Searches for Low-Mass Higgs in Υ Decays

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Representing the BABAR Collaboration

Outline

- Theoretical motivations

- I will discuss the previous BABAR results on

  1. $\Upsilon(3S) \to \gamma A^0$, $A^0 \to \tau^+\tau^-$ $[122 \times 10^6\ \Upsilon(3S)]$

     PRL 103, 181801 (2009)

  2. $\Upsilon(2S, 3S) \to \gamma A^0$, $A^0 \to \mu^+\mu^-$ $[99 \times 10^6\ \Upsilon(2S)]$ & $[122 \times 10^6\ \Upsilon(3S)]$

     PRL 103, 081803 (2009)

- I will discuss new BABAR results on

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

  PRD 87, 031102 (2013)

- Summary

Motivations

- Theoretical models predicted for existence of a light CP-odd Higgs boson ($A^0 \equiv a_1$) including Next-to-Minimal Supersymmetric Model (NMSSM)

- NMSSM contains (updating MSSM)
  3 CP-even, 2 CP-odd, and 2 charged Higgs

- Light means $m_{A^0} <$ mass of $\Upsilon(4S)$.
  $m_{A^0} <$ twice the mass of the b-quark

- Branching fractions of A^0 depend on its mass and $tan\ \beta$ and $cos\theta_A$ (parameter in NMSSM)

- Light CP-odd Higgs can be directly produced in the radiative decays of heavy quarkonium states like $\Upsilon(nS)$ $(n = 1, 2, 3)$

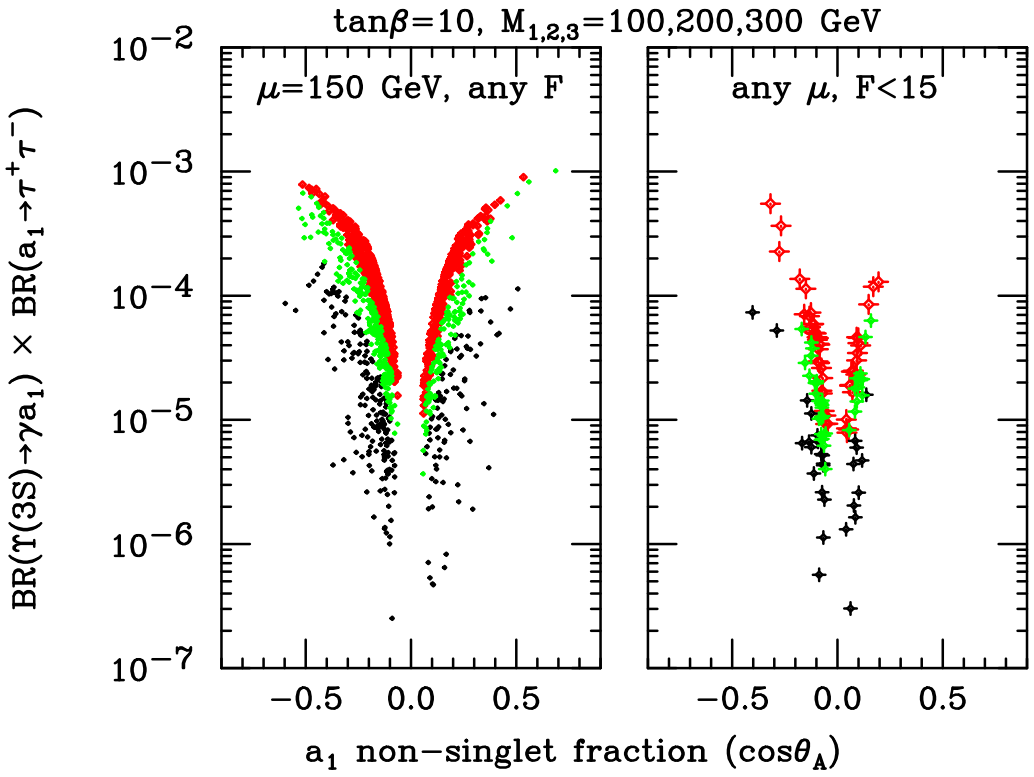
NMSSM Higgs PRD 76, 051105 (2007): Dermisek, Gunion, McElrath

☐ **Next-to-Minimal Supersymmetric Standard Model (NMSSM)**

→ **Light CP-Odd Pseudoscalar:**

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

☐ **For $m_{a_1} < 2m_b$, the lightest CP-even Higgs (h^0)**



F = Electroweak Symmetry Breaking (EWSB) fine tuning

$tan\ \beta$ = ratio of the vacuum expectation values

$m_{a_1} < 2m_\tau$

$2m_\tau < m_{a_1} < 7.5$ GeV

7.5 GeV $< m_{a_1} <$ 8.8 GeV

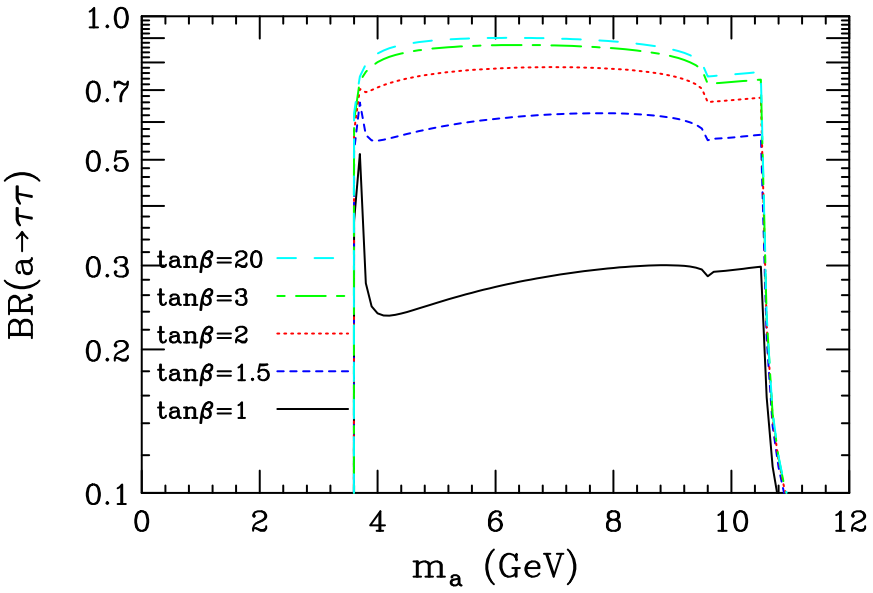
8.8 GeV $< m_{a_1} <$ 9.2 GeV

Prediction Higgs A^0: PRD 81, 075003 (2010): Dermisek, Gunion

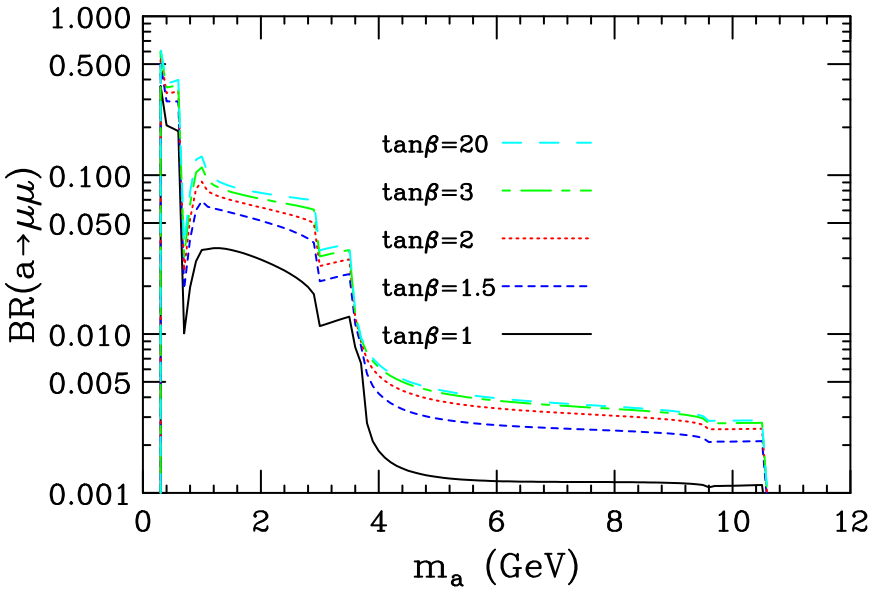
- $\mathcal{B}(a_1 \to \tau^+\tau^-)$ and $\mathcal{B}(a_1 \to \mu^+\mu^-)$ as a function of $tan\ \beta$

  $tan\ \beta = h_u/h_d$ = ratio of the vacuum expectation value

$a_1 \to \tau^+\tau^-$



$a_1 \to \mu^+\mu^-$



- For $tan\ \beta > 2$, $\mathcal{B}(a_1 \to \tau^+\tau^-)$ and $\mathcal{B}(a_1 \to \mu^+\mu^-)$

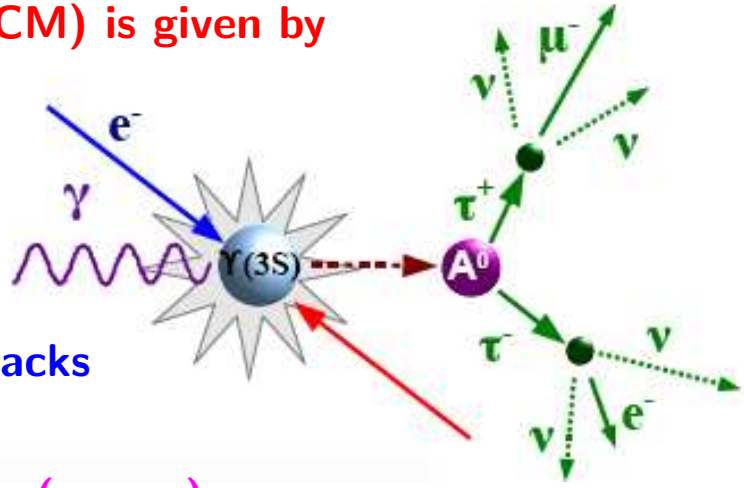
  change very little with increasing $tan\ \beta$ at any given m_{a_1}

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

♢ Search for $\Upsilon(3S) \to \gamma A^0$, $A^0 \to \tau^+\tau^-$, PRL 103, 181801 (2009)

□ The photon energy in the Center-of-Mass (CM) is given by

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



□ $E_\gamma > 100$ MeV, and exactly two charged tracks

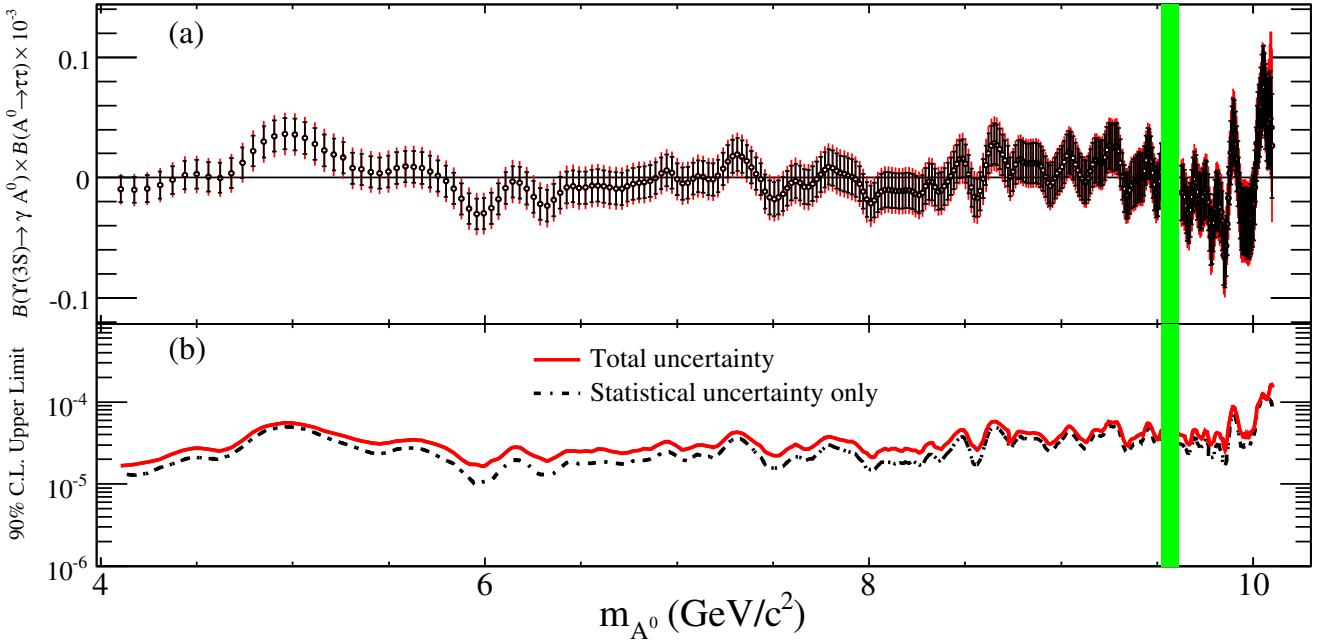
□ Both charged tracks are identified as leptons (e or μ)

□ Backgrounds

- $e^+e^- \to \gamma\tau^+\tau^-$ (mostly)
- QED process including two-photon productions:
  - ▷ $e^+e^- \to e^+e^-e^+e^-$
  - ▷ $e^+e^- \to e^+e^-\mu^+\mu^-$
- $e^+e^- \to q\bar{q}$ $(q = u, d, s, c)$ (small)

$\Upsilon(3S) \to \gamma A^0$, $A^0 \to \tau^+\tau^-$ PRL 103, 181801 (2009)

- The residual background is suppressed by 8 kinematic and angular variables
- Peaking contributions
  - $\Upsilon(3S) \to \gamma\ \chi_{bJ}(2P)(J = 0, 1, 2)$
    - $\hookrightarrow \chi_{bJ}(2P) \to \gamma\Upsilon(nS)(n = 1, 2)$
    - $\hookrightarrow \Upsilon(nS) \to \tau^+\tau^-$

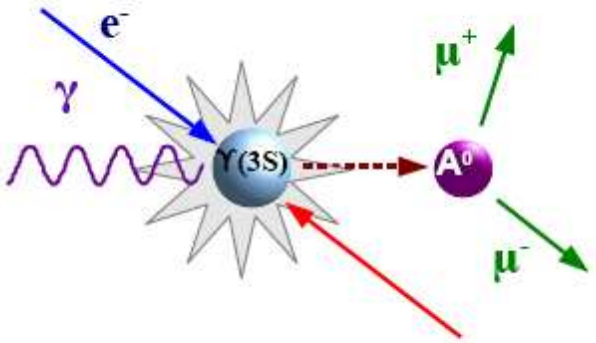


- Search A^0 in E_γ spectrum over a range of $4.03 < m_{A^0} < 10.10$ GeV/c^2

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

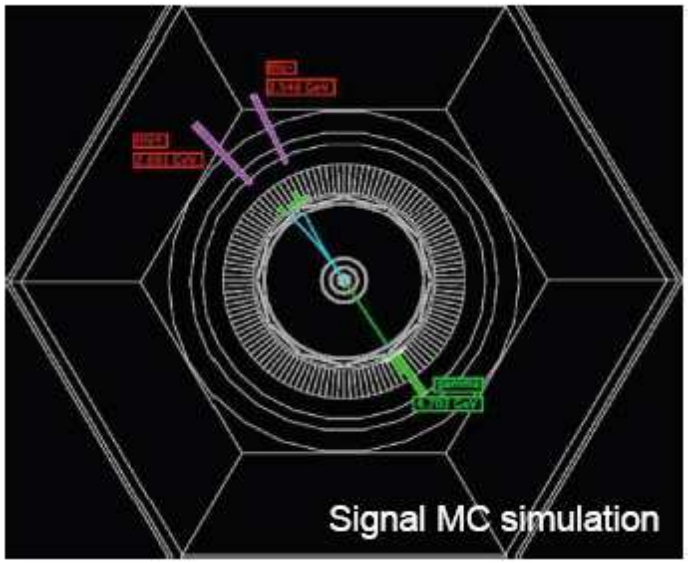
$\Upsilon(2S,3S) \to \gamma A^0,\ A^0 \to \mu^+\mu^-$ Previous BABAR Results

- Search for A^0 scalar boson in the radiative decays of $\Upsilon(2S)$ and $\Upsilon(3S)$



- Assuming no invisible (neutralino) decays

  $\mathcal{B}(A^0 \to \mu^+\mu^-) \approx$ sizable at low $m_{A^0} < 2m_\tau$



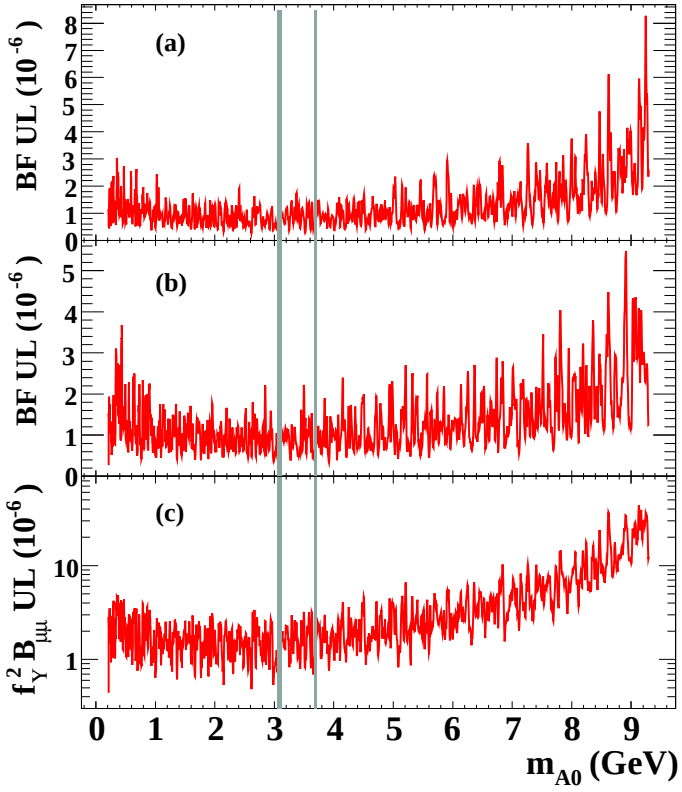
- Require one γ and 2 oppositely charged tracks at least one of which is identified as a muon

- $E_\gamma > 200$ MeV (CM), while allowing few additional γ with energy lower than 200 MeV

- Use kinematic fit of $\gamma\mu^+\mu^-$ system, including the beam energy and decay vertex constraints

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

- Search for A^0 as a function of mass m_{A^0}



Scan range $0.212 < m_{A^0} < 9.3$ GeV

(a) $\mathcal{B}(\Upsilon(2S) \to \gamma A^0) \times \mathcal{B}(A^0 \to \mu^+\mu^-)$

(b) $\mathcal{B}(\Upsilon(3S) \to \gamma A^0) \times \mathcal{B}(A^0 \to \mu^+\mu^-)$

(c) $f_\Upsilon^2 \times \mathcal{B}(A^0 \to \mu^+\mu^-)$

$\mathcal{B}(\Upsilon(nS) \to \gamma A^0)$ are related to the effective Yukawa coupling f_Υ of bound b quark to A^0

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

- Shaded area is excluded from the search around the J/ψ and $\psi(2S)$ resonances
- We do not observed any significant signal, set at 90% CL
- Most significant fluctuation using $\Upsilon(2S,3S) \sim 3.24\sigma$ at $m_{A^0} = 3.88$ GeV/c^2

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

☐ **New BABAR results PRD 87, 031102 (2013)**

♢ Select 4 tracks ($\pi\pi$ plus $\mu\mu$)

+ one gamma, $E_\gamma > 100$ MeV

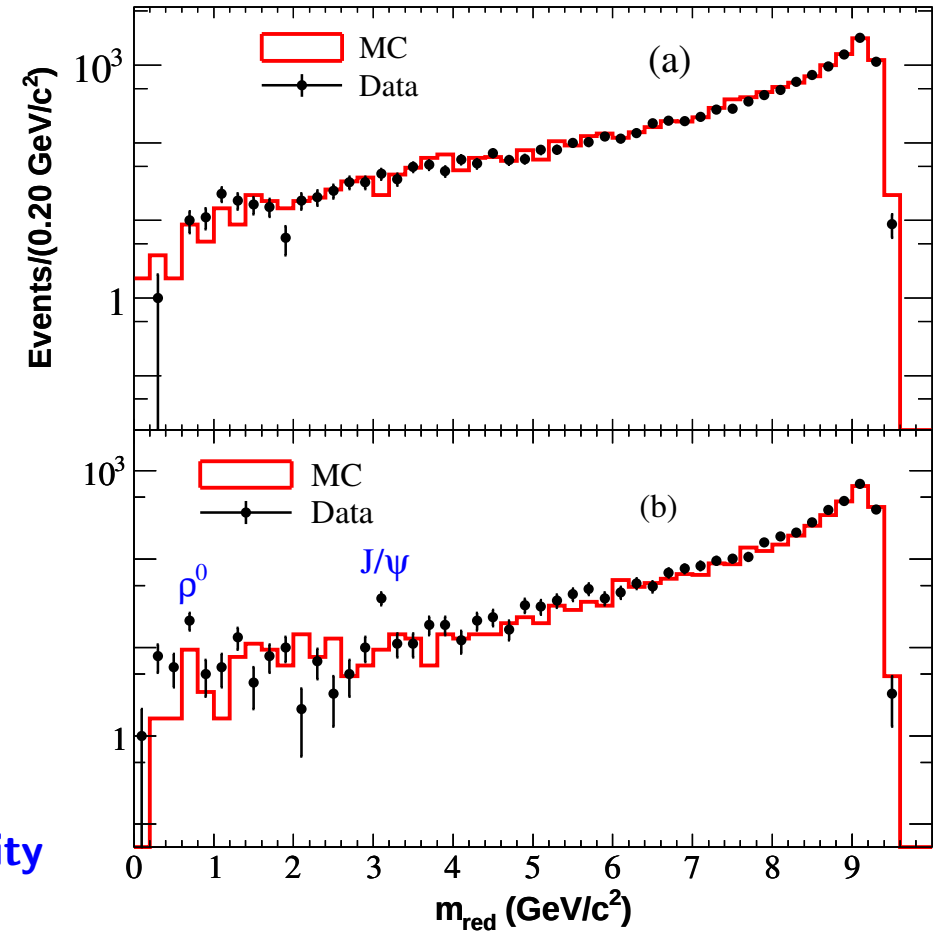
♢ Scan di-muon reduced mass

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

with Background from MC

(a) $\Upsilon(2S)$ data

(b) $\Upsilon(3S)$ data



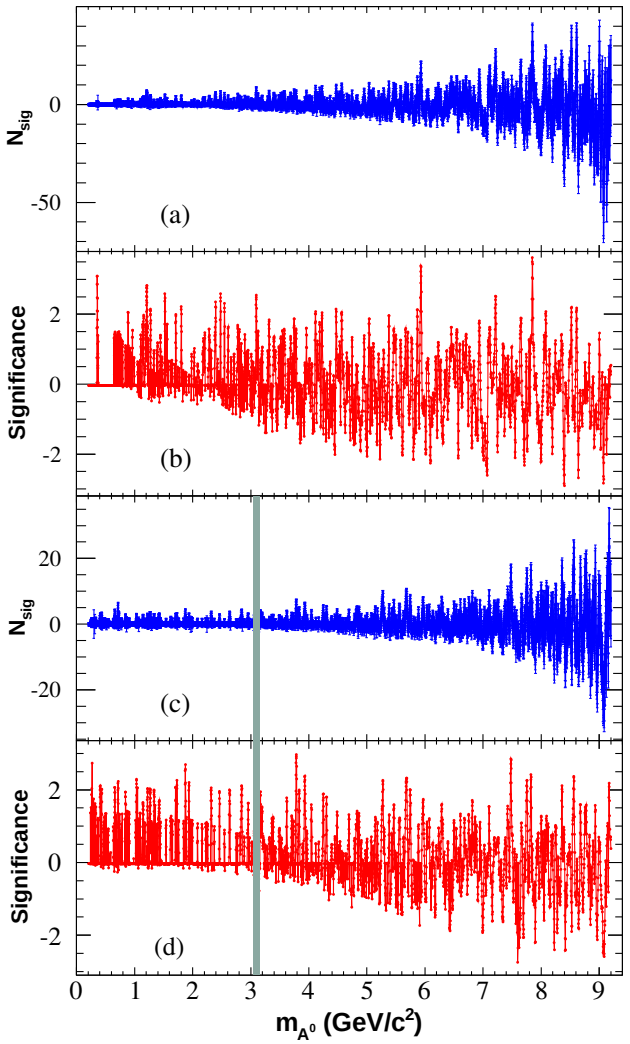
♢ MC is normalized to data luminosity

♢ MC did not include J/ψ and ρ^0 contributions

♢ Observed deviations are consistent with bkg fluctuation

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

☐ $\Upsilon(1S)$ mesons are selected from di-pion transition to reduce background



Shaded area: J/ψ excluded

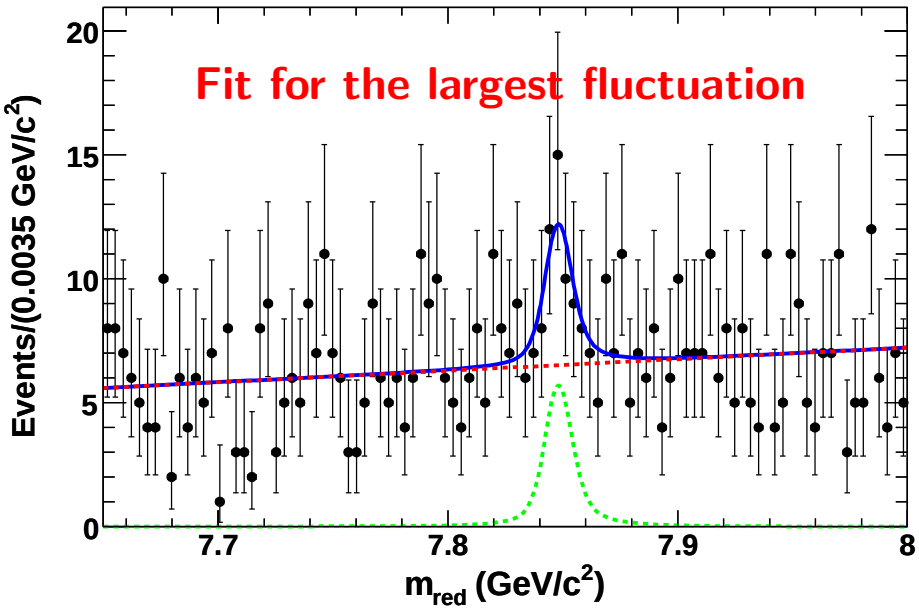
a-b: $\Upsilon(2S)$, c-d: $\Upsilon(3S)$

Data $92.8\times10^6\Upsilon(2S)$, $116.8\times10^6\Upsilon(3S)$

$$S = sign(N_{sig})\sqrt{-2ln\ \mathcal{L}_o/\mathcal{L}_{max}}$$

$\mathcal{L}_o$ = likelihood value for $N_{sig} = 0$

$\mathcal{L}_{max}$ = maximum likelihood value

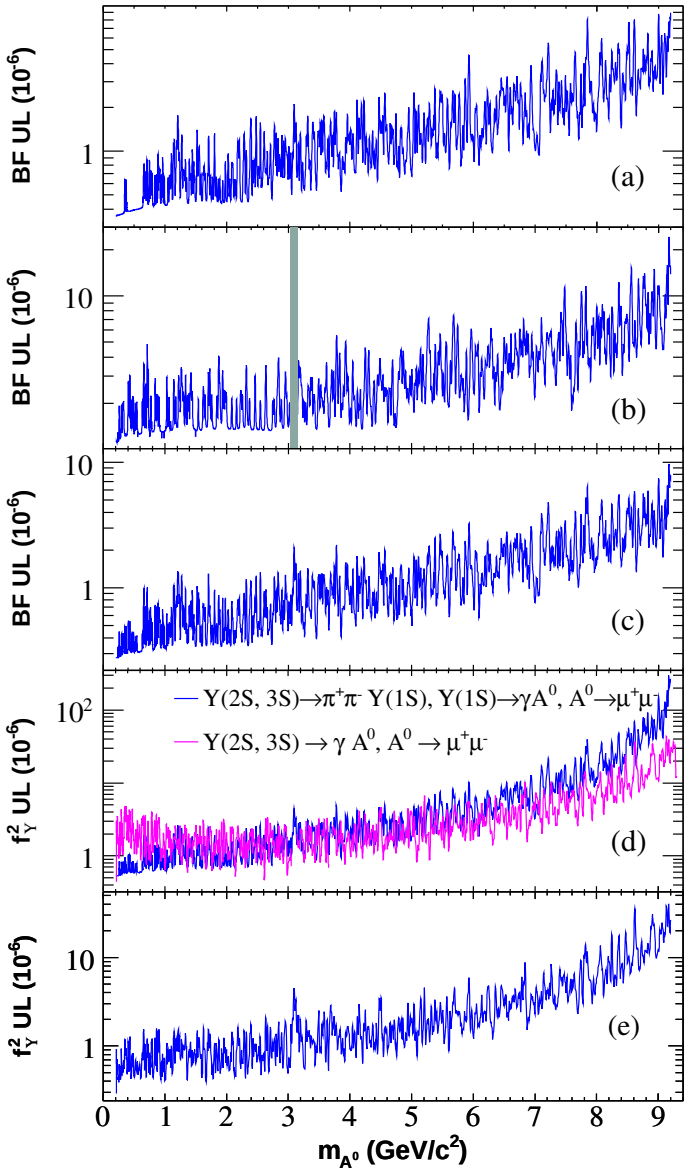


Most significance fluctuation is 3.62σ

at $m_{A^0} = 7.85$ GeV in $\Upsilon(2S)$

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

☐ **Branching Fraction upper limit at 90% C.L. as a function of mass m_{A^0}**



Scan range $0.212 < m_{A^0} < 9.20$ GeV

To measure $\mathcal{B}(\Upsilon(1S) \to \gamma A^0) \times \mathcal{B}_{\mu\mu}$:

(a) $\Upsilon(2S) \to (0.37 - 8.97) \times 10^{-6}$

(b) $\Upsilon(3S) \to (1.13 - 24.2) \times 10^{-6}$

(c) $\Upsilon(2S,3S) \to (0.28 - 9.7) \times 10^{-6}$

(d) Overlay with the previous results (2009)

(e) Combined with previous results (2009)

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

for $m_{A^0} \leq 9.2$ GeV/c^2

Summary

- No evidence for A^0 production is found and we set upper limits
- BABAR previous results:
  - $\Upsilon(3S) \to \gamma A^0$, $A^0 \to \tau^+\tau^-$ PRL 103, 181801 (2009)

    $\mathcal{B}(\Upsilon(3S) \to \gamma A^0) \times \mathcal{B}(A^0 \to \tau^+\tau^-) < (1.5 - 16) \times 10^{-5}$ at 90% C.L.
  - $\Upsilon(2S, 3S) \to \gamma A^0$, $A^0 \to \mu^+\mu^-$ PRL 103, 081803 (2009)

    Most significant fluctuation using $\Upsilon(2S, 3S) \sim 3.24\sigma$ at $m_{A^0} = 3.88$ GeV/c^2
- BABAR new results:
  - $\Upsilon(2S, 3S) \to \pi^+\pi^-\Upsilon(1S)$, $\Upsilon(1S) \to \gamma A^0$, $A^0 \to \mu^+\mu^-$

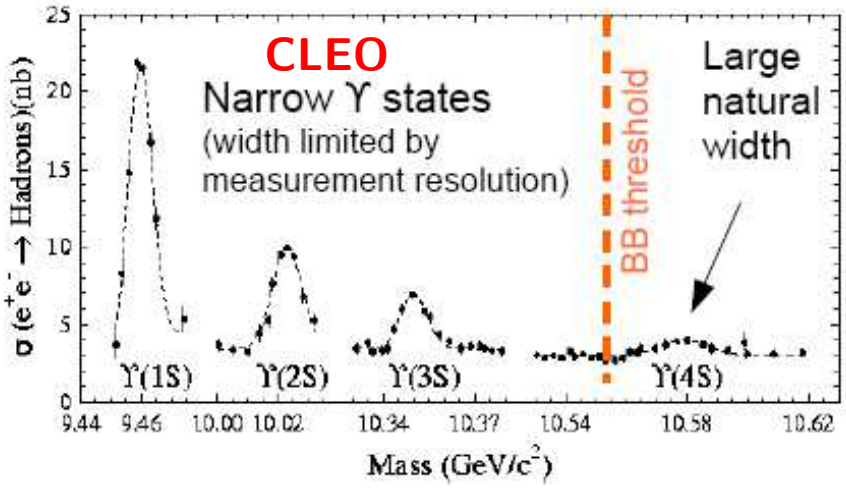
    PRD 87, 031102 (2013)

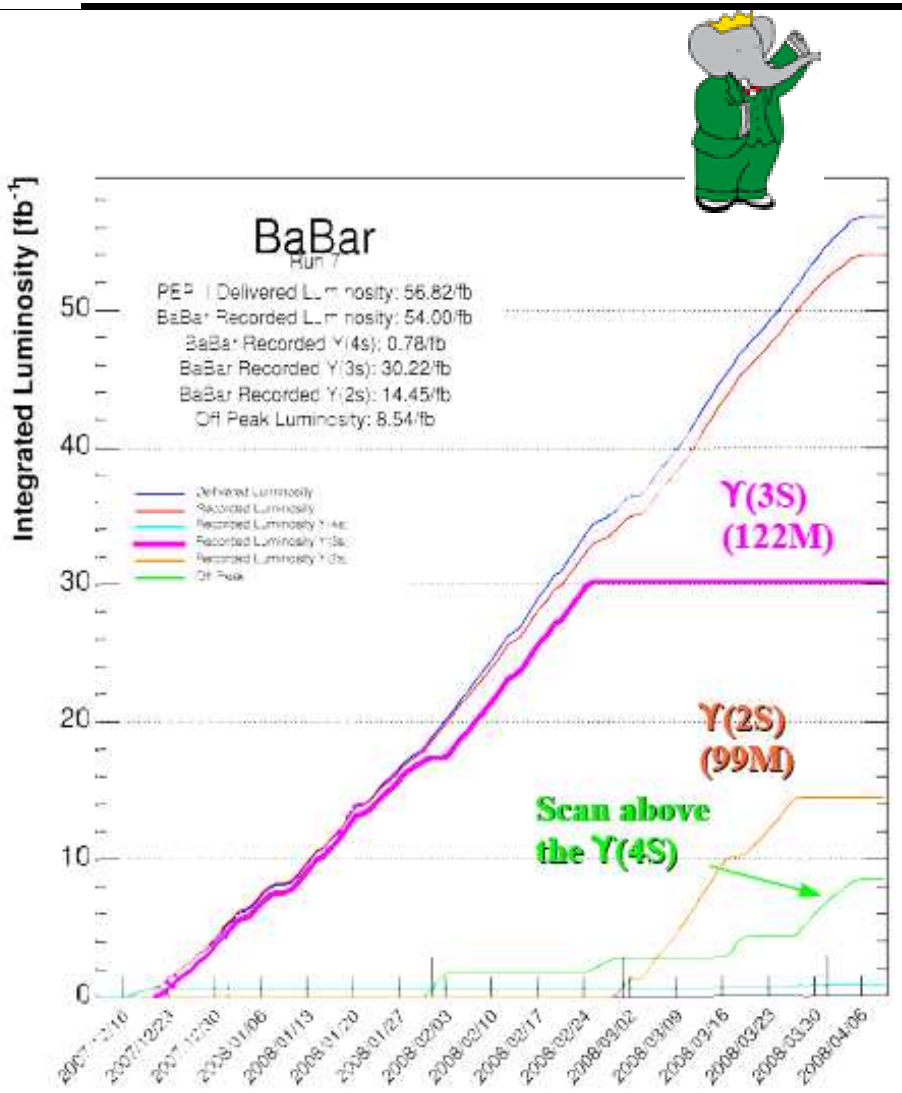
    $f_\Upsilon^2 \times \mathcal{B}(A^0 \to \mu^+\mu^-) < (0.29 - 40) \times 10^{-6}$ at 90% C.L.
- Important input to rule out much of the parameter space allowed for the light Higgs

BABAR Data: $\Upsilon(nS)$ (Backup Slide)

Final BABAR Data

- BaBar data sets:
  - 122 x 10^6 $\Upsilon(3S)$ decays
  - 99 x 10^6 $\Upsilon(2S)$ decays
  - "offpeak" samples of 1.4fb^{-1} and 2.4fb^{-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

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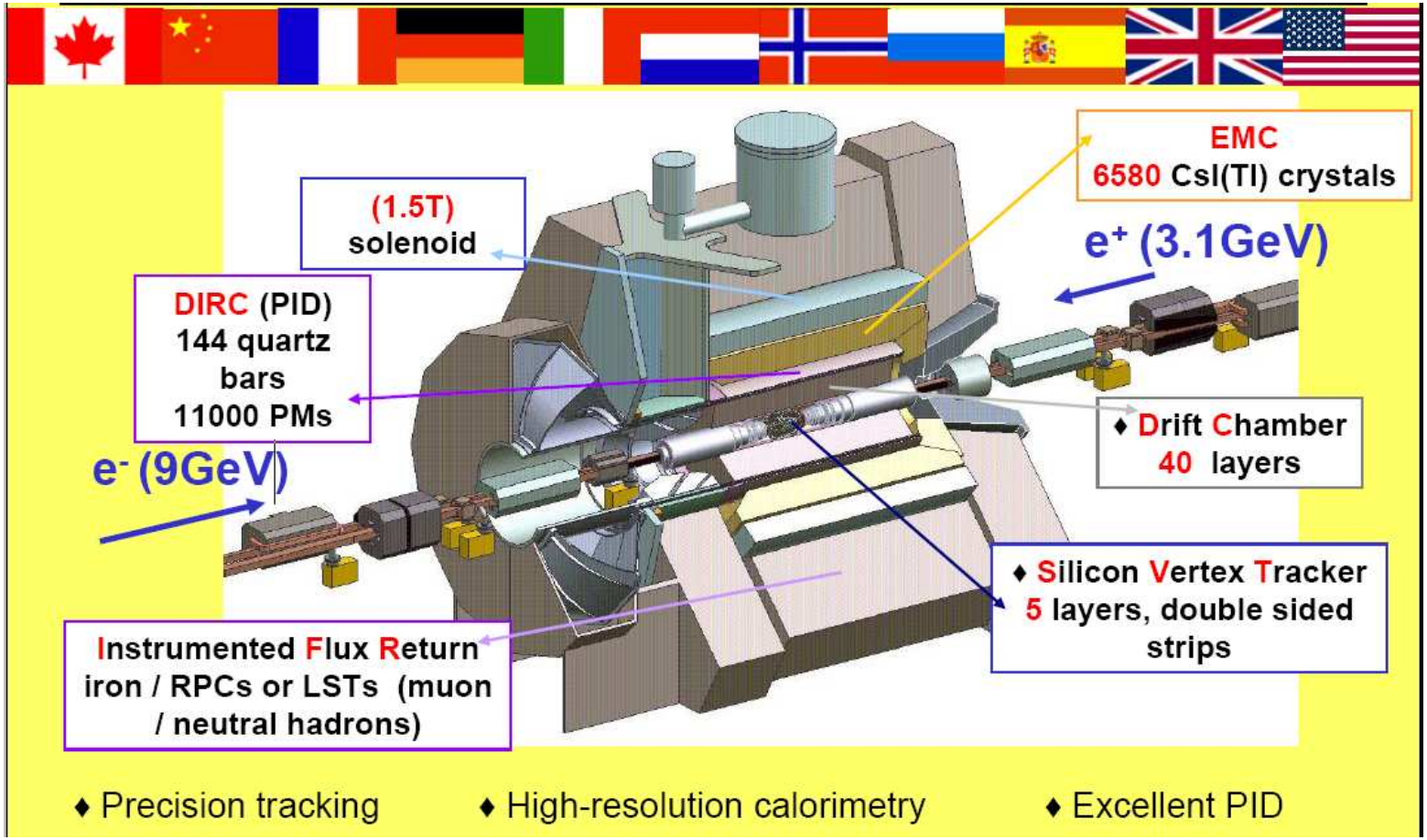
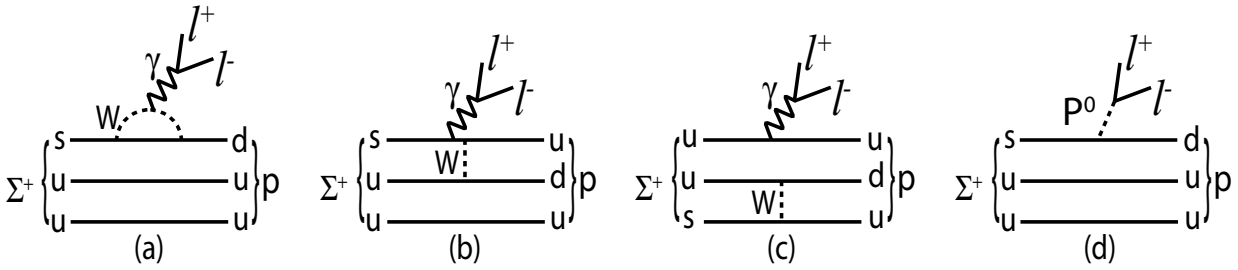
BABAR Detector (Backup Slide)



- Collides (9 GeV) $e^- \bowtie e^+$ (3.1 GeV) $\hookrightarrow \Upsilon(4S)$ with $E_{CM} = 10.58$ GeV
- Peak luminosity : $\sim 1.21 \times 10^{34}\ cm^{-2}s^{-1}$, $B^0\overline{B}^0$ production ~ 12 Hz
- Boost $\beta\gamma = 0.56$ allows to measure B decay times

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

☐ **HyperCP: Evidence $\Sigma^+ \to p\mu^+\mu^-$, PRL, 94, 021801 (2005)**



(a-c) $\Sigma^+_{p\ell\ell}$ in SM

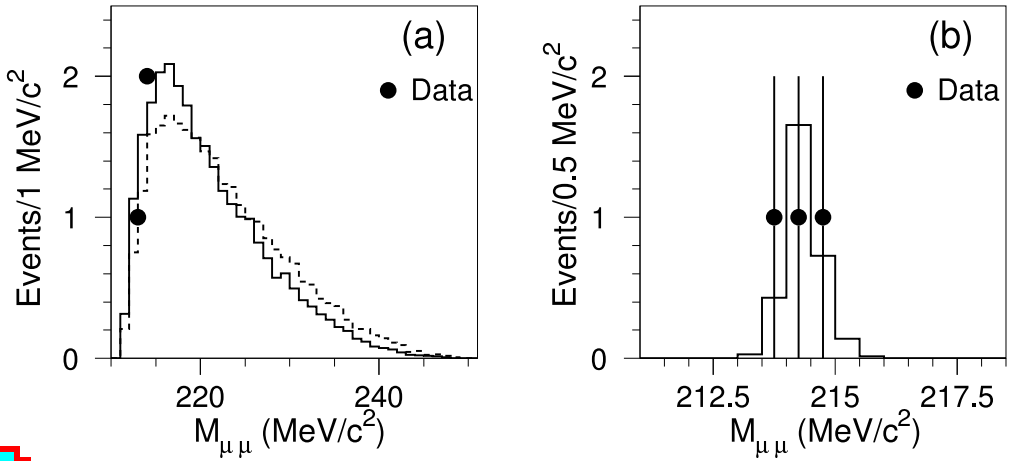
(d) $\Sigma^+_{p\ell\ell}$ in NP

(a) Data and MC: form factor (solid) and phase space (dashed)

$\Sigma^+ \to p\mu^+\mu^-$ (SM)

(b) Data and normalized MC

$\Sigma^+ \to pP^0$, $P^0 \to \mu^+\mu^-$ (3 events)



$\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = (3.1^{+2.4}_{-1.9} \pm 1.5) \times 10^{-8}$

☐ **These events have been interpreted as a light Higgs boson (A^0) with mass of 214.3 MeV, PRL 98, 081802 (2007): X-G He, Tandean, Valencia**