resonant $\Upsilon(1S) \rightarrow \gamma + A^0$ ($\rightarrow$invisible, BF~10^{4}) [1] or $\Upsilon(1S) \rightarrow \gamma\ \chi\bar{\chi}$ (BF~10^{-5} -10^{-4}) [2]
- $A^0 \rightarrow \chi^0\chi^0$ can be dominant decay in some NMSSM scenarios with a light neutralino (LSP)
- Signature:
  - two pions and one photon (> 0.15 GeV)
  - missing energy and momentum
- Used a Neural Network discriminant to suppress the main background, trained in MC and Off-peak data

99 x 10^6 $\Upsilon(2S)$ decays



[1] PRD76,051105(2007)

[2] PRD 80,115019(2009), arXiv: 0712.0016[hep-ph] (2007)

Main background comes from:

- $e^+e^- \rightarrow \gamma\ \pi^+\pi^-$, $\Upsilon(1S) \rightarrow \gamma l^+l^-$ (continuum)
- peaking background: $\Upsilon(1S) \rightarrow \gamma\ K^0_L\ K^0_L$ and $\Upsilon(1S) \rightarrow \gamma n\bar{n}$

Υ(1S)→ γ invisible

PRL 107, 021804 (2011)

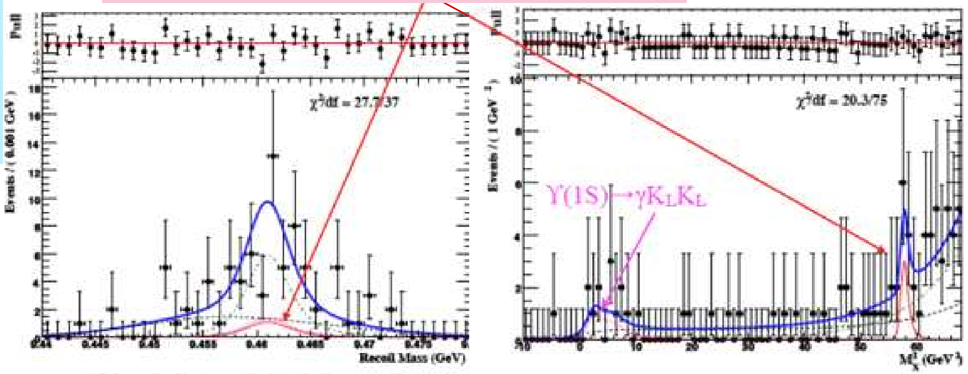
Fit & Results

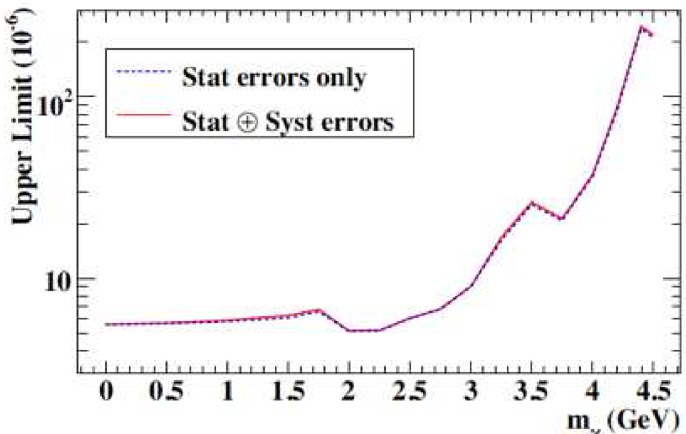
- Extract signal yield as function of m_{A0} ($0 \le m_{A0} \le 8$ GeV,196 steps) ($7.5 \le m_{A0} \le 9.2$ GeV,146 steps) and m_χ ($0 \le m_\chi \le 4.5$ GeV,17steps) performing 2D fit to:

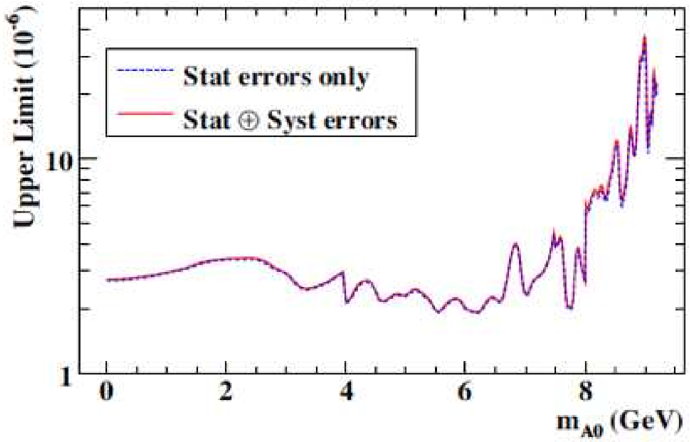
$$M^2_{\rm recoil} = M^2_{\Upsilon(2S)} + m^2_{\pi\pi} - 2M_{\Upsilon(2S)}E^*_{\pi\pi}$$

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

m_{A0}=7.58 GeV, 2.0σ significance







$B(\Upsilon(1S)\to\gamma\chi\chi < (0.5\text{-}24)\times10^{-5}$ at 90% C.L

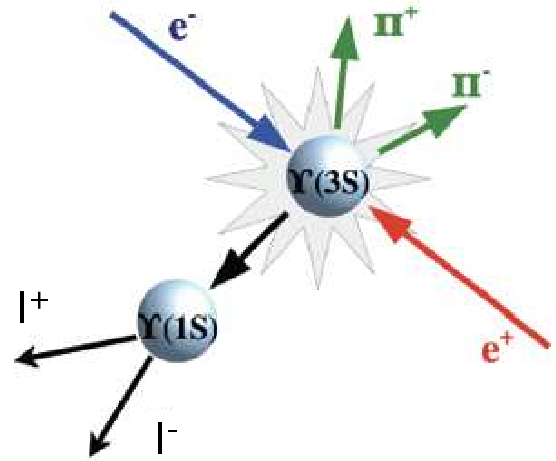
$B(\Upsilon(1S)\to\gamma(A^0\to\text{invisible}) < (1.9\text{-}37)\times10^{-6}$ at 90% C.L

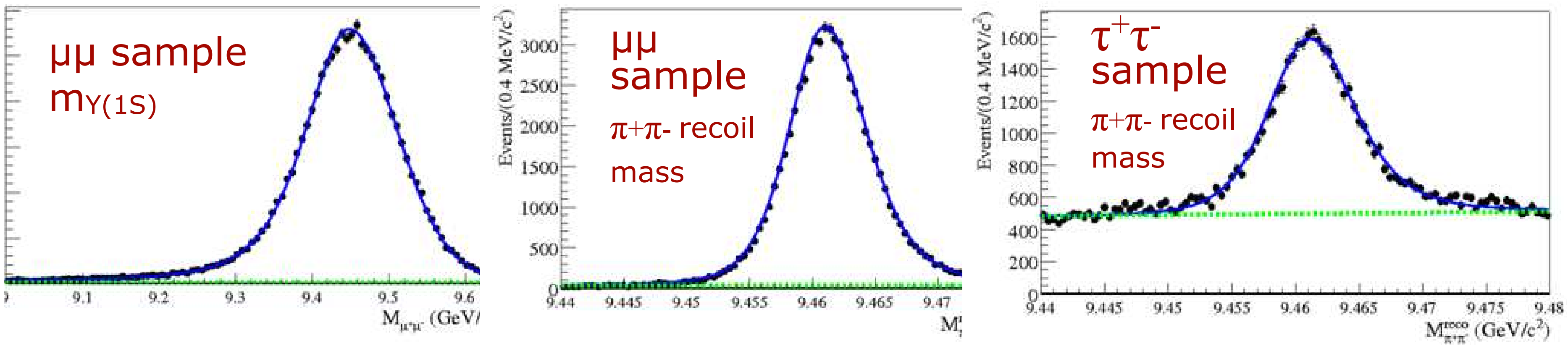
Previous limits: $B(\Upsilon(1S)\to\gamma\chi\chi \sim 10^{-3}$ (CLEO), $B(\Upsilon(1S)\to\gamma(X\to\text{invisible}) < 3\times10^{-5}$ ($m_X \sim< 7.2$GeV) at 90% C.L

Lepton universality Violation in Υ(*nS*) decays

BABAR PRL 98 (2007) 052002

- data sample: ~122*M* e^+e^- collisions at Υ(3*S*) peak
- select $\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)$ followed by $\Upsilon(1S) \to \mu^+\mu^-$ or $\Upsilon(1S) \to \tau^+\tau^-$
- tau channel has undetected neutrinos
  - use $M_{recoil} = M[\Upsilon(1S)]$, multivariate analysis
  - subtract backgrounds

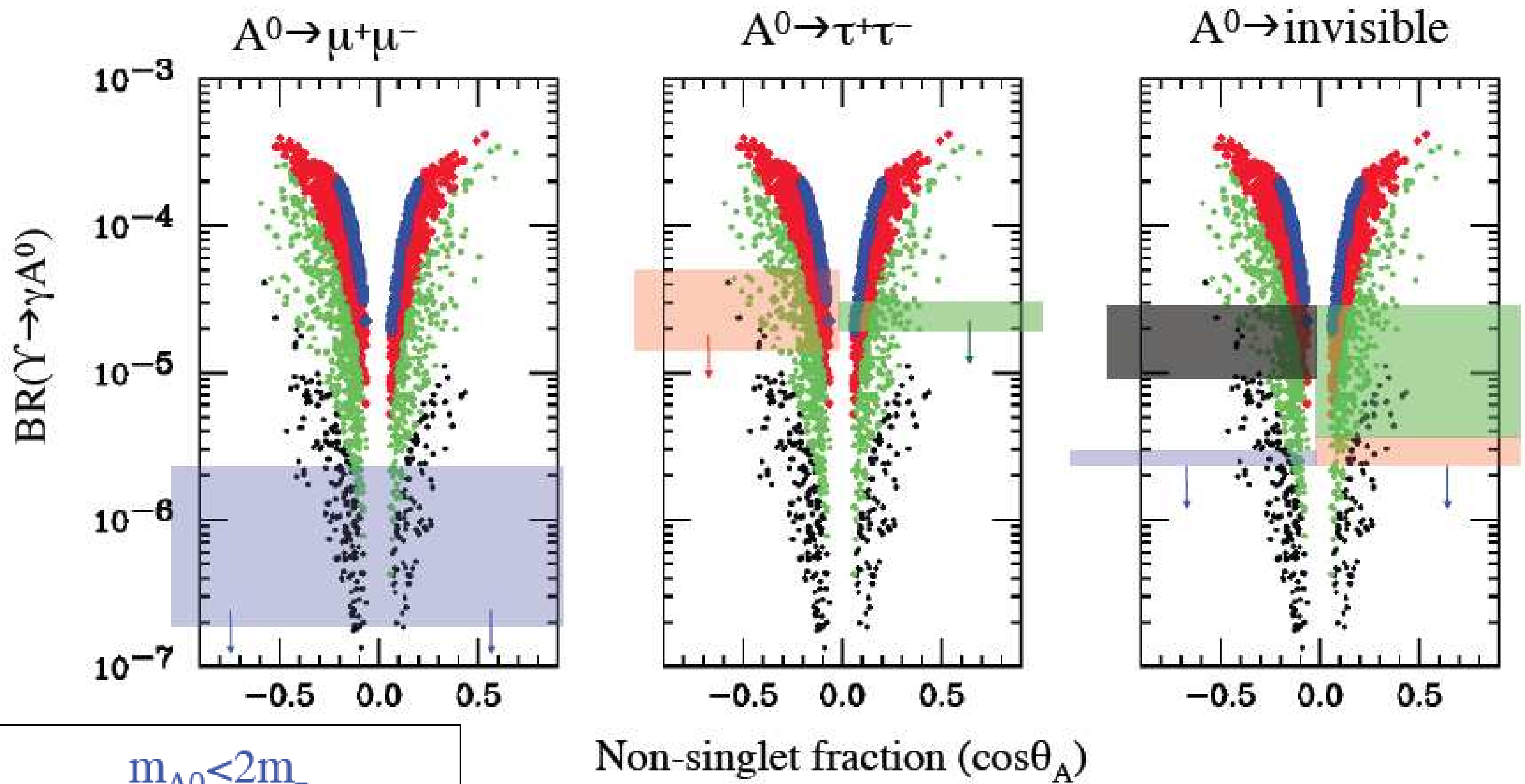




$R_{\tau\mu}[\Upsilon(1S)] = 1.005 \pm 0.013 \pm 0.022$

(CLEO: $R_{\tau\mu}[\Upsilon(1S)] = 1.02 \pm 0.02 \pm 0.05$ SM: $R_{\tau\mu}[\Upsilon(1S)] = 0.992$)

Light Higgs constraints on Dermisek/Gunion/McElrath, PRD 76 (2007) 051105



$m_{A0}<2m_\tau$

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

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

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

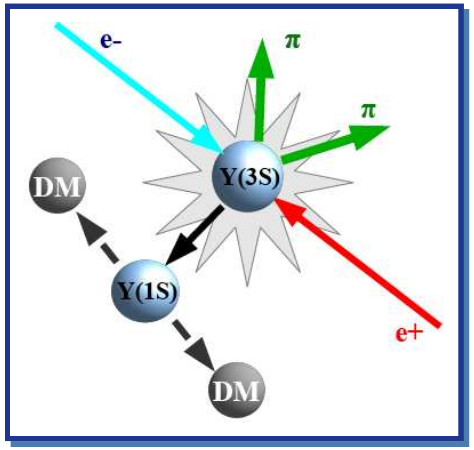
Also place significant constraints on other models

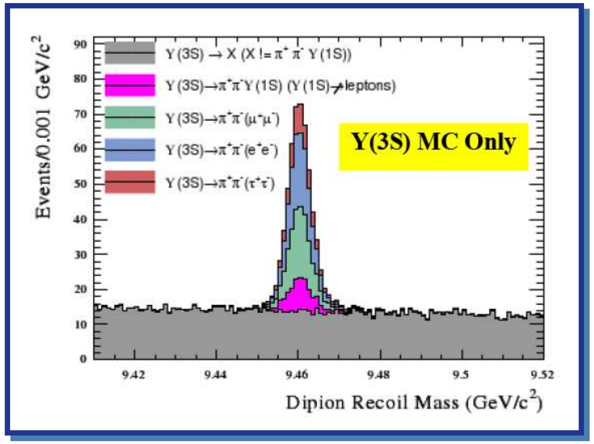
Dark Matter secluded sector light particle searches

$\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)$, $\Upsilon(1S) \to$ invisible

BABAR, PRL 103 (2009) 251801

- Event selection
  - require $\pi^+\pi^-$ pair
  - require no additional tracks
  - control samples requiring 1, 2 tracks
- Major backgrounds
  - $\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)$, $\Upsilon(1S) \to \ell^+\ell^-$ with undetected tracks
    - estimate peaking background from MC
    - data-MC matching using control samples with 1,2 tracks
- Signal yield
  - fit $M_{\text{recoil}} = \sqrt{s + m^2_{\pi\pi} - 2\sqrt{s}E_{\pi\pi}}$ as expected from $M[\Upsilon(1S)]$
  - subtract continuum and peaking backgrounds





$\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)$, $\Upsilon(1S) \to$ invisible

BABAR, PRL 103 (2009) 251801

Fit procedure

- Extended unbinned maximum likelihood fit of recoil mass M_{rec}
- Signal and peaking background
  - Crystal-Ball function
- Non-peaking background
  - 1st order polynomial

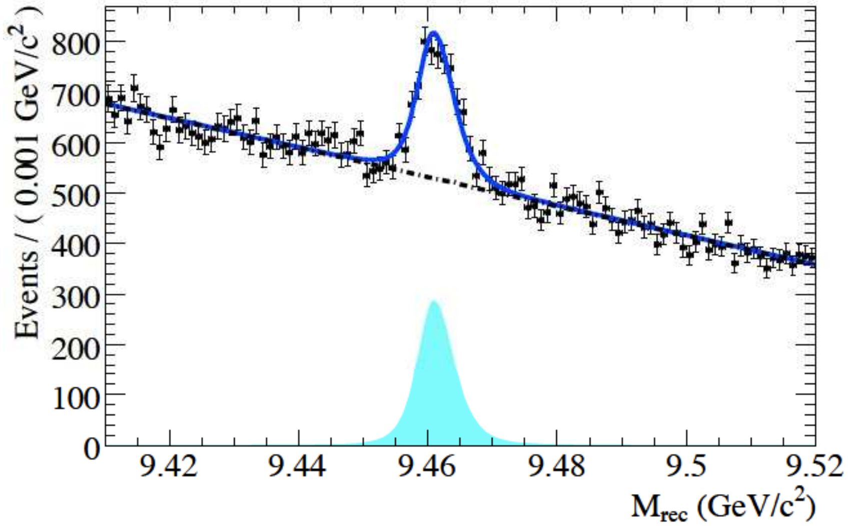
Signal efficiency ~ 18%

Results

Yield (fit)	2326 ± 105
Background	2444 ± 123
Signal	-118 ± 105 ± 124

Upper limit (90% CL)

$$BF(\Upsilon(1S) \to \text{invisible}) < 3.0 \times 10^{-4}$$



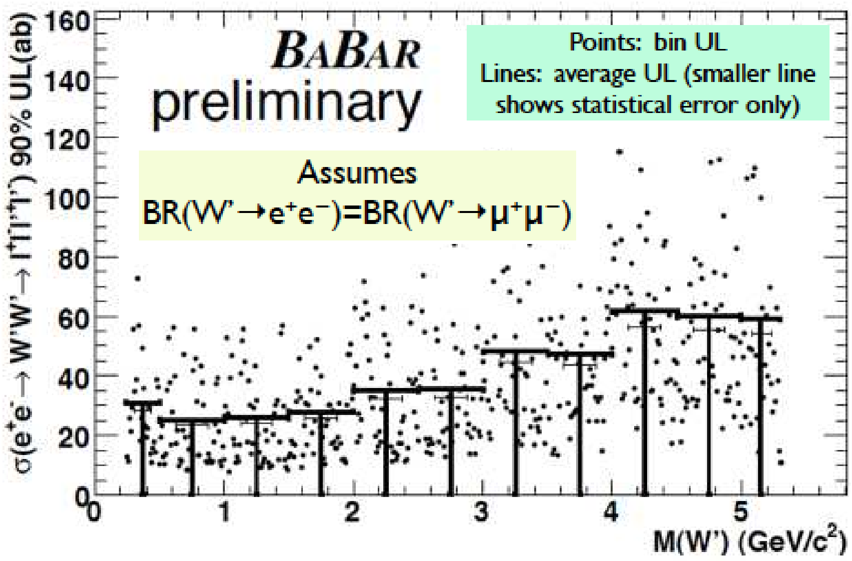
Previous measurements BF(Υ(1S) → invisible)

CLEO:	BF < 3.9 x 10^{-3} @ 90% CL	PRD 75 (2007) 031104
Belle:	BF < 2.5 x 10^{-3} @ 90% CL	PRL 98 (2007) 132001

Search for $e^+e^- \to A'^* \to W'W' \to \ell^+\ell^-\ell^+\ell^-$

BABAR prelim. arXiv:0908.2821 [hep-ex]

- Signature: 4 leptons (4e,2e+2μ,4μ) with zero total charge carrying the full beam momentum where the two dilepton invariant masses are equal (bkg from 4-lepton QED processes)
- Look for a narrow peak in the mass distribution of W' in the mass range from 0.24 and 5.3 GeV
- Signal extraction by a cut-and-count analysis in bins of m_W (10MeV step)



No significant signal observed-->Set UL (90%CL)

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

Conclusions

- no evidence for light new physics found by *BABAR* in e^+e^- collisions at and around the $\Upsilon(4S)$
  - **no evidence of light Higgs found**
  - **no evidence of light Dark Matter sector particles found**
- former upper limits on exotic $\Upsilon(nS)$ decays (typically by CLEO) improved by factor $\sim$10
  → significant constraints on several NP model predictions
- additional analyses are ongoing in *BABAR*, the quest continues

End of the presentation