# Recent BABAR studies of bottomonium, charmonium and charmonium-like states

**Elisa Guido**

INFN Genova

(on behalf of **BABAR Collaboration**)

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# Outline

- Recent bottomonium results:

  ✓ Evidence for the $h_b(1P)$ in $\Upsilon(3S) \to \pi^0 h_b(1P)$ **arXiv:1102.4565**

  ✓ Search for the $h_b(1P)$ in $\Upsilon(3S) \to \pi^+\pi^- h_b(1P)$ and study of dipion transitions **arXiv:1105.4234**

  ✓ Study of radiative bottomonium transitions using converted $\gamma$ **arXiv:1104.5254**

- Recent charmonium(-like) results:

  ✓ Evidence for the decay $X(3872) \to J/\psi\omega$ **PRD 82, 011101 (2010) [arXiv:1005.5190]**

  ✓ Observation of $\eta_c(1,2S) \to K^+K^-\pi^+\pi^-\pi^0$ in $2\gamma$ interactions **PRD 84, 012004 (2011) [arXiv:1103.3971]**

# BABAR data samples

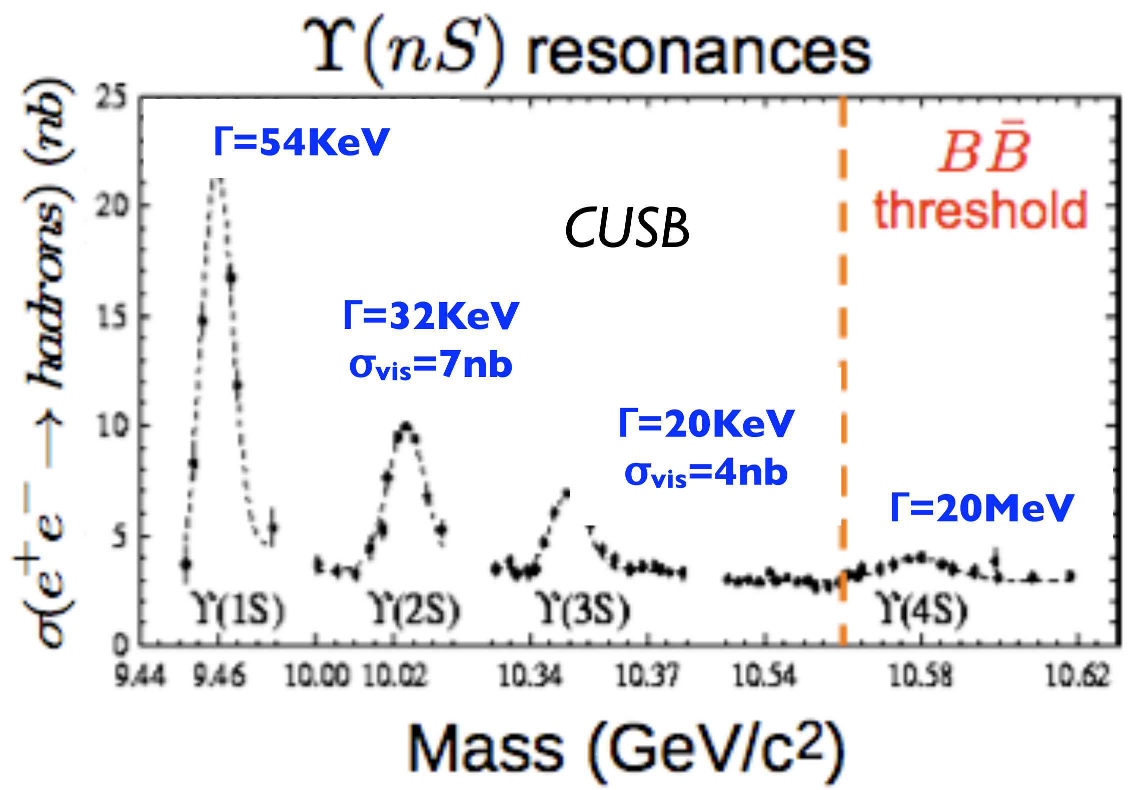
- ✓ PEP-II asymmetric energy $e^+e^-$-collider operating at the Υ resonances
- ✓ BABAR recorded luminosity

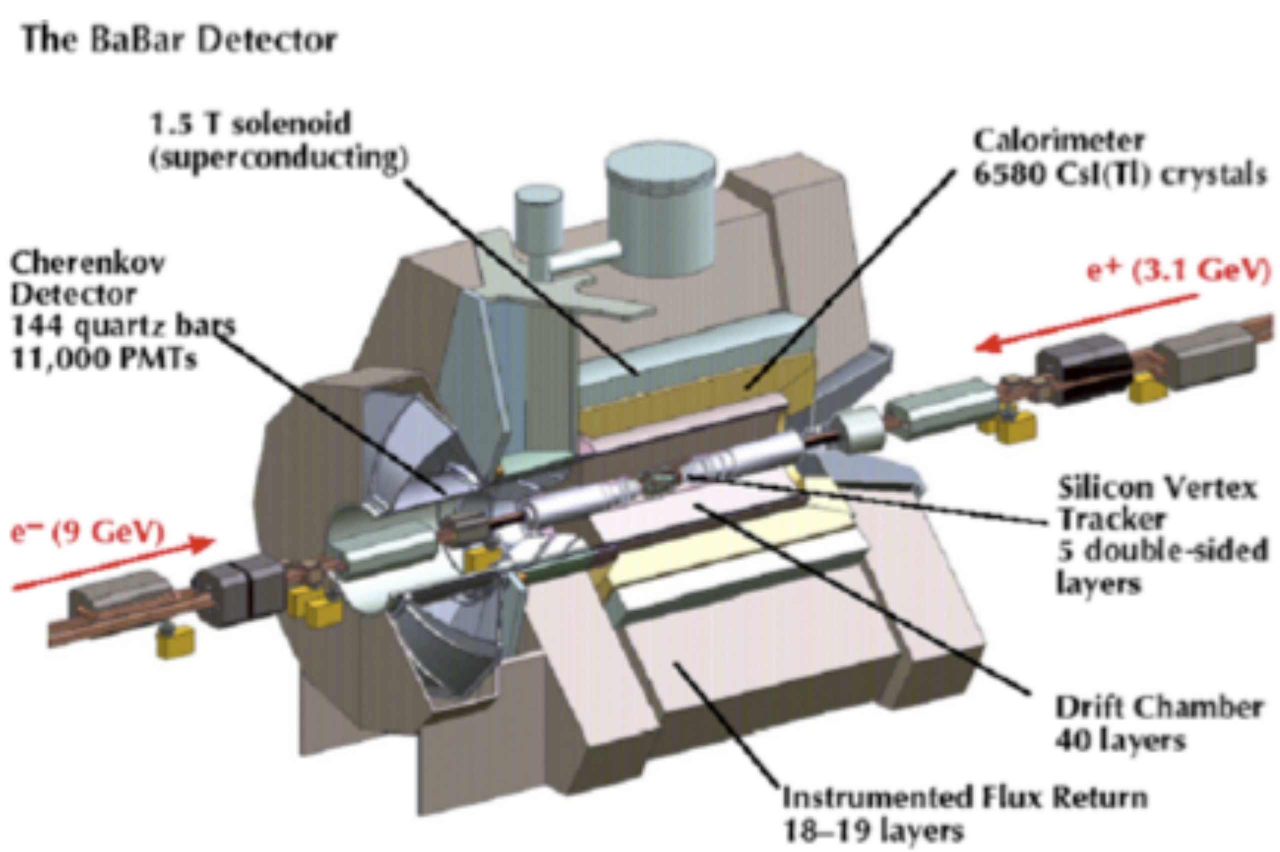
✓ 425.6 $fb^{-1}$ of data at Υ(4S) → **~467·10⁶ $B\bar{B}$ pairs**

✓ 28.0 $fb^{-1}$ of data at Υ(3S) → **~122·10⁶ Υ(3S)**

✓ 13.6 $fb^{-1}$ of data at Υ(2S) → **~99·10⁶ Υ(2S)**

✓ 3.9 $fb^{-1}$ scan above Υ(4S)



# Bottomonium Physics

# Search for $h_b(1P)$ in $\Upsilon(3S)$ decays

✓After the 30-years long $\eta_b(1S)$ hunting...

**PRL 101, 071801 (2008)**

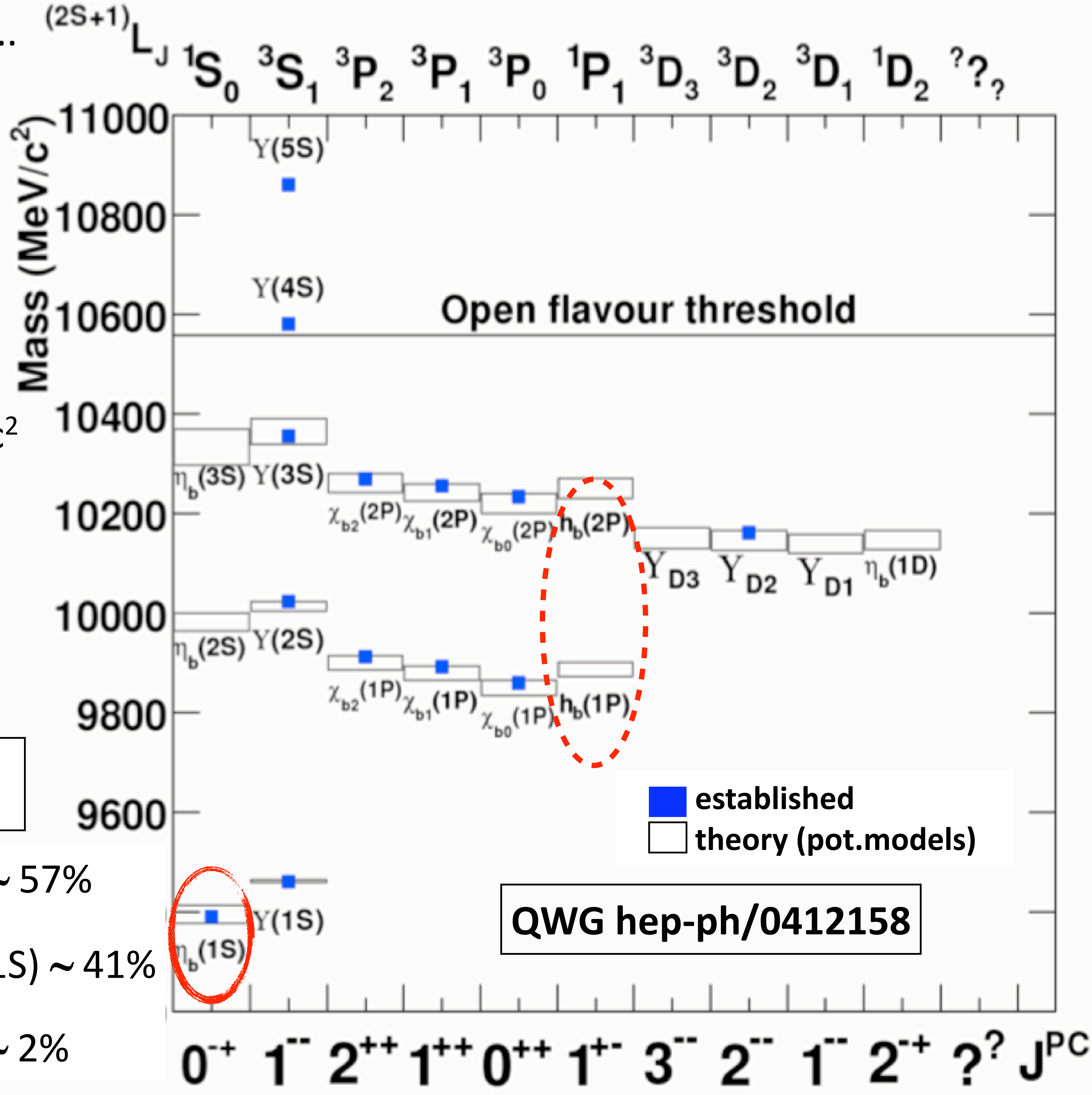
✓...search for $h_b(1P)$ state:

- ✓ to understand hyperfine mass splitting for P-wave states
- ✓ expected mass = spin-weighted C.O.G. of $\chi_{bJ}(1P)$ system ~ 9900 MeV/$c^2$
- ✓ expected production:
  - $\Upsilon(3S)\to\pi^0 h_b(1P) \sim 10^{-3}$
  - $\Upsilon(3S)\to\pi^+\pi^- h_b(1P) \sim 10^{-2}$-$10^{-3}$

**Voloshin, Sov.J.Nucl.Phys. 43,1011 (1986)**
**Kuang et al. PRD 37,1210 (1988)**

✓ expected decay modes:
- $h_b(1P)\to ggg \sim 57\%$
- $h_b(1P)\to\gamma\eta_b(1S) \sim 41\%$
- $h_b(1P)\to\gamma gg \sim 2\%$

**Godfrey & Rosner**
**PRD 66,014012 (2002)**



# $\Upsilon(3S) \to \pi^0 h_b(1P)$

**sub.PRD-RC**
**arXiv:1102.4565**

✓ $h_b(1P) \to \gamma\eta_b(1S)$: events with a $\pi^0$ and a photon consistent with this decay (energy range well defined by the precision measurement of the $\eta_b$ mass)

✓ Signal extraction:

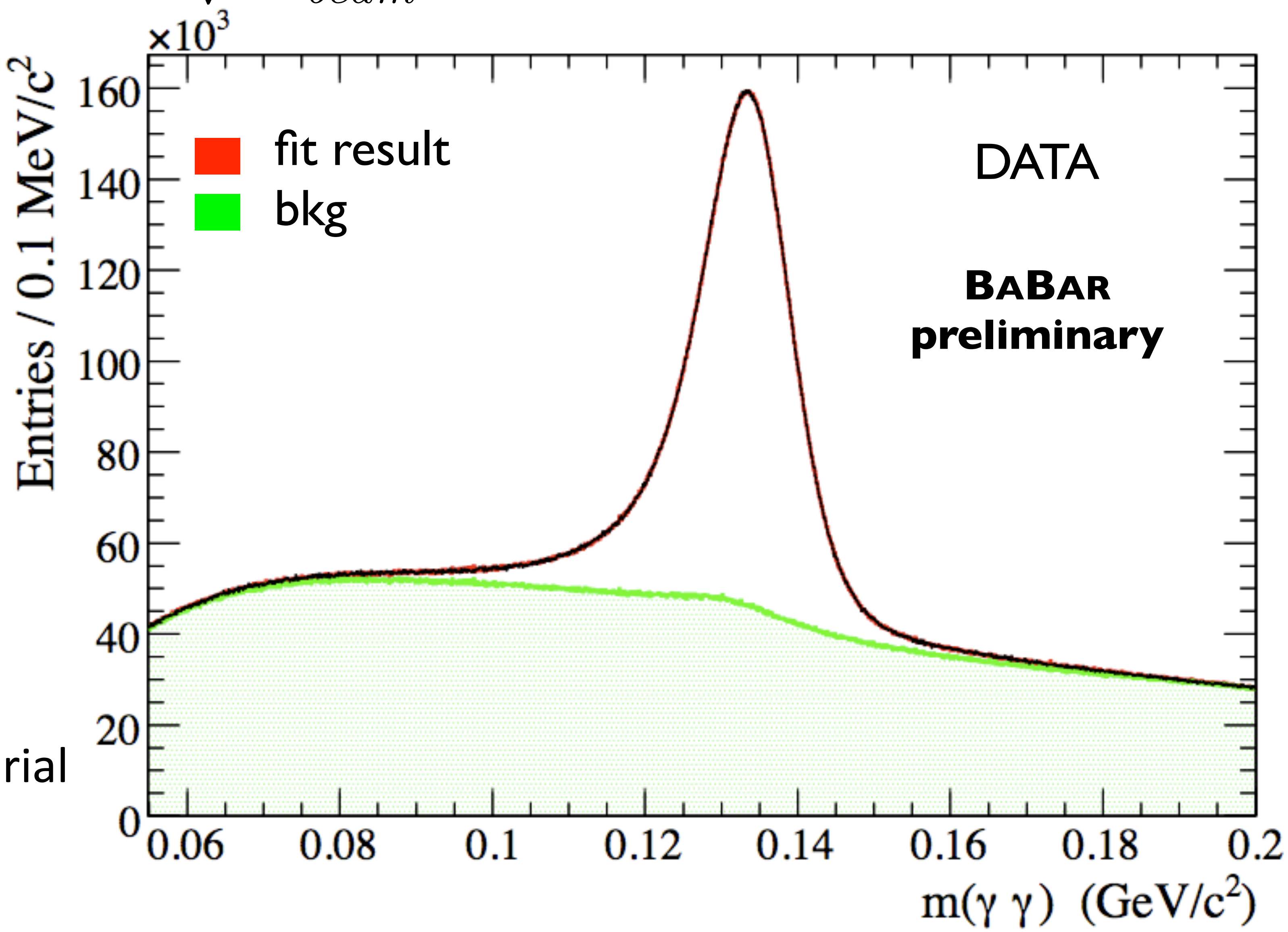
- consider the recoil mass distribution against the $\pi^0$

$$m_{recoil}(\pi^0) = \sqrt{(E^*_{beam} - E^*(\pi^0))^2 - p^*(\pi^0)^2}$$

- fit to two-photons invariant mass in bins of $m_{recoil}(\pi^0)$ -> determine the number of $\pi^0$ in each bin

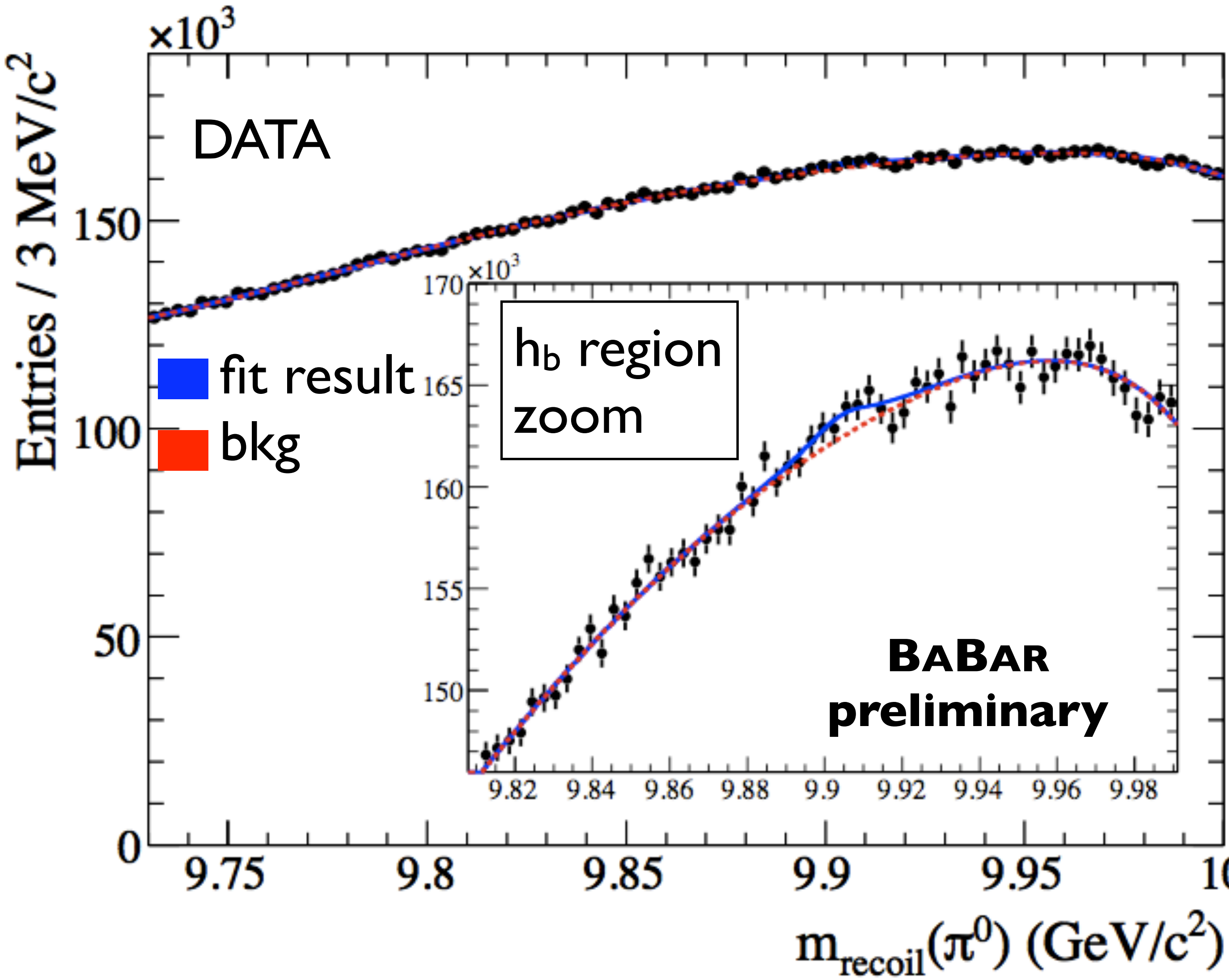
- distribution of the number of events recoiling against $\pi^0$ as a function of $m_{recoil}$

✓ Bkg: small peak at $\pi^0$ mass (interactions in the detector material $n\pi^+ \to p\pi^0$, $p\pi^- \to n\pi^0$)



✓ Fit to $m_{recoil}(\pi^0)$ distribution on data:

sub.PRD-RC
arXiv:1102.4565

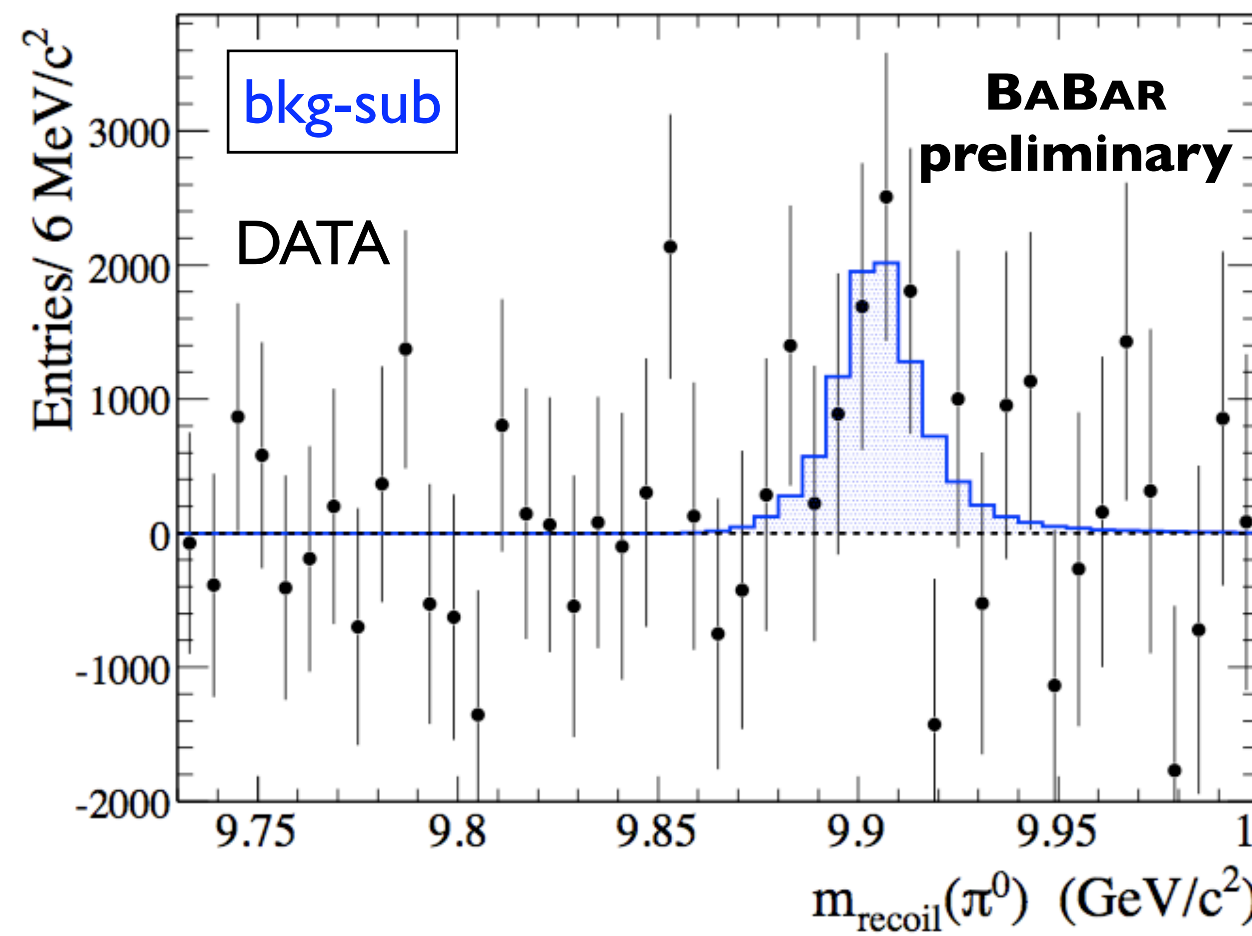



✓ After bkg subtraction: **9145 ± 2804 events**

**$m(h_b)=9902 \pm 4_{(stat)} \pm 1_{(syst)}$ MeV/$c^2$**

**$B(\Upsilon(3S)\to\pi^0 h_b)\times B(h_b\to\gamma\eta_b)=(3.7\pm1.1\pm0.7)\times10^{-4}$**

Previous UL: $B(\Upsilon(3S)\to\pi^0 h_b)<2.7\times10^{-3}$ **PRD 49,40(1994)**




✓ Statistical significance 3.2σ

-> **3.0σ** when including systematic uncertainties

✓ Main systematics from: bkg and signal descriptions

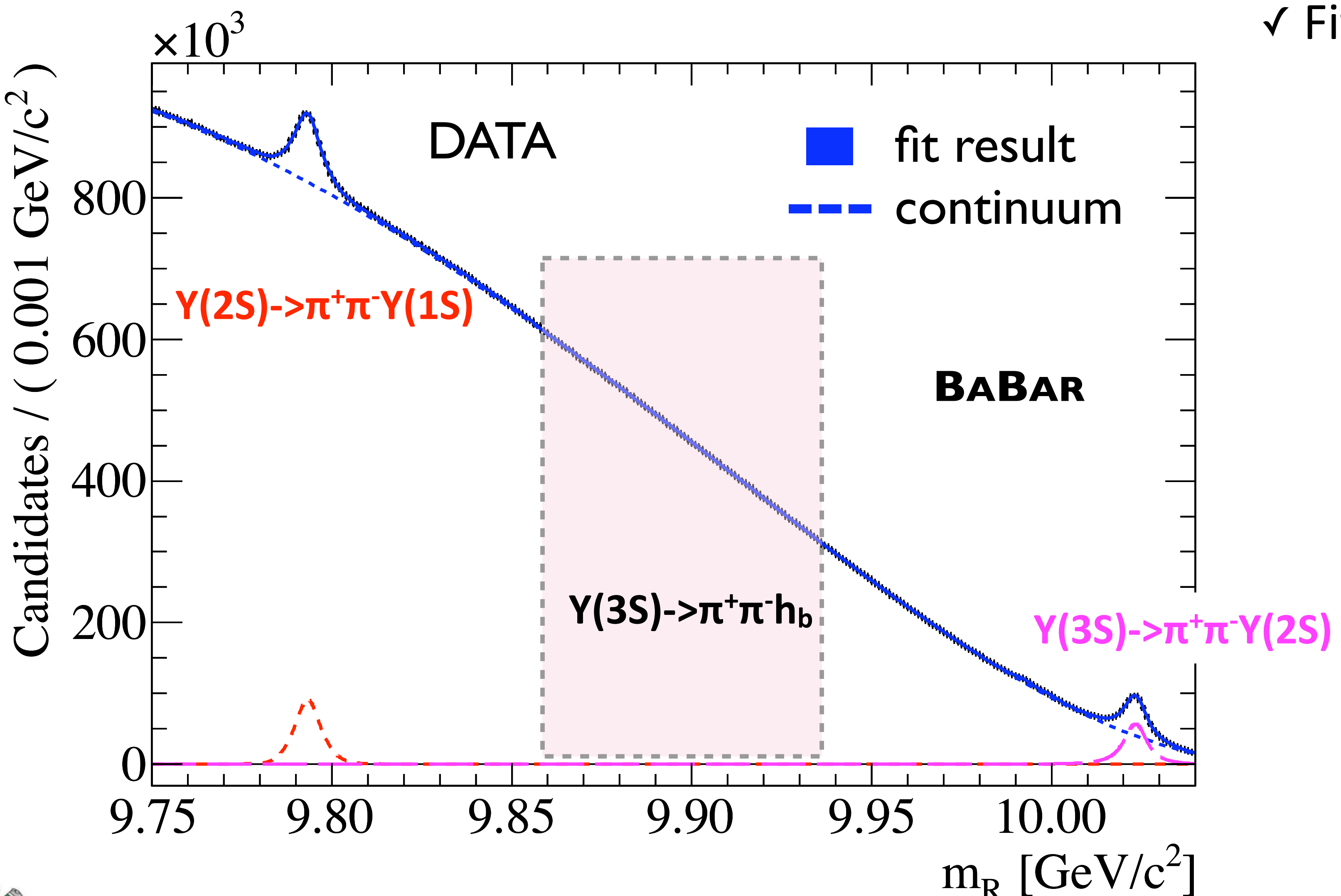
# Search for $h_b(1P)$ in $\Upsilon(3S) \to \pi^+\pi^- X$

**accepted PRD-RC**
**arXiv:1105.4234**

✓ Fit to the recoil mass against the dipion system:

$$m_R = \sqrt{(m(\Upsilon(3S)) - E^*(\pi^+\pi^-))^2 - p^*(\pi^+\pi^-)^2}$$

✓ $h_b$ signal expected as a peak on top of a smooth non-peaking bkg (continuum events, and $K_S^0 \to \pi^+\pi^-$) and bottomonium decays

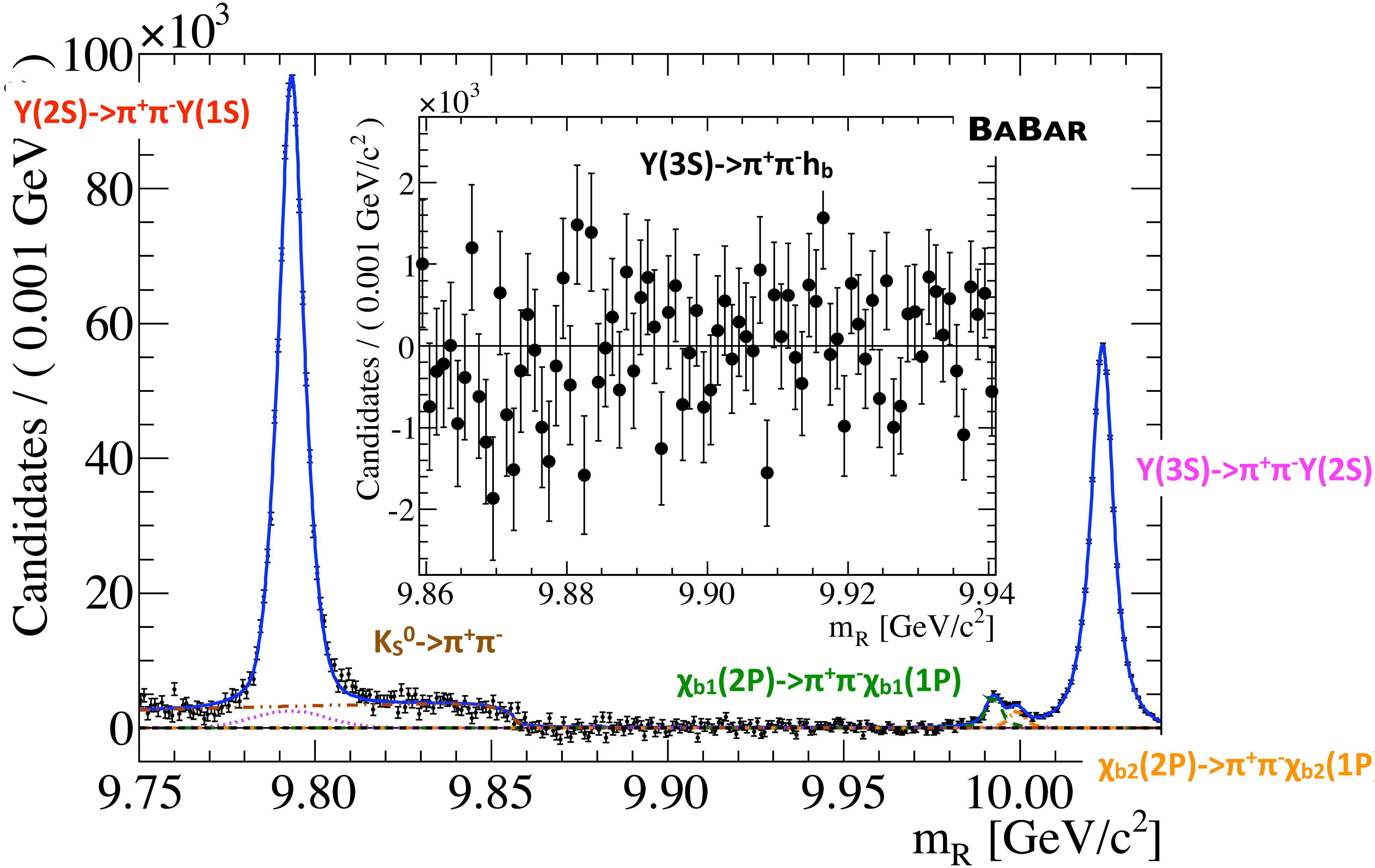



✓ Fit components:

- signal ($\Upsilon(3S) \to \pi^+\pi^- h_b(1P)$)
- dipion transitions
  - $\Upsilon(3S) \to \pi^+\pi^- \Upsilon(2S)$
  - $\Upsilon(2S) \to \pi^+\pi^- \Upsilon(1S)$ (with $\Upsilon(2S)$ produced through $\Upsilon(3S) \to \Upsilon(2S)X$ and ISR)
- $\chi_{bJ}(2P) \to \pi^+\pi^- \chi_{bJ}(1P)$
- bkgs (continuum, $K_S^0$ decays)

accepted PRD-RC
arXiv:1105.4234

✓ After non-peaking bkg subtraction:




✓ No evidence for $h_b$ -> 90% CL UL on the branching fraction **$B(\Upsilon(3S)\to\pi^+\pi^- h_b(1P))<1.2\times10^{-4}$**

Previous UL: $B(\Upsilon(3S)\to\pi^+\pi^- h_b)<1.8\times10^{-3}$ **PRD 43,1448(1991)**

# Precision measurements of dipion transitions

- $B(\Upsilon(3S)\to\pi^+\pi^-\Upsilon(2S)) = (3.00 \pm 0.02_{(stat)} \pm 0.14_{(syst)})\%$
- $B(\Upsilon(3S)\to X\Upsilon(2S)) \times B(\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S))=(1.16 \pm 0.07_{(stat)} \pm 0.12_{(syst)}) \times 10^{-4}$

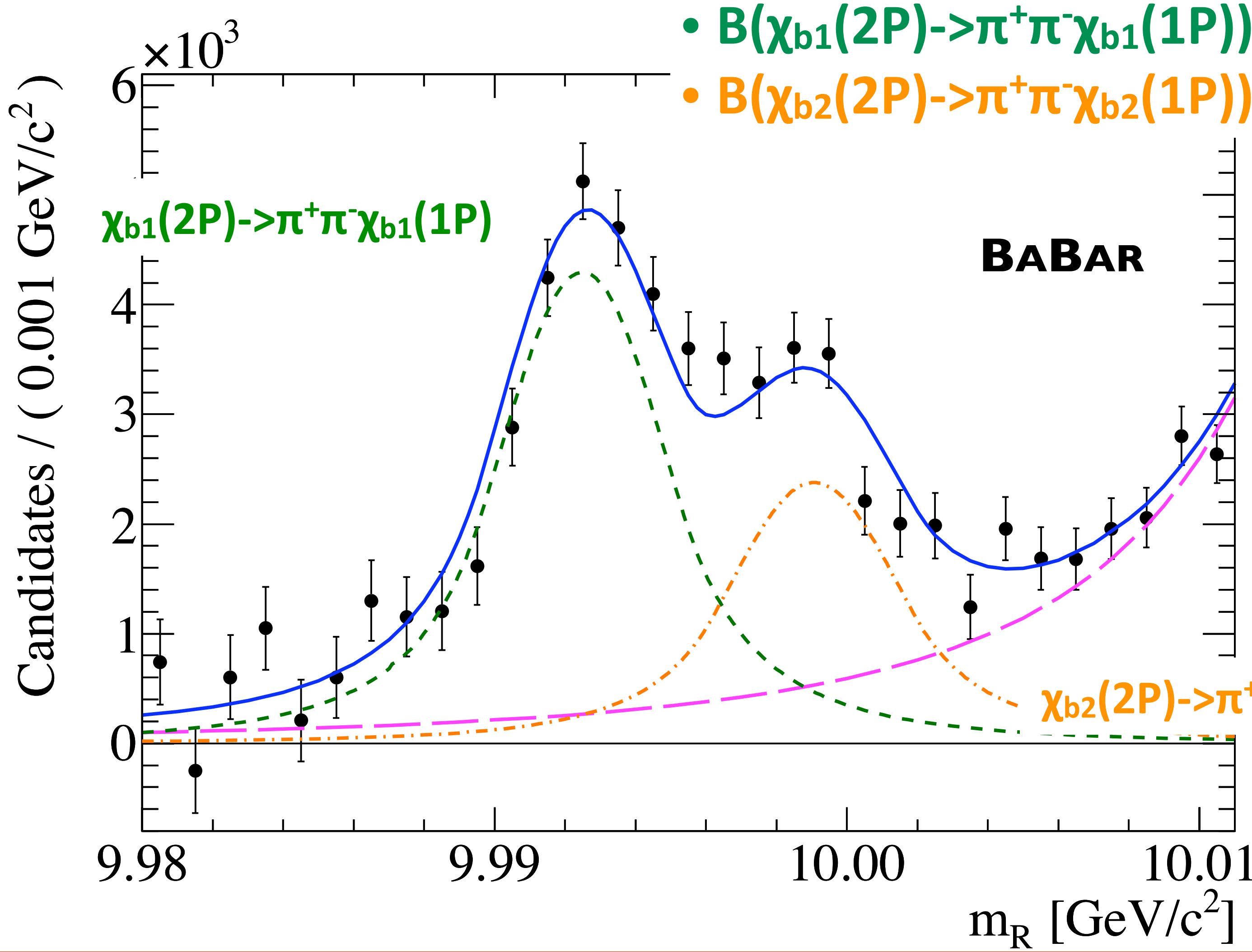
**accepted PRD-RC**
**arXiv:1105.4234**

- $M(\Upsilon(3S))-M(\Upsilon(2S)) = 331.50 \pm 0.02_{(stat)} \pm 0.13_{(syst)}$ MeV/$c^2$

✓ In particular for the first time the dipion transitions between $\chi_{b1,2}(2P)$ and $\chi_{b1,2}(1P)$ separated

- $B(\Upsilon(3S)\to X\chi_{b1}(2P)) \times B(\chi_{b1}(2P)\to\pi^+\pi^-\chi_{b1}(1P))=(1.16 \pm 0.07_{(stat)} \pm 0.12_{(syst)}) \times 10^{-4}$
- $B(\Upsilon(3S)\to X\chi_{b2}(2P)) \times B(\chi_{b2}(2P)\to\pi^+\pi^-\chi_{b2}(1P))=(0.64 \pm 0.05_{(stat)} \pm 0.08_{(syst)}) \times 10^{-3}$

- $B(\chi_{b1}(2P)\to\pi^+\pi^-\chi_{b1}(1P))=(9.2 \pm 0.6 \pm 0.9) \times 10^{-3}$
- $B(\chi_{b2}(2P)\to\pi^+\pi^-\chi_{b2}(1P))=(4.9 \pm 0.4 \pm 0.6) \times 10^{-3}$




Consistent with previous measurement (not resolved)

**PRD 73,012003(2006)**

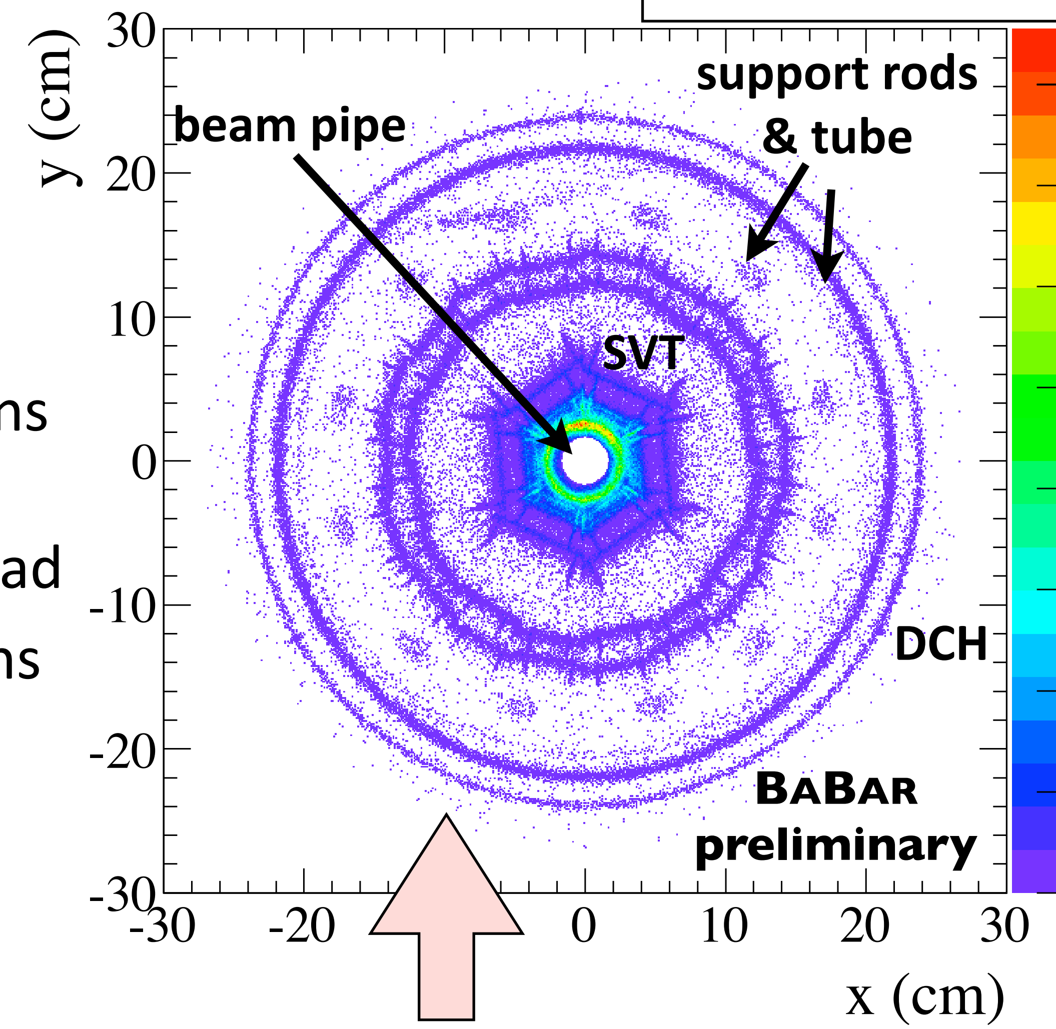
# Radiative transitions with converted γ

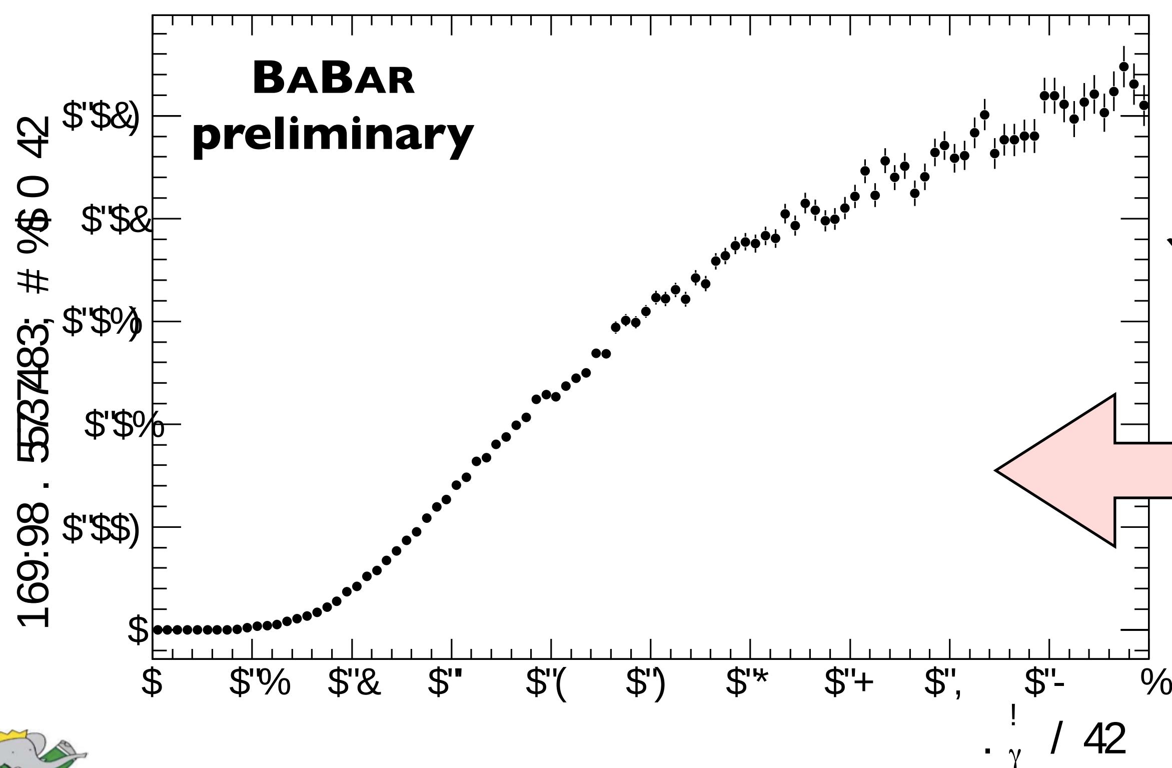
**sub. PRD**
**arXiv:1104.5254**

✓ Radiative transitions between bottomonia well described by <u>effective potential models</u> (non-relativistic limit)

✓ Cases of suppressed E1 [i.e. $\Upsilon(3S) \to \gamma\chi_{bJ}(1P)$] and "hindered" M1 [i.e. $\Upsilon(3,2S) \to \gamma\eta_b(1S)$] dipole transitions

✓ Doppler broadening and detector resolution may lead to unresolved photon energies for different transitions
-> aim: separate the individual contributions




✓ Use of converted photons ($\gamma \to e^+e^-$ in the detector material):

✓ allows a greatly improved resolution (25->5 MeV)

✓ decreases efficiencies (ranging in 0.1-2.5%)

$E^*_\gamma$ = photon energy calculated in the CM frame

# $E^*_\gamma$ spectrum regions

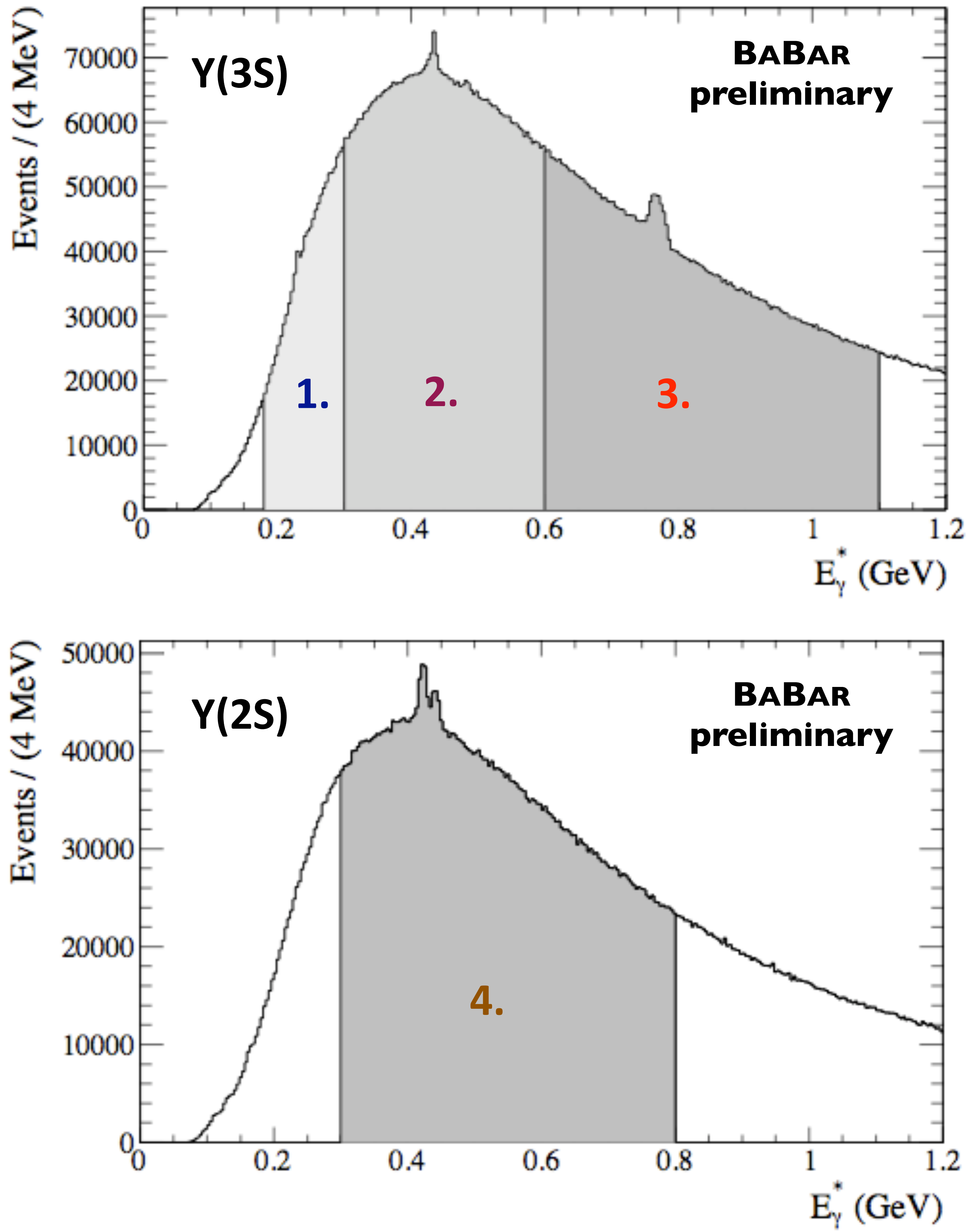
**sub. PRD**
**arXiv:1104.5254**

✓ Converted photons are reconstructed as pairs of tracks, selected with:

- ✓ a $\chi^2$ fit identifying secondary vertices;
- ✓ cuts on $m(e^+e^-)$, $\rho_\gamma$, $|\cos\theta_{thrust}|$, $N_{tracks}$, $\pi^0$-veto

✓ Fit to the $E^*_\gamma$ spectrum in 4 different regions:

1. **Υ(3S): $180 < E^*_\gamma < 300$ MeV**
2. **Υ(3S): $300 < E^*_\gamma < 600$ MeV**
3. **Υ(3S): $600 < E^*_\gamma < 1100$ MeV**
4. **Υ(2S): $300 < E^*_\gamma < 800$ MeV**



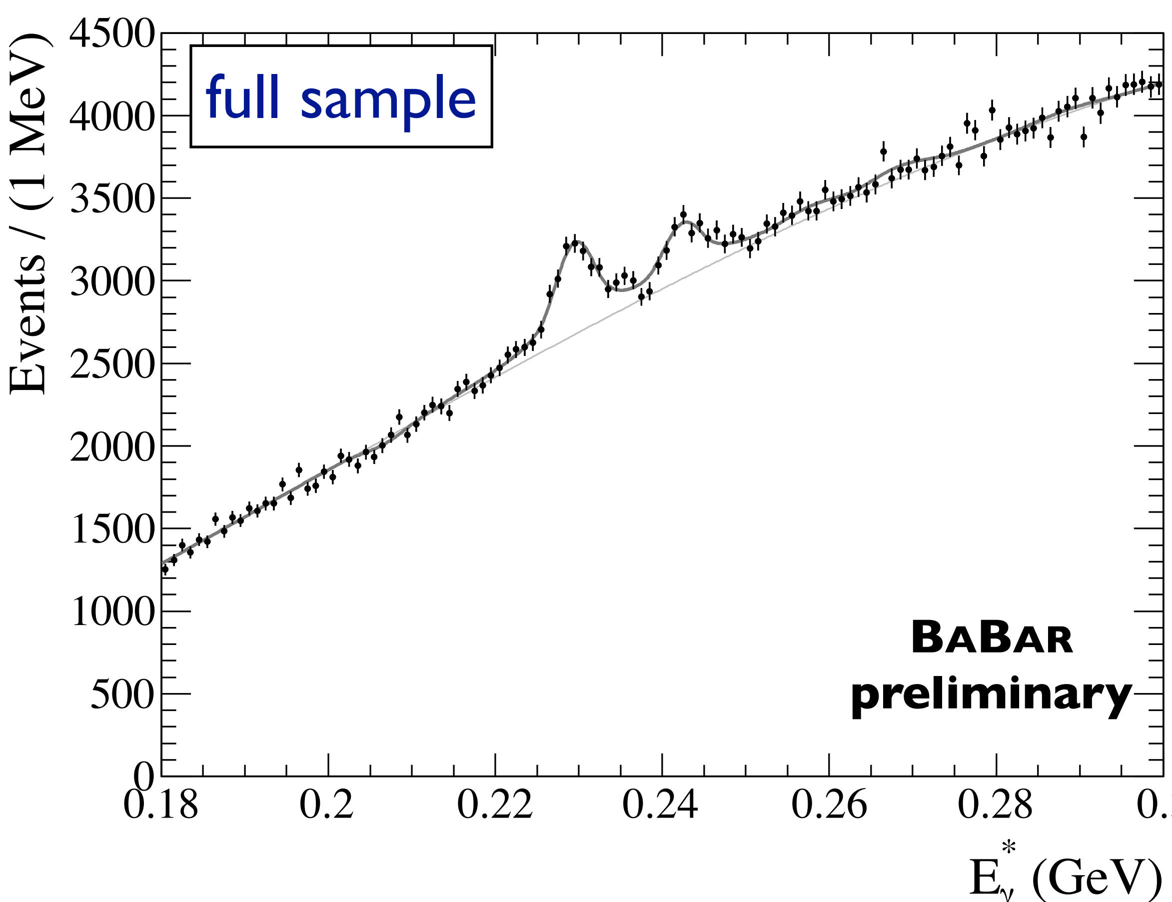
# 1. Υ(3S): $180<E^{*}_{\gamma}<300$ MeV

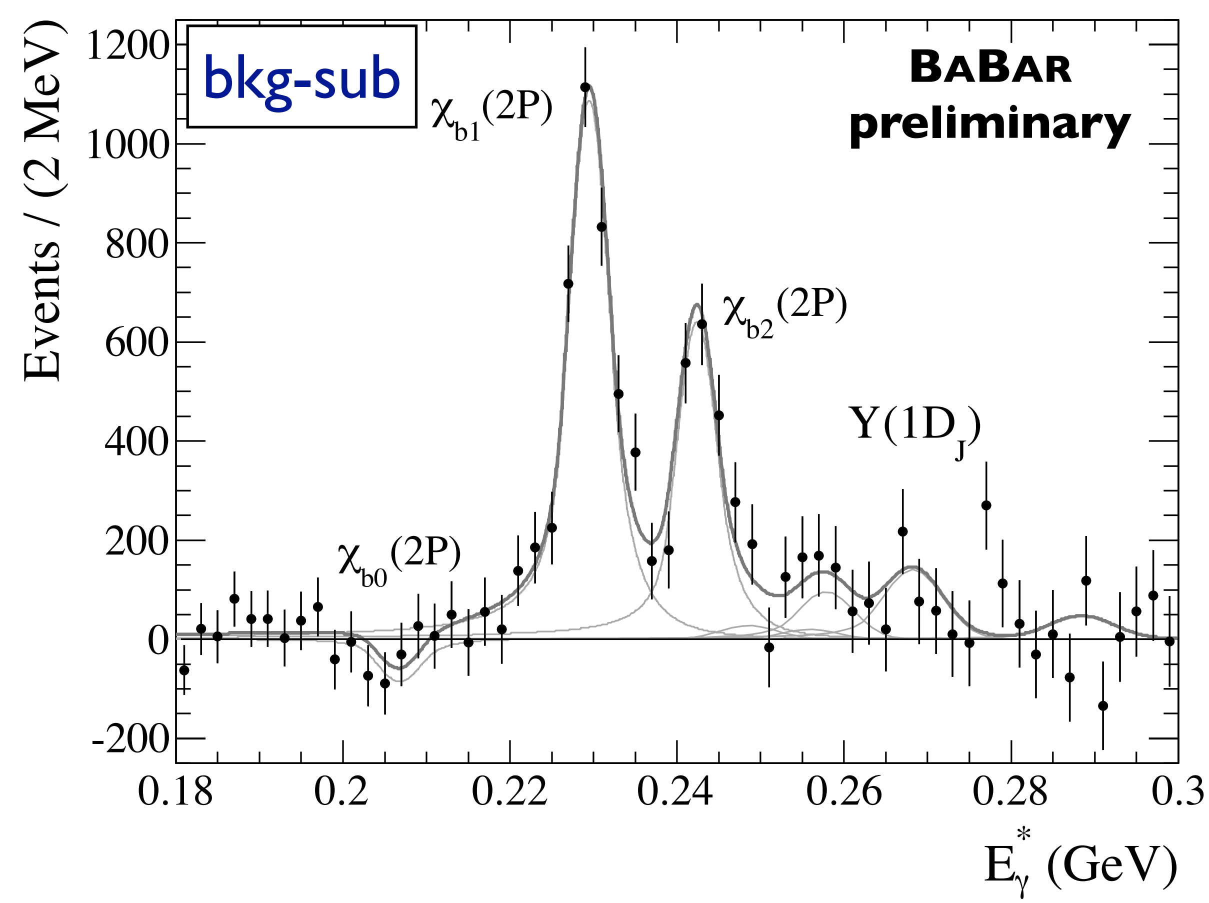
**sub. PRD arXiv:1104.5254**

✓ Transitions of interest: **$\chi_{bJ}(2P)\to\gamma\Upsilon(2S)$** (and potentially sensitive to **$\Upsilon(1D_J)\to\gamma\chi_{bJ}(2P)$**)

✓ Most precise measurement of $B(\chi_{b1,2}(2P)\to\gamma\Upsilon(2S))$

| Transition | $E^*_\gamma$ (MeV) | Yield | $\epsilon$ (%) | Derived Branching Fraction (%) BABAR | CUSB | CLEO |
|---|---|---|---|---|---|---|
| $\chi_{b0}(2P)\to\gamma\Upsilon(2S)$ | 205.0 | $-347\pm209$ | 0.105 | $-4.9\pm2.9^{+0.7}_{-0.8}\pm0.5\ (<2.9)$ | $3.6\pm1.6$ | $<5.2$ |
| $\chi_{b1}(2P)\to\gamma\Upsilon(2S)$ | 229.7 | $4294\pm251$ | 0.152 | $19.5\pm1.1^{+1.1}_{-1.0}\pm1.9$ | $13.6\pm2.4$ | $21.1\pm4.5$ |
| $\chi_{b2}(2P)\to\gamma\Upsilon(2S)$ | 242.3 | $2462\pm243$ | 0.190 | $8.6^{+0.9}_{-0.8}\pm0.5\pm1.1$ | $10.9\pm2.2$ | $9.9\pm2.7$ |



# 2. Υ(3S): 300<$E^*_\gamma$<600 MeV

**sub. PRD arXiv:1104.5254**

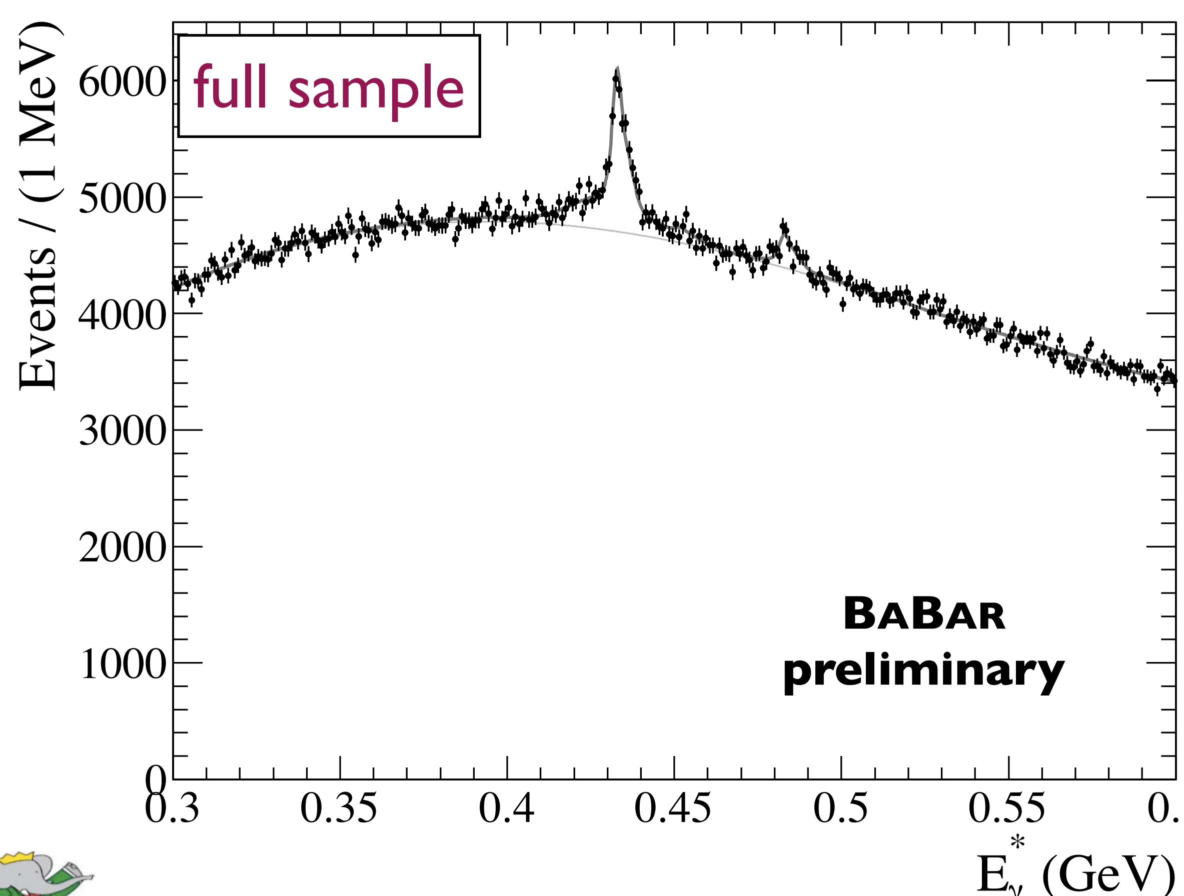
✓ Complicated region of the spectrum!

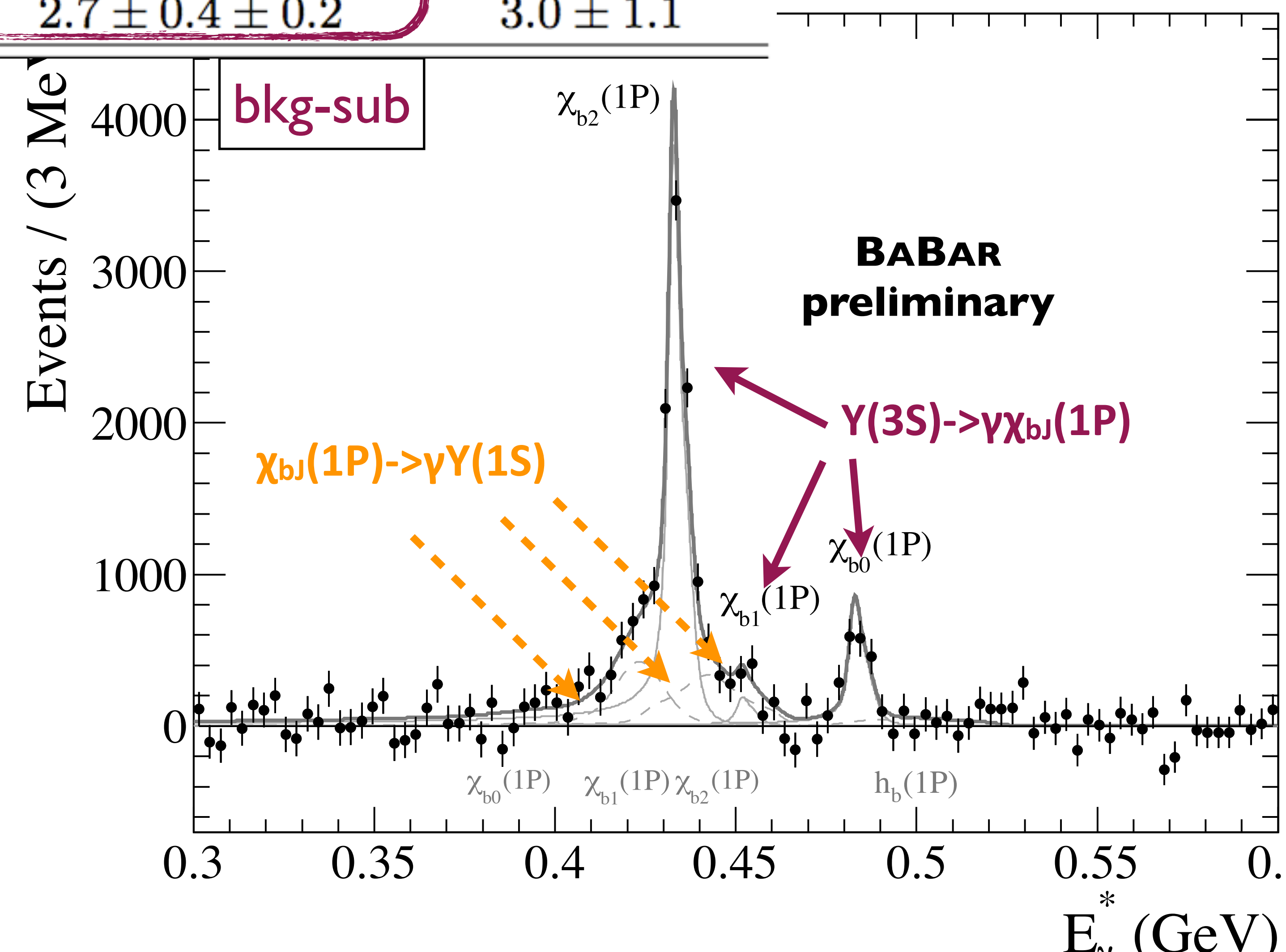
✓ Transitions of interest: **Υ(3S)->γ$\chi_{bJ}$(1P)** with overlapping Doppler-broadened paths to $\chi_{bJ}$(1P) and feed-down from **$\chi_{bJ}$(1P)->γΥ(1S)** and **Υ(3S)->γ$\eta_b$(2S)**

✓ Clear observations of B(Υ(3S)->γ$\chi_{b0,2}$(1P))

✓ No evidence for $\eta_b$(2S)

| Transition | $E^*_\gamma$ (MeV) | Yield | $\epsilon$ (%) | Derived Branching Fraction ($\times 10^{-3}$) *BABAR* | CLEO |
|---|---|---|---|---|---|
| $\Upsilon(3S) \to \gamma\chi_{b2}(1P)$ | 433.1 | $9699 \pm 318$ | 0.794 | $10.6 \pm 0.3 \pm 0.6$ | $7.7 \pm 1.3$ |
| $\Upsilon(3S) \to \gamma\chi_{b1}(1P)$ | 452.2 | $483 \pm 315$ | 0.818 | $0.5 \pm 0.3^{+0.2}_{-0.1}$ (< 1.1) | $1.6 \pm 0.5$ |
| $\Upsilon(3S) \to \gamma\chi_{b0}(1P)$ | 483.5 | $2273 \pm 307$ | 0.730 | $2.7 \pm 0.4 \pm 0.2$ | $3.0 \pm 1.1$ |



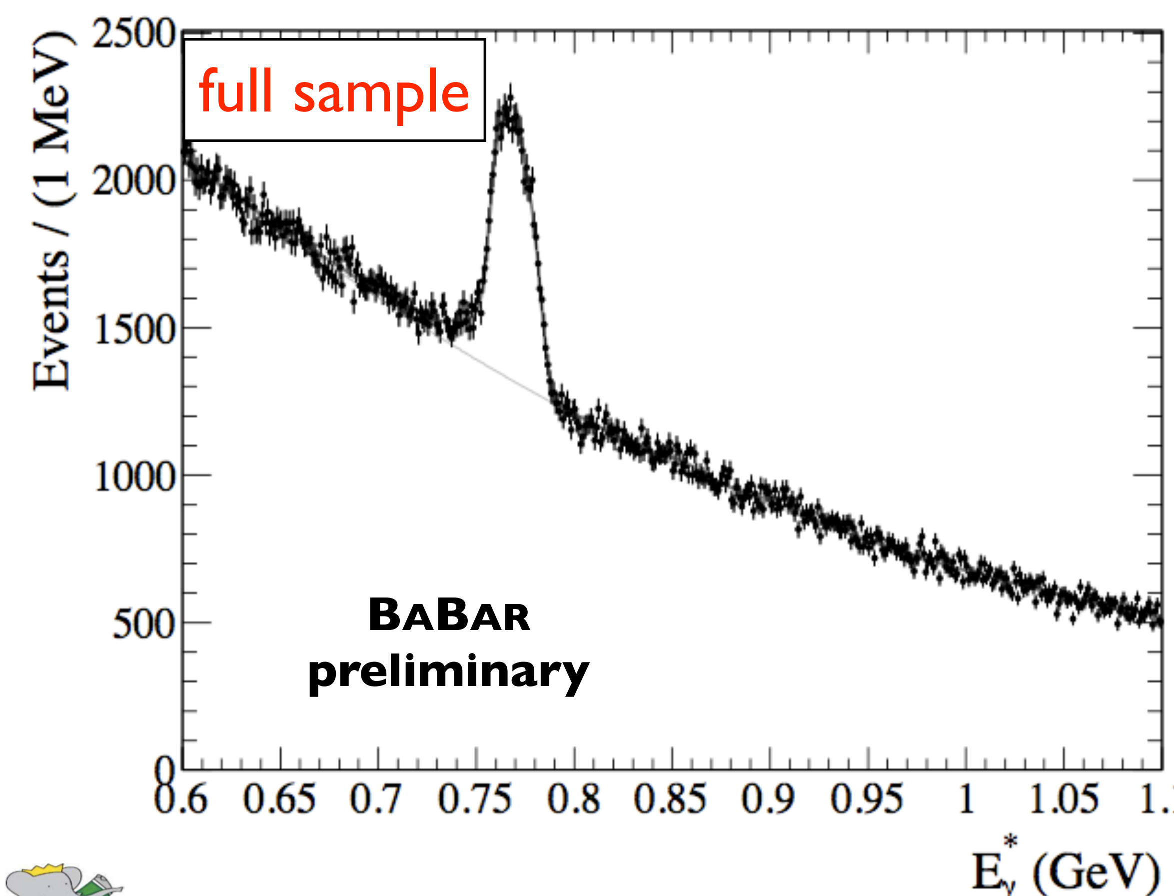



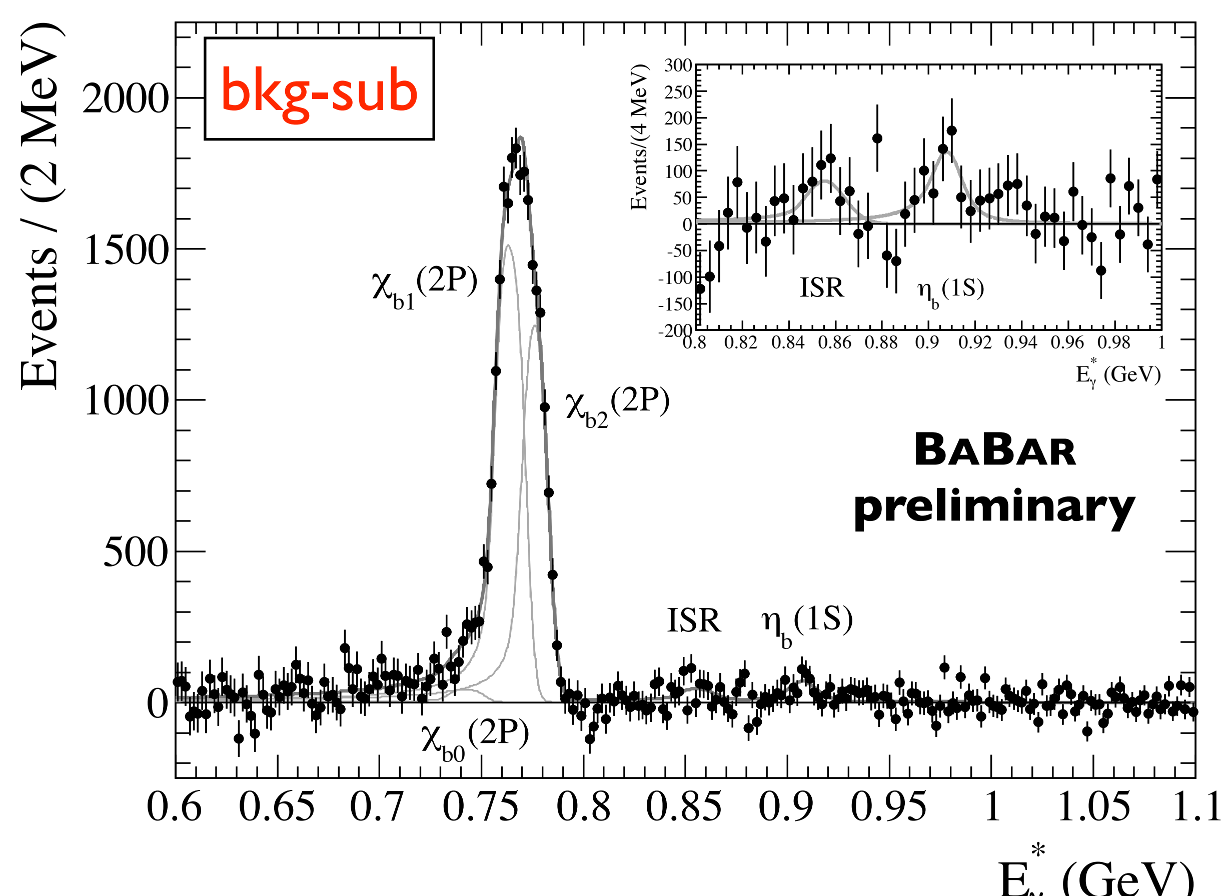
# 3. Υ(3S): 600<$E^*_\gamma$<1100 MeV

sub. PRD
arXiv:1104.5254

- ✓ Transitions of interest: $\chi_{bJ}(2P)\to\gamma\Upsilon(1S)$ and $\Upsilon(3S)\to\gamma\eta_b(1S)$
- ✓ Most precise measurements of $B(\chi_{b1,2}(2P)\to\gamma\Upsilon(1S))$
- ✓ Statistics insufficient for a conclusive $\eta_b(1S)$ study (2.7σ significance w/ systematics)

| Transition | $E^*_\gamma$ (MeV) | Yield | $\epsilon$ (%) | Derived Branching Fraction (%) BABAR | CUSB | CLEO |
|---|---|---|---|---|---|---|
| $\chi_{b0}(2P)\to\gamma\Upsilon(1S)$ | 742.7 | $469^{+260}_{-259}$ | 1.025 | $0.7\pm0.4^{+0.2}_{-0.1}\pm0.1\ (<1.2)$ | $<1.9$ | $<2.2$ |
| $\chi_{b1}(2P)\to\gamma\Upsilon(1S)$ | 764.1 | $14965^{+381}_{-383}$ | 1.039 | $9.9\pm0.3\pm0.4\pm0.9$ | $7.5\pm1.3$ | $10.4\pm2.4$ |
| $\chi_{b2}(2P)\to\gamma\Upsilon(1S)$ | 776.4 | $11283^{+384}_{-385}$ | 1.056 | $7.1\pm0.2\pm0.3\pm0.9$ | $6.1\pm1.2$ | $7.7\pm2.0$ |
| $\Upsilon(3S)\to\gamma\eta_b(1S)$ | $907.9\pm2.8\pm0.9$ | $933^{+263}_{-262}$ | 1.388 | $0.059\pm0.016^{+0.014}_{-0.016}$ | - | - |



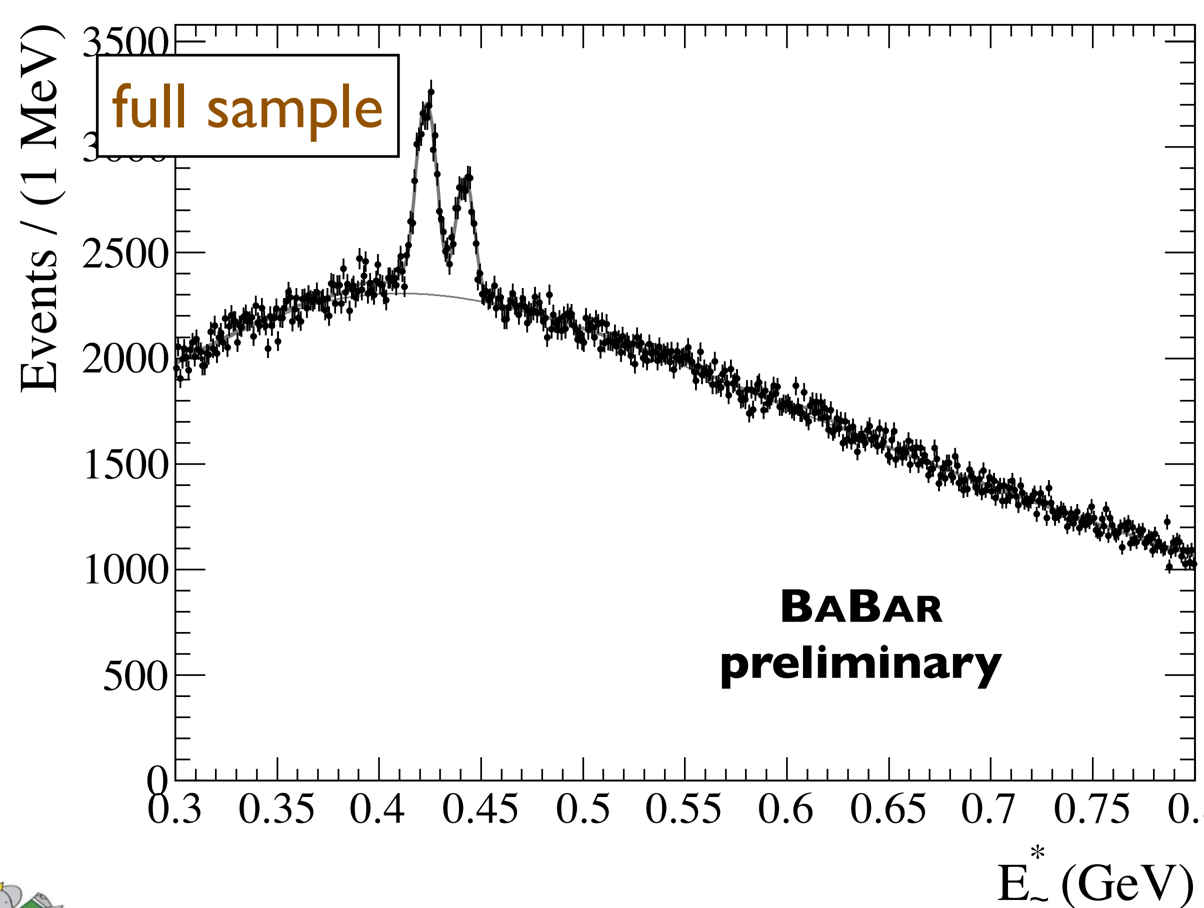



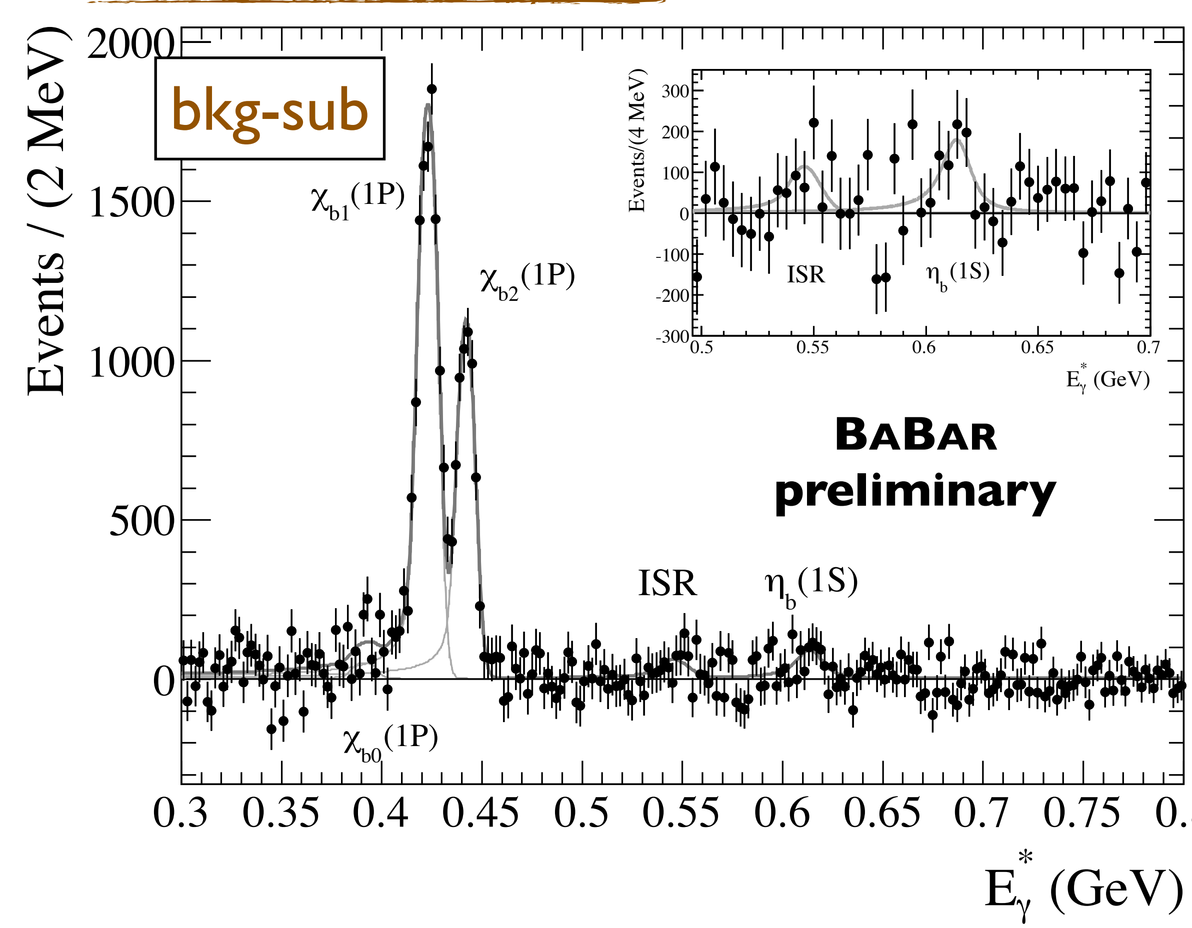
# 4. Υ(2S): 300<$E^*_\gamma$<800 MeV

**sub. PRD arXiv:1104.5254**

- ✓ Transitions of interest: **$\chi_{bJ}$(1P)->γΥ(1S)** and **Υ(2S)->γ$\eta_b$(1S)**
- ✓ Most precise measurement of B($\chi_{b1,2}$(1P)->γΥ(1S)), no evidence for $\chi_{b0}$(1P)->γΥ(1S)
- ✓ Statistics insufficient for a conclusive $\eta_b$(1S) study (1.7σ significance w/ systematics)

| Transition | $E^*_\gamma$ (MeV) | Yield | $\epsilon$ (%) | Derived Branching Fraction (%) *BABAR* | CB | CUSB | CLEO |
|---|---|---|---|---|---|---|---|
| $\chi_{b0}(1P) \to \gamma\Upsilon(1S)$ | 391.5 | $391 \pm 267$ | 0.496 | $2.3 \pm 1.5^{+1.0}_{-0.7} \pm 0.2$ ($< 4.6$) | $< 5$ | $< 12$ | $1.7 \pm 0.4$ |
| $\chi_{b1}(1P) \to \gamma\Upsilon(1S)$ | 423.0 | $12604 \pm 285$ | 0.548 | $36.2 \pm 0.8 \pm 1.7 \pm 2.1$ | $34 \pm 7$ | $40 \pm 10$ | $33.0 \pm 2.6$ |
| $\chi_{b2}(1P) \to \gamma\Upsilon(1S)$ | 442.0 | $7665^{+270}_{-272}$ | 0.576 | $20.2 \pm 0.7^{+1.0}_{-1.4} \pm 1.0$ | $25 \pm 6$ | $19 \pm 8$ | $18.5 \pm 1.4$ |
| $\Upsilon(2S) \to \gamma\eta_b(1S)$ | $613.7^{+3.0+0.7}_{-2.6-1.1}$ | $1109 \pm 348$ | 1.050 | $0.11 \pm 0.04^{+0.07}_{-0.05}$ ($< 0.22$) | - | - | - |



# Comparison with predictions

**sub. PRD**
**arXiv:1104.5254**

✓ General good agreement in B($\chi_{bJ}$(1,2P)->γϒ(1,2S)) between our results and predictions

**Kwong & Rosner PRD 38,279 (1988)**

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

✓ Limited compatibility between our results and theory about 3S->1P rates

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

# Charmonium(-like) States

# Charmonium spectrum

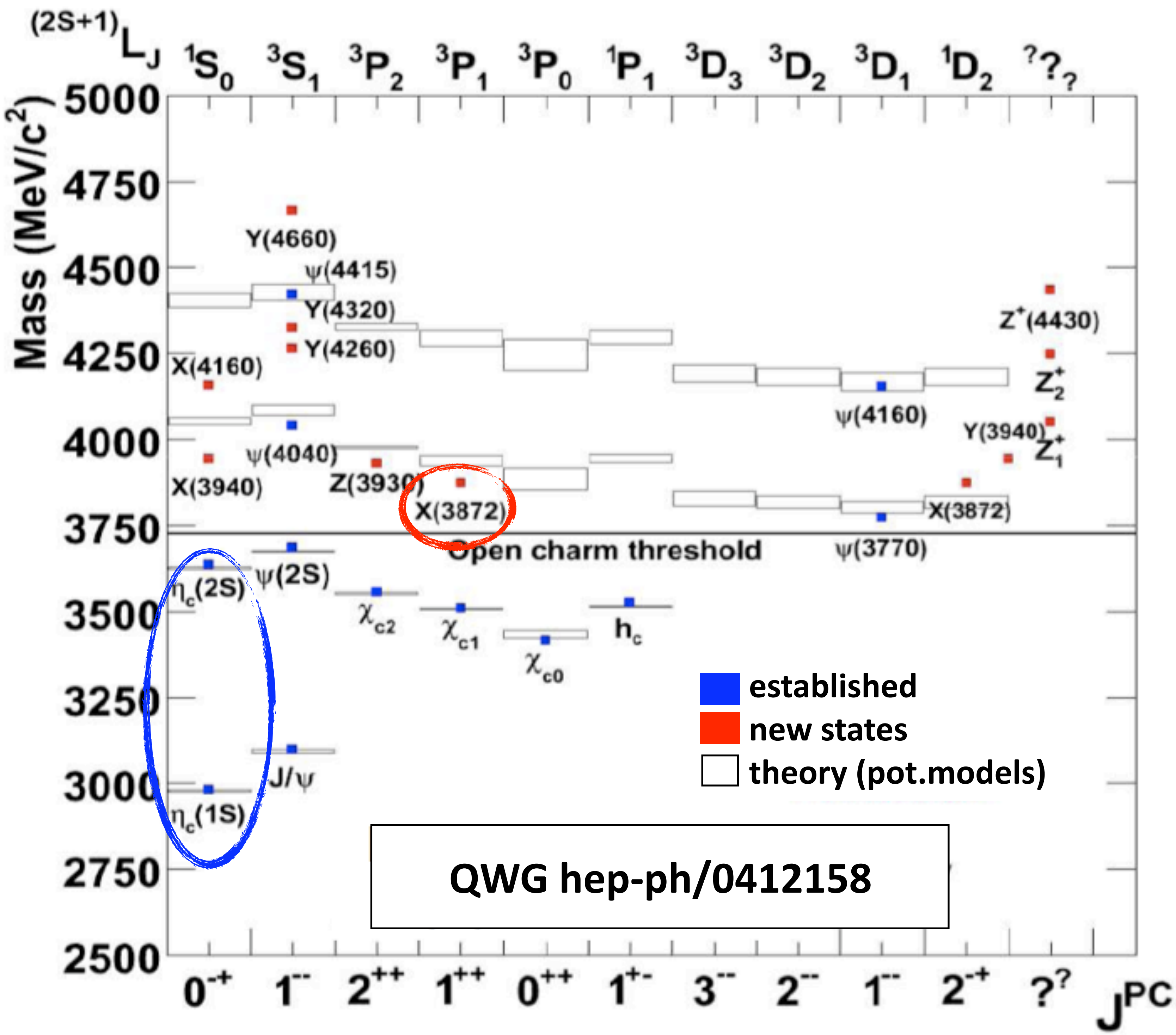
✓ Below the $D\bar{D}$ threshold established (and expected) states of charmonium spectrum and their measured decay properties in good agreement with theory

✓ A plethora of unexpected states above the $D\bar{D}$ threshold

✓ Genealogy started with **X(3872)** by Belle

**PRL 91,262001 (2003)**

✓ Dialogue with theory and experimental new discoveries not yet finished...



# Evidence for X(3872)->J/ψω

PRD 82, 011101 (2010)

✓ X(3872) observed primarily in $J/\psi\pi^+\pi^-$ PRL 91,262001 (2003) et al.

✓ Then, evidence for X(3872)->J/ψγ, establishing positive C parity PRL 102, 132001 (2009)

✓ Analyses of the $\pi^+\pi^-$ mass distribution and of the angular distribution -> $J^P=1^+$ or $2^-$

PRL 96, 102002 (2006)
PRL 98, 132002 (2007)

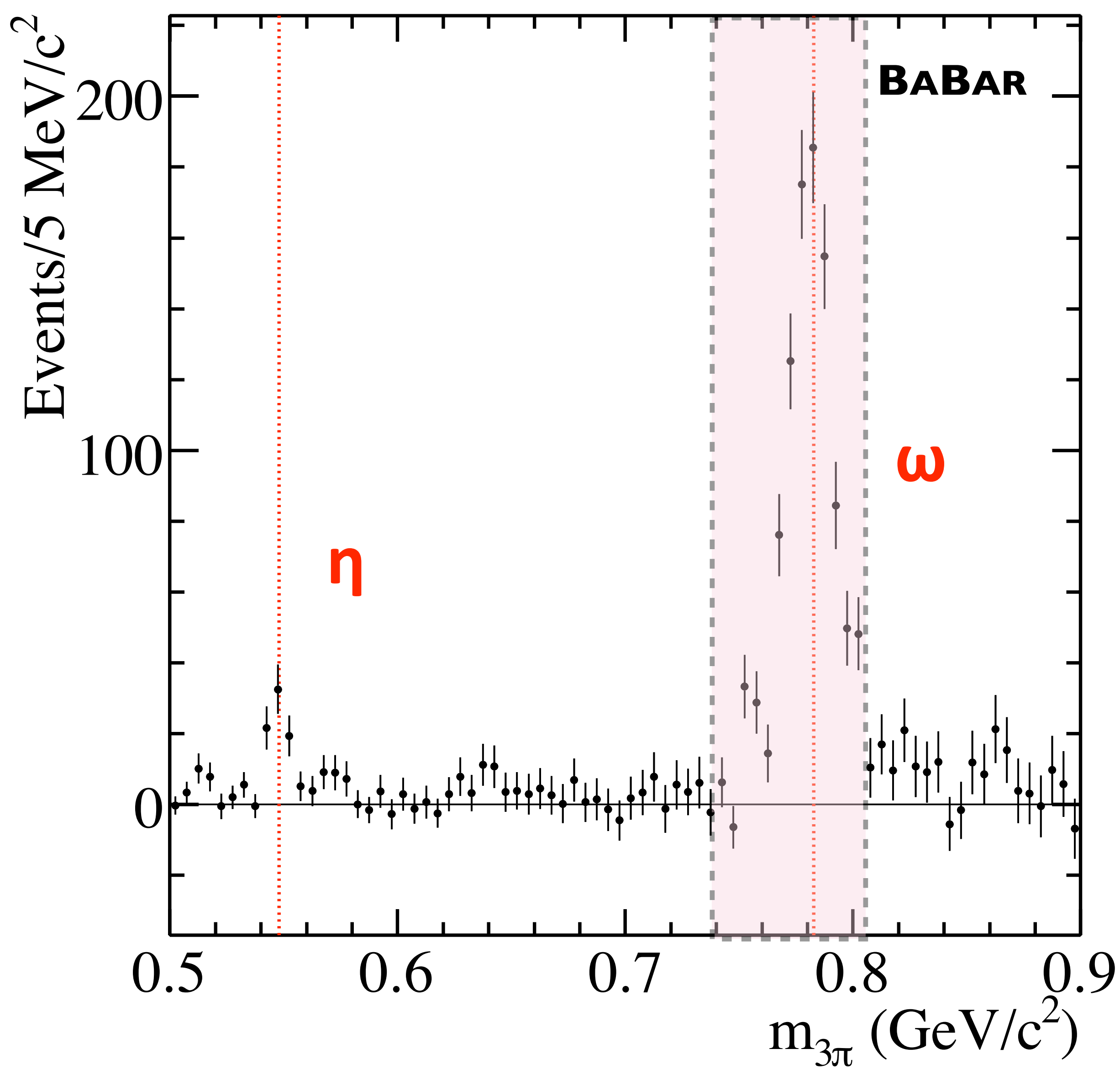
✓ **$B^{0,+}\to J/\psi\pi^+\pi^-\pi^0K^{0,+}$** selecting **$0.5<m_{3\pi}<0.9$ GeV/c²**

✓ Already analyzed in PRL 101, 082001 (2008) but $0.750<m_{3\pi}<0.775$ GeV/c² (confirming Y(3940)->J/ψω)

✓ Same selection criteria

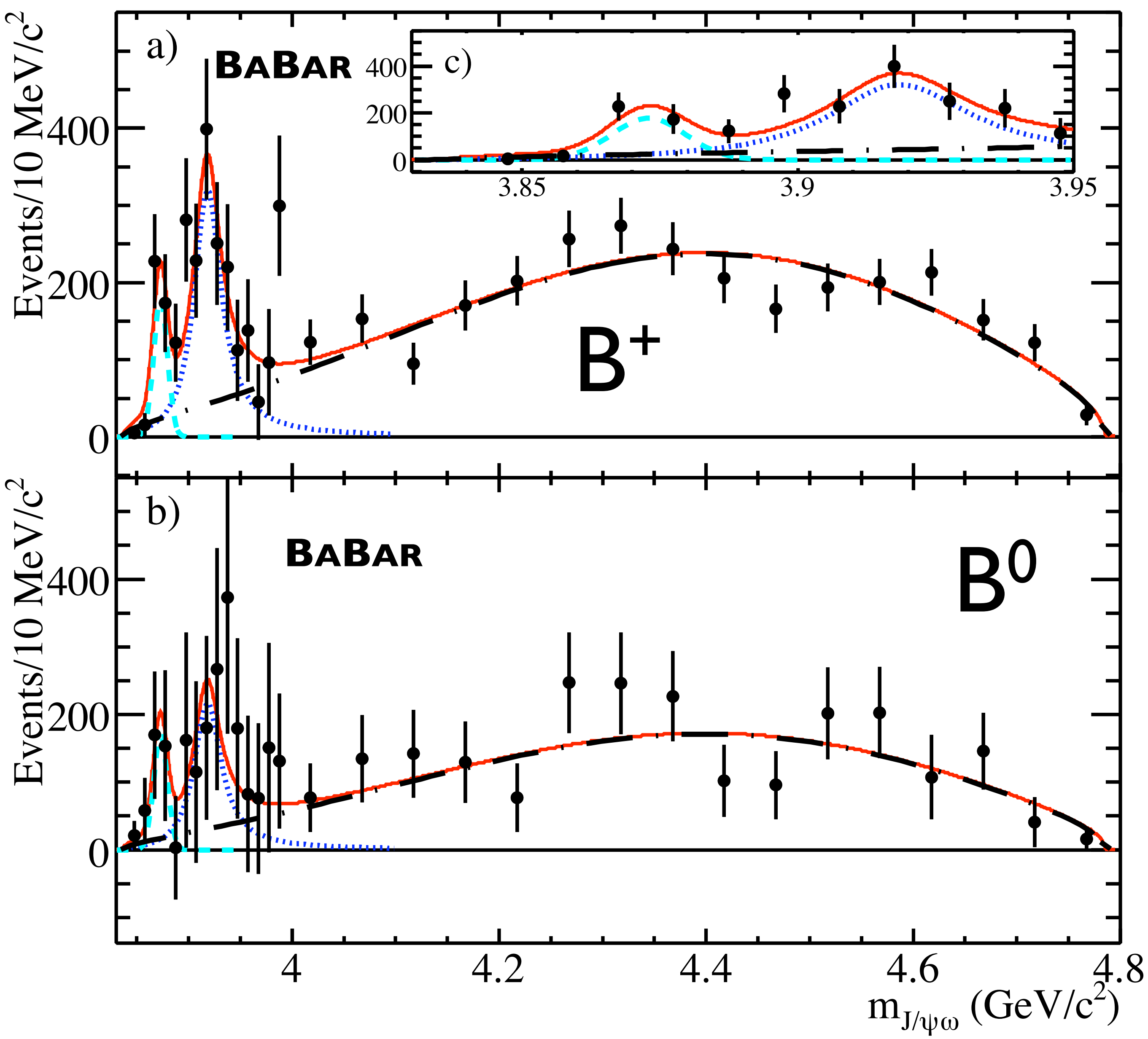
✓ $m_{3\pi}$ distribution for $B^+$ candidates:

- ✓ clear ω signal
- ✓ small η enhancement
- ✓ nothing significant in between

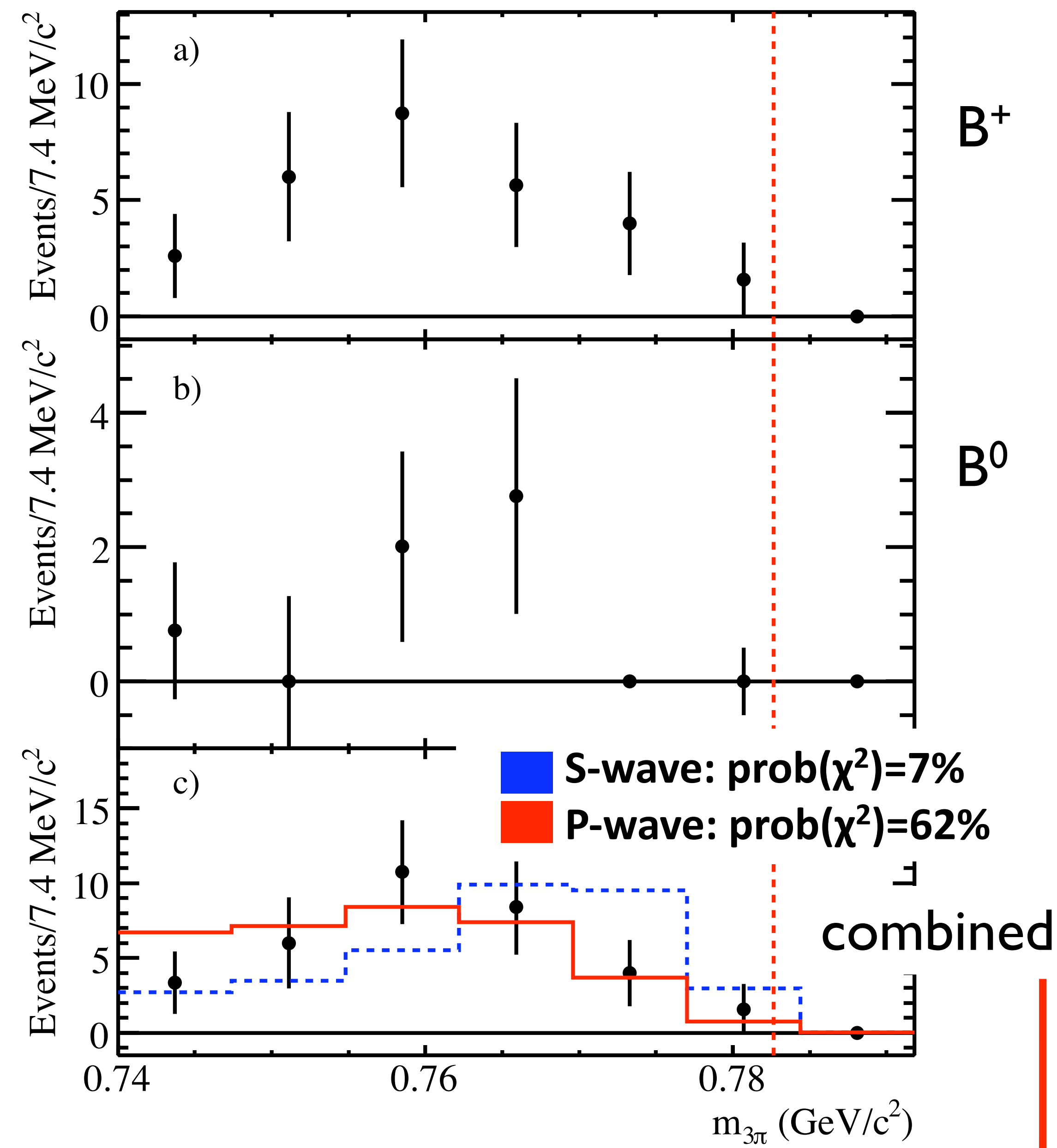


✓ J/ψω mass distributions for charged and neutral B decays:

**PRD 82, 011101 (2010)**




- fit result
- X(3872) (Gaussian resolution)
- Y(3940) (relativistic BW)
- non resonant




**$m_X = 3873.0^{+1.8}_{-1.6}$(stat) ± 1.3(syst) MeV/c²**

**$m_Y = 3919.1^{+3.8}_{-3.4}$(stat) ± 2.0(syst) MeV/c²**

**$\Gamma_Y = 31^{+10}_{-8}$(stat) ± 5(syst) MeV**

significance: 4.0σ **EVIDENCE** for X(3872)-> J/ψω

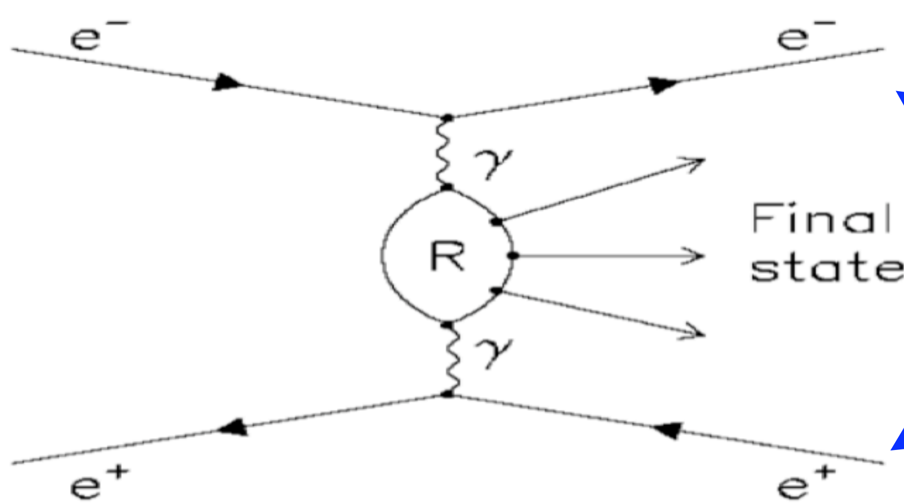
Favoring the P-wave description -> $J^P=2^-$
Consistent with $\eta_{c2}$(1D) charmonium state

# Observation of $\eta_c(1,2S) \to K^+K^-\pi^+\pi^-\pi^0$

✓ **$\eta_c$(1,2S)** are established states, but many decay properties still little explored (mainly for $\eta_c$(2S))

**PRD 84, 012004 (2011)**

✓ Production mechanism:




UNDETECTED -> quasi-real γ
-> $J^P=0^{\pm},2^{\pm},3^{+},4^{\pm}$

**Yang PR 77,242 (1950)**

(and J>2 suppressed by decay phase space)

✓ Final states:

- $\gamma\gamma \to K_S^0 K^{\pm}\pi^{\mp}$
- $\gamma\gamma \to K^+K^-\pi^+\pi^-\pi^0$

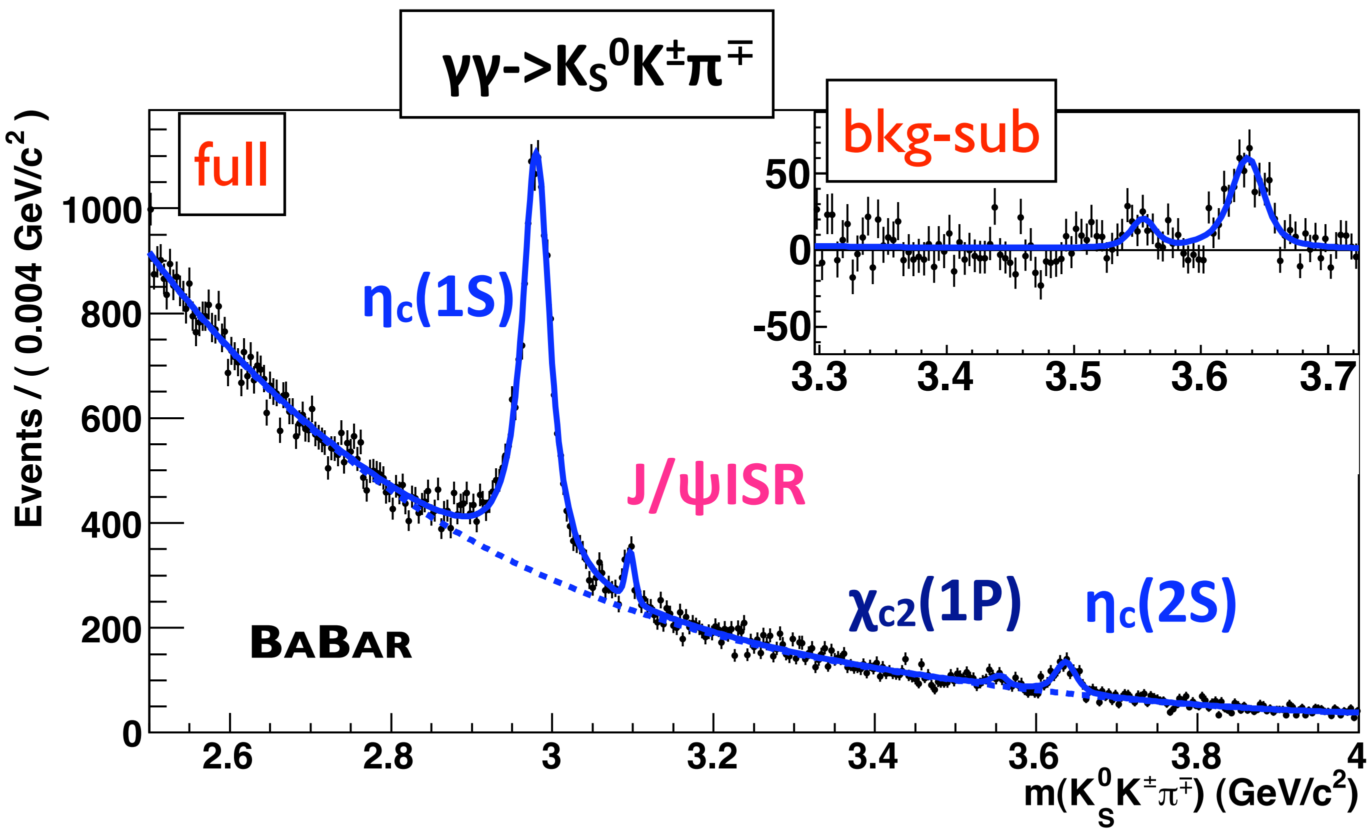
with $K_S^0 \to \pi^+\pi^-$ and $\pi^0 \to \gamma\gamma$

✓ Background from combinatorial, other 2γ collisions, and ISR processes

✓ Signal identified by number of charged tracks and additional reconstructed γ, $p_T$ distribution, missing mass

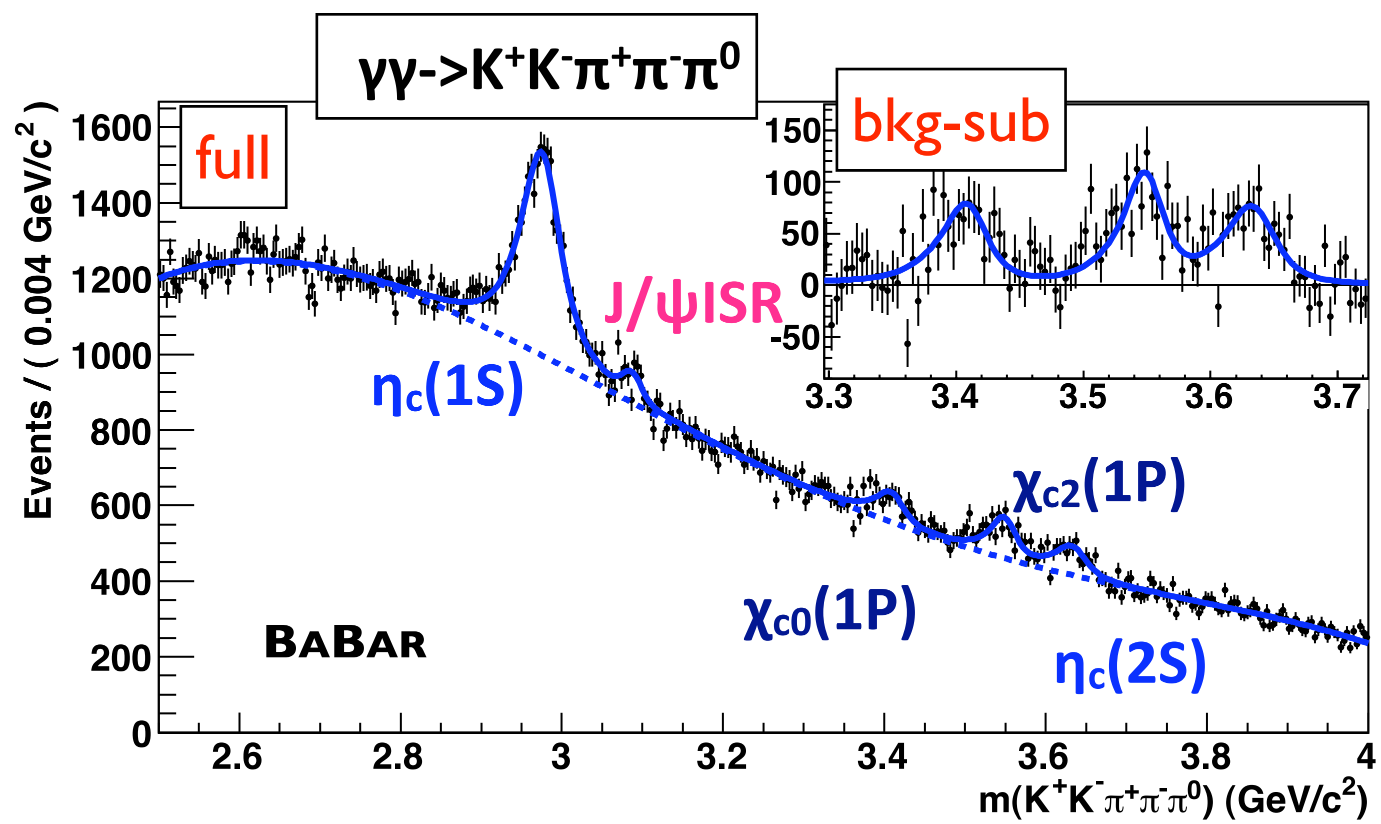
PRD 84, 012004 (2011)

✓ Binned ML fit to the invariant mass distributions of final state particles:




✓ Components for:

- $\eta_c(1S)$, $\eta_c(2S)$ ⟵ [NR-BW + resolution]
- $\chi_{c0}(1P)$ (forbidden $K_S^0 K^{\pm}\pi^{\mp}$ final states), $\chi_{c2}(1P)$
- **combinatorial bkg** [$4^{th}$ ord.poly]
- J/ψ ISR [Gaussian]




✓ No signal for $\chi_{c2}(2P)$

✓ Signal yields corrected for background peaking contributions

✓ Systematic uncertainties from fit procedure, peaking bkg, reconstruction and selection efficiencies

**PRD 84, 012004 (2011)**

✓ Most precise mass and width measurements:

- $M(\eta_c(2S)) = 3638.5 \pm 1.5_{(stat)} \pm 0.8_{(syst)}$ MeV/$c^2$
- $\Gamma(\eta_c(2S)) = 13.4 \pm 4.6_{(stat)} \pm 3.2_{(syst)}$ MeV

✓ Branching fraction results:

(ULs are 90% CL Bayesian with uniform priors)

**BABAR**

| Process | $\Gamma_{\gamma\gamma} \times \mathcal{B}$ (keV ) |
|---|---|
| $\eta_c(1S)\to K\overline{K}\pi$ | $0.386 \pm 0.008 \pm 0.021$ |
| $\chi_{c2}(1P)\to K\overline{K}\pi$ | $(1.8 \pm 0.5 \pm 0.2) \times 10^{-3}$ |
| $\eta_c(2S)\to K\overline{K}\pi$ | $0.041 \pm 0.004 \pm 0.006$ |
| $\chi_{c2}(2P)\to K\overline{K}\pi$ | $< 2.1 \times 10^{-3}$ |
| $\eta_c(1S)\to K^+K^-\pi^+\pi^-\pi^0$ | $0.190 \pm 0.006 \pm 0.028$ |
| $\chi_{c0}(1P)\to K^+K^-\pi^+\pi^-\pi^0$ | $0.026 \pm 0.004 \pm 0.004$ |
| $\chi_{c2}(1P)\to K^+K^-\pi^+\pi^-\pi^0$ | $(6.5 \pm 0.9 \pm 1.5) \times 10^{-3}$ |
| $\eta_c(2S)\to K^+K^-\pi^+\pi^-\pi^0$ | $0.030 \pm 0.006 \pm 0.005$ |
| $\chi_{c2}(2P)\to K^+K^-\pi^+\pi^-\pi^0$ | $< 3.4 \times 10^{-3}$ |

**First observations**: 18.1σ ($\eta_c(1S)\to K^+K^-\pi^+\pi^-\pi^0$), 5.4σ ($\chi_{c0}(1P)\to K^+K^-\pi^+\pi^-\pi^0$), 5.3σ ($\eta_c(2S)\to K^+K^-\pi^+\pi^-\pi^0$)

**First evidence**: 4.0σ ($\chi_{c2}(1P)\to K^+K^-\pi^+\pi^-\pi^0$)

In particular, first $\eta_c(2S)$ exclusive hadronic decay other than to $K\overline{K}\pi$

# Conclusions

✓ A summary of the most recent bottomonium and charmonium(-like) results:

- Evidence for the $h_b(1P)$ in $\Upsilon(3S) \to \pi^0 h_b(1P)$ **arXiv:1102.4565**

- Search for the $h_b(1P)$ in $\Upsilon(3S) \to \pi^+\pi^- h_b(1P)$ and precise study of dipion transitions **arXiv:1105.4234**

- Precise measurements of a number of radiative transitions using converted $\gamma$ **arXiv:1104.4254**

- Evidence for the decay $X(3872) \to J/\psi\omega$ (favoring $J^P=2^-$) **PRD 82, 011101 (2010)**

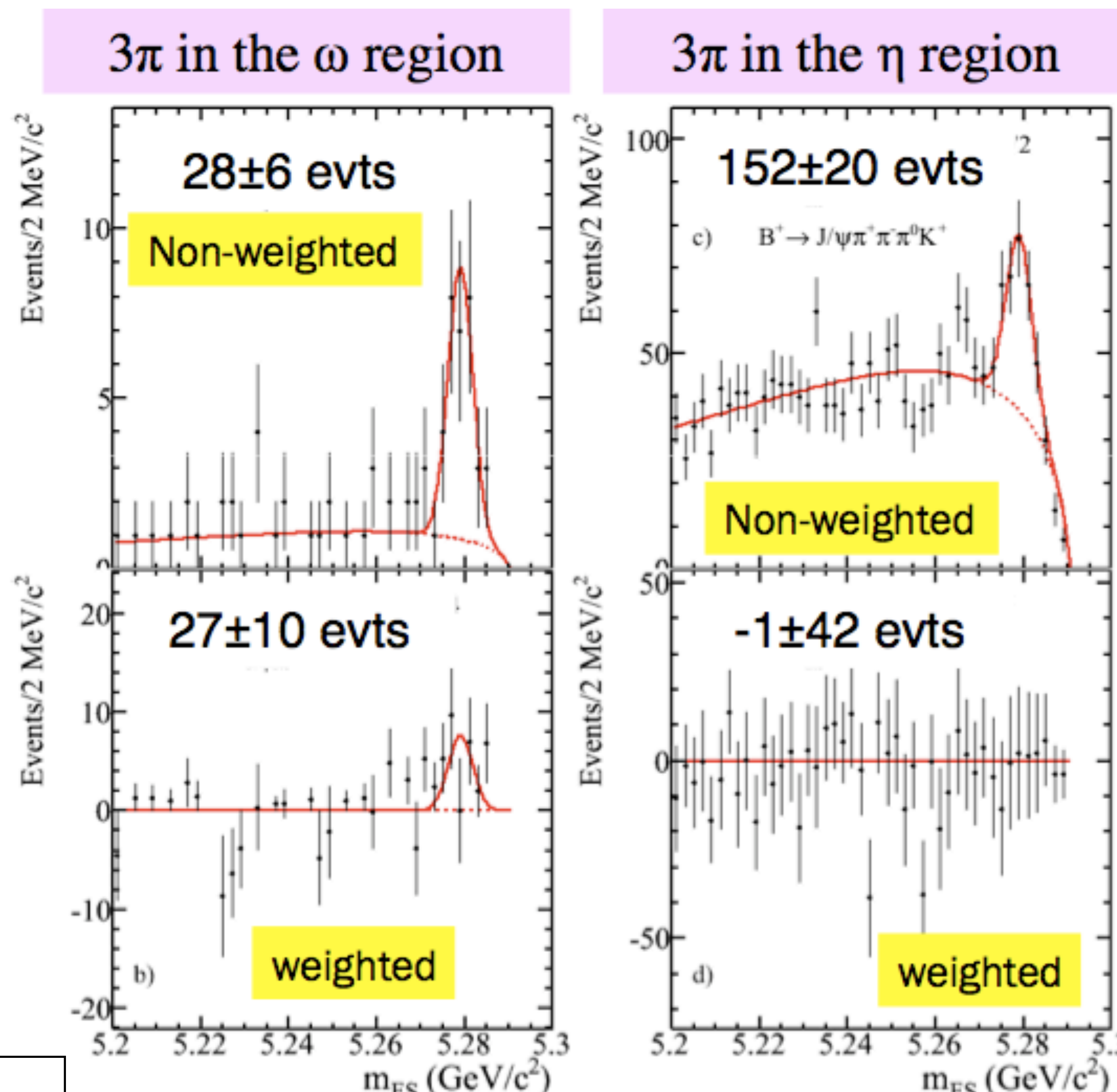
- Observation of $\eta_c(1,2S) \to K^+K^-\pi^+\pi^-\pi^0$ in $2\gamma$ interactions **PRD 84, 012004 (2011)**

✓ Many other results coming soon!

# BACKUP SLIDES

# X(3872)->J/ψω: Dalitz plot weighting technique

Each event is given weight of $(5/2)(1-3\cos^2\theta_h)$, where $\theta_h$ is the angle between the $\pi^+$ and $\pi^0$ in the $\pi^+\pi^-$ rest frame




Non-ω events projected away

**from: A.Mokhtar's talk at QWG workshop, Fermilab May2010**