Studies of Upsilon spectroscopy

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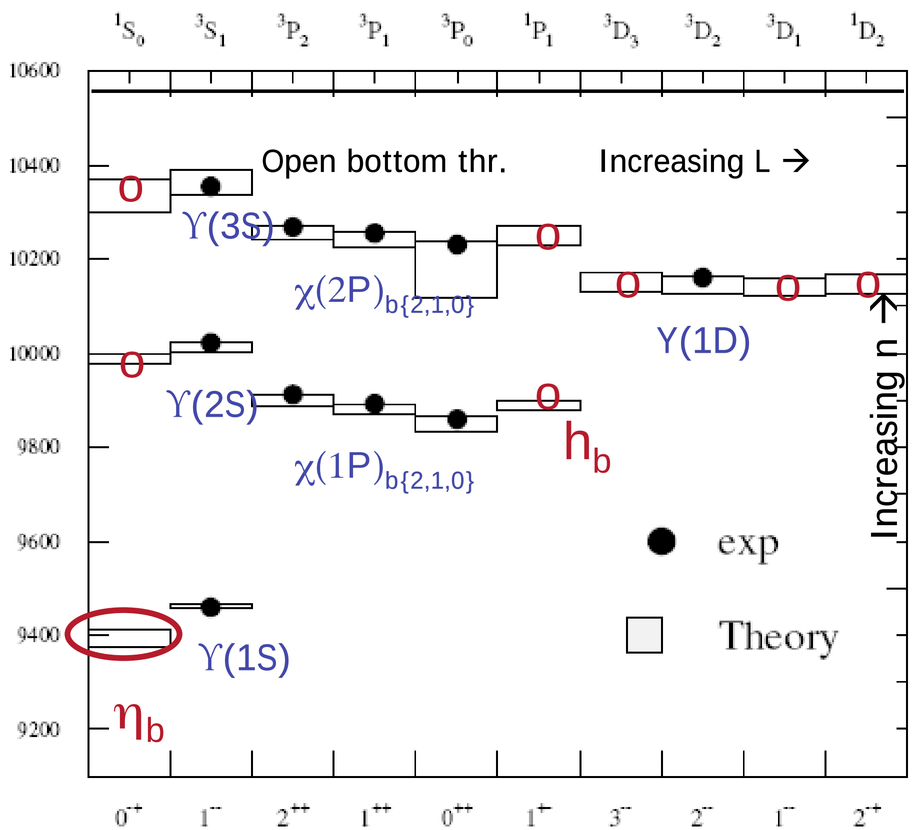
Outline

1- Discovery of the bottomonium ground state η_b

2- Plans at the $\Upsilon(3S)$ and $\Upsilon(2S)$

Bottomonium Spectrum (until yesterday!)



Below $B\bar{B}$ threshold, 8 states still missing:

S-wave η_b(1S,2S,3S)

P-wave h_b(1P,2P)

D-wave 1^3D_1, 1^3D_2 and 1^3D_3

Ground state still to be observed

Search for the η_b at Babar

Inclusive search in the decay: $e^+e^- \rightarrow \Upsilon(3S) \rightarrow \gamma\eta_b$

Branching fraction predictions: $\approx 10^{-4}$

Monochromatic line in $E\gamma$ spectrum: $M(\eta_b)$=9.4 GeV $\rightarrow$ $E\gamma$ = 911 MeV

$\rightarrow$ look for a bump near 900 MeV in inclusive photon energy spectrum

Analysis strategy: one dimensional fit to the $E\gamma$ distribution

$\rightarrow$ Huge background: crucial to reduce the background, and understand the yield and line-shape of the various components

Reducing the background: cut optimization

Cut selection: best $S/\sqrt{B}$

- o Signal yield from Monte Carlo
- o Background from Data: 1/10 of full statistics

Selection using:

- Hadronic cuts (number of tracks)
- Photon cuts
- π^0 veto

Summary of cuts:

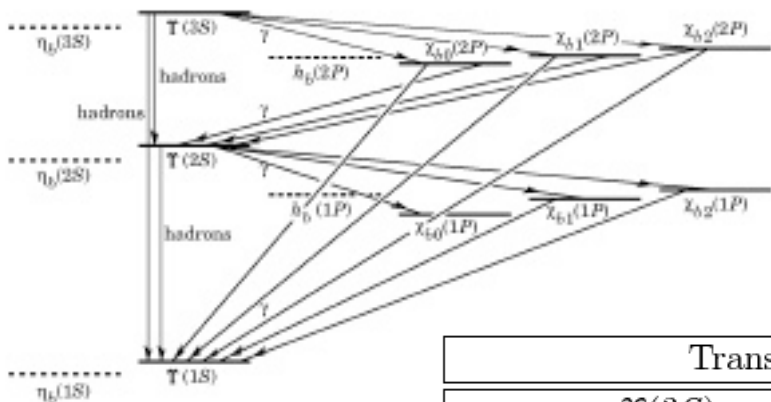
ε(signal)=37%

ε(bkd)=6%

Cut	Efficiency (%)
Reconstruction	70.5
Hadronic selection	97.2
LAT<0.55	98.0
In barrel	89.9
$\|\cos\theta_T\| < 0.7$	68.9
π^0 - 50 MeV cut	89.8
Total	37.0

Checking the cut optimization

Use of exclusive decay: $\Upsilon(3S) \rightarrow \gamma\chi_{bJ}(2P)$, $\chi_{bJ}(2P) \rightarrow \gamma\Upsilon(1S)$

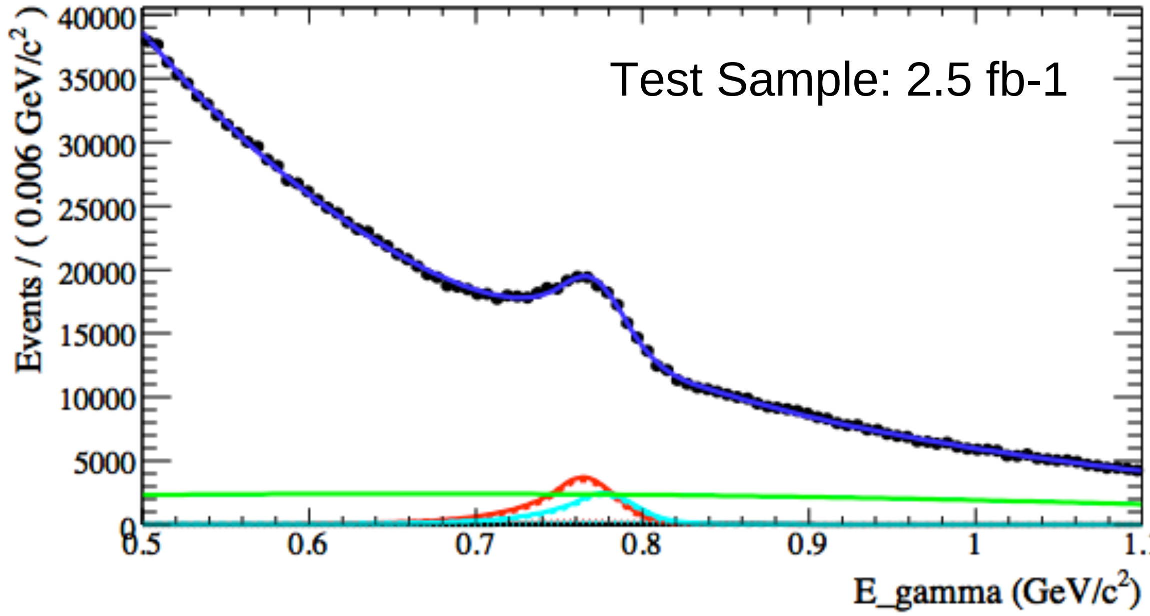


Transition	BR	E_γ MeV	N(10^6) for 30 fb^{-1}
$\Upsilon(3S) \rightarrow \gamma\chi_{b2}(2P)$	0.131	86	
$\Upsilon(3S) \rightarrow \gamma\chi_{b1}(2P)$	0.126	99	
$\Upsilon(3S) \rightarrow \gamma\chi_{b0}(2P)$	0.059	122	
$\chi_{b2}(2P) \rightarrow \gamma\Upsilon(1S)$	0.071	777	
$\chi_{b1}(2P) \rightarrow \gamma\Upsilon(1S)$	0.085	764	
$\chi_{b0}(2P) \rightarrow \gamma\Upsilon(1S)$	0.009	743	
$\Upsilon(3S) \rightarrow \gamma\chi_{b2}(2P), \chi_{b2}(2P) \rightarrow \gamma\Upsilon(1S)$	0.0093		1.116
$\Upsilon(3S) \rightarrow \gamma\chi_{b1}(2P), \chi_{b1}(2P) \rightarrow \gamma\Upsilon(1S)$	0.0107		1.284
$\Upsilon(3S) \rightarrow \gamma\chi_{b0}(2P), \chi_{b0}(2P) \rightarrow \gamma\Upsilon(1S)$	0.0005		0.06

$\chi_{bJ}(2P) \rightarrow \gamma\Upsilon(1S)$ Peaks close to signal

Checking the cut optimization

Same sample used for optimization



Cut	Eff. (from χ_b peak)	Eff. (signal MC)
No cut	-	0.629
BGFMultiHadron	0.973	0.977
≥ 4 ChargedTracks	0.903	0.995
LAT<0.55	0.997	0.991
$-0.762 < \cos(\theta_{\gamma,LAB}) < 0.890$	0.928	0.901
$\lvert\cos(\theta_T)\rvert < 0.7$	0.672	0.690
π^0-50 MeV cut	0.849	0.899

Compare Eff. between η_b signal MC and χ_b Data: very reasonable agreement

Background to the Eγ spectrum

1- Non-peaking (continuous):

- $q\bar{q}$(uds) and generic ISR events
- Υ(3S) cascade decays
- Υ(1S) decays, in particular γgg decays

Fitted together in same PDF, or separated contributions ?

$\rightarrow$ worked on both options, but chose to fit a single component:

$$A\left(C + e^{-\alpha E_\gamma - \beta E_\gamma^2}\right)$$

2- Peaking, next to signal (around 900 MeV):

- $\Upsilon(3S)\rightarrow\gamma\chi_{bJ}(2P)$, $\chi_{bJ}(2P)\rightarrow\gamma\Upsilon(1S)$: 770 MeV
- e+e- $\rightarrow\gamma_{ISR}\,\Upsilon(1S)$: 855 MeV

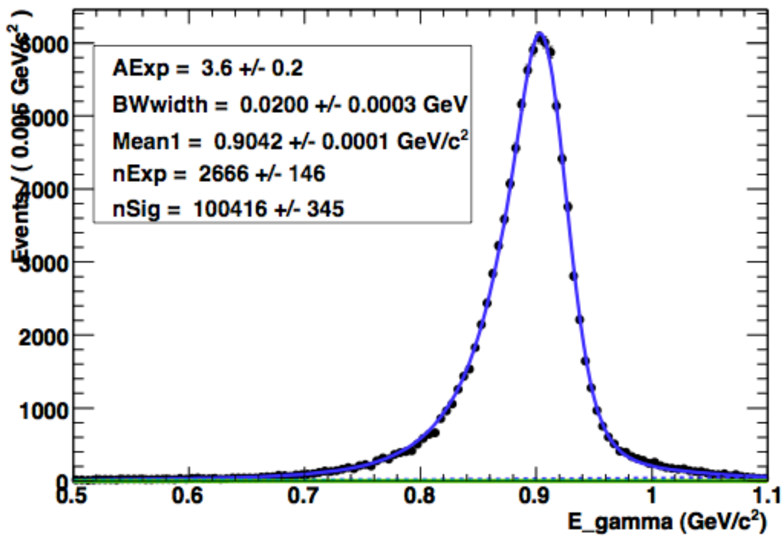
Extremely important to understand (yield and line-shape)

Background to the Eγ spectrum: Peaking χ_b

Second transition in Y(3S)->$\gamma\chi_b$, χ_b->γY(3S)

Three overlapping peaks:

- χ_{b0}(2P) $E_{\gamma,\,CM}$ = 743 MeV
- χ_{b1}(2P) $E_{\gamma,\,CM}$ = 764 MeV
- χ_{b2}(2P) $E_{\gamma,\,CM}$ = 777 MeV



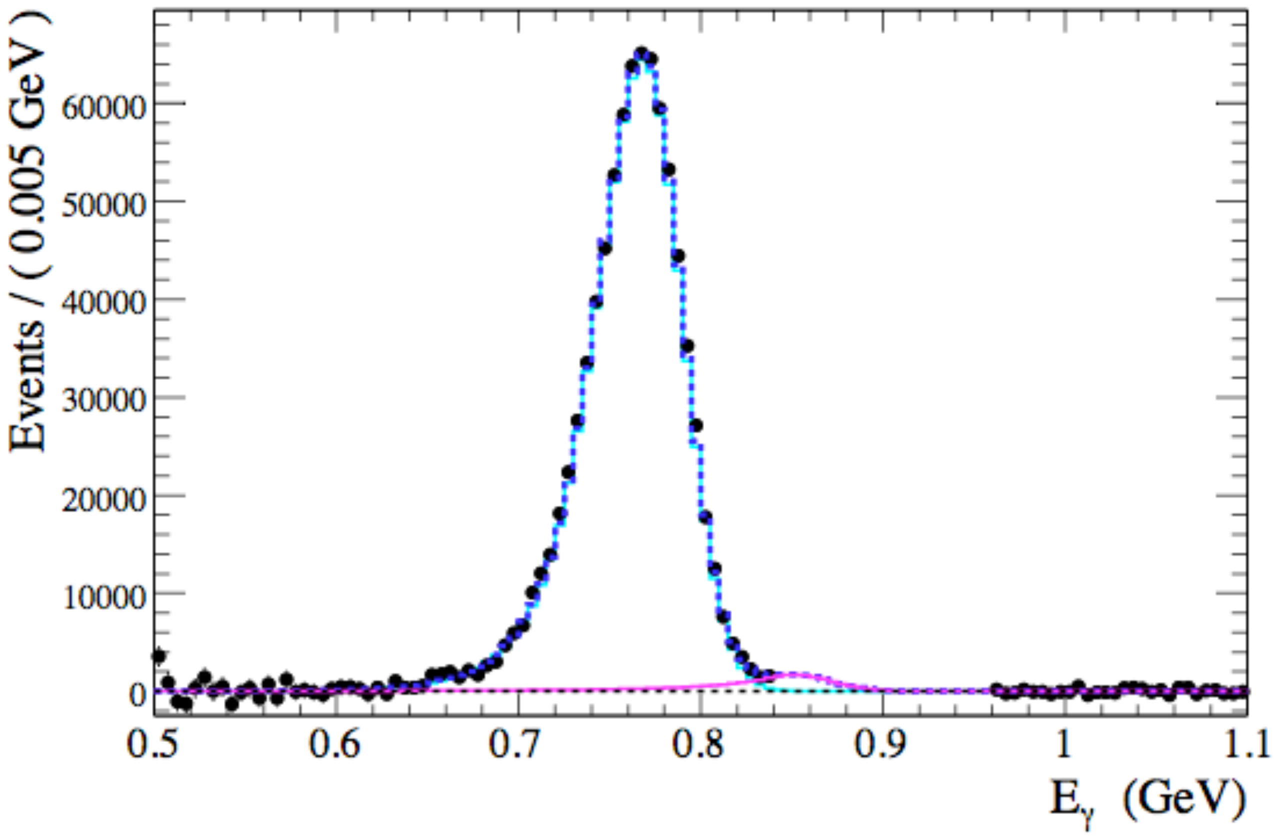
Model each as a Crystal Ball function

- Transition point and power law tail parameter fixed to same value for each peak
- Peak positions fixed to PDG values minus a common offset
- Ratio of yields taken from PDG

Offset of 3.8 MeV observed in data used to correct energy scale of other peaks.

Background to the Eγ spectrum: Peaking χ_b

Fit to the full data, with the ISR Υ(1S) and signal regions excluded



Offset of 3.8 MeV observed: used to correct all other peaks

Background to the Eγ spectrum: Peaking $\gamma_{ISR}\Upsilon(1S)$

Both line-shape and yield are very important to determine: peak at 855 MeV!

Depending on η_b mass, both peaks are going to overlap.

Several options have been investigated:

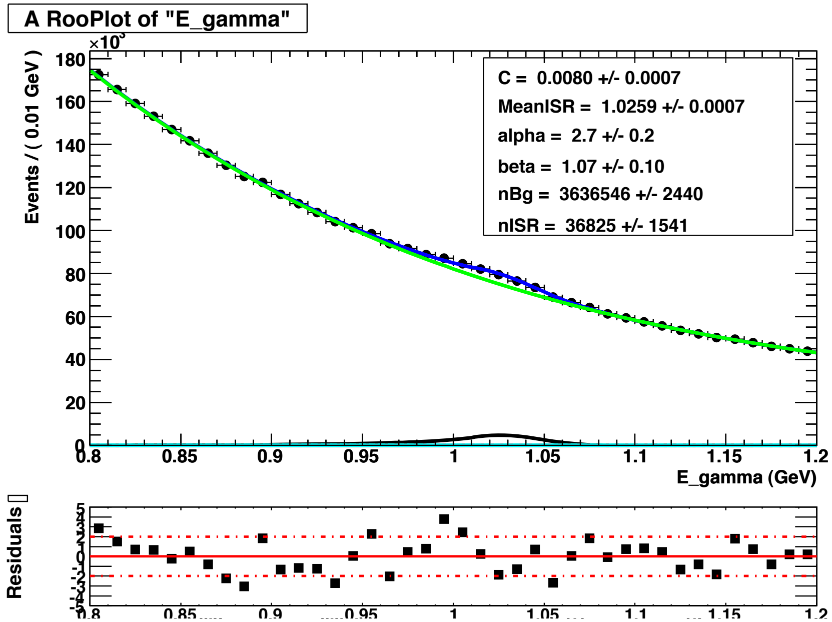
- use e+e- $\rightarrow\gamma_{ISR}$ $\Upsilon(1S)$ $\rightarrow\mu\mu$ decay: no sign of ISR peak, too much radiative $\mu\mu$ background….
- Use of $\Upsilon(3S)$ Off-Peak data: scale to On-Peak luminosity (errors)
- Use of $\Upsilon(4S)$ Off-Peak data: more luminosity than $\Upsilon(3S)$ On-Peak
- Use of $\Upsilon(4S)$ On-Peak data: technically nearly impossible to handle
- Use of signal MC and trust efficiency

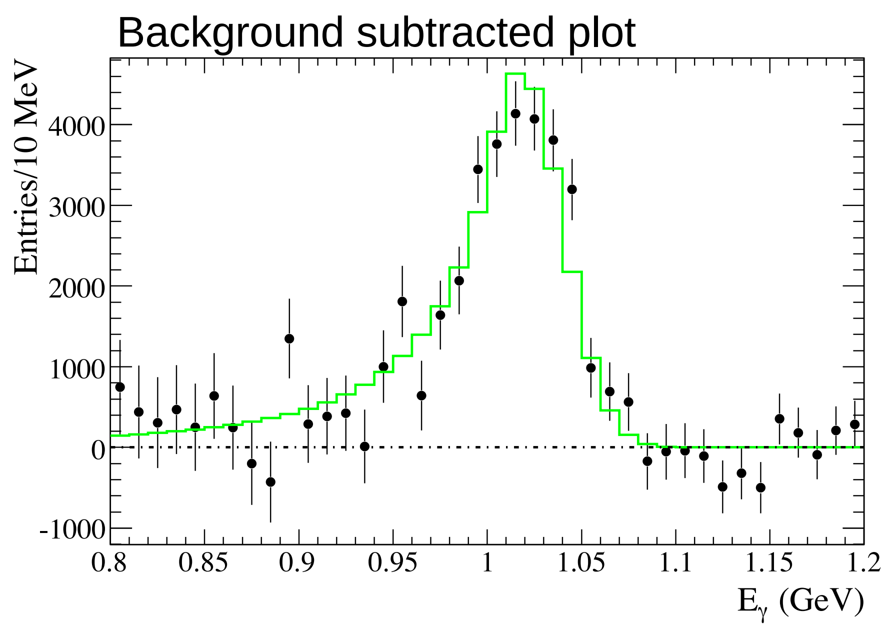
$\Rightarrow$Use of $\Upsilon(4S)$ Off-Peak data, and extrapolate yield to $\Upsilon(3S)$ On-Peak data (using proper cross-sections, efficiencies and integrated luminosities)

(extrapolated yields from $\Upsilon(3S)$ Off-Peak data and extrapolate yield to $\Upsilon(4S)$ Off-Peak data in good agreement)

Background to the Eγ spectrum: Peaking $\gamma_{ISR}\Upsilon(1S)$

Fit to the Υ(4S) Off-Peak data (use of a Crystal Ball for PDF)





Measured yield: 35759±1576

Extrapolated yield to Υ(3S): 25153±1109±1258

Fit Strategy

Float background parameters

Fix χ_b parameters except yield

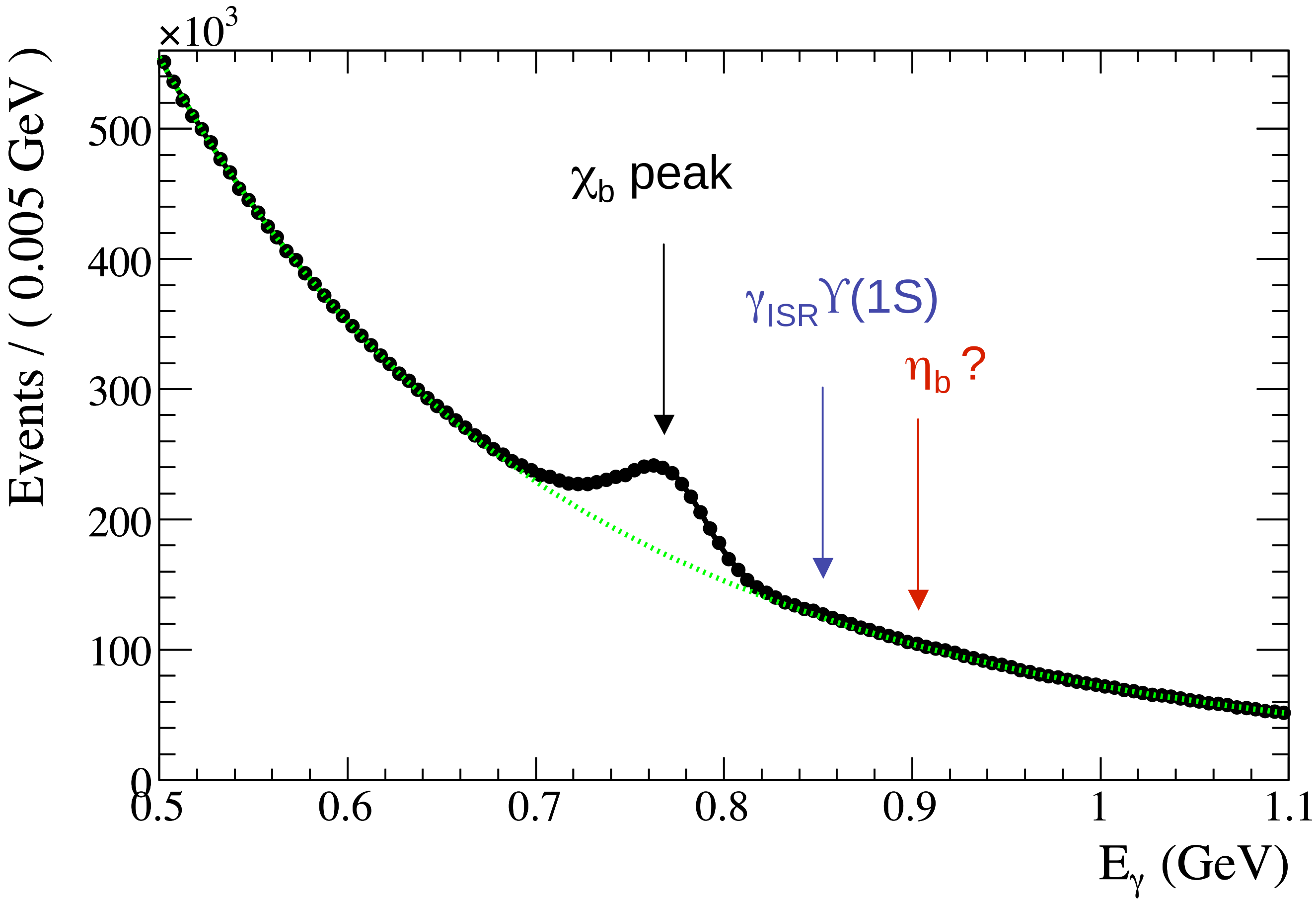
Fix ISR $\gamma\Upsilon(1S)$ yield from $\Upsilon(4S)$ off-peak

Signal PDF: Crystal Ball $\otimes$ BW

Fix signal Crystal Ball parameters from zero-width MC

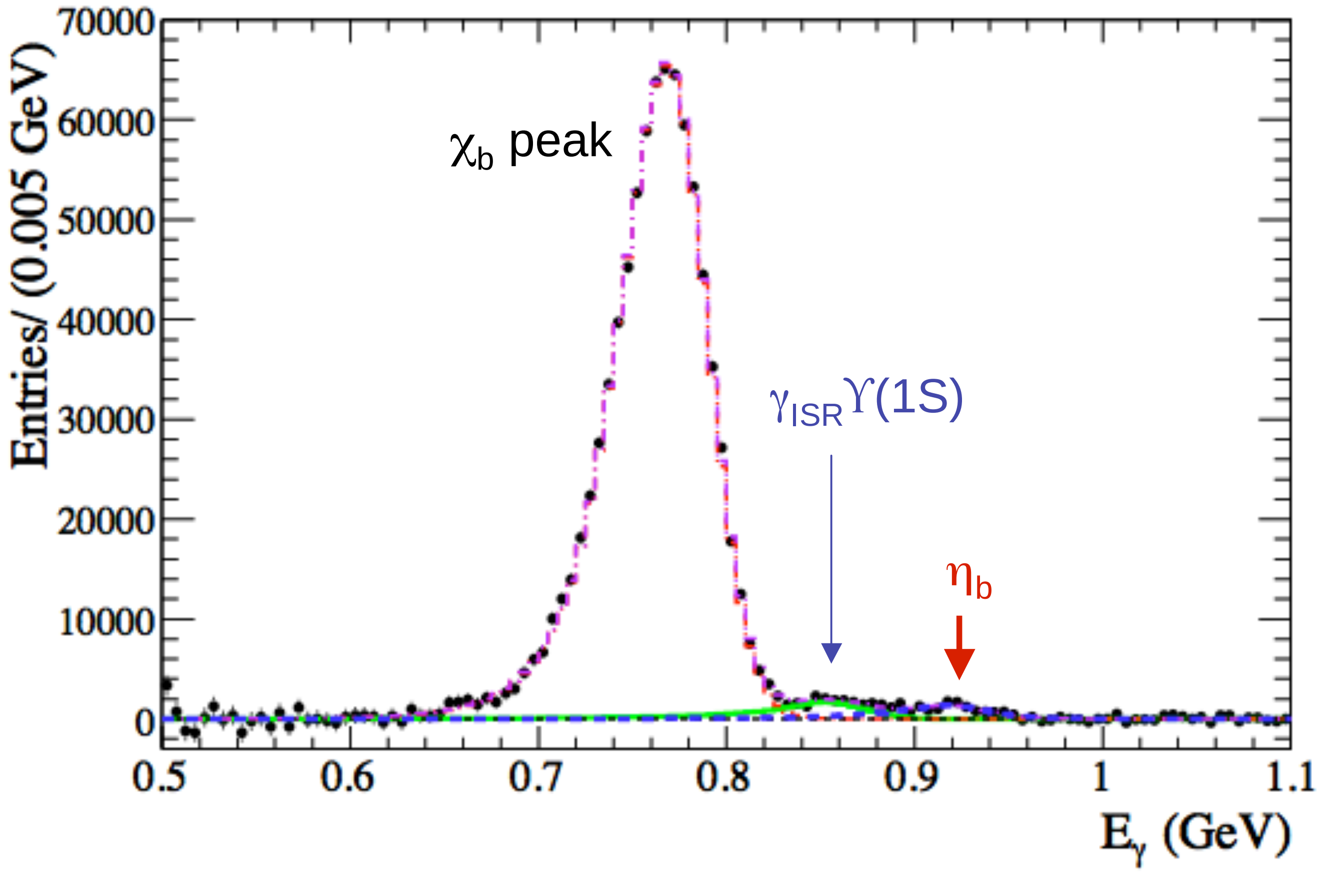
We are not sensitive to the width of the η_b and so we fit the data with each of the following widths to study systematic errors: 5, 10, 15, 20 MeV

Fit to Full Data set



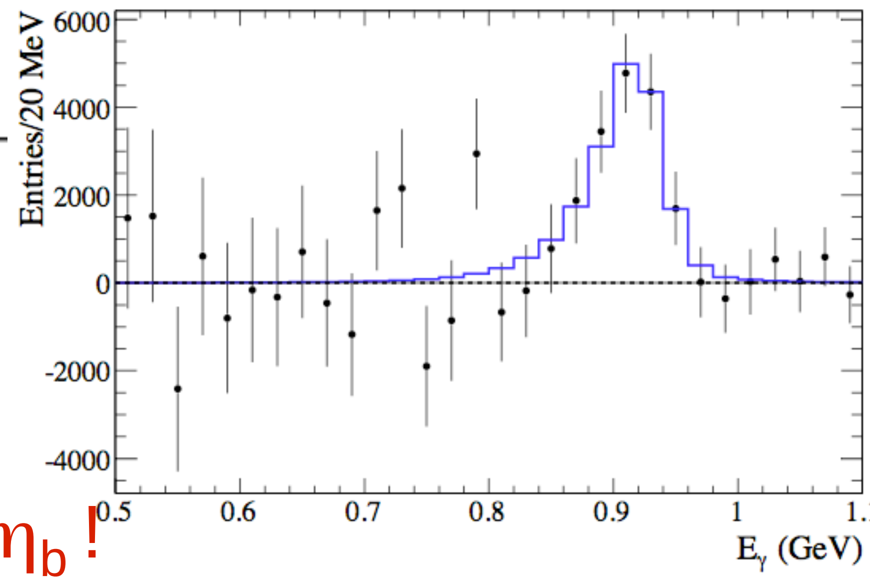
Fit to Full Data set

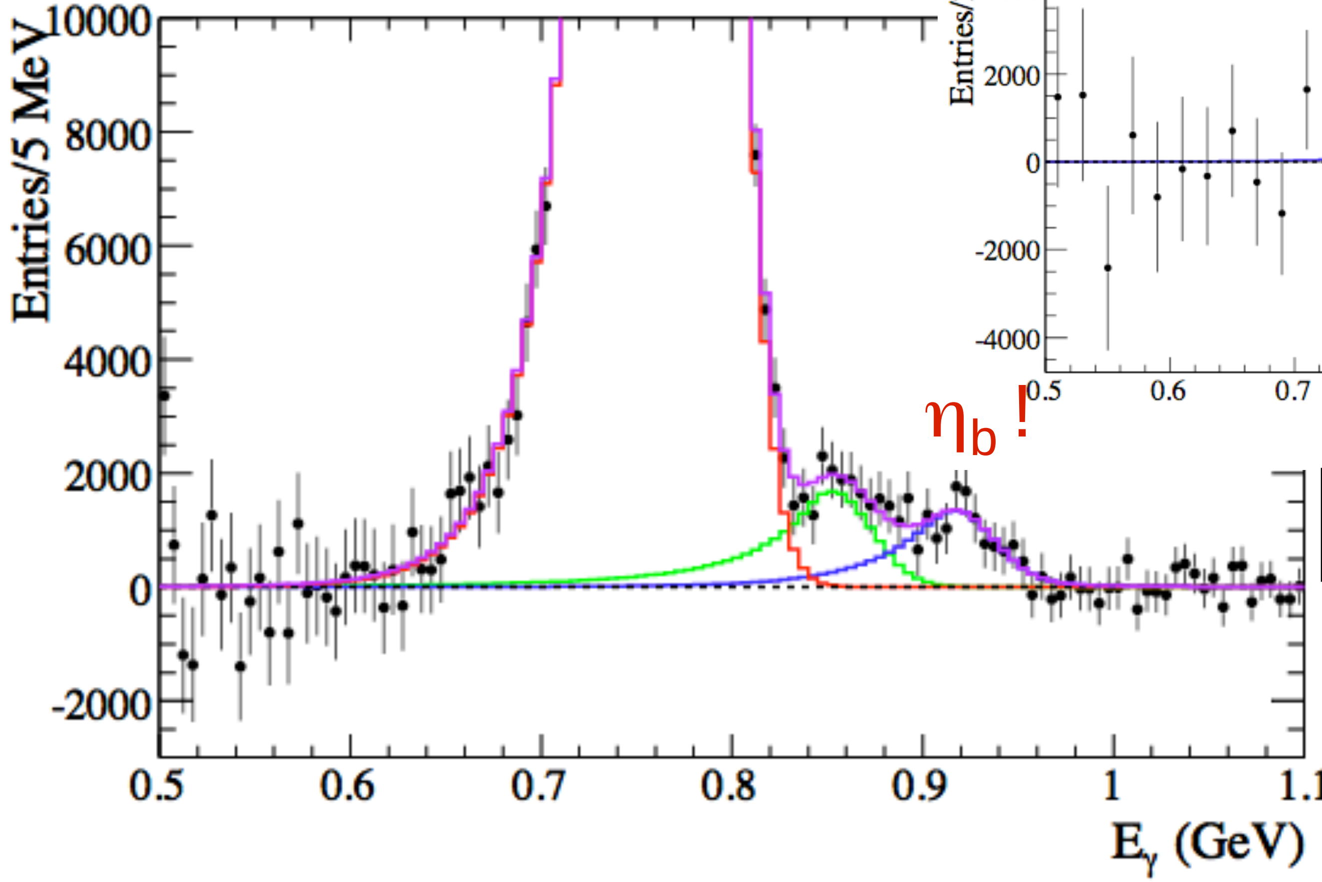
Continuum background subtracted plot



Fit to Full Data set

Continuum background subtracted plot





η_b !

19152±2010 events

Results

Letter submitted yesterday (during Hassan's talk!) to PRL

In conclusion, we have observed the decay $\Upsilon(3S) \to \gamma\eta_b$ with a significance of 10 standard deviations. This is the first evidence for the η_b bottomonium state, the pseudoscalar partner of the $\Upsilon(1S)$. The mass of the η_b is $9388.9^{+3.1}_{-2.3} \pm 2.7$ MeV$/c^2$, which corresponds to a mass splitting between the $\Upsilon(1S)$ and the η_b of $71.4^{+2.3}_{-3.1} \pm 2.7$ MeV$/c^2$. The estimated branching fraction of the decay $\Upsilon(3S) \to \gamma\,\eta_b$ is found to be $(4.8 \pm 0.5 \pm 1.2) \times 10^{-4}$.

Bottomonium studies at the $\Upsilon(3S)$ and $\Upsilon(2S)$

Further studies of the η_b:

$\Upsilon(3S) \rightarrow \gamma\chi_b(2P) \rightarrow \gamma\eta\eta_b$ (on-going analysis)

$\Upsilon(3S) \rightarrow \gamma\eta_b(2S)$

$\Upsilon(2S) \rightarrow \gamma\eta_b$

Search for the missing h_b:

$\Upsilon(3S) \rightarrow \pi^0 h_b$ or $\pi^+\pi^- h_b$

Study of Y(nS) → Y(mS) transitions (η, π, etc…)

Conclusion

We discovered the η_b but we still have a lot of data to analyse, and hopefully make new findings