
New Physics Searches in Quarkonium Decays – Experimental Results

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QWG 2011 – 8th International Workshop on Heavy Quarkonium

GSI, Darmstadt, Germany

October 6, 2011

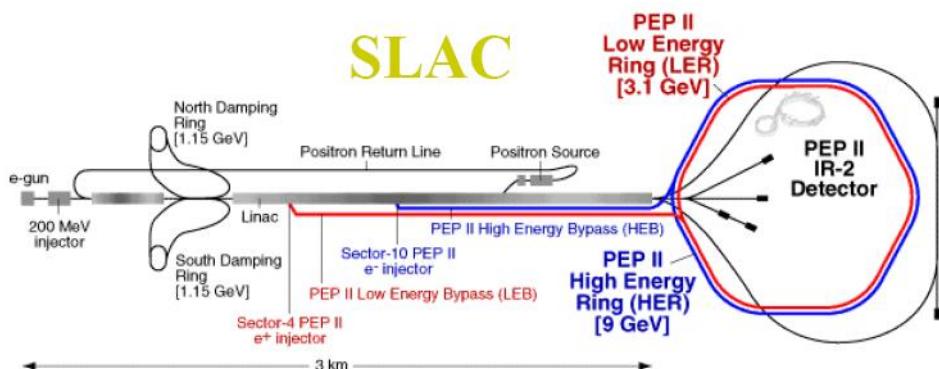
Introduction

Outline

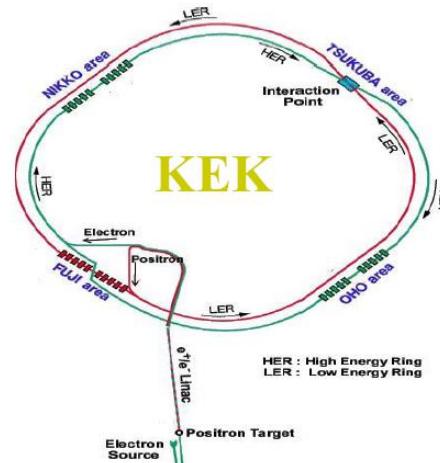
- Review of experimental results from BaBar and Belle
- Topics to be covered
 - Light Higgs
 - Invisible Decays
 - Leptonic Violations
- Results to be covered
 - Review from QWG 7 (May 2010)
 - New for QWG 8 (Oct 2011)
 - Work in progress

The Experiments

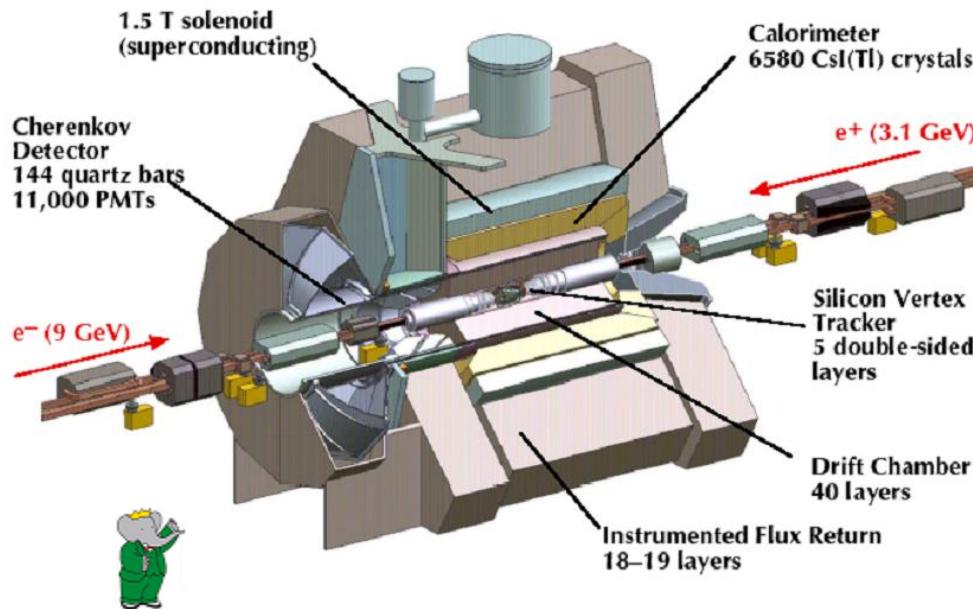
SLAC



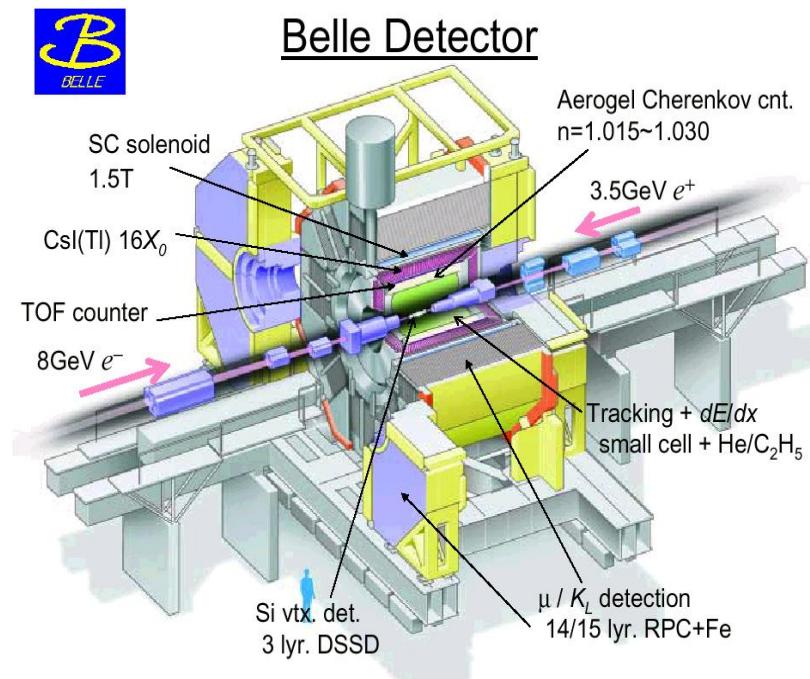
KEK



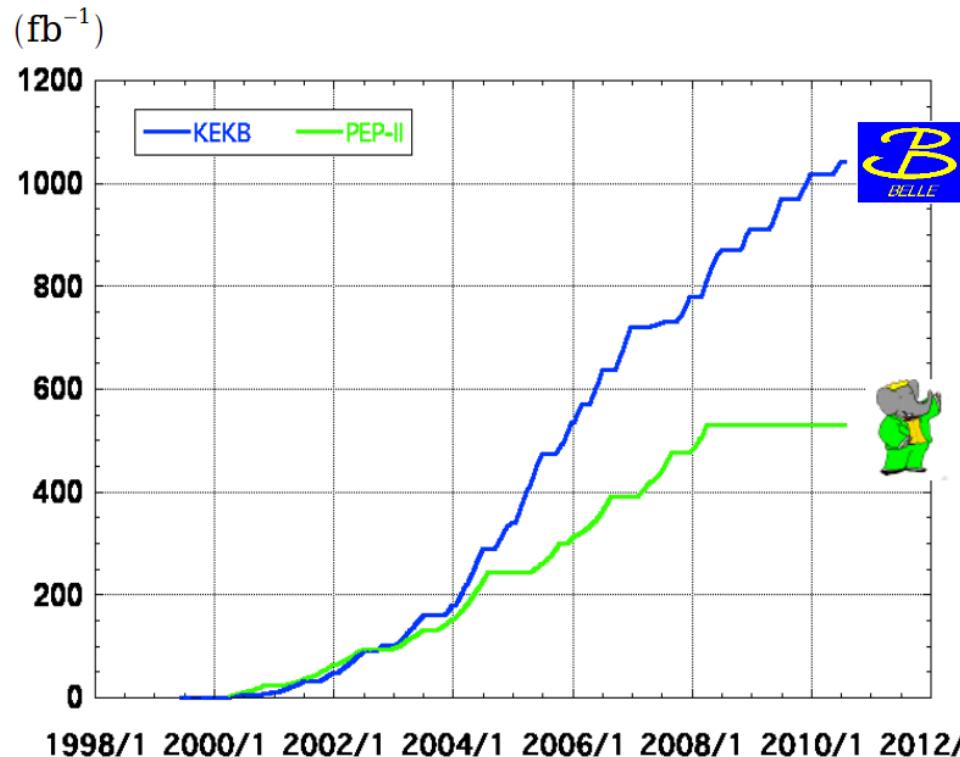
The BaBar Detector



Belle Detector



The Data



> 1 ab⁻¹

On resonance:

$\Upsilon(5S)$: 121 fb⁻¹

$\Upsilon(4S)$: 711 fb⁻¹

$\Upsilon(3S)$: 3 fb⁻¹

$\Upsilon(2S)$: 25 fb⁻¹

$\Upsilon(1S)$: 6 fb⁻¹

Off reson./scan:

~ 100 fb⁻¹

~ 550 fb⁻¹

On resonance:

$\Upsilon(4S)$: 433 fb⁻¹

$\Upsilon(3S)$: 30 fb⁻¹

$\Upsilon(2S)$: 14 fb⁻¹

Off resonance:

~ 54 fb⁻¹

Resonance	BaBar	Belle
$\Upsilon(3S)$	121 M	12 M
$\Upsilon(2S)$	98+(3) M	175 M
$\Upsilon(1S)$	(23) M	113+(32) M

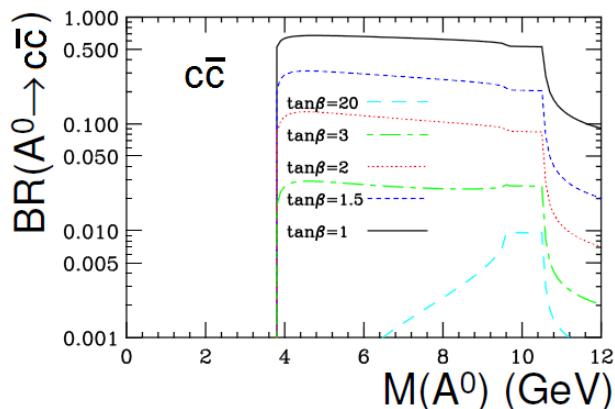
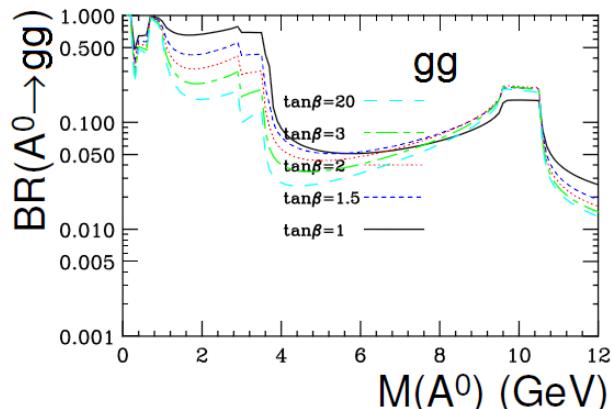
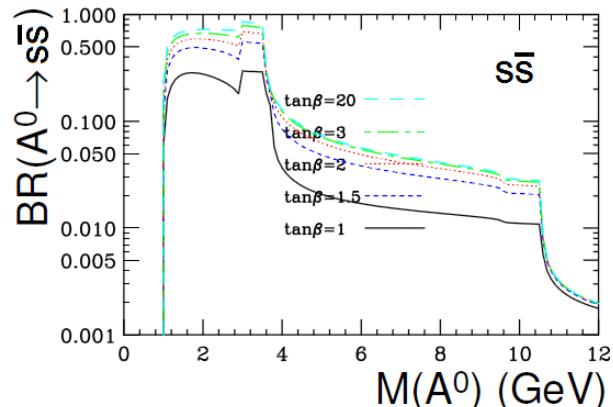
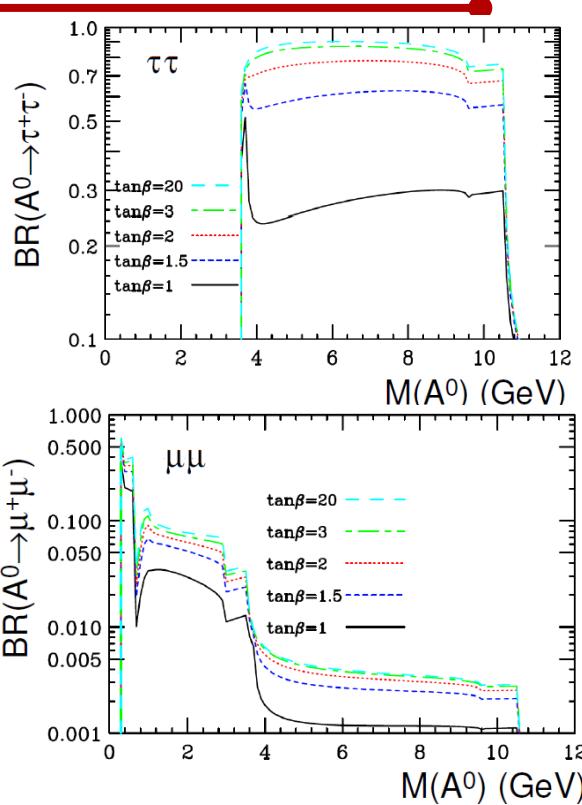
- (#) from dipion feeddown

Light Higgs

Light Higgs – Search Motivation

- CP-odd light Higgs (A^0) predicted in NMSSM
 - If $m_{A^0} < 2m_b$, $\Upsilon(nS) \rightarrow \gamma A^0$ is allowed
 - Predict $B(\Upsilon(nS) \rightarrow \gamma A^0) \times (A^0 \rightarrow f\bar{f})$ up to 10^{-4}
 - Search for $A^0 \rightarrow f\bar{f}$ ($\mu^+\mu^-$, $\tau^+\tau^-$, gg, $s\bar{s}$, $c\bar{c}$)
 - Favoured decay depends on $m(A^0)$ and parameter values

PRD 81, 075003 (2010)





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

- Analysis
 - Oppositely-charged trks plus photon
 - Constrained to beam energy/vertex
 - Scan window to search for signals
 - Known resonances excluded

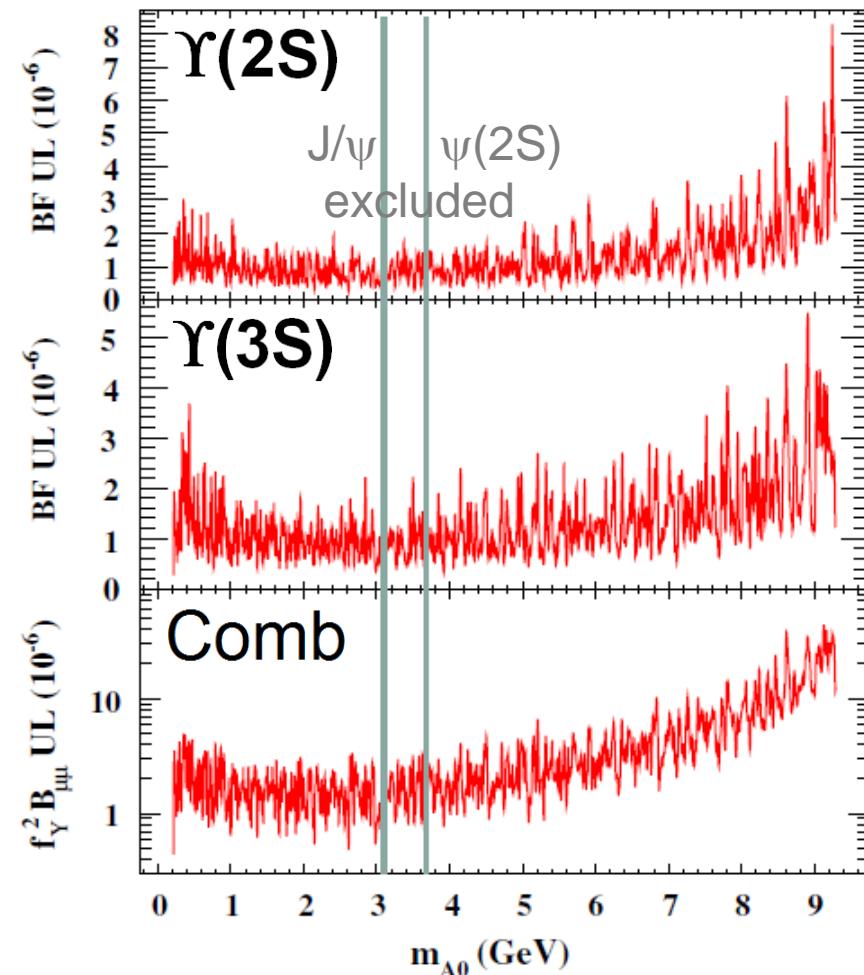
- Results
 - No significant signals
 - Set 90% CL upper limits:

$$B(\Upsilon(2S) \rightarrow \gamma A^0 (\mu^+ \mu^-)) < (0.26 - 8.3) \times 10^{-6}$$

$$B(\Upsilon(3S) \rightarrow \gamma A^0 (\mu^+ \mu^-)) < (0.27 - 5.5) \times 10^{-6}$$

- Effective Yukawa coupling

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



PRL 103, 081803 (2009)

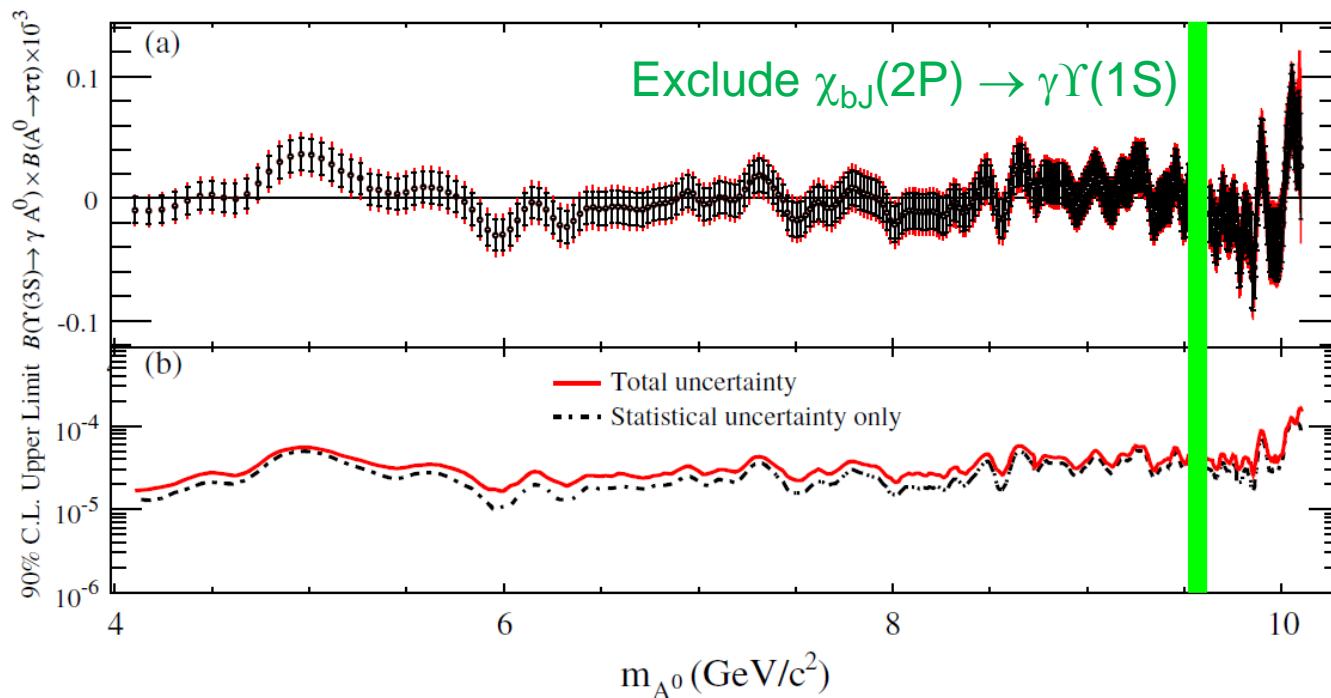


$\Upsilon(3S) \rightarrow \gamma A^0 \rightarrow \tau^+\tau^-$

- Analysis & Results

- Oppositely-charged tracks plus photon
- Identify $\tau \rightarrow e\bar{\nu}_e \nu_\tau, \mu\bar{\nu}_\mu \nu_\tau$ looking at mass recoiling against the photon
- Scan for peaks in E_γ distribution
- No significant signals, set 90% CL upper limit:

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





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

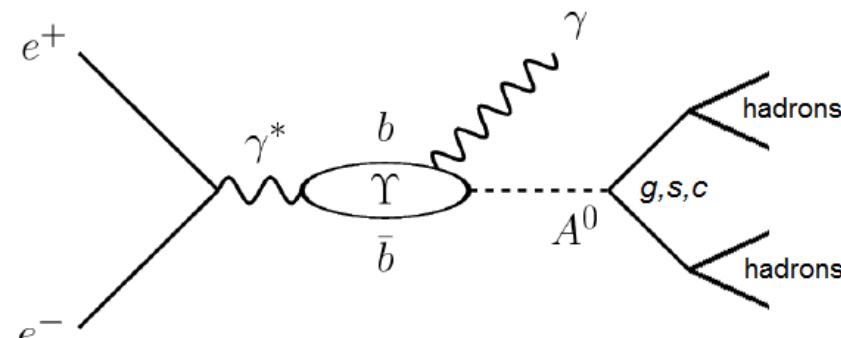


- Reconstruction & Selection Criteria

- Fully-reconstructed hadronic events
 - Highest energy photon is radiative photon
 - Reconstruct A^0 using ROE

- $K_s^0 \rightarrow \pi^+\pi^-$ candidates near $m_{K_s^0}$
 - p, K^\pm, π^\pm PID-assigned mass
 - $\pi^0 \rightarrow \gamma\gamma$ candidates near m_{π^0}
 - Add leftover γ

- Constrain vertex and energy, requirement on vertex $P(\chi^2)$
 - Require $E_\gamma > 2.2, 2.5$ GeV for $\Upsilon(2,3S)$
 - m_{π^0} and m_η veto on radiative photon
 - Bhabha and muon pair background rejection
 - Either of two highest momentum tracks identified as e or μ
 - Angle between γ and 2nd highest momentum track < 1 rad

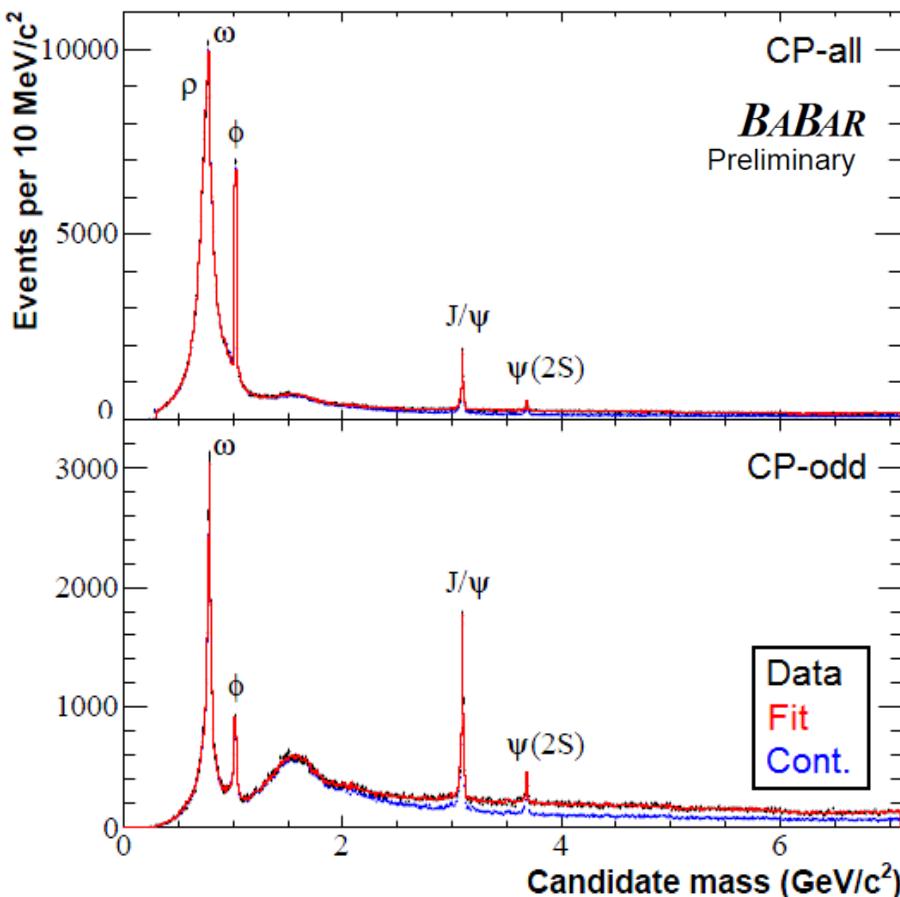




$\Upsilon(2,3S) \rightarrow \gamma A^0 \rightarrow \text{hadrons (cont.)}$



- CP-all: All events considered
- CP-odd: remove $A^0 \rightarrow \pi^+\pi^-, K^+K^-$
- Backgrounds
 - Continuum
 - $\Upsilon(4S)$ & off-peak floating scale
 - $\Upsilon(nS) \rightarrow \gamma f_J(X)$ decays
 - Seen by CLEO in $\Upsilon(1S)$ decay
 - Non-resonant radiative decays
 - Cubic-spline fit
- Analysis
 - Mass window (3 – 26 MeV/c²) scan (0.29 – 7 GeV/c²)
 - Main systematics due to uncertainty on ε of $A^0 \rightarrow gg/c\bar{c}/s\bar{s}$ decay, and background continuum scaling / presence of light resonances

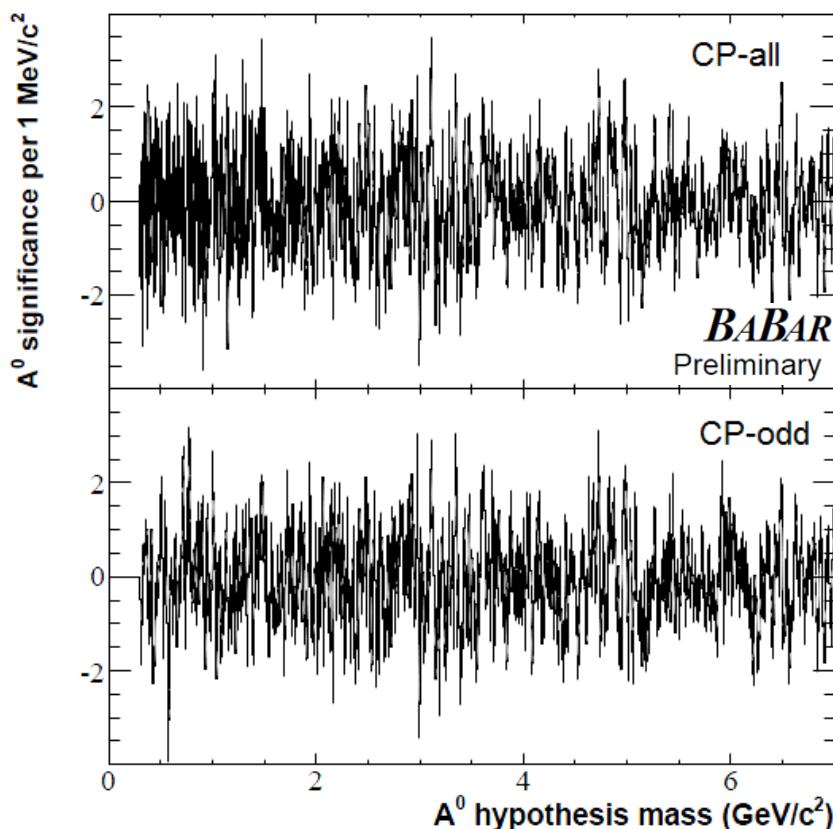




$\Upsilon(2,3S) \rightarrow \gamma A^0 \rightarrow \text{hadrons}$ (cont.)



- Results
 - CP-all
 - 3.5σ @ $3.107 \text{ GeV}/c^2$ (stat. only)
 - 2.9σ @ $1.295 \text{ GeV}/c^2$ (stat + syst)
 - CP-odd
 - 3.2σ @ $0.772 \text{ GeV}/c^2$ (stat. only)
 - 3.1σ @ $4.727 \text{ GeV}/c^2$ (stat + syst)
 - Toy studies to determine significance
 - Probability of these fluctuations
 - anywhere* in dataset 33% (CP-all), 63% (CP-odd)





$\Upsilon(2,3S) \rightarrow \gamma A^0 \rightarrow \text{hadrons (cont.)}$

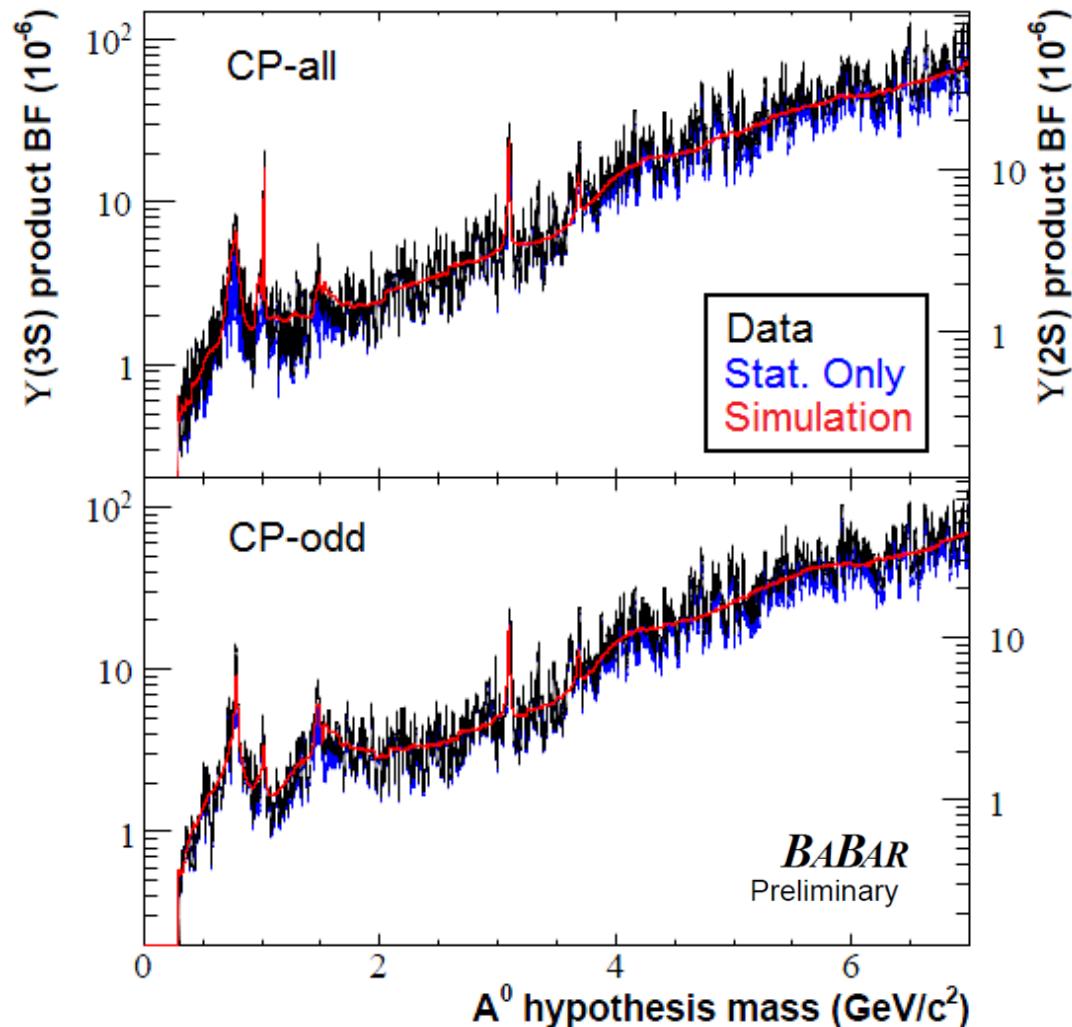


- No significant signals observed

- 90% CL upper limits
 - Assume both decays have same matrix element

$$B(\Upsilon(nS) \rightarrow \gamma A^0(\text{hadrons})) < (0.1\text{-}8) \times 10^{-5}$$

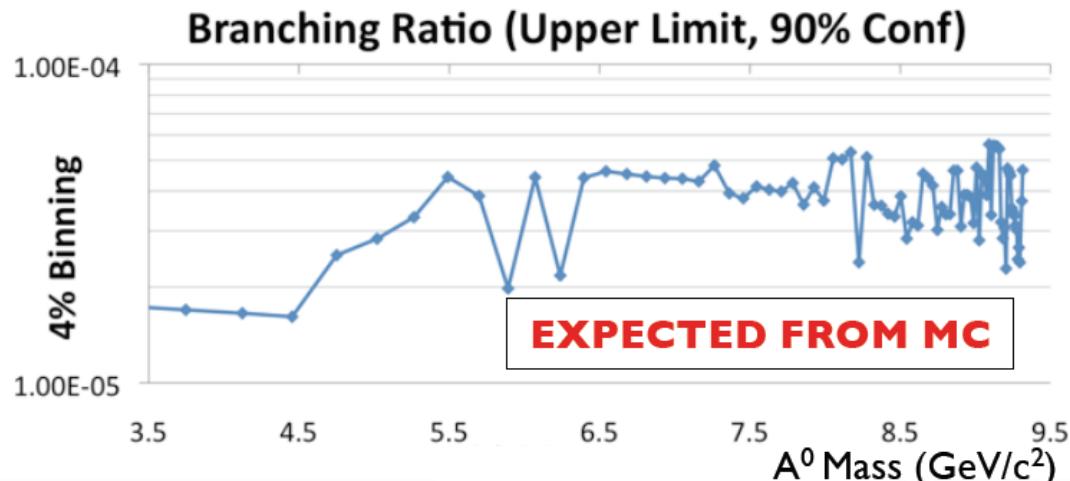
arXiv:1108.3549



BABAR
Preliminary

Work in Progress

- BaBar: complementary analyses with dipion tags
 - $\Upsilon(nS) \rightarrow \pi^+ \pi^- \Upsilon(1S) \rightarrow \gamma A^0 \rightarrow (\mu^+ \mu^-, \tau^+ \tau^-)$
 - $\Upsilon(nS) \rightarrow \pi^+ \pi^- \Upsilon(1S) \rightarrow \gamma A^0 \rightarrow (\text{hadrons})$
- Belle: $\Upsilon(1S) \rightarrow \gamma A^0 \rightarrow (\tau^+ \tau^-)$
 - Scan for peaks in E_γ distribution
 - Expected sensitivity to match CLEO, improve for high mass
 - Currently includes $e\mu$ tau modes, will include ee and $\mu\mu$



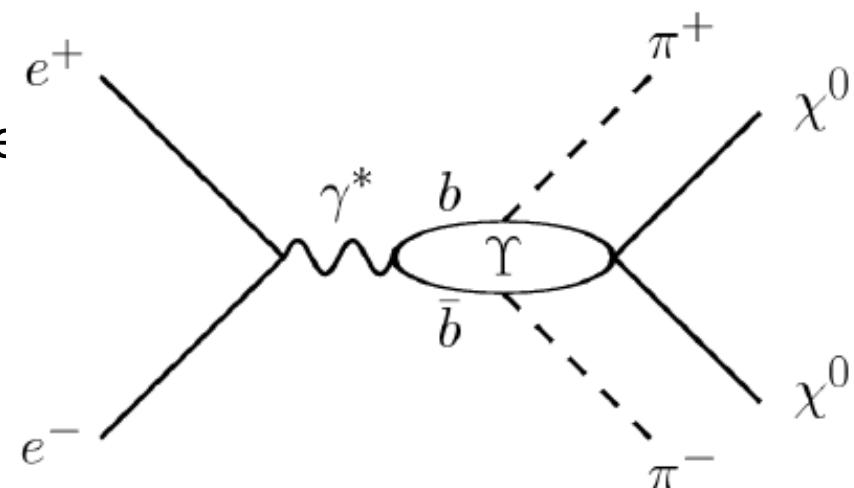
J. Rorie, EPS 2011

Invisible Decays

Invisible Searches

- Motivations

- $A^0 \rightarrow \chi^0 \bar{\chi}^0$ dominant in some nMSSM with light LSP χ



- Dark Matter may consist of several components
- B-Factories fill in gaps for detection
- Low mass DM could be observed in $\Upsilon(nS)$ decays
- $B(\Upsilon(1S) \rightarrow \chi\bar{\chi})$ up to $(4-18) \times 10^{-4}$

[arXiv:0712.0016](https://arxiv.org/abs/0712.0016)

- Search Strategy

- Single photon recoil against invisible decay ($\Upsilon(nS) \rightarrow \gamma A^0 (\chi\bar{\chi})$)
- Tag $\Upsilon(nS) \rightarrow \pi^+\pi^- \Upsilon(1S)$ with $\pi^+\pi^-$ recoil mass, with “empty” ROE



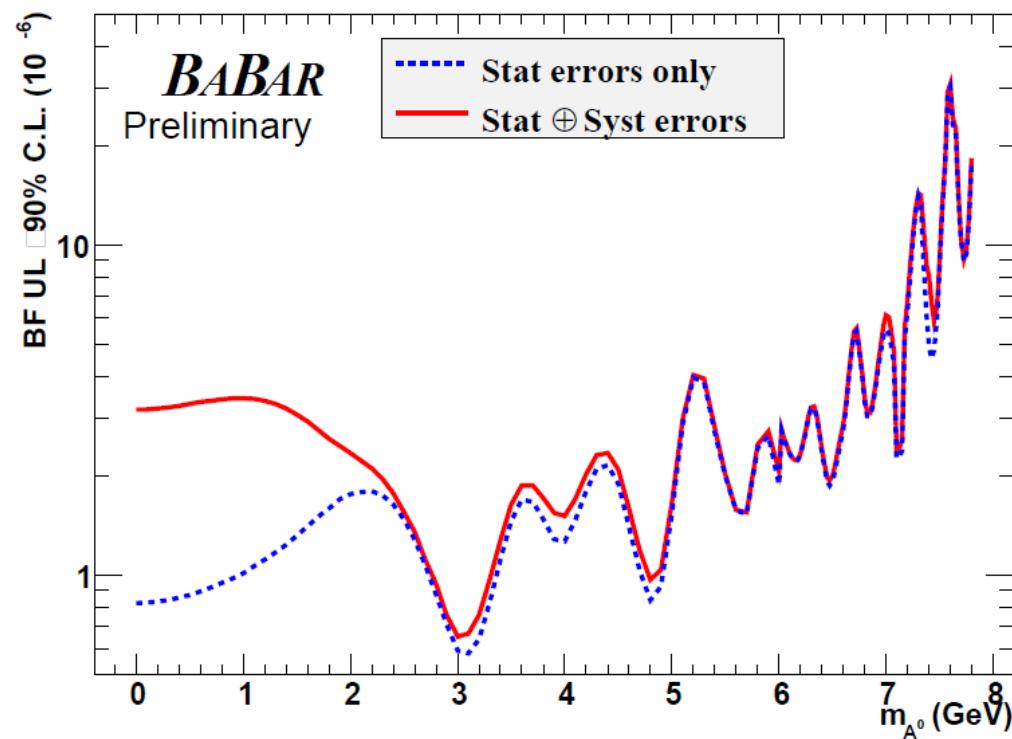
$\Upsilon(3S) \rightarrow \gamma A^0 \rightarrow \chi^0 \chi^0$

- Strategy
 - Search for peak in E_γ
 - Compute mass recoiling against photon
- No significant signals observed
- Set 90% CL upper limit

$$B(\Upsilon(3S) \rightarrow \gamma A^0(\text{invisible})) \\ < (0.7 - 31) \times 10^{-6}$$

- O(10) improvement

arXiv:0808.0017





$\Upsilon(3S) \rightarrow \pi^+\pi^- \Upsilon(1S) \rightarrow \text{invisible}$

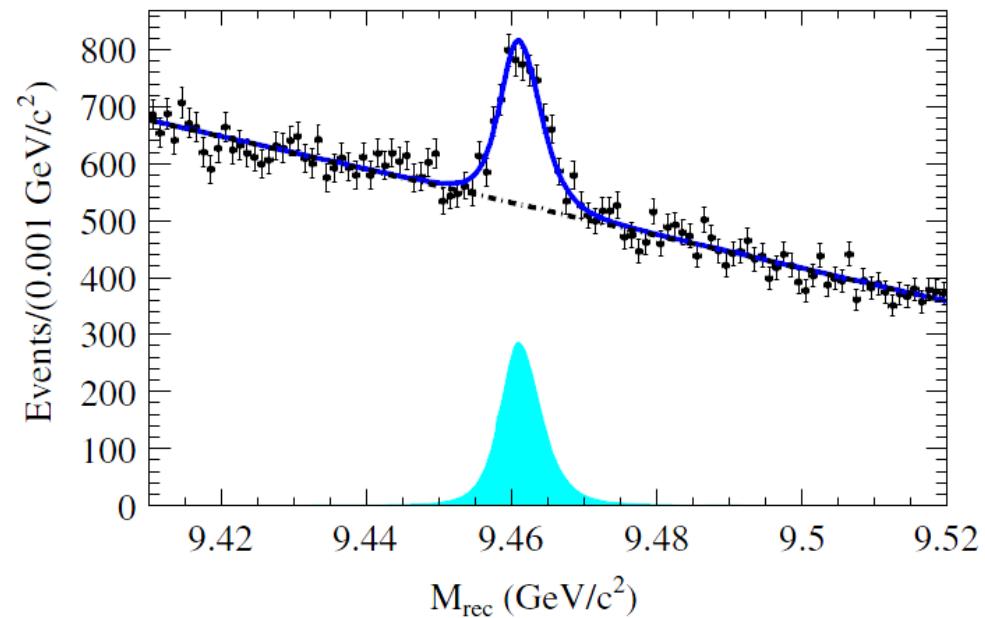
- Analysis Strategy

- Tag $\Upsilon(3S) \rightarrow \pi^+\pi^- \Upsilon(1S)$ with $\pi^+\pi^-$ recoil mass
- SM: $B(\Upsilon(1S) \rightarrow \nu\nu) \sim 10^{-5}$, DM: $B(\Upsilon(1S) \rightarrow \chi^0\chi^0)$ up to 10^{-3}
- Fit to recoil mass distribution
 - Combinatorial/continuum background from sidebands
 - Peaking background (undetected $\Upsilon(1S)$ decays) + signal

- Results

- Fit: 2326 ± 105
- Bkgd: 2444 ± 123
- Signal: $-118 \pm 105 \pm 24$

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



PRL 103, 251801 (2009)



$\Upsilon(2S) \rightarrow \pi^+\pi^- \Upsilon(1S) \rightarrow \gamma + \text{invisible}$



- Analysis Strategy

- Tag $\Upsilon(2S) \rightarrow \pi^+\pi^- \Upsilon(1S)$ with $\pi^+\pi^-$ recoil mass
- Search for $\Upsilon(1S) \rightarrow \gamma A^0/\chi\bar{\chi}$ (invisible)
- Fit to m_R and missing mass $M_X^2 = (\mathcal{P}_{e^+e^-} - \mathcal{P}_{\pi\pi} - \mathcal{P}_\gamma)^2$
- Scan ranges: $0 < m_{A^0} < 8 \text{ GeV}$ and $7.5 < m_{A^0} < 9.2 \text{ GeV}$ ($0 < m_{\chi\bar{\chi}} < 4.5 \text{ GeV}$)

- Reconstruction

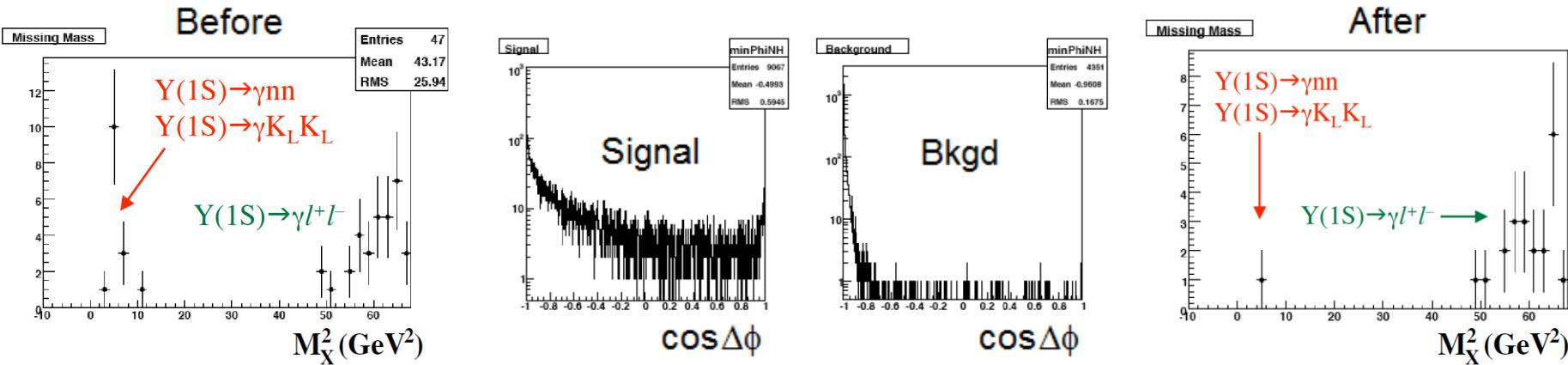
- Trigger on dipion and single photon
- Require only two tracks, “standard” photon quality cuts
- Combine many $\pi^+\pi^-$ kinematic variables into MVA
- Additional cuts to suppress specific backgrounds:
 - $\Upsilon(1S) \rightarrow \gamma n\bar{n}$, $\Upsilon(1S) \rightarrow \gamma K_L \bar{K}_L$
 - Two-photon η' production



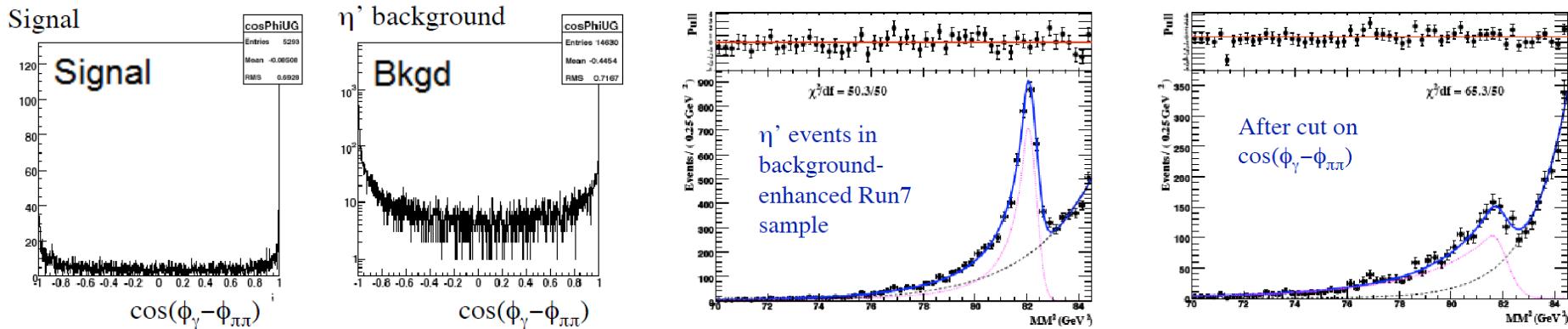
$\Upsilon(2S) \rightarrow \pi^+\pi^- \Upsilon(1S) \rightarrow \gamma + \text{invisible}$



- IFR veto to suppress $\Upsilon(1S) \rightarrow \gamma n\bar{n}$, $\Upsilon(1S) \rightarrow \gamma K_L \bar{K}_L$
 - Cut on azimuthal angle between photon and neutral cluster in IFR



- Angular cut to reduce $e^+e^- \rightarrow \gamma^*\gamma^* e^+e^- \rightarrow \eta'(\gamma \pi^+\pi^-)$ events
 - Cut on azimuthal angle between photon and dipion system



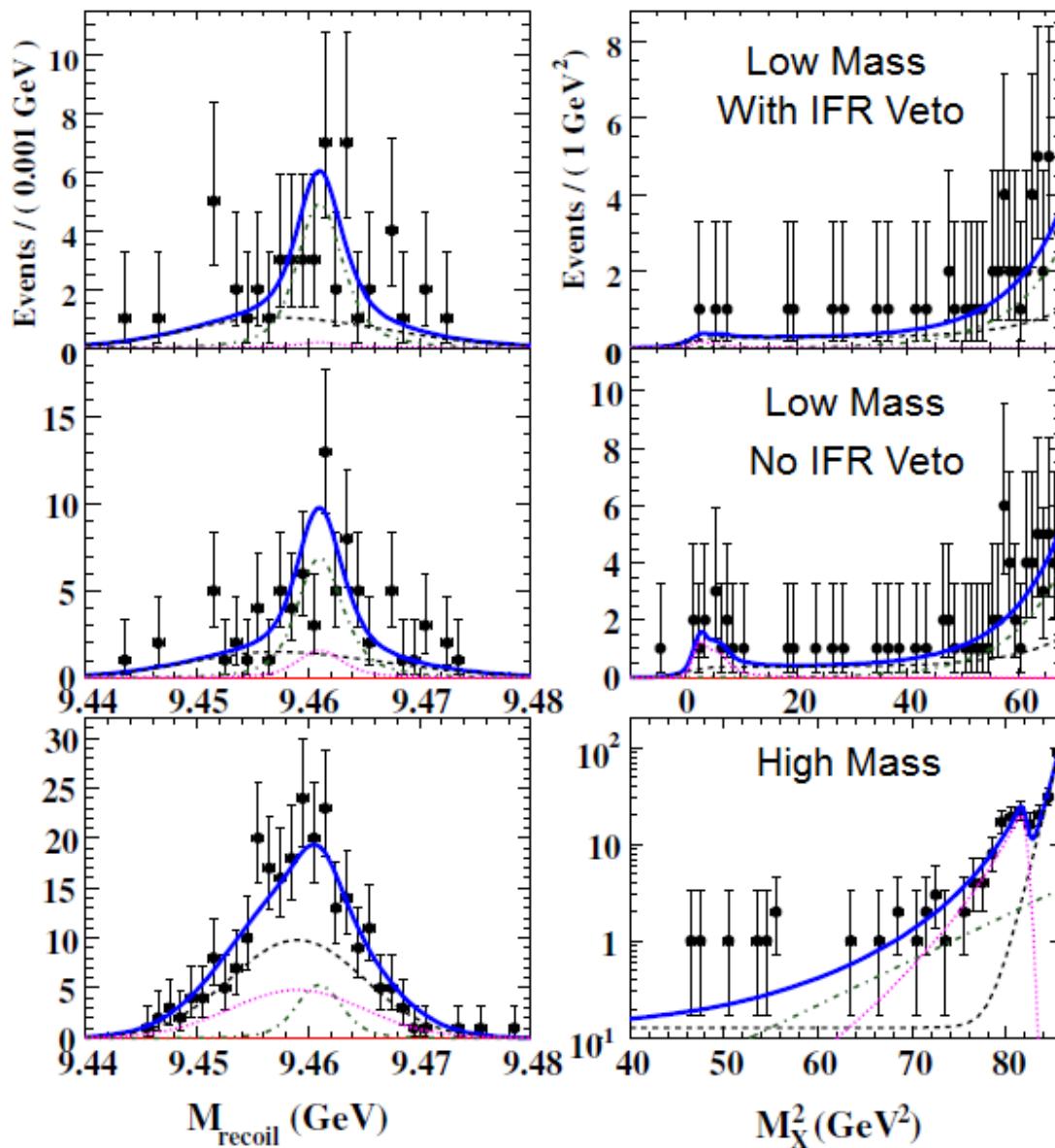


$\Upsilon(2S) \rightarrow \pi^+\pi^- \Upsilon(1S) \rightarrow \gamma + \text{invisible}$

NEW

- Fit to the data

Total Fit (Nsig=0)
Continuum
Leptonic $\Upsilon(1S)$
Hardonic $\Upsilon(1S)$
& η' Bkgds



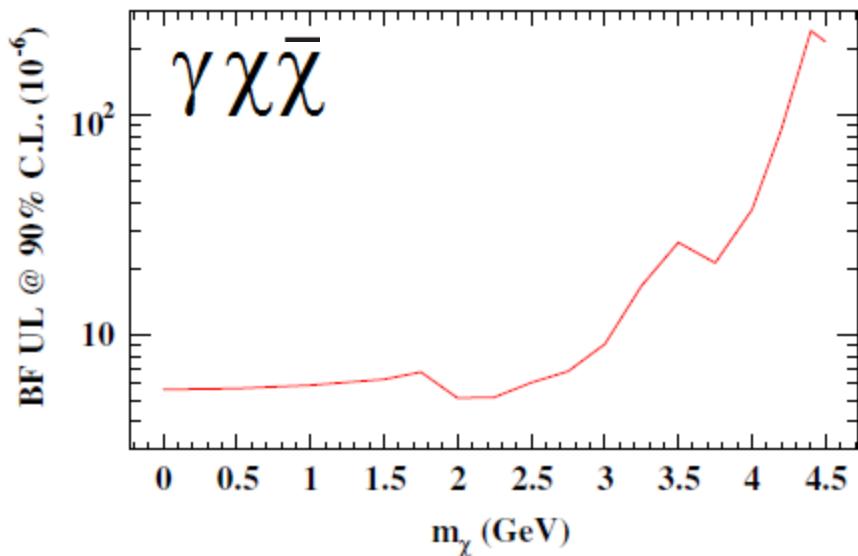
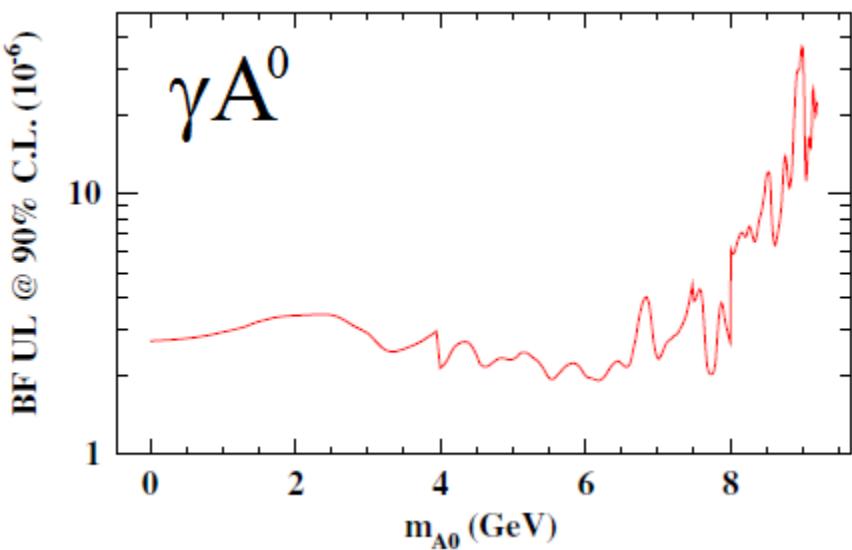


$\Upsilon(2S) \rightarrow \pi^+ \pi^- \Upsilon(1S) \rightarrow \gamma + \text{invisible}$



- No significant signals found
 - Largest fluctuation 2.0σ @ $m_{A^0} = 7.58$ GeV
 - Probability of this fluctuation occurring *anywhere* >30%

PRL 107, 021804 (2011)



- Set 90% CL upper limits
 - $B(\Upsilon(1S) \rightarrow \gamma A^0(\text{invisible})) < (1.9 - 37) \times 10^{-6}$
 - $B(\Upsilon(1S) \rightarrow \gamma \chi \bar{\chi}) < (0.5 - 24) \times 10^{-5}$

Leptonic Decays

Leptonic Decays

- Lepton Flavour Violation ($\Upsilon(nS) \rightarrow \ell \ell'$)
 - SM LFV $B(\Upsilon(nS) \rightarrow \ell \ell') \sim O(10^{-48})$
 - Many BSM mechanisms to enhance LFV in $\Upsilon(nS)$ decays
 - Search for back-to-back $e\tau/\mu\tau$ final state
- Lepton Universality
 - SM coupling of gauge bosons to leptons indpt. of flavour
 - Ie: $B(\Upsilon(nS) \rightarrow \mu^+\mu^-)/B(\Upsilon(nS) \rightarrow \tau^+\tau^-) \sim 1$
 - nMSSM introduces A^0 that can contribute to $\Upsilon(nS) \rightarrow \ell\ell$
 - If $m_{A^0} \sim m_{\eta_b}/m_{\Upsilon(nS)}$, E_γ is small
 - $\Upsilon(nS) \rightarrow \gamma A^0(\ell\ell)$ can mimic $\Upsilon(nS) \rightarrow \ell\ell$
 - Leads to apparent LU violation

JHEP 0901, 061 (2009)

PLB 653, 67 (2007)

Int.J.Mod.Phys A19, 2183 (2004)



Lepton Flavour Violation ($\Upsilon(nS) \rightarrow \ell \ell'$)

- Strategy

- High energy lepton (e, μ) plus $\tau(\ell\nu\nu, \pi^\pm\pi^0\nu, \pi^\pm\pi^0\pi^0\nu)$ in opposite hemisphere
- Fit to $x = p_\ell^* / E_B$
- Signal: bump near end of spectrum
- Bkgd: τ -pairs, Bhabhas/ μ -pairs

- Results

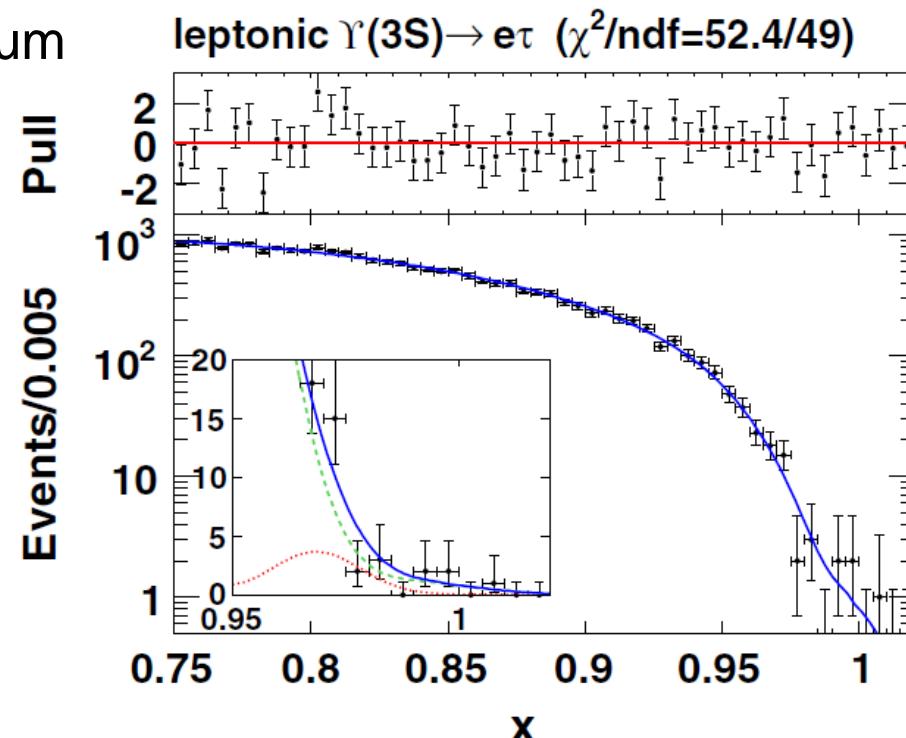
- Consistent with zero
- Set best 90% CL upper limits

$$B(\Upsilon(2S) \rightarrow e\tau) < 3.2 \times 10^{-6}$$

$$B(\Upsilon(2S) \rightarrow \mu\tau) < 3.3 \times 10^{-6}$$

$$B(\Upsilon(3S) \rightarrow e\tau) < 4.2 \times 10^{-6}$$

$$B(\Upsilon(3S) \rightarrow \mu\tau) < 3.1 \times 10^{-6}$$

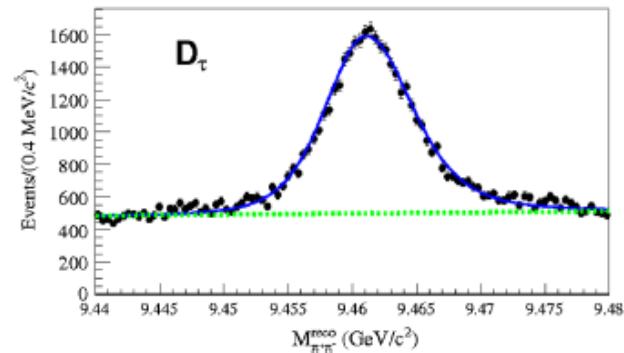
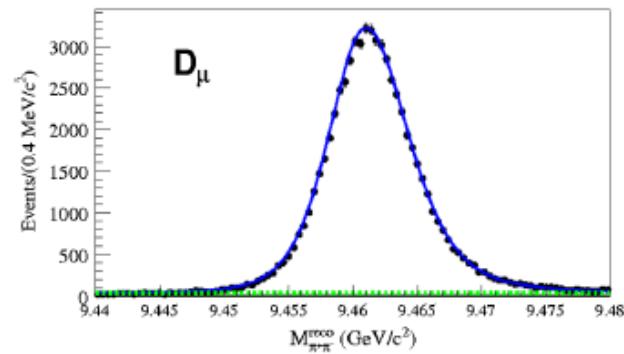
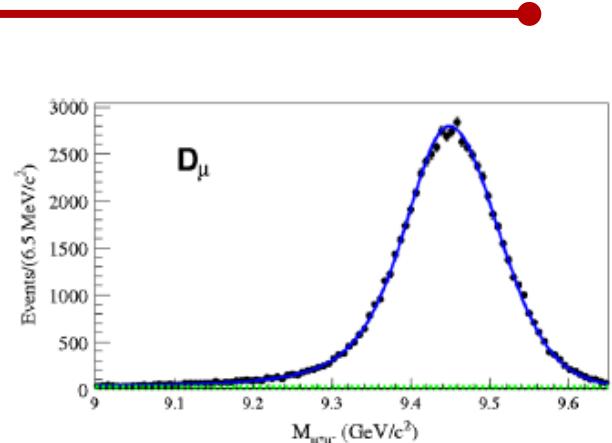


PRL 104, 151802 (2010)



Lepton Universality

- Strategy
 - Tag $\Upsilon(3S) \rightarrow \pi^+\pi^- \Upsilon(1S)$ with $\pi^+\pi^-$ recoil mass
 - Reconstruct $\tau \rightarrow$ one prong (4 tracks in total)
 - Fit to $m_R(\pi^+\pi^-)$ ($\tau\tau$), $m_R(\pi^+\pi^-)$ and $m_{\mu\mu}$ ($\mu\mu$)



PRL 104, 191801 (2010)





Work in Progress

- BaBar
 - Direct (non-dipion) $\Upsilon(nS) \rightarrow (\mu^+\mu^- / \tau^+\tau^-)$ lepton universality
 - Expected LU enhancement for $\Upsilon(2,3S)$ compared to $\Upsilon(1S)$
- Belle
 - Lepton universality in $\Upsilon(2S) \rightarrow \pi^+\pi^- \Upsilon(1S) \rightarrow (\mu^+\mu^- / \tau^+\tau^-)$
 - $\Upsilon(2S) \rightarrow \pi^+\pi^- \Upsilon(1S)$ dipion tag leads to large, clean $\Upsilon(1S)$ sample

Hyperfine Splitting

$\eta_b(nS) - \Upsilon(nS)$ hyperfine splitting

- Proposal
 - $\eta_b(nS)$ - A^0 mixing can lead to distortions in bottomonium spectrum
 - Could produce $\eta_b(2S)$ - $\Upsilon(2S)$ splitting in disagreement with SM

PRL 103, 111802 (2009)

- Experimental
 - Several $\eta_b(1S)$ - $\Upsilon(1S)$ measurements (40-70 MeV from theory)

BaBar $\Upsilon(3S)$	BaBar $\Upsilon(2S)$	CLEO $\Upsilon(3S)$	Belle $\Upsilon(5S)$
71.4 ± 4.0	66.1 ± 5.2	68.5 ± 6.9	59.3 ± 3.4



- No evidence yet for $\eta_b(2S)$
- Future searches?
 - $\Upsilon(3S) \rightarrow \gamma \eta_b(2S)$ in inclusive photon spectrum
 - Reconstruct $\eta_b(nS)$ with multihadronic final states
 - $h_b(nP) \rightarrow \gamma \eta_b(nS)$ at Belle

Conclusions

Conclusions

- Large $\Upsilon(nS)$ datasets probe new physics
- Light Higgs searches limit parameter space
- No evidence for light DM
- No new physics via LFV
- Still more results will come...
 - Analysis of Belle $\Upsilon(1,2S)$
 - BaBar searches continue

JHEP 16, 1104 (2011)

