

# Bottomonium Decays at BaBar

Peter Kim  
SLAC National Accelerator Laboratory  
(representing BaBar Collaboration)

**8<sup>th</sup> International Workshop on Heavy Quarkonium  
(QWG2011)  
October 4 – 7, 2011  
GSI, Germany**

## Bottomonium transitions with converted photons

- Radiative decays of  $\Upsilon(2S)/\Upsilon(3S)$  and  $\chi_b(1P)/\chi_b(2P)$
- Search for  $\eta_b(1S)$  (C.Patrignani, Oct. 5)

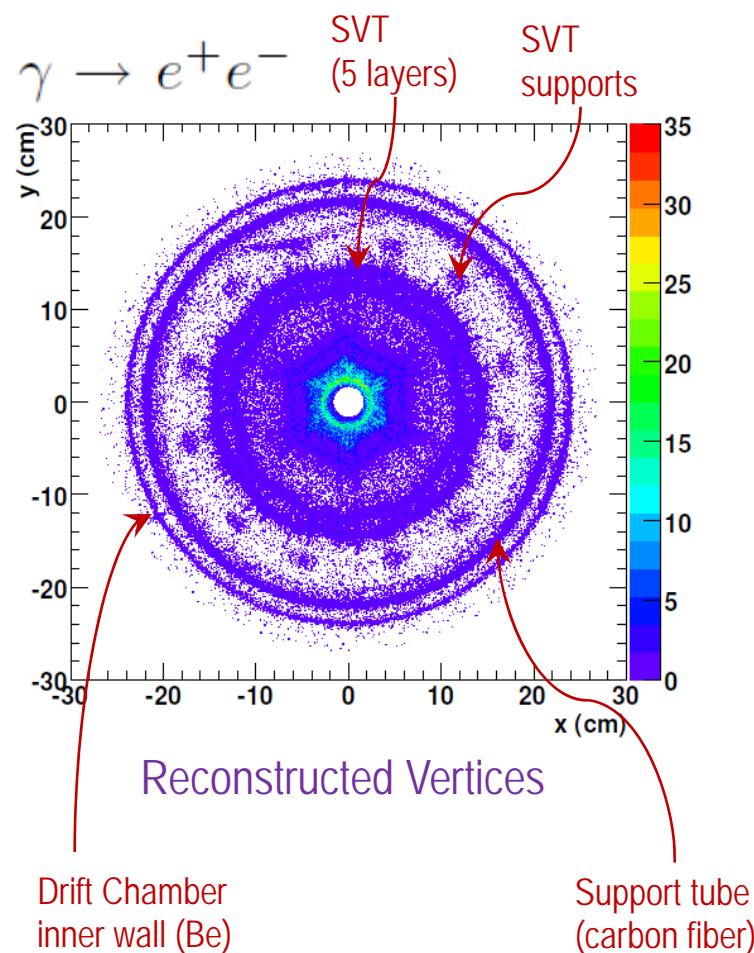
## Recoil against $\pi^+\pi^-$ in $\Upsilon(3S)$

- $\chi_{bJ}(2P) \rightarrow \pi^+\pi^- \chi_{bJ}(1P)$  transitions
- Search for  $h_b(1P)$  (C.Patrignani, Oct. 5)

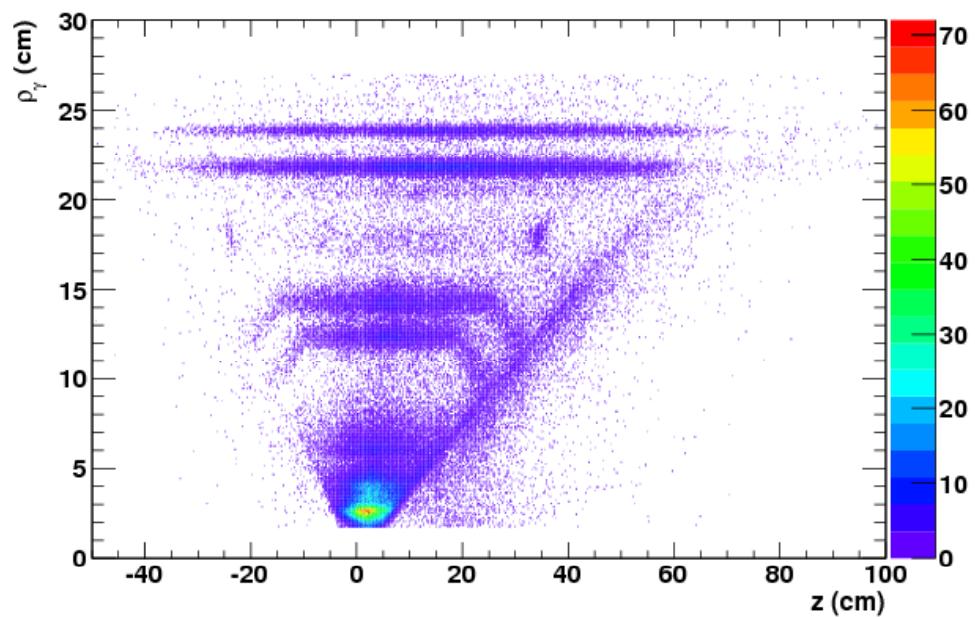
## Hadronic transitions between $\Upsilon(3S)/\Upsilon(2S)$ and $\Upsilon(1S)$

- $\Upsilon(2S)$  or  $\Upsilon(3S) \rightarrow \pi^+\pi^- \Upsilon(1S)$ ;  $\Upsilon(1S) \rightarrow l^+l^-$
- $\Upsilon(2S)$  or  $\Upsilon(3S) \rightarrow \eta \Upsilon(1S)$ ;  $\eta \rightarrow \pi^+\pi^-\pi^0$  or  $\gamma\gamma$ ;  $\Upsilon(1S) \rightarrow l^+l^-$

# Converted Photon Reconstruction with BaBar detector

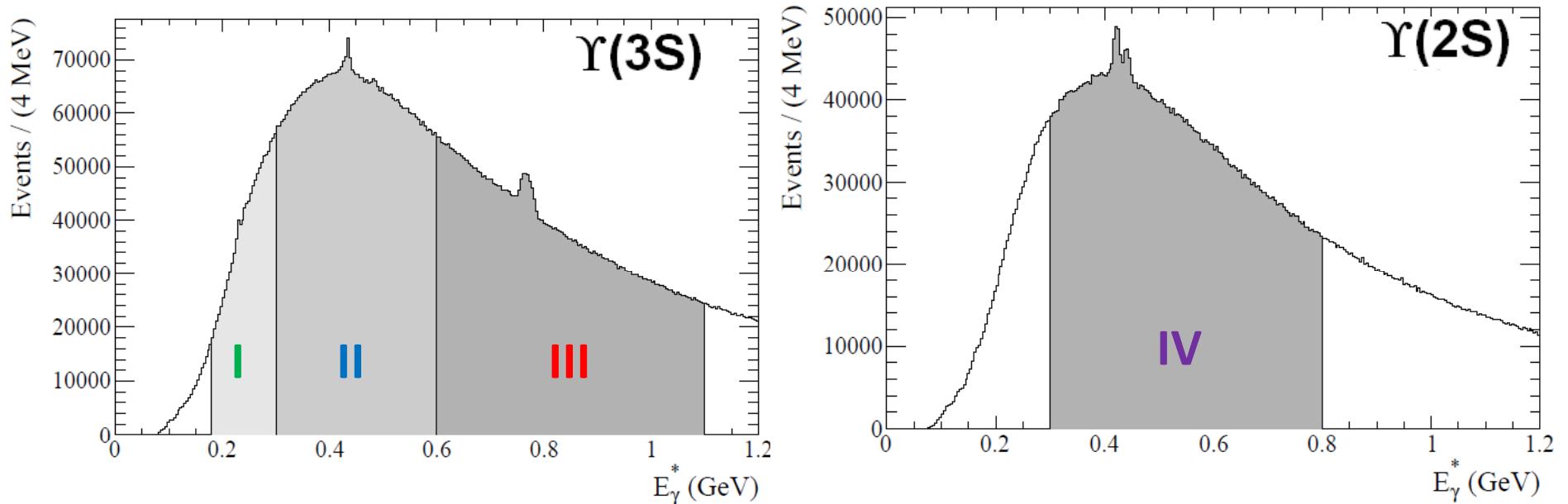


- Reconstruct pair of tracks, selected with  $\chi^2$  fitter,  $m_\gamma$ ,  $p_\gamma$

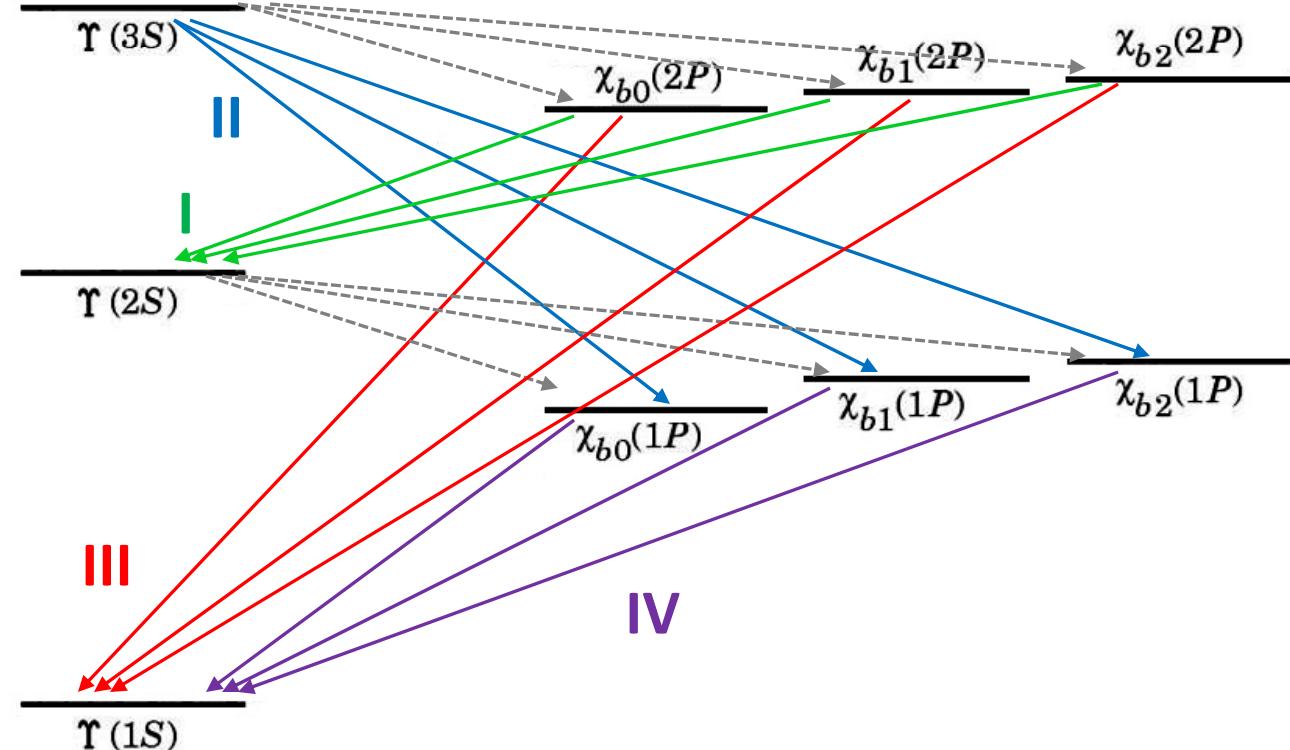


# Physics with Converted Photons

- Converted photons ( $\gamma \rightarrow e^+e^-$ ) improve energy resolution (e.g.: 25  $\rightarrow$  5 MeV at 900 MeV)
  - Caveat: Conversion rate & low reconstruction efficiency (yield  $\sim 1\%$  compared to EMC )  
Not as effective for resonances with large widths  
or secondary transitions with Doppler broadening
- BaBar data: 100M  $\Upsilon(2S)$  and 122M  $\Upsilon(3S)$  events
- Fit  $E_\gamma^*$  (photon energy in CM) spectrum in four regions of interest (I-IV)



# Radiative $\chi_b$ Transitions



$J^{PC} =$

$1^{--}$

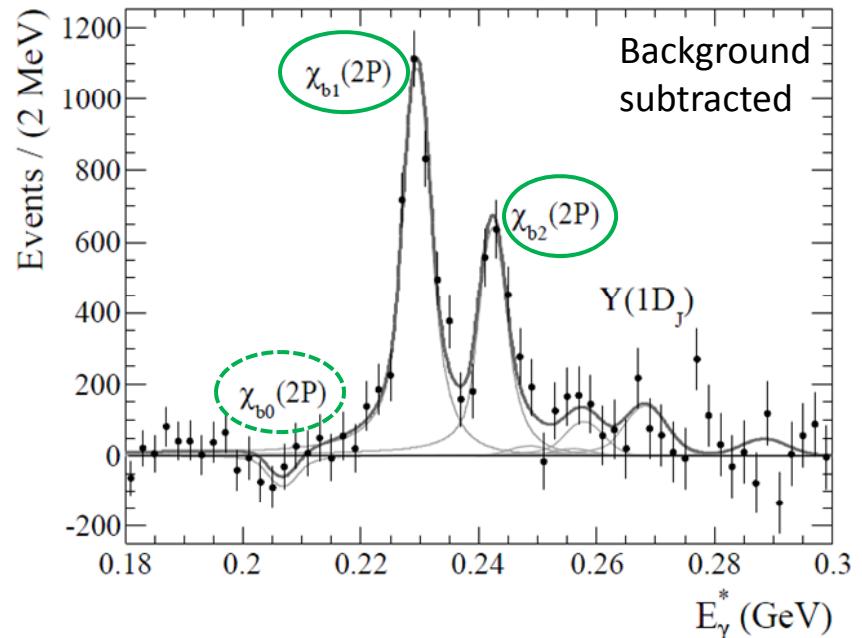
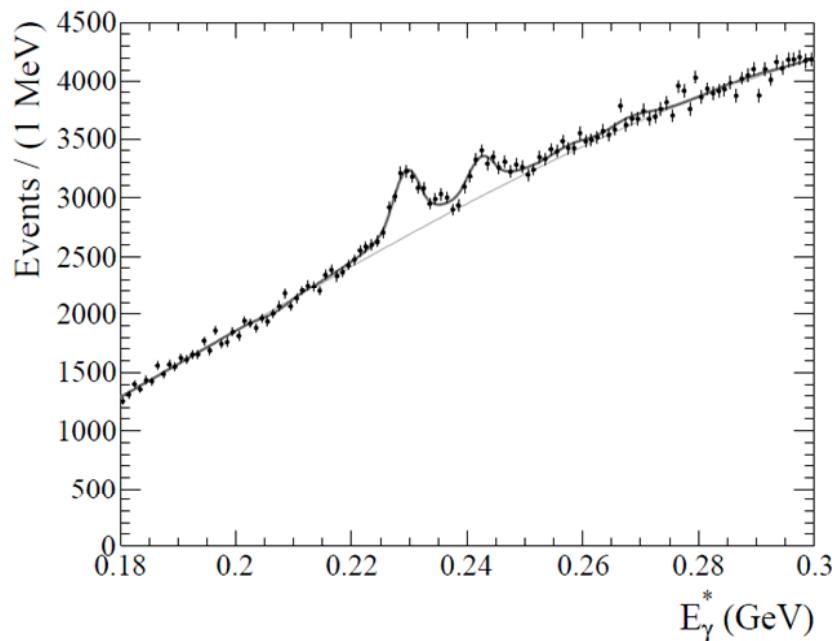
$0^{++}$

$1^{++}$

$2^{++}$

# I. $180 < E_\gamma^* < 300$ MeV $\Upsilon(3S)$

- Three “signal” transitions ( $\chi_{bJ}(2P) \rightarrow \gamma\Upsilon(2S)$ ) and six  $\Upsilon(1D)$ -related lines



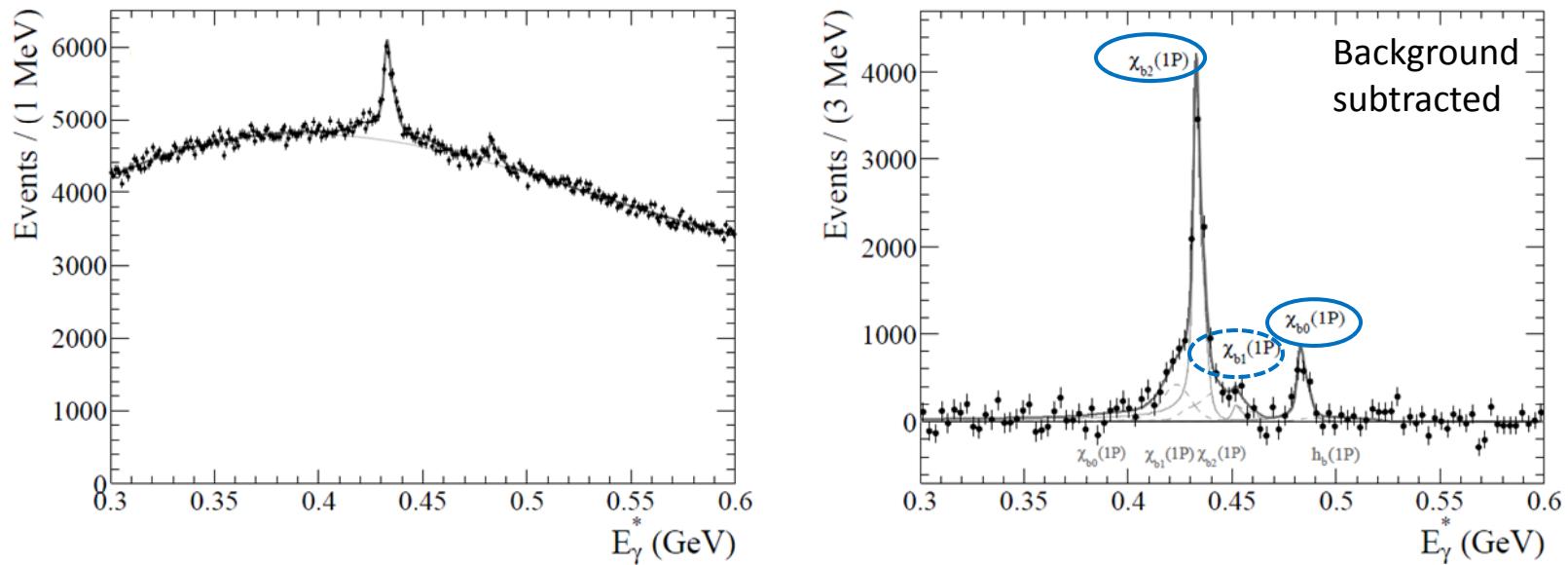
- Precision measurements of  $\text{BF}(\chi_{bJ}(2P) \rightarrow \gamma\Upsilon(2S))$

arXiv:1104.5254

Transition	$E_\gamma^*$ ( MeV)	Yield	$\epsilon$ (%)	Derived Branching Fraction (%)	BABAR	CUSB	CLEO
$\chi_{b0}(2P) \rightarrow \gamma\Upsilon(2S)$	205.0	$-347 \pm 209$	0.105	$-4.7 \pm 2.8^{+0.7}_{-0.8} \pm 0.5 (< 2.8)$	$-4.7 \pm 2.8^{+0.7}_{-0.8} \pm 0.5 (< 2.8)$	$3.6 \pm 1.6$	$< 5.2$
$\chi_{b1}(2P) \rightarrow \gamma\Upsilon(2S)$	229.7	$4294 \pm 251$	0.152	$18.9 \pm 1.1 \pm 1.2 \pm 1.8$	$18.9 \pm 1.1 \pm 1.2 \pm 1.8$	$13.6 \pm 2.4$	$21.1 \pm 4.5$
$\chi_{b2}(2P) \rightarrow \gamma\Upsilon(2S)$	242.3	$2462 \pm 243$	0.190	$8.3 \pm 0.8 \pm 0.6 \pm 1.0$	$8.3 \pm 0.8 \pm 0.6 \pm 1.0$	$10.9 \pm 2.2$	$9.9 \pm 2.7$

## II. $300 < E_\gamma^* < 600$ MeV $\Upsilon(3S)$

- Complicated photon spectrum: many overlapping signals



- Observation and precise measurement of  $\Upsilon(3S) \rightarrow \gamma \chi_{b0,2}(1P)$  transitions

Transition	$E_\gamma^*$ ( MeV)	Yield	$\epsilon$ (%)	Derived Branching Fraction ( $\times 10^{-3}$ )	
				BABAR	CLEO
$\Upsilon(3S) \rightarrow \gamma \chi_{b2}(1P)$	433.1	$9699 \pm 318$	0.794	$10.5 \pm 0.3^{+0.7}_{-0.6}$	$7.7 \pm 1.3$
$\Upsilon(3S) \rightarrow \gamma \chi_{b1}(1P)$	452.2	$483 \pm 315$	0.818	$0.5 \pm 0.3^{+0.2}_{-0.1} (< 1.0)$	$1.6 \pm 0.5$
$\Upsilon(3S) \rightarrow \gamma \chi_{b0}(1P)$	483.5	$2273 \pm 307$	0.730	$2.7 \pm 0.4 \pm 0.2$	$3.0 \pm 1.1$

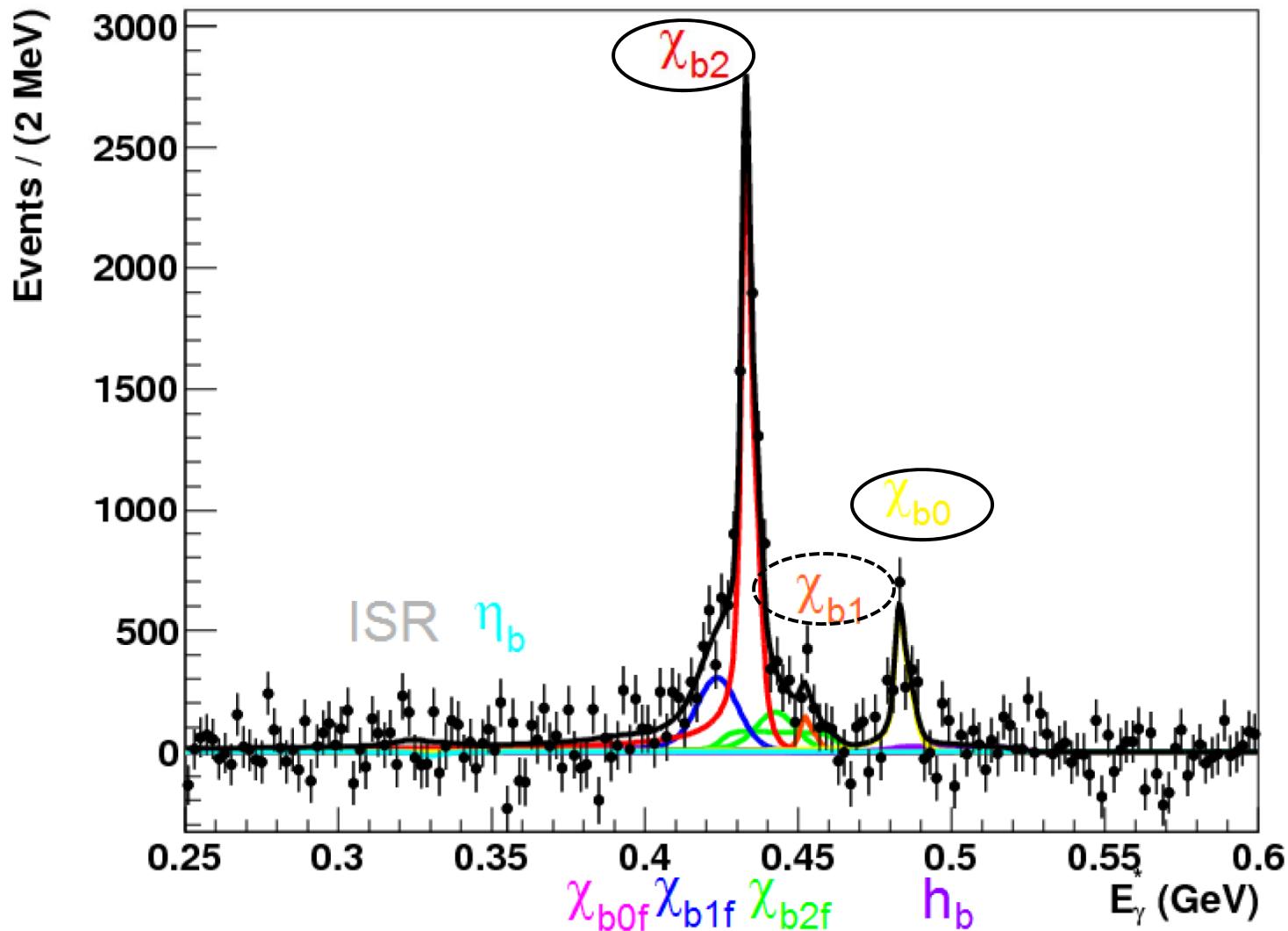
arXiv:1104.5254

- Transition rate pattern of  $(J = 1) < (J = 0)$  unusual for quarkonium

# Fit to $E_\gamma^*$ Spectrum (II.)

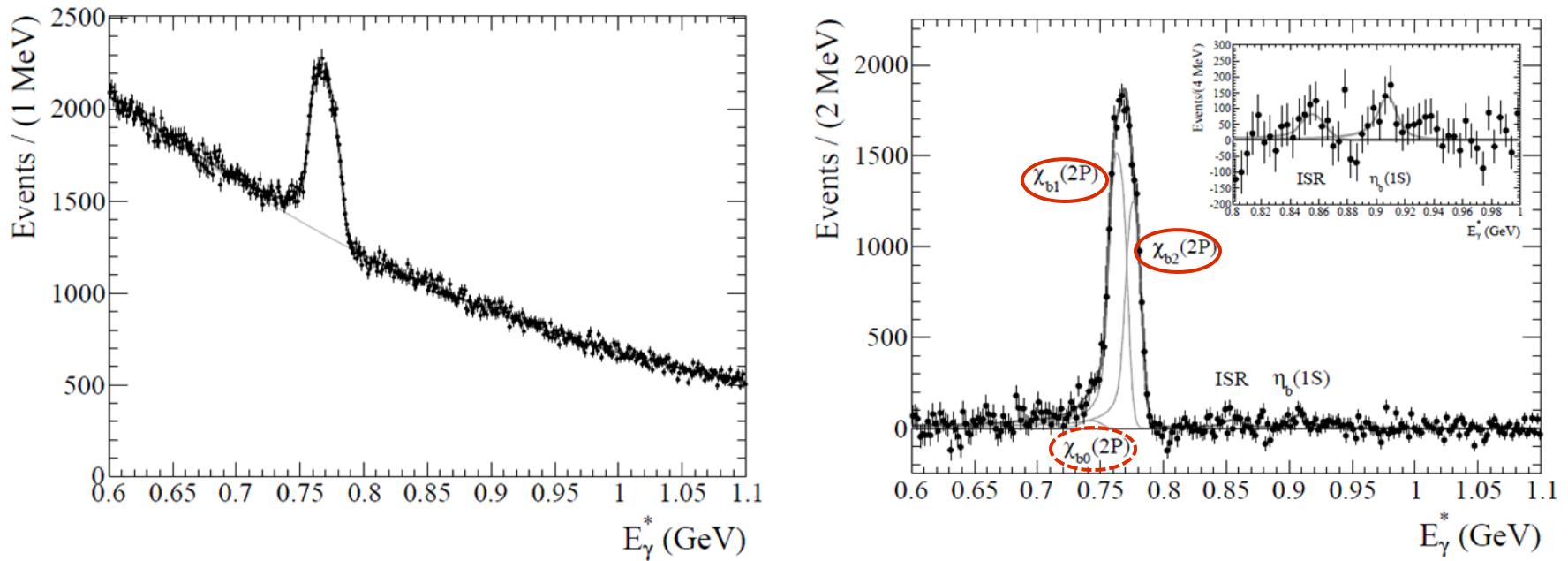
- “Direct” decays:
  - $Y(3S) \rightarrow \gamma \chi_{bJ}(1P)$ : Two-sided Crystal Ball (CB) + Gaussian
  - $Y(3S) \rightarrow \gamma \eta_b(2S)$ : CB \* Breit-Wigner
  - $e^+ e^- \rightarrow \gamma_{\text{ISR}} Y(2S)$ : CB
- Feed-down:
  - $\chi_{bJ}(1P) \rightarrow \gamma Y(1S)$  from “direct”: Doppler-broadened CB
    - Yield related to direct transition
$$f = N \cdot \left[ f_1 + \frac{\epsilon_1}{\epsilon_2} \cdot \mathcal{B} \cdot \frac{\int f_1}{\int f_2} \cdot f_2 \right]$$
  - $\chi_{bJ}(1P) \rightarrow \gamma Y(1S)$  from all other modes: CB, fixed yield
  - $Y(3S) \rightarrow \pi^0 h_b(1P) \rightarrow \gamma \eta_b(1S)$ : Doppler-broadened CB, fixed
  - $Y(3S) \rightarrow \pi^+ \pi^- h_b(1P) \rightarrow \gamma \eta_b(1S)$ : CB, fixed

# Fit Result (II.)



### III. $600 < E_\gamma^* < 1100$ MeV $\Upsilon(3S)$

- Measure  $\chi_{bJ}(2P) \rightarrow \gamma\Upsilon(1S)$  and search for  $\eta_b(1S)$  signal



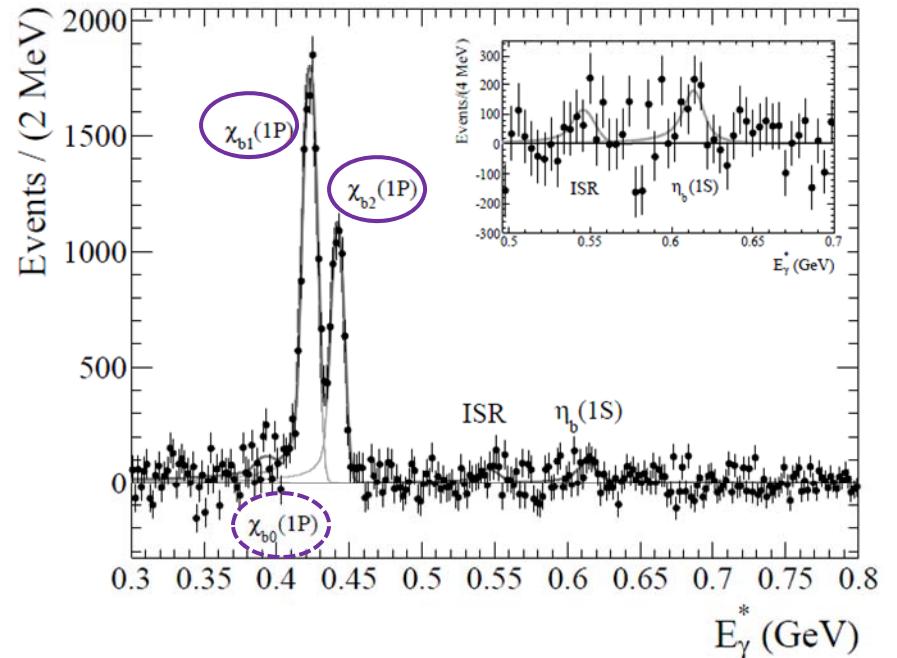
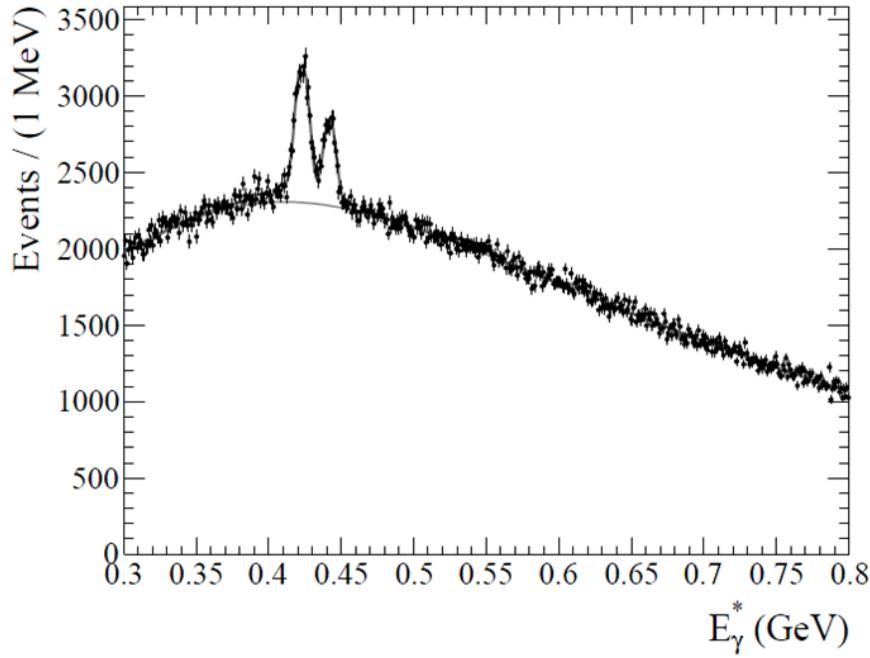
- $\eta_b$  significance  $< 3\sigma$ ; No observation of  $\chi_{b0}(2P)$  transition

arXiv:1104.5254

Transition	$E_\gamma^*$ (MeV)	Yield	$\epsilon$ (%)	Derived Branching Fraction (%)	BABAR	CUSB	CLEO
$\chi_{b0}(2P) \rightarrow \gamma\Upsilon(1S)$	742.7	$469^{+260}_{-259}$	1.025	$0.7 \pm 0.4^{+0.2}_{-0.1} \pm 0.1 (< 1.2)$	$0.7 \pm 0.4^{+0.2}_{-0.1} \pm 0.1 (< 1.2)$	$< 1.9$	$< 2.2$
$\chi_{b1}(2P) \rightarrow \gamma\Upsilon(1S)$	764.1	$14965^{+381}_{-383}$	1.039	$9.9 \pm 0.3^{+0.5}_{-0.4} \pm 0.9$	$9.9 \pm 0.3^{+0.5}_{-0.4} \pm 0.9$	$7.5 \pm 1.3$	$10.4 \pm 2.4$
$\chi_{b2}(2P) \rightarrow \gamma\Upsilon(1S)$	776.4	$11283^{+384}_{-385}$	1.056	$7.0 \pm 0.2 \pm 0.3 \pm 0.9$	$7.0 \pm 0.2 \pm 0.3 \pm 0.9$	$6.1 \pm 1.2$	$7.7 \pm 2.0$
$\Upsilon(3S) \rightarrow \gamma\eta_b(1S)$	$907.9 \pm 2.8 \pm 0.9$	$933^{+263}_{-262}$	1.388	$0.058 \pm 0.016^{+0.014}_{-0.016} (< 0.085)$	$0.058 \pm 0.016^{+0.014}_{-0.016} (< 0.085)$	-	-

## IV. $300 < E_\gamma^* < 800$ MeV $\Upsilon(2S)$

- Measure  $\chi_{bJ}(1P) \rightarrow \gamma \Upsilon(1S)$  and search for  $\eta_b(1S)$  signal



- No evidence for  $\Upsilon(2S) \rightarrow \gamma \eta_b(1S)$

[arXiv:1104.5254](https://arxiv.org/abs/1104.5254)

Transition	$E_\gamma^*$ (MeV)	Yield	$\epsilon$ (%)	Derived Branching Fraction (%)			
				BABAR	CB	CUSB	CLEO
$\chi_{b0}(1P) \rightarrow \gamma \Upsilon(1S)$	391.5	$391 \pm 267$	0.496	$2.2 \pm 1.5^{+1.0}_{-0.7} \pm 0.2 (< 4.6)$	< 5	< 12	$1.7 \pm 0.4$
$\chi_{b1}(1P) \rightarrow \gamma \Upsilon(1S)$	423.0	$12604 \pm 285$	0.548	$34.9 \pm 0.8 \pm 2.2 \pm 2.0$	$34 \pm 7$	$40 \pm 10$	$33.0 \pm 2.6$
$\chi_{b2}(1P) \rightarrow \gamma \Upsilon(1S)$	442.0	$7665^{+270}_{-272}$	0.576	$19.5 \pm 0.7^{+1.3}_{-1.5} \pm 1.0$	$25 \pm 6$	$19 \pm 8$	$18.5 \pm 1.4$
$\Upsilon(2S) \rightarrow \gamma \eta_b(1S)$	$613.7^{+3.0+0.7}_{-2.6-1.1}$	$1109 \pm 348$	1.050	$0.11 \pm 0.04^{+0.07}_{-0.05} (< 0.21)$	-	-	-

# Summary of BF measurements of $Y(nS)$ radiative decays using converted photons

Precise measurements of  
 $\chi_{bJ}(nP)_{n=1,2} \rightarrow \gamma Y(mS)_{m=1,2}$  BFs

Good agreement with theory  
 Kwong & Rosner, PRD38, 279 (1988)

Measurements of BFs for  
 $Y(3S) \rightarrow \gamma \chi_{bJ}(1P)$  transitions

- ☞ transition to  $\chi_{b1}(1P)$  not seen
- ☞ in general inconsistent with theoretical predictions

(except Moxhay-Rosner PRD28, 1132 (1983))

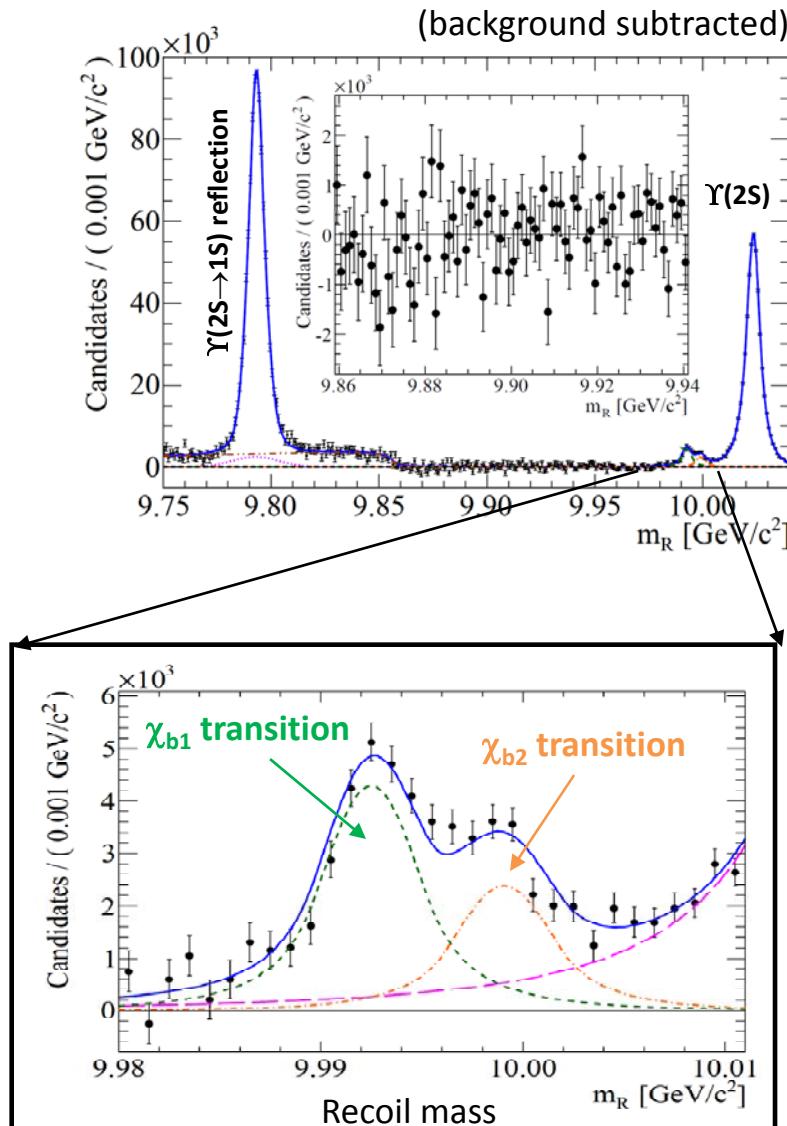
arXiv:1104.5254 (accepted by PRD)

Decay	BABAR (%)	Theory (%)
$\mathcal{B}(\chi_{b0}(2P) \rightarrow \gamma Y(2S))$	(< 2.9)	1.27
$\mathcal{B}(\chi_{b1}(2P) \rightarrow \gamma Y(2S))$	$19.1 \pm 2.3$	20.2
$\mathcal{B}(\chi_{b2}(2P) \rightarrow \gamma Y(2S))$	$8.2 \pm 1.4$	10.1
$\mathcal{B}(\chi_{b0}(2P) \rightarrow \gamma Y(1S))$	(< 1.2)	0.96
$\mathcal{B}(\chi_{b1}(2P) \rightarrow \gamma Y(1S))$	$9.9 \pm 1.1$	11.8
$\mathcal{B}(\chi_{b2}(2P) \rightarrow \gamma Y(1S))$	$7.1^{+1.0}_{-0.9}$	5.3
$\mathcal{B}(\chi_{b0}(1P) \rightarrow \gamma Y(1S))$	(< 4.6)	3.2
$\mathcal{B}(\chi_{b1}(1P) \rightarrow \gamma Y(1S))$	$36.2 \pm 2.8$	46.1
$\mathcal{B}(\chi_{b2}(1P) \rightarrow \gamma Y(1S))$	$20.2^{+1.6}_{-1.8}$	22.2

Source	$J = 0$	$J = 1$	$J = 2$
BABAR	$55 \pm 10$	$< 22$	$216 \pm 25$
Moxhay-Rosner	25	25	150
Grotch <i>et al.</i>	114	3.4 ?	194
Daghighian-Silverman	16	100	650
Fulcher	10	20	30
Lähde	150	110	40
Ebert <i>et al.</i>	27	67	97

partial widths (in units of eV)

# $\chi_b(2P) \rightarrow \pi^+\pi^- \chi_b(1P)$ transitions in $\pi^+\pi^-$ Recoil



Phys.Rev. D 84, 011104(R)

- Search for  $h_b$  in  $\Upsilon(3S) \rightarrow \pi^+\pi^- X$
- No evidence for  $h_b$  at 9.9 GeV/c $^2$   
 $BF(\Upsilon(3S) \rightarrow \pi^+\pi^- h_b) < 1.0 \times 10^{-4}$  (@90% C.L.)

First separate observation of  
 $\chi_b(2P) \rightarrow \pi^+\pi^- \chi_b(1P)$  transitions

$$BF(\chi_{b1}(2P) \rightarrow \pi^+\pi^- \chi_{b1}(1P)) = (9.2 \pm 0.6 \pm 0.9) \times 10^{-3}$$

$$BF(\chi_{b2}(2P) \rightarrow \pi^+\pi^- \chi_{b2}(1P)) = (4.9 \pm 0.4 \pm 0.6) \times 10^{-3}$$

$$\Upsilon(2S)/\Upsilon(3S) \rightarrow [\pi^+\pi^-\Upsilon(1S)] \text{ or } [\eta\Upsilon(1S)]$$

- QCD Multipole Expansion (QCDME) model to describe hadronic transitions  
(E.Eichten; QWG7, 2010)
- $R(n) = BR[\Upsilon(nS) \rightarrow \eta\Upsilon(1S)] / BR[\Upsilon(nS) \rightarrow \pi^+\pi^-\Upsilon(1S)]$ 

$R(2): 1.2 \times 10^{-3}$  (exp)       $(1.7-3.9) \times 10^{-3}$  (theory)  
 $R(3): < 4 \times 10^{-3}$  (exp) vs  $(11 - 20) \times 10^{-3}$  (theory)  
 $R(4): 2.2$  (exp)       $2.2 \times 10^{-3}$  (theory) &  $1.8-2.9$  (theory\*)
- Measure both  $\pi^+\pi^-$  and  $\eta$  transitions to reduce common systematics
- Full reconstruction of  $\Upsilon(2S)/\Upsilon(3S)$  in final states:  $\pi^+\pi^-|^{+/-}$     $\pi^+\pi^-|^{+/-}\gamma\gamma$     $|^{+/-}\gamma\gamma$

# $[\pi^+\pi^-\Upsilon(1S)]$ and $[\eta\Upsilon(1S)]$ Analysis

- Event candidates are kinematically constrained to the  $\Upsilon(nS)$  mass and beam energy
- Veto photons that are compatible with radiative  $\chi_b$  transitions
- Veto di-pion crossfeeds from other known di-pion transitions
- Low efficiency in the electron channel due to anti-Bhabha cuts in  $\Upsilon(2S)$  data (use  $\mu^+\mu^-$  channel only)
- Signal extraction: unbinned ML fit of 2-D distributions

$$\Delta M_\eta = M(\pi^+\pi^-\gamma\gamma\ell^+\ell^-) - M(\ell^+\ell^-) - M(\pi^+\pi^-\gamma\gamma) \text{ vs. } M(\pi^+\pi^-\gamma\gamma)$$

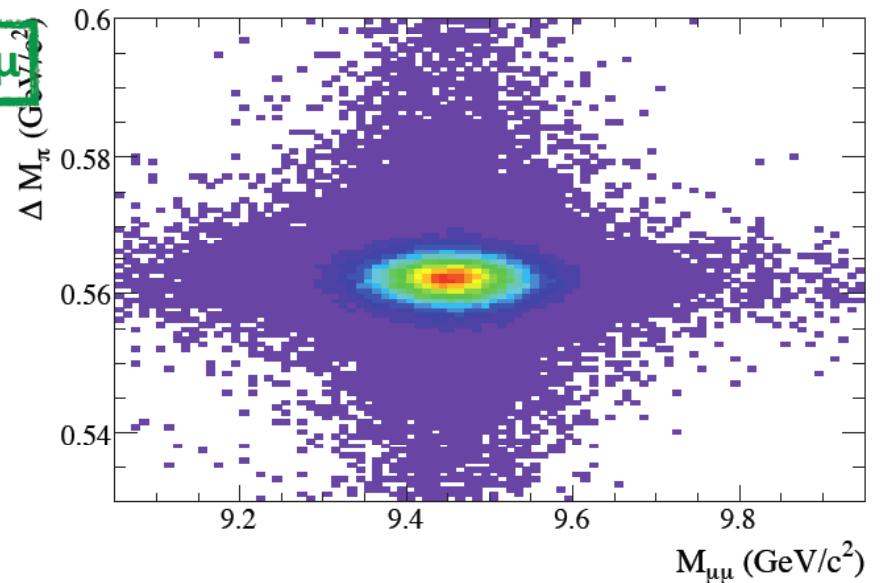
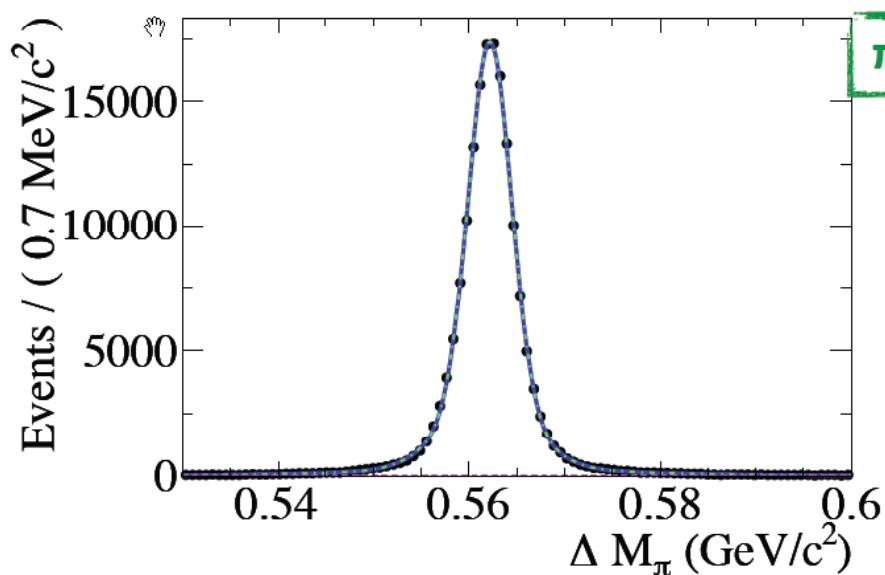
$$\Delta M'_\eta = M(\gamma\gamma\ell^+\ell^-) - M(\ell^+\ell^-) - M(\gamma\gamma) \text{ vs. } M(\gamma\gamma)$$

$$\Delta M_\pi = M(\pi^+\pi^-\ell^+\ell^-) - M(\ell^+\ell^-) \text{ vs. } M(\ell^+\ell^-)$$

- PDF's are determined from MC and data  
Function shapes: Cruijf, doubl/triple Gaussian, Poly.background

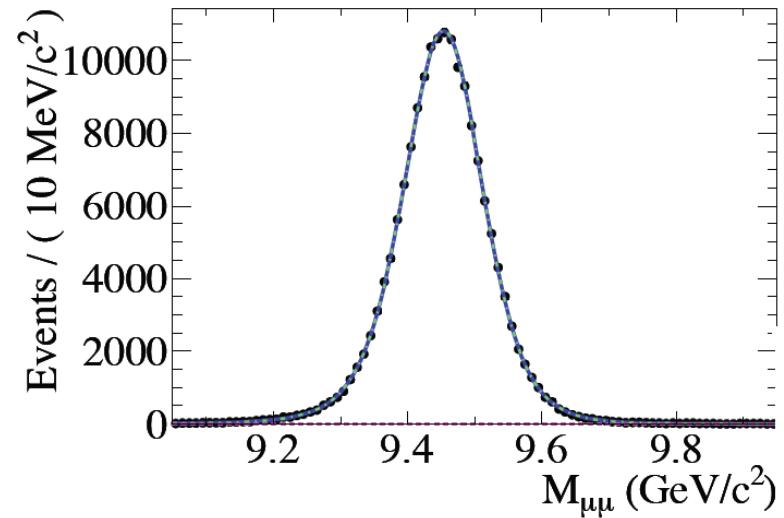
E. Guido (PhD thesis, Genova, 2011)

## $\Upsilon(2S) \rightarrow \pi^+ \pi^- \Upsilon(1S)$ Fit Result

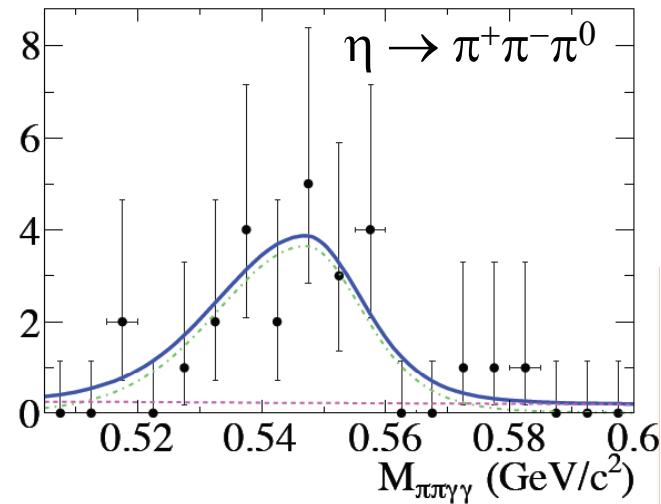
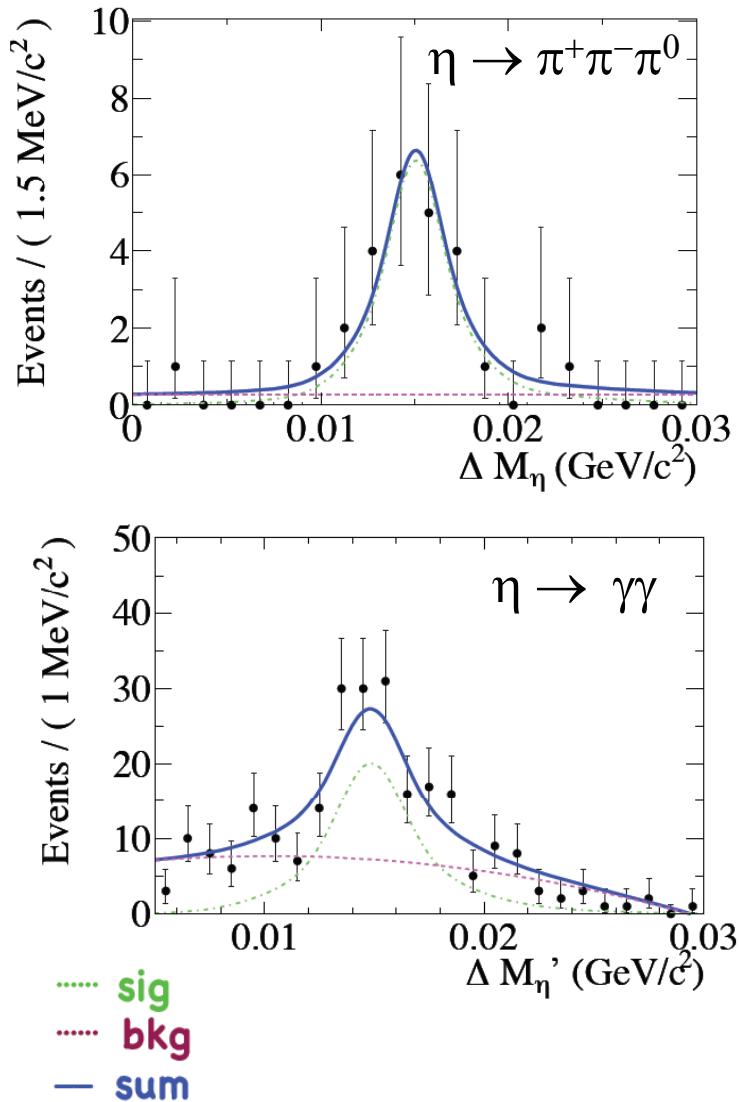


<i>Variable</i>	<i>Signal</i>	<i>Background</i>
$M(\mu^+ \mu^-)$	Cruijff	Polynomial 0 <sup>th</sup>
$\Delta M_\pi$	Triple Gaussian	Polynomial 0 <sup>th</sup>

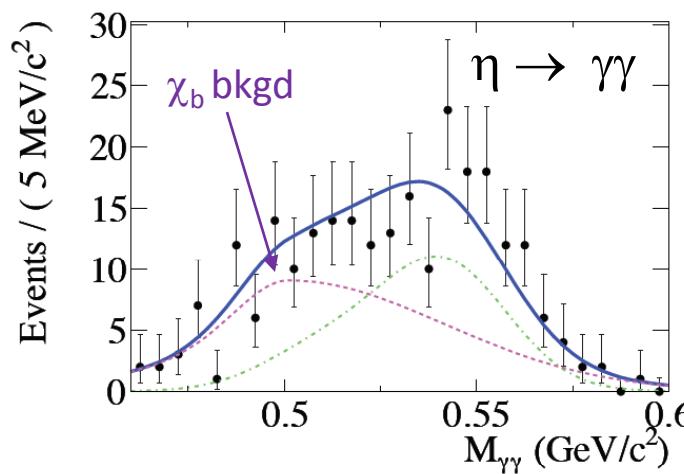
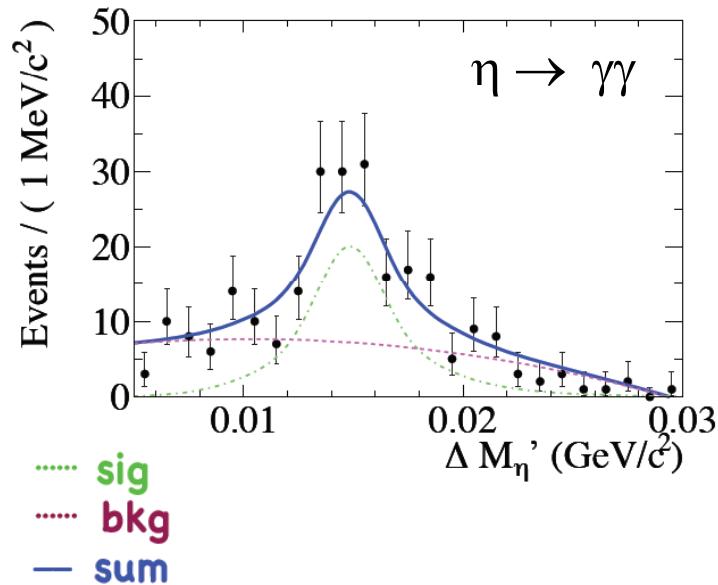
$$N_{sig} = 170,061 \pm 413$$



## $\Upsilon(2S) \rightarrow \eta \Upsilon(1S)$ Fit Result



$N_{sig} = 22 \pm 5$



$N_{sig} = 90 \pm 14$

# Event Yields and Systematics

Transition	Final state	$\epsilon_{sel}$ (%)	$N$
$\Upsilon(2S) \rightarrow \pi^+ \pi^- \Upsilon(1S)$	$\pi^+ \pi^- \mu^+ \mu^-$	39.1	$170061 \pm 413$
$\Upsilon(2S) \rightarrow \eta \Upsilon(1S)$	$\pi^+ \pi^- \gamma\gamma \mu^+ \mu^-$ $\gamma\gamma \mu^+ \mu^-$	18.5 37.2	$22 \pm 5$ $90 \pm 14$
$\Upsilon(3S) \rightarrow \pi^+ \pi^- \Upsilon(1S)$	$\pi^+ \pi^- e^+ e^-$ $\pi^+ \pi^- \mu^+ \mu^-$	25.0 42.8	$31330 \pm 186$ $58500 \pm 247$
$\Upsilon(3S) \rightarrow \eta \Upsilon(1S)$	$\pi^+ \pi^- \gamma\gamma e^+ e^-$ $\pi^+ \pi^- \gamma\gamma \mu^+ \mu^-$ $\gamma\gamma \mu^+ \mu^-$	18.1 8.9 18.5	$4 \pm 2$ ( $<8$ ) $4 \pm 2$ ( $<8$ ) $7 \pm 11$ ( $<26$ )

- Main sources of systematic uncertainties
  - $\Upsilon(2S) \rightarrow \eta \Upsilon(1S)$ :  $\pi^0$  or  $\gamma$  efficiency (3.6%) Fit (5.4%) Selection (2.6% or 5.6%)  
Tracking (2% or 1%) for  $\eta \rightarrow \pi^+ \pi^- \pi^0$  or  $\gamma\gamma$
  - $\Upsilon(2S) \rightarrow \pi^+ \pi^- \Upsilon(1S)$ : M[ $\pi^+ \pi^-$ ] model (0.5%) Fit (0.1%) Selection (0.4%)  
Tracking (2%) muon-id (1.1%)
  - Common for ratios:  $\Upsilon(1S) \rightarrow l^+ l^-$  from PDG (2%) &  $N_{\Upsilon(2S)}$  (0.9%)
- CLEO M[ $\pi^+ \pi^-$ ] model was varied for efficiency systematics. Full di-pion mass and polarization study results not yet available.

	<i>BABAR</i>	PDG	Predictions
$\mathcal{B}[\Upsilon(2S) \rightarrow \eta \Upsilon(1S)]$ ( $10^{-4}$ )	$2.39 \pm 0.31 \pm 0.14$	$2.1^{+0.8}_{-0.7}$	7-16
$\mathcal{B}[\Upsilon(2S) \rightarrow \pi^+ \pi^- \Upsilon(1S)]$ ( $10^{-2}$ )	$17.80 \pm 0.05 \pm 0.37$	$18.1 \pm 0.4$	40
$\frac{\Gamma[\Upsilon(2S) \rightarrow \eta \Upsilon(1S)]}{\Gamma[\Upsilon(2S) \rightarrow \pi^+ \pi^- \Upsilon(1S)]}$ ( $10^{-3}$ )	$1.35 \pm 0.17 \pm 0.08$	$1.2 \pm 0.4$	1.7-3.8
$\mathcal{B}[\Upsilon(3S) \rightarrow \eta \Upsilon(1S)]$ ( $10^{-4}$ )	$< 1.0$	$< 1.8$	5-10
$\mathcal{B}[\Upsilon(3S) \rightarrow \pi^+ \pi^- \Upsilon(1S)]$ ( $10^{-2}$ )	$4.32 \pm 0.07 \pm 0.13$	$4.40 \pm 0.10$	5
$\frac{\Gamma[\Upsilon(3S) \rightarrow \eta \Upsilon(1S)]}{\Gamma[\Upsilon(3S) \rightarrow \pi^+ \pi^- \Upsilon(1S)]}$ ( $10^{-3}$ )	$< 2.3$	$< 4.2$	11-20

Y.-P. Kuan, Front. Phys. China 1, 19 (2006)

Yu.A. Simonov and A.I. Veselov, arXiv:0806.2919 (2008)

C. Meng and K.T. Chao, Phys.Rev. D 78, 074001 (2008)

- More precise measurements, testing theoretical models
- Other hadronic decays that could be helpful for better understanding:
  - Transitions to and from  $\chi_b$  and 1D states
  - Transitions from  $\Upsilon(5S)$ :  $\eta X$ ,  $KK X$ ,  $\phi X$
  - Full analysis of  $M_{\pi\pi}$  and polarization in  $\pi\pi$  transitions

# Conclusions

- Good energy resolution with converted photons provides improved measurement of radiative decay rates
  - Radiative decays of  $\chi_{b0}$  states not observed  
(Could use more data!)
- More precise determination of  $\eta$  and  $\pi^+\pi^-$  transitions rates
  - Reduce systematic uncertainties in other measurements that utilize these channels
- Further results expected from BaBar/Belle could shed light on the mysteries of hadronic transitions