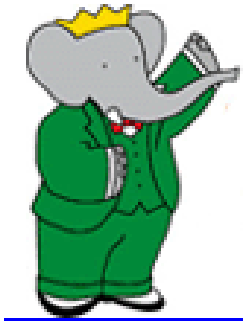
Recent Bottomonium Results from BaBar

Veronique Ziegler (SLAC)

On behalf of the BaBar Collaboration

DIS Workshop, Madrid, Spain, 04-27-2009

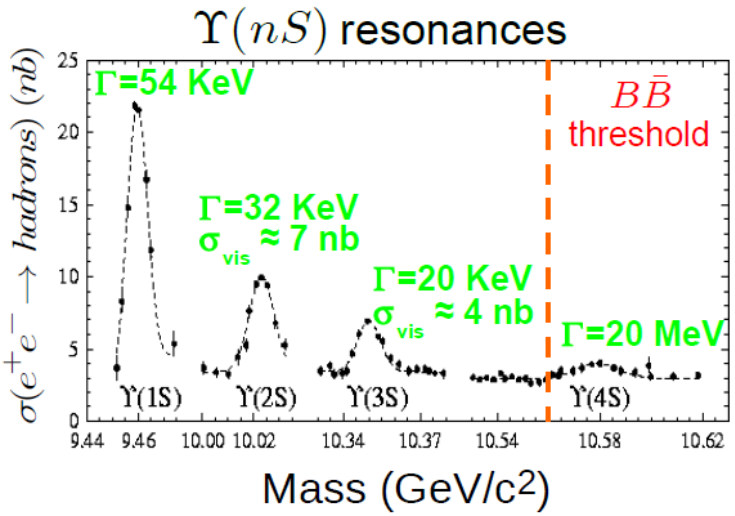


OVERVIEW

- Observation of the Bottomonium Ground State, $\eta_b(1S)$ in $\Upsilon(3S) \rightarrow \gamma\, \eta_b(1S)$ Decay
- Confirmation of the Observation of the $\eta_b(1S)$ in $\Upsilon(2S) \rightarrow \gamma\, \eta_b(1S)$ Decay
- Searches for light *Higgs-like* particle in $\Upsilon(3S, 2S)$ decays
- Search for the Lepton-Flavor Violating Decays $\Upsilon(3S) \rightarrow e^{\pm}\tau^{\mp}$ and $\Upsilon(3S) \rightarrow \mu^{\pm}\tau^{\mp}$
- R_b Scan above the $\Upsilon(4S)$

BaBar RUN 7 (Dec. 2007 – Apr. 2008)

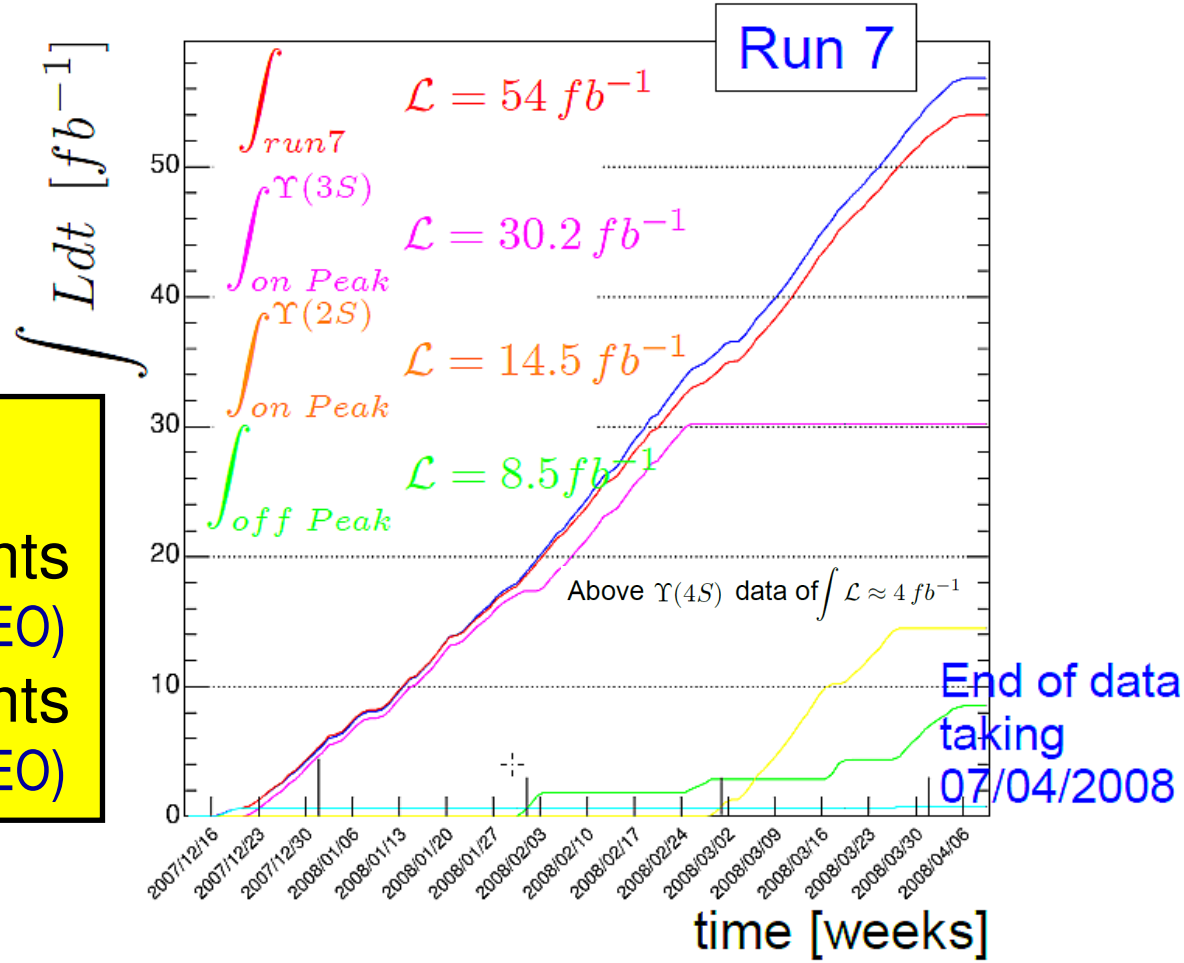
PEP-II e^+e^- Asymmetric Collider Running at the Υ(2S,3S)...



BABAR DATASETS:

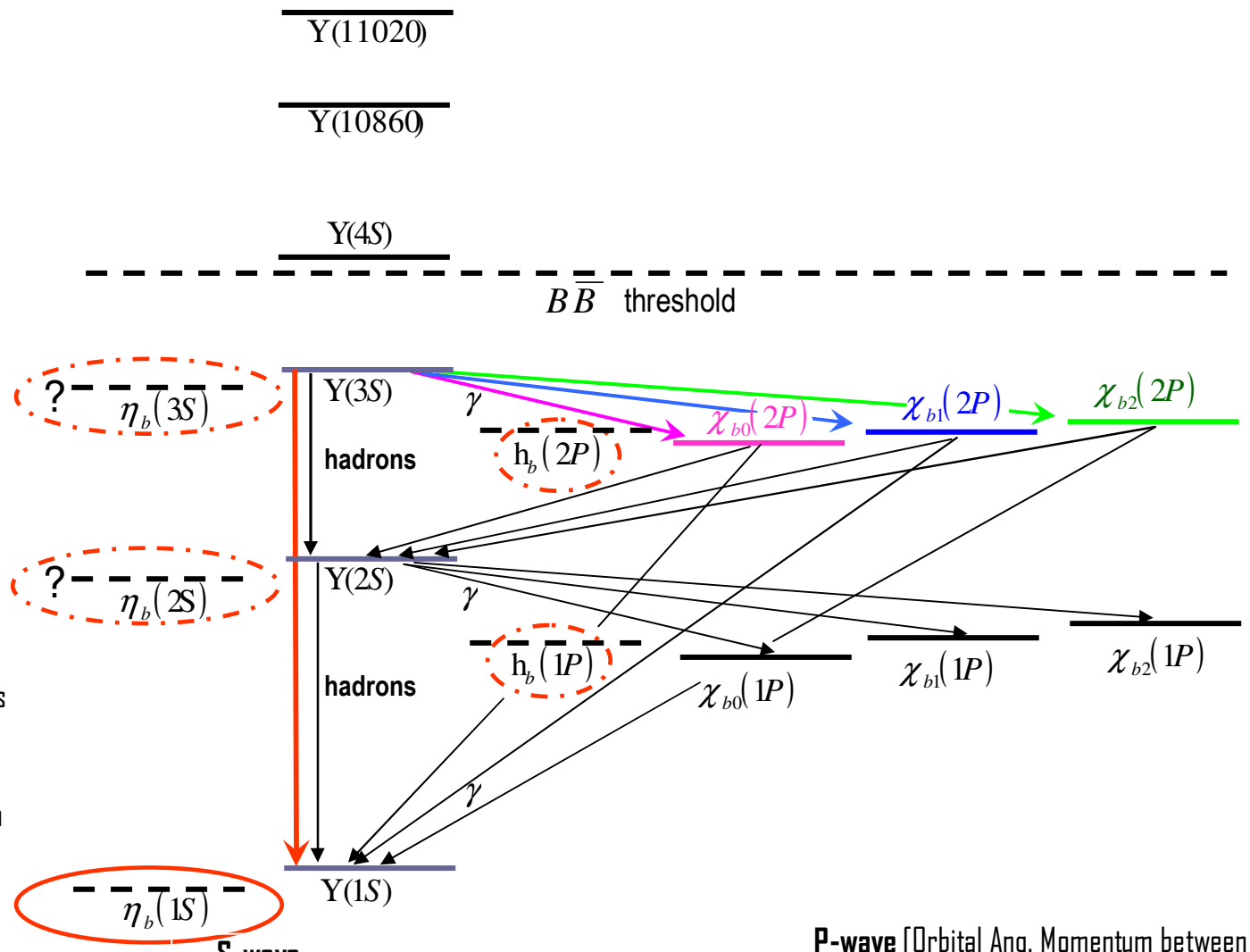
~ 120 x 10^6 **Y(3S)** events
≈ 20 X previous dataset (CLEO)

~ 100 x 10^6 **Y(2S)** events
≈ 11 X previous dataset (CLEO)



The Observation of the Bottomonium Ground State, $\eta_b(1S)$, at BaBar

Current Picture of the Bottomonium Spectrum

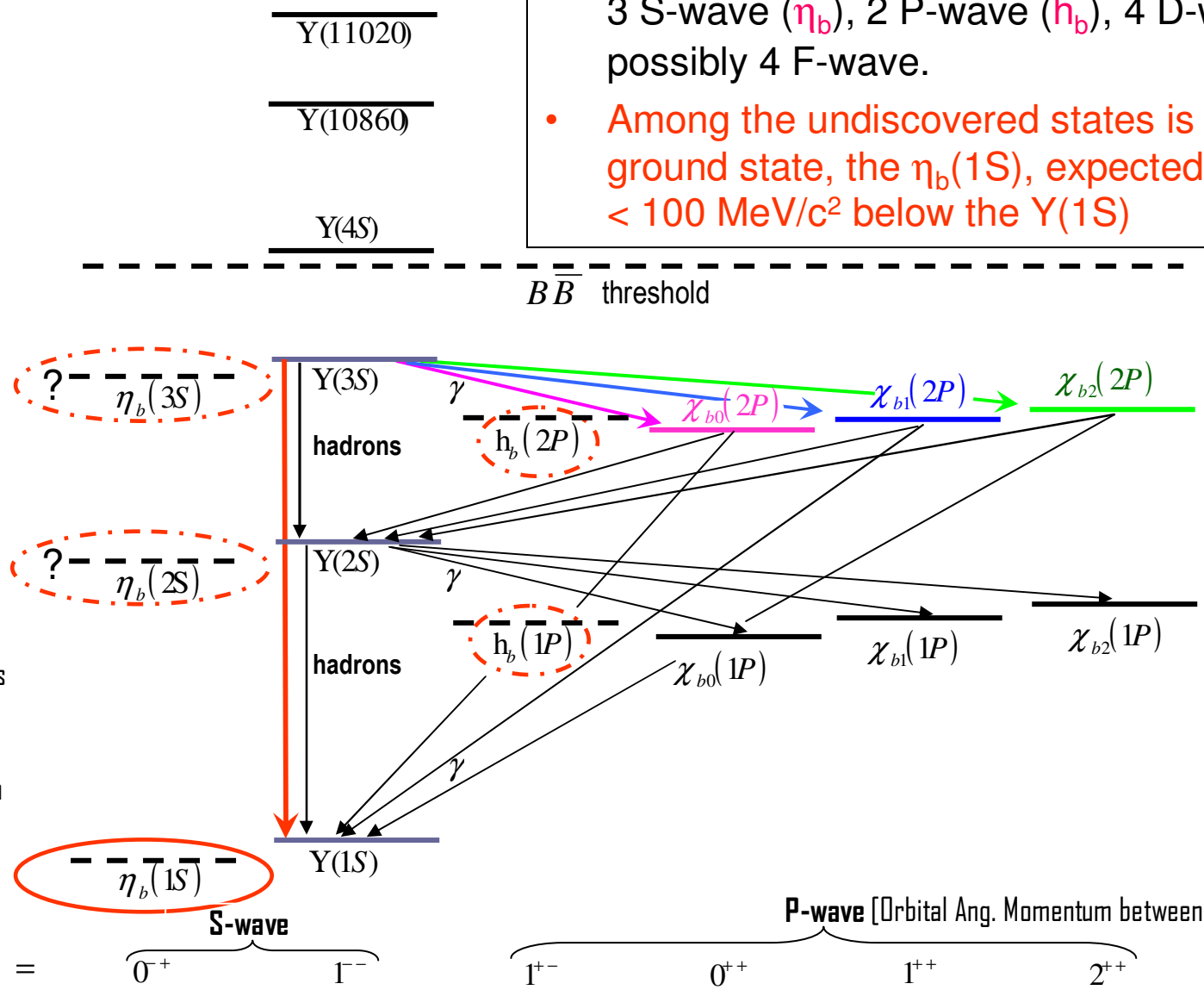


(nL) where n is the principal quantum number and L indicates the $b\bar{b}$ angular momentum in spectroscopic notation (L=S, P, D,...)

J^{PC} = S-wave: 0^{-+}, 1^{--} P-wave [Orbital Ang. Momentum between quarks]: 1^{+-}, 0^{++}, 1^{++}, 2^{++}

Current Picture of the Bottomonium Spectrum

- $b\bar{b}$ states below Y(3S) not yet discovered: 3 S-wave (η_b), 2 P-wave (h_b), 4 D-wave & possibly 4 F-wave.
- Among the undiscovered states is the ground state, the η_b(1S), expected to be < 100 MeV/c^2 below the Y(1S)



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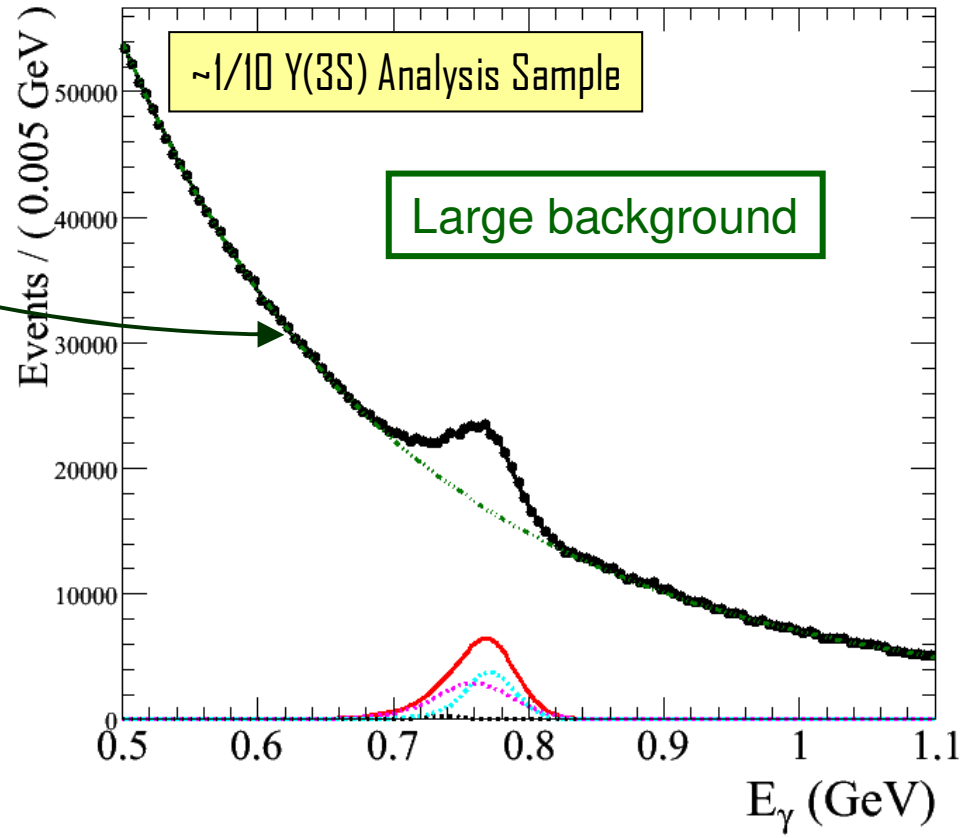
- Decays of η_b not known ➔ Search for η_b signal in **inclusive photon spectrum**
  - **Search for the radiative transition $\Upsilon(3S) \rightarrow \gamma\eta_b(1S)$**
- In c.m. frame: $E_\gamma = \frac{s - m^2}{2\sqrt{s}}$ $\left\{ \begin{array}{l} \sqrt{s} = \text{c.m. energy} = m(\Upsilon(3S)) \\ m = m(\eta_b) \end{array} \right\}$
  - For η_b mass m = 9.4 GeV/c^2 ➔ monochromatic line in E_γ spectrum at 911 MeV, i.e. look for a bump near 900 MeV in inclusive photon energy spectrum from data taken at the $\Upsilon(3S)$

The Inclusive Photon Spectrum

The Inclusive Photon Spectrum

- Use ~9% of the Full Υ(3S) Data Sample

Non-Peaking background components:



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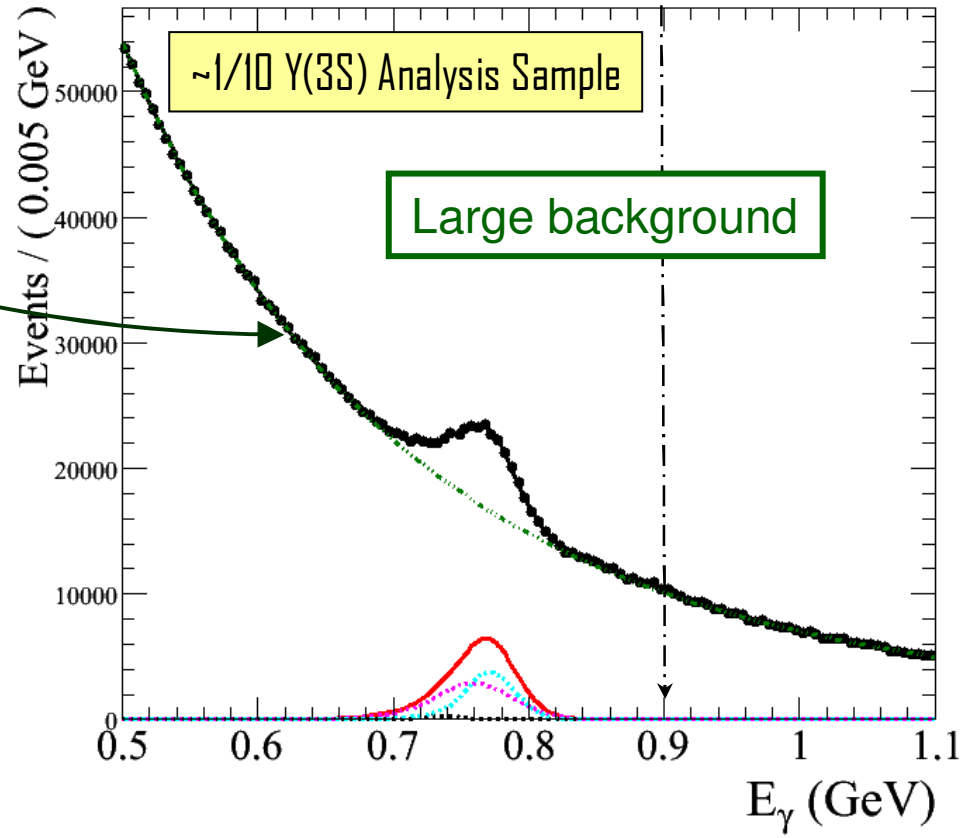

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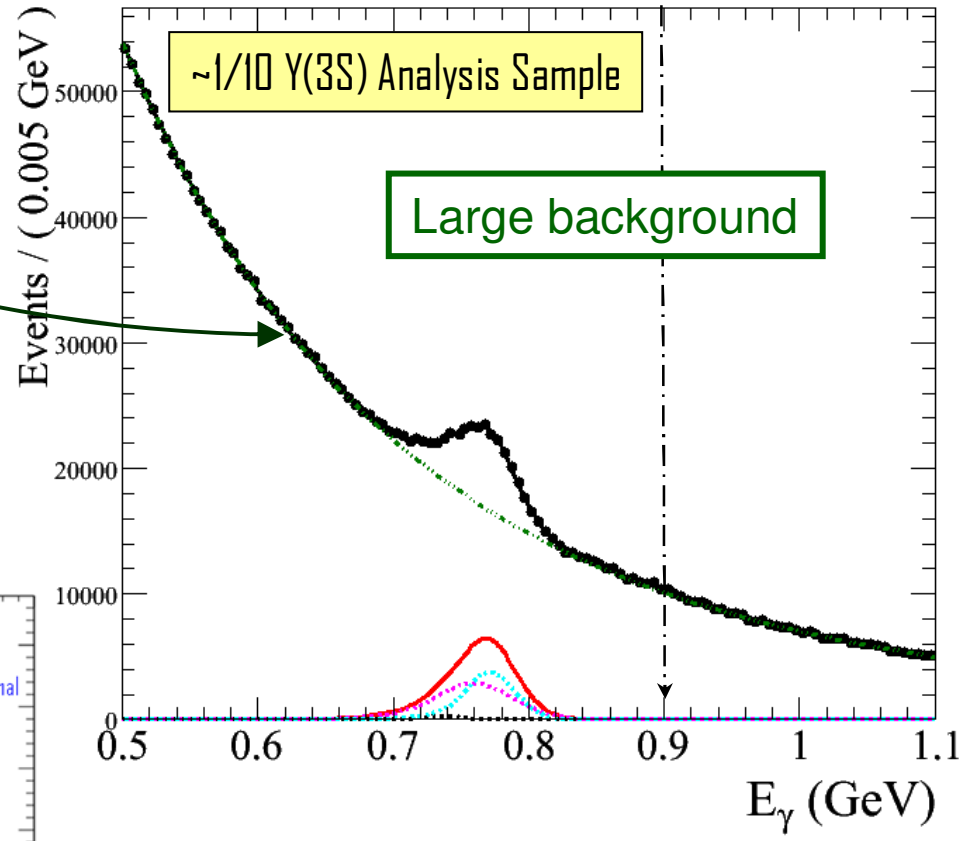
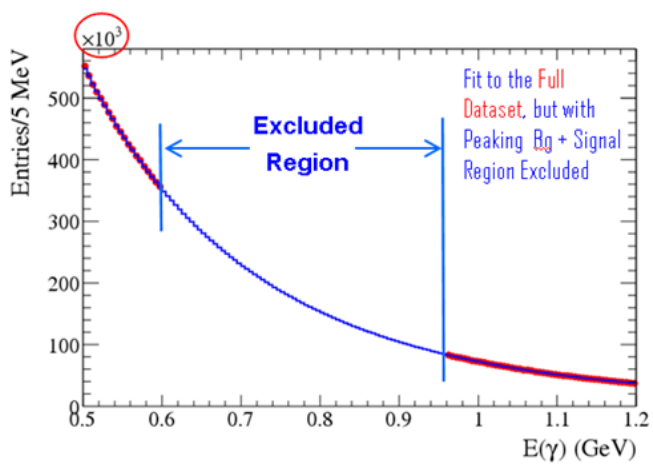


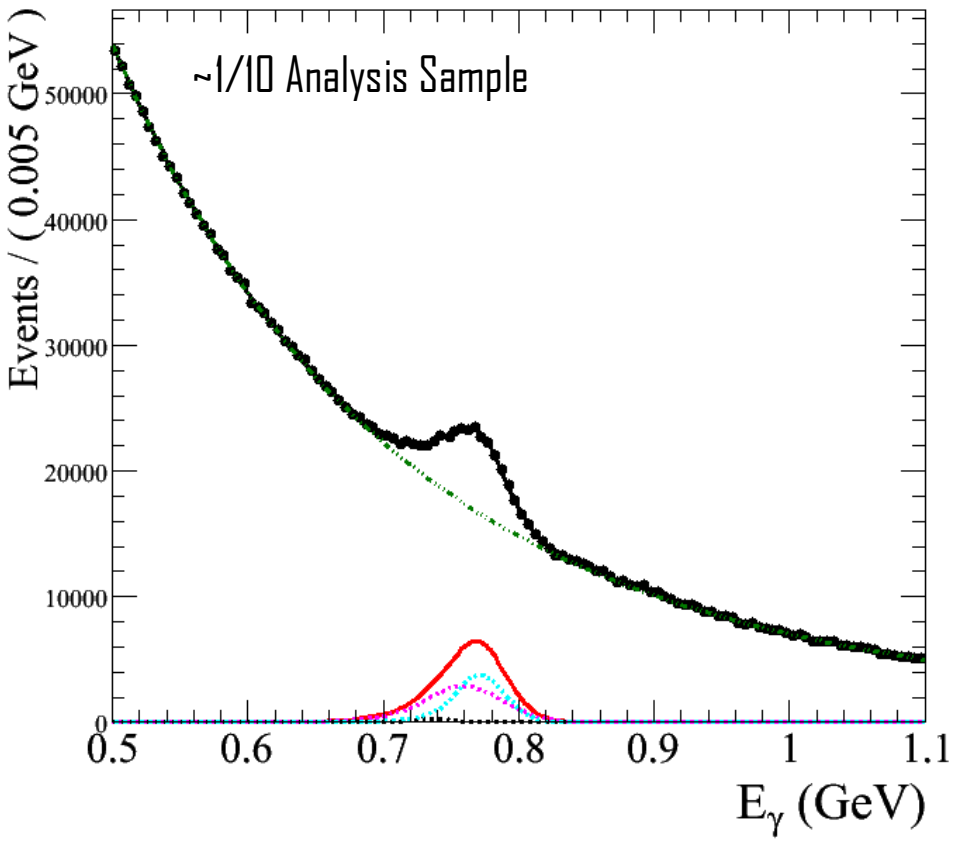
Non-peaking background parametrization:

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



The Inclusive Photon Spectrum

Peaking background components:



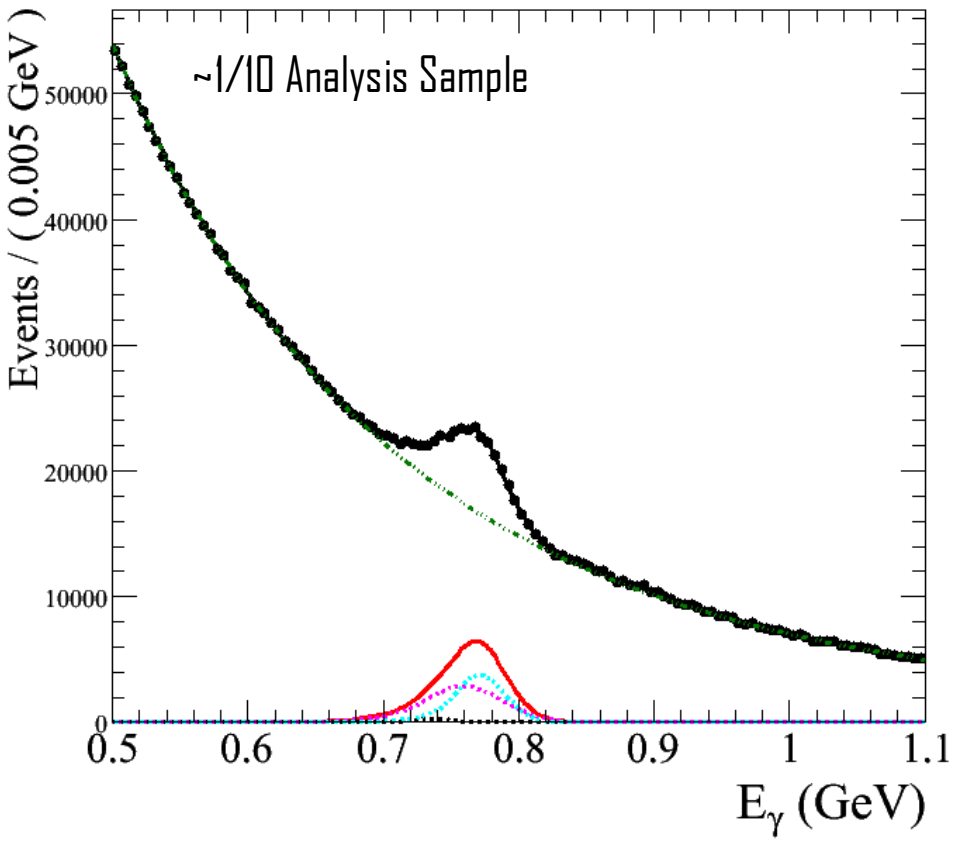
The Inclusive Photon Spectrum

Peaking background components (1):

$\Upsilon(3S) \rightarrow \chi_{b0}(2P)\ \gamma^{soft}$ $E(\gamma^{soft}) = 122$ MeV

$\Upsilon(3S) \rightarrow \chi_{b1}(2P)\ \gamma^{soft}$ $E(\gamma^{soft}) = 99$ MeV

$\Upsilon(3S) \rightarrow \chi_{b2}(2P)\ \gamma^{soft}$ $E(\gamma^{soft}) = 86$ MeV



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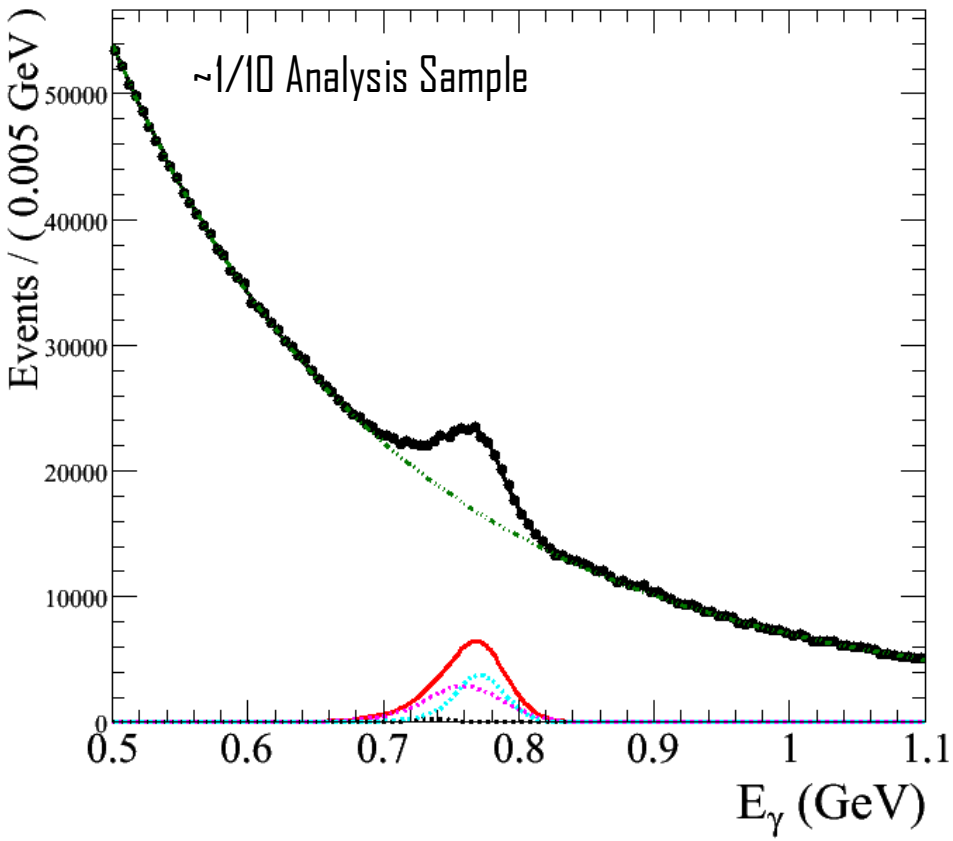

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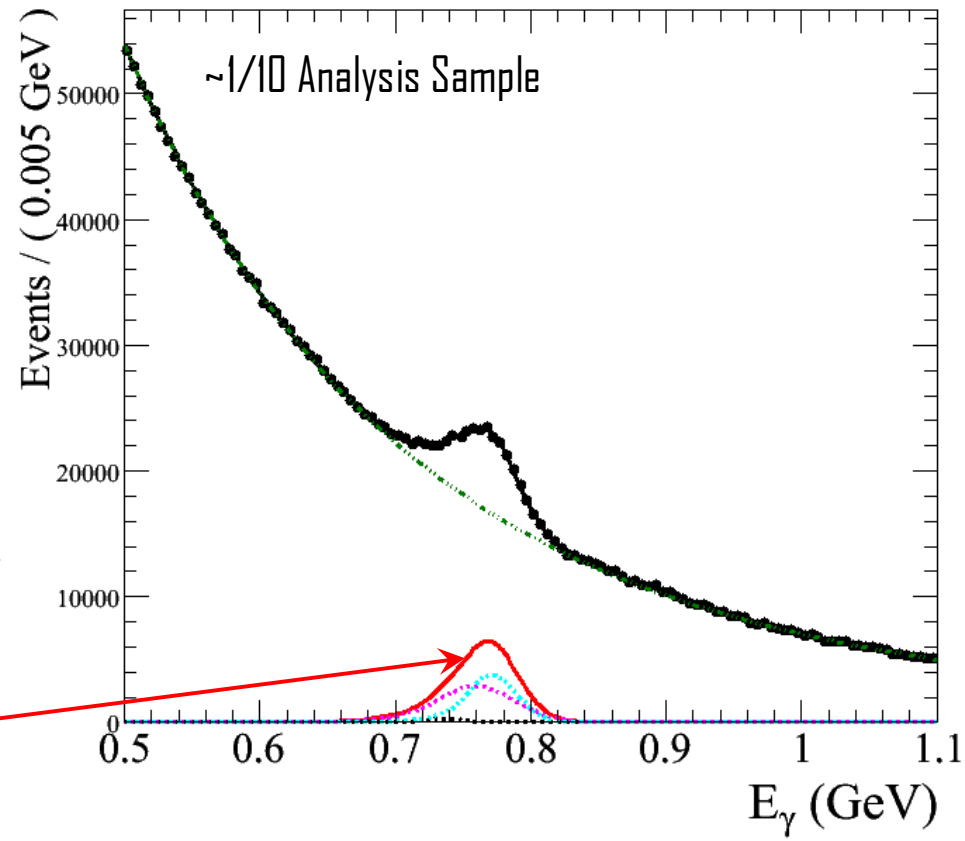

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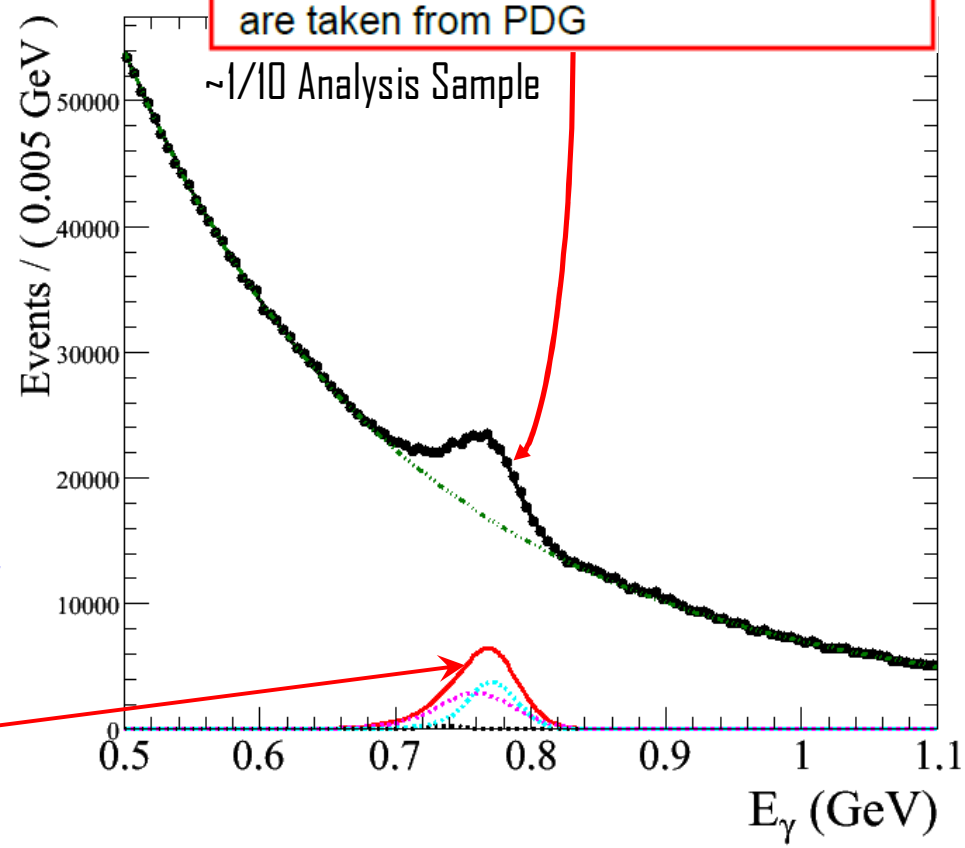
$\chi_{bJ}(2P) \rightarrow \gamma\ \Upsilon(1S)$ (Peaking)

background parametrization:

PDF: 3 Crystal Ball fct

Relative peak positions and yield ratios are taken from PDG



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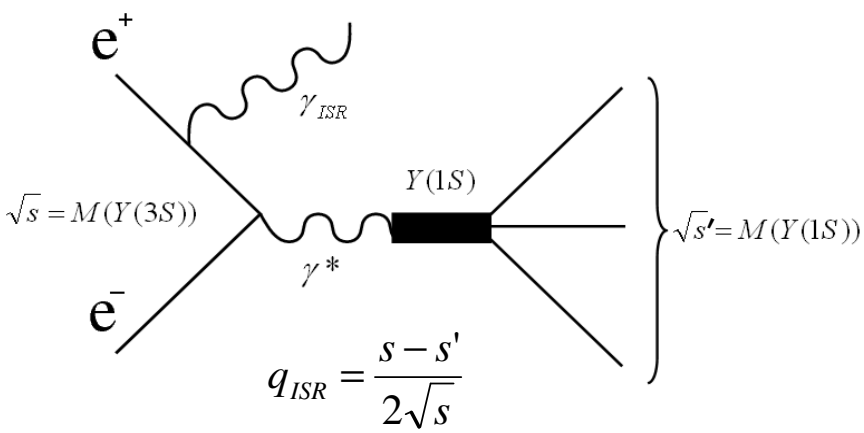
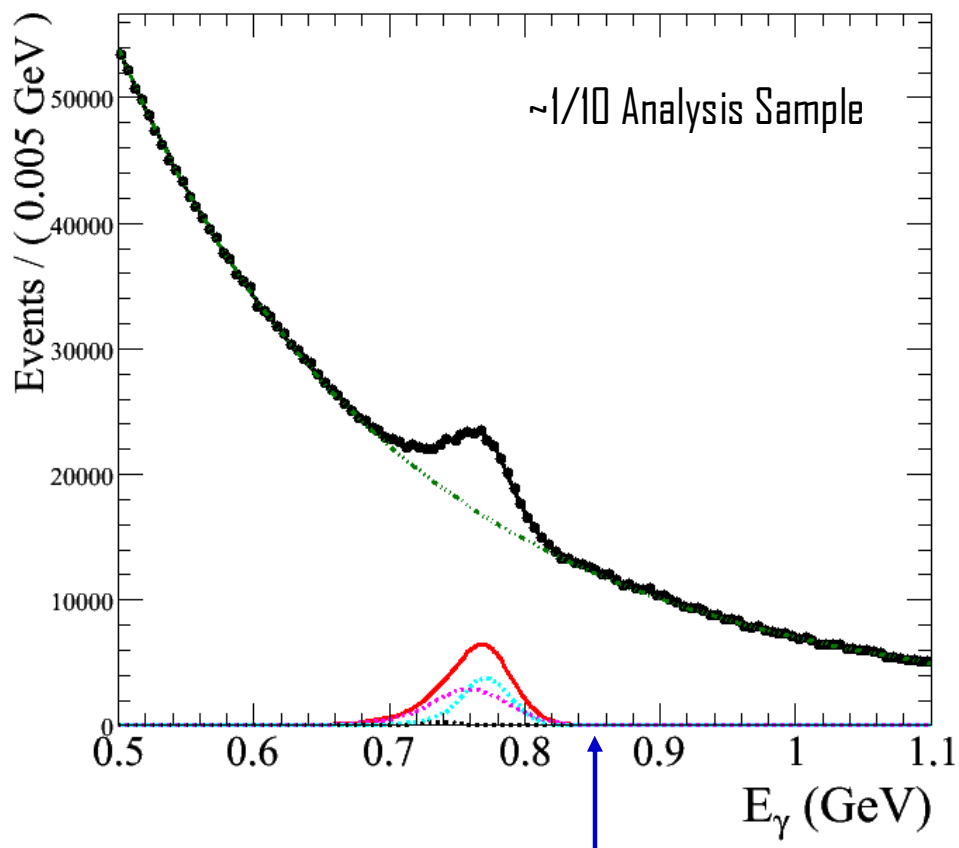
The Inclusive Photon Spectrum

Peaking background component:

Radiative return from Y(3S) to Y(1S): $e^+e^- \rightarrow \gamma_{ISR}\, Y(1S)$





[$E_{\gamma_{ISR}}$ = 856 MeV]

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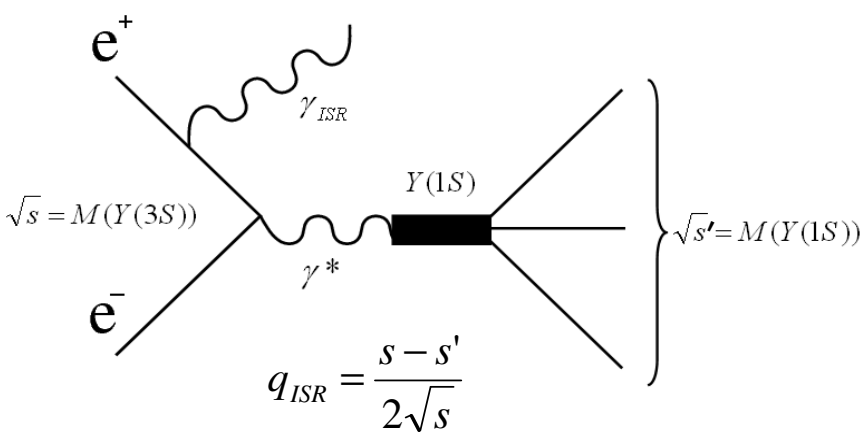

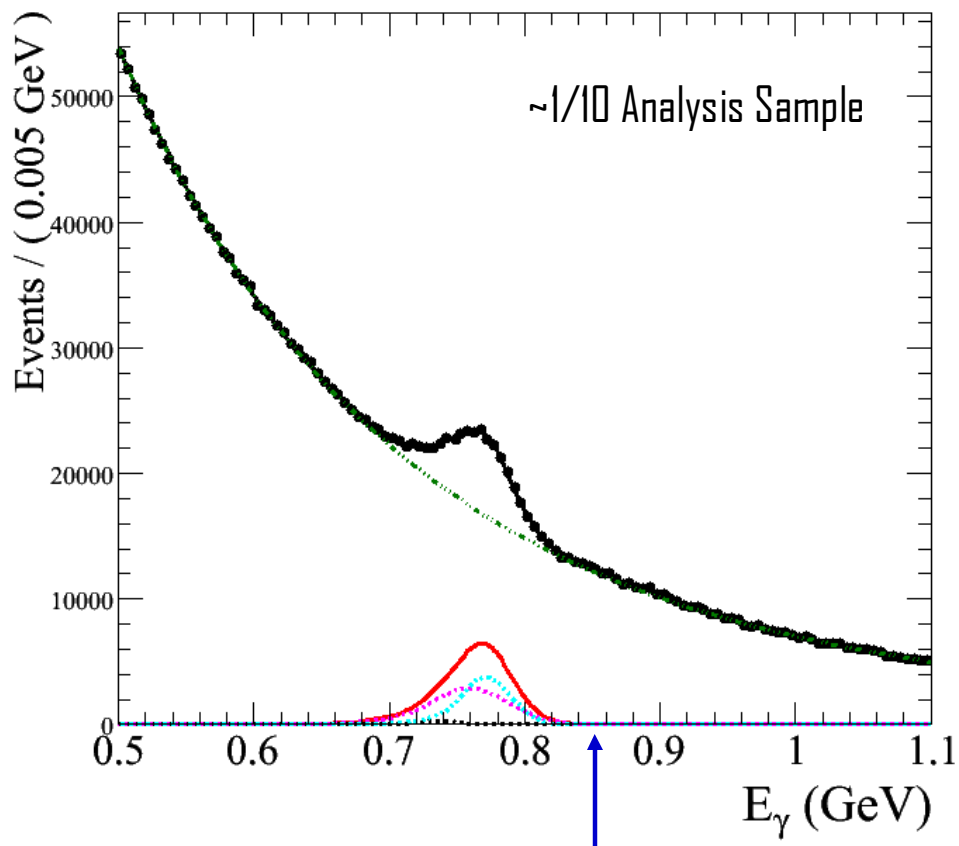

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☞ Depending on η_b mass, the peaks may overlap!

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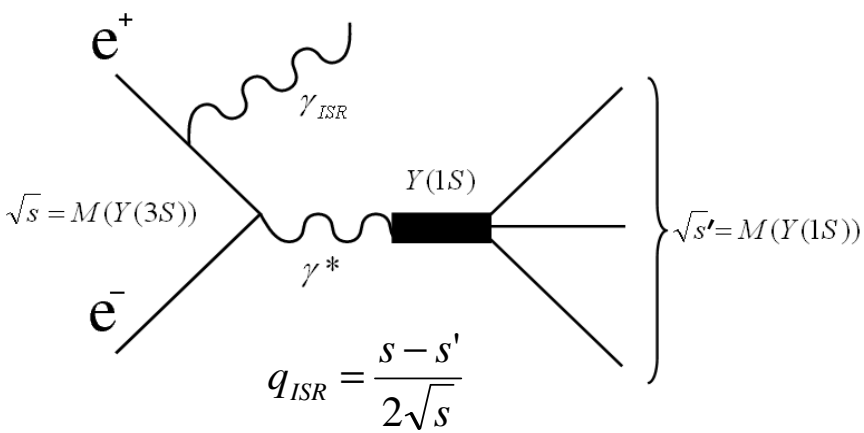

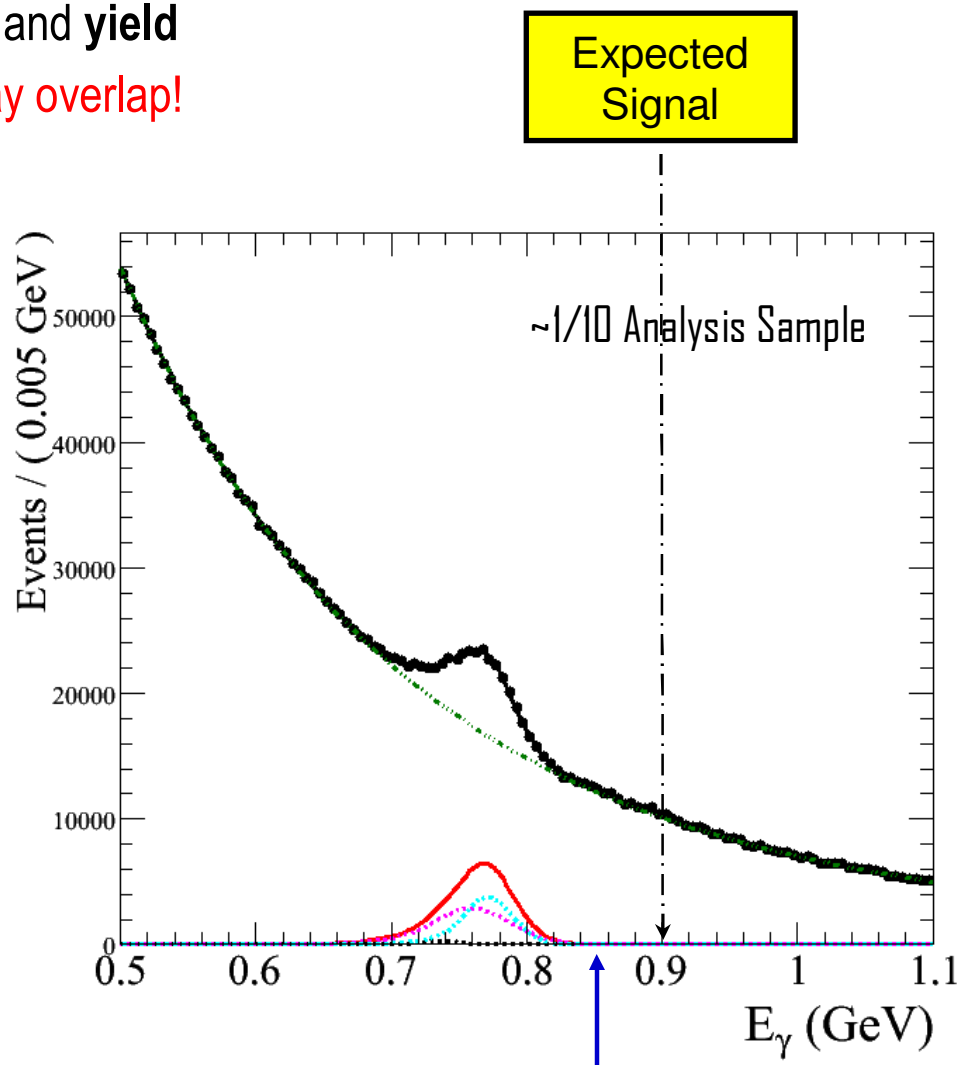

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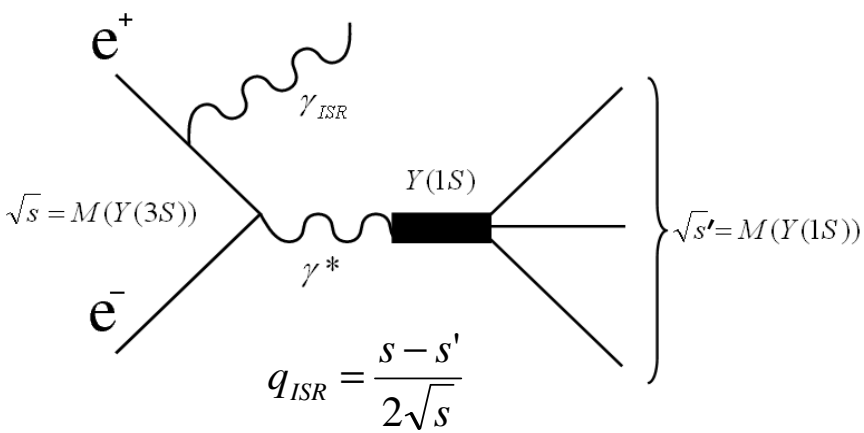

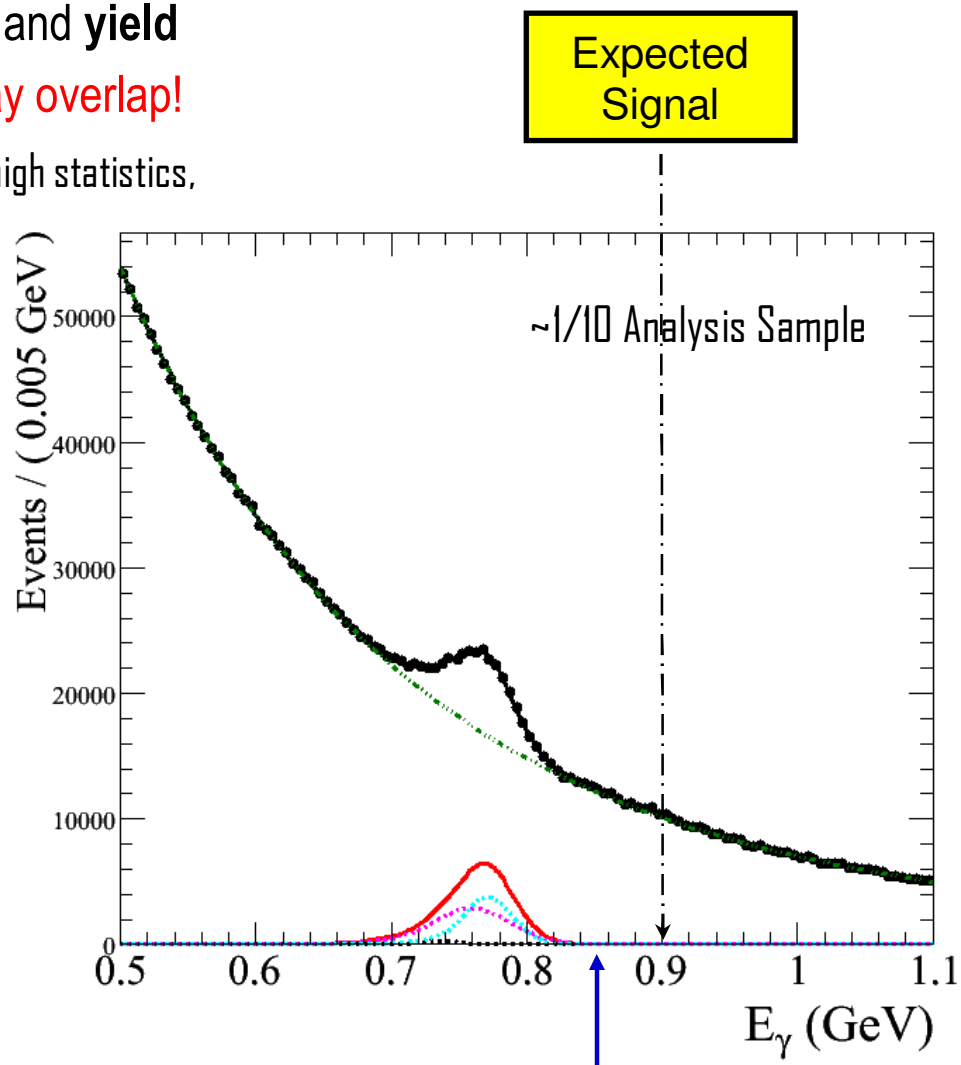

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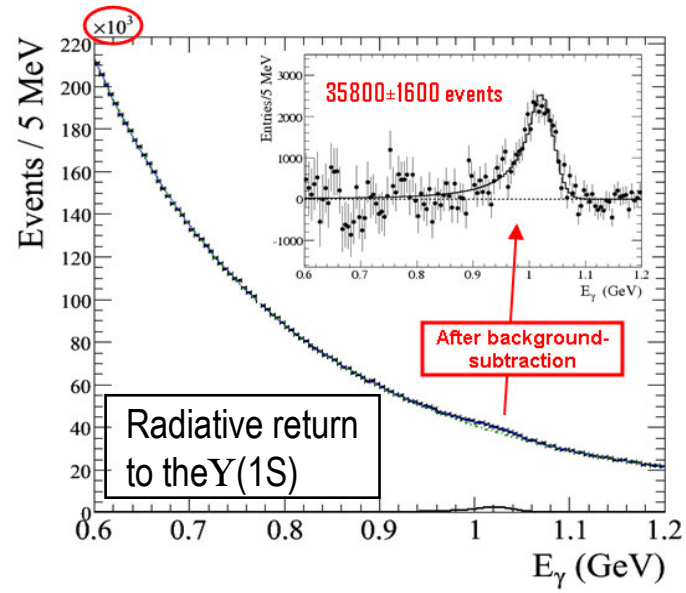

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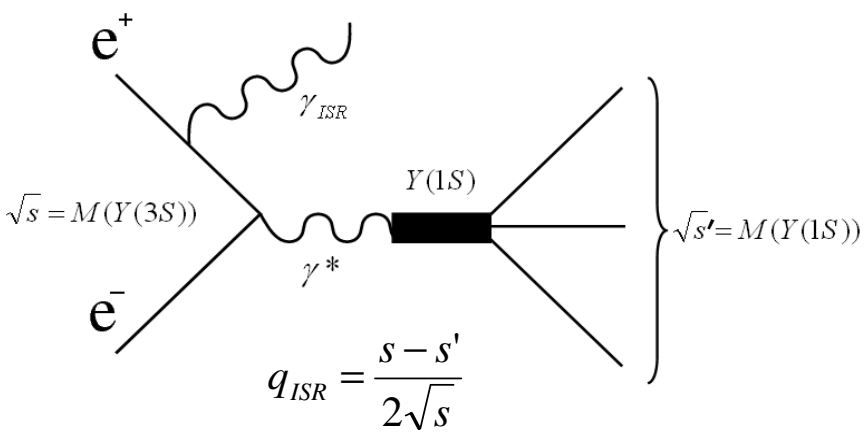

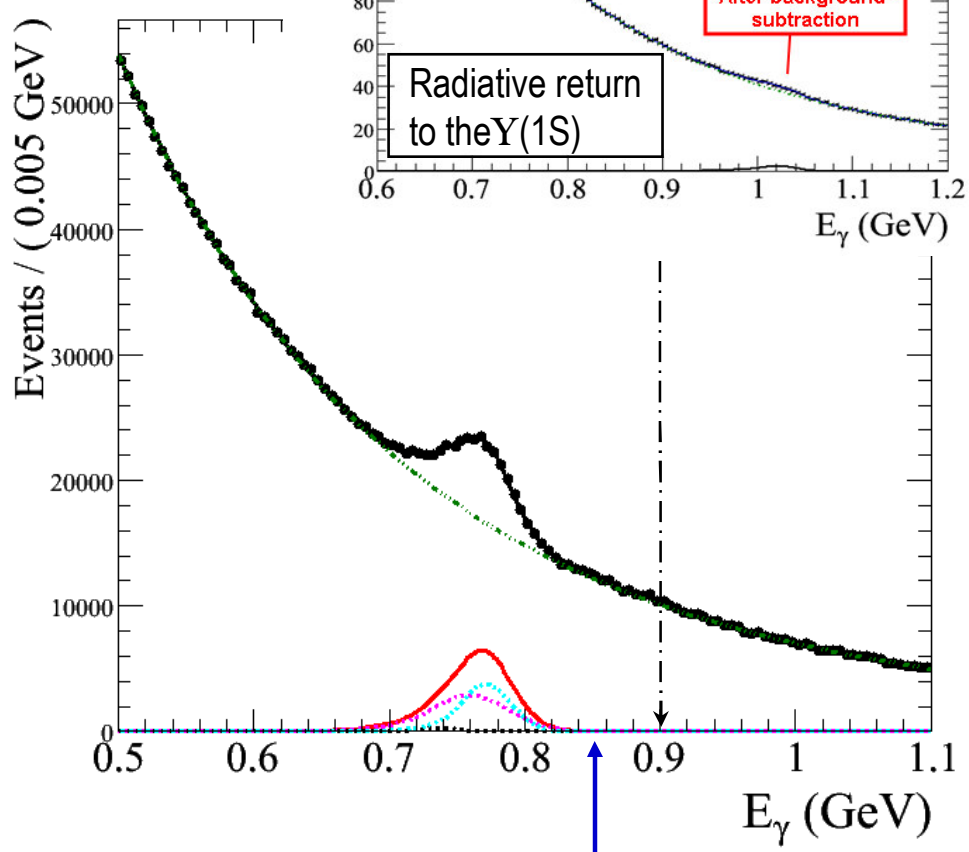

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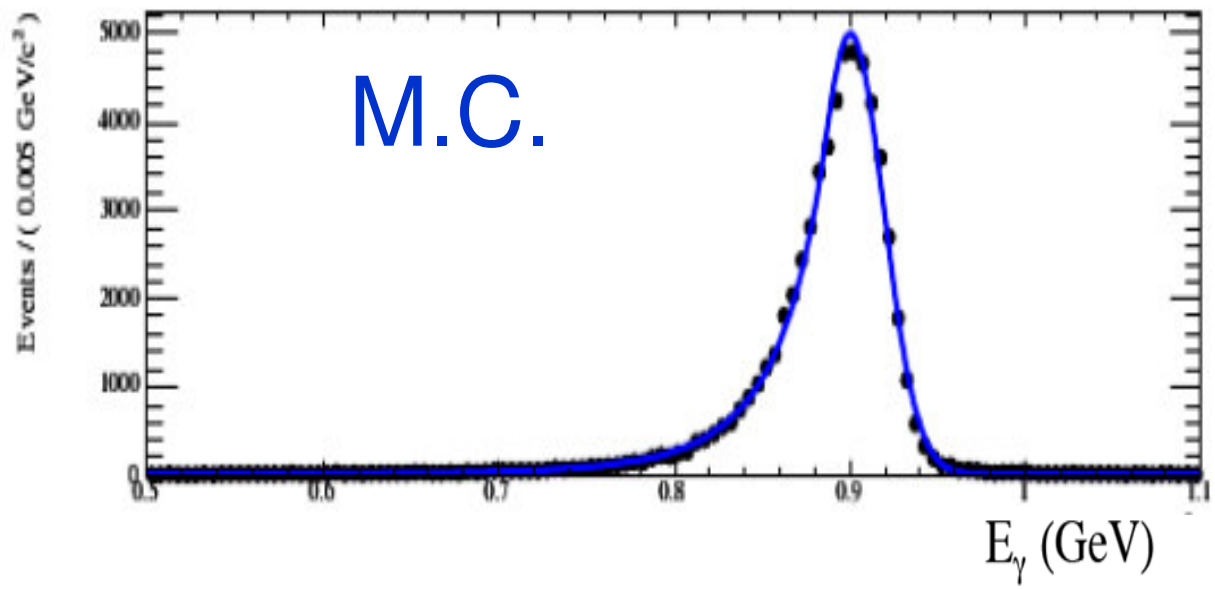
Signal Parametrization

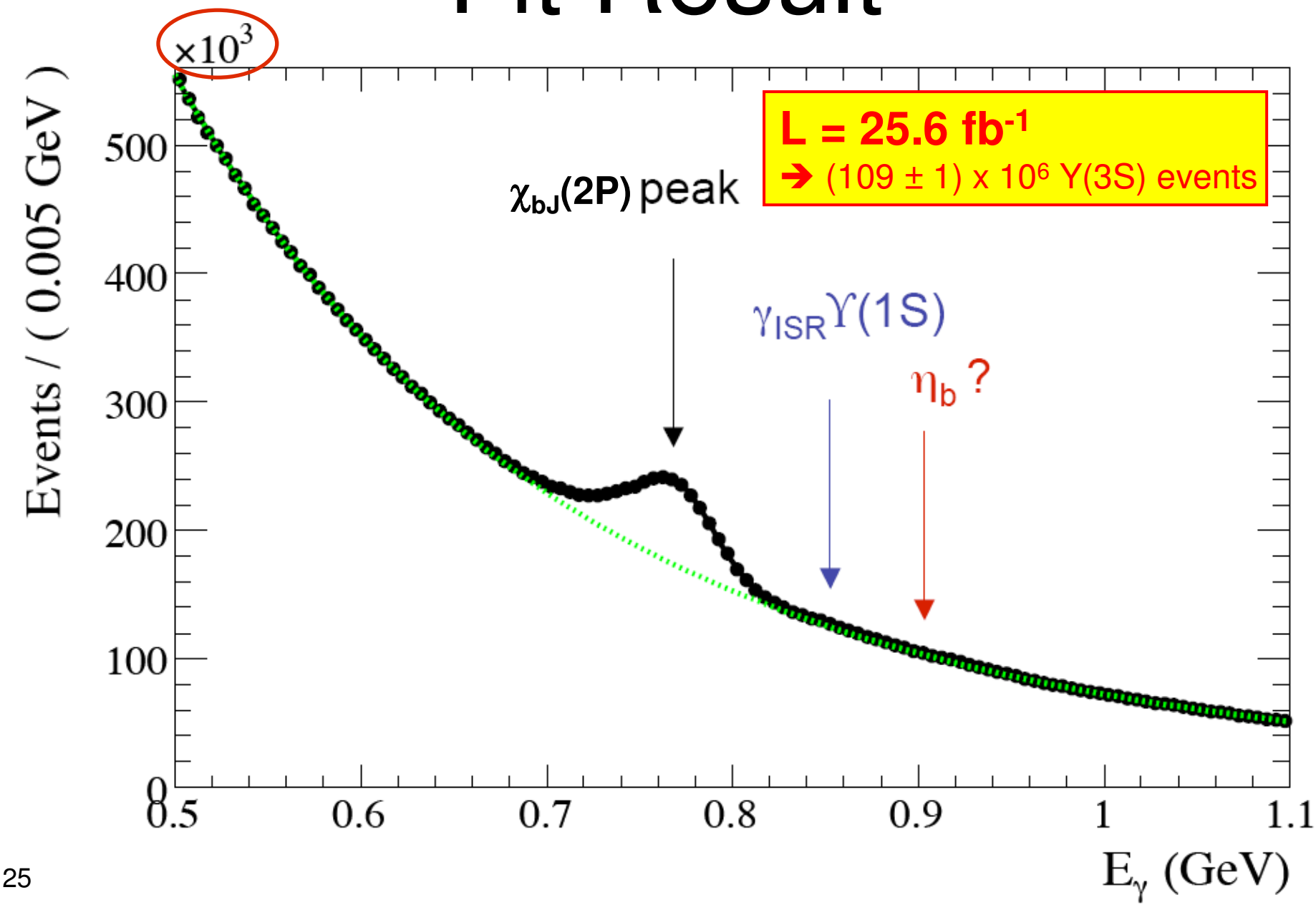
$\Upsilon(3S) \rightarrow \gamma\, \eta_b(1S)$ parametrization:

PDF: Crystal Ball $\otimes$ Breit-Wigner
Width of the Breit-Wigner fixed 10 MeV

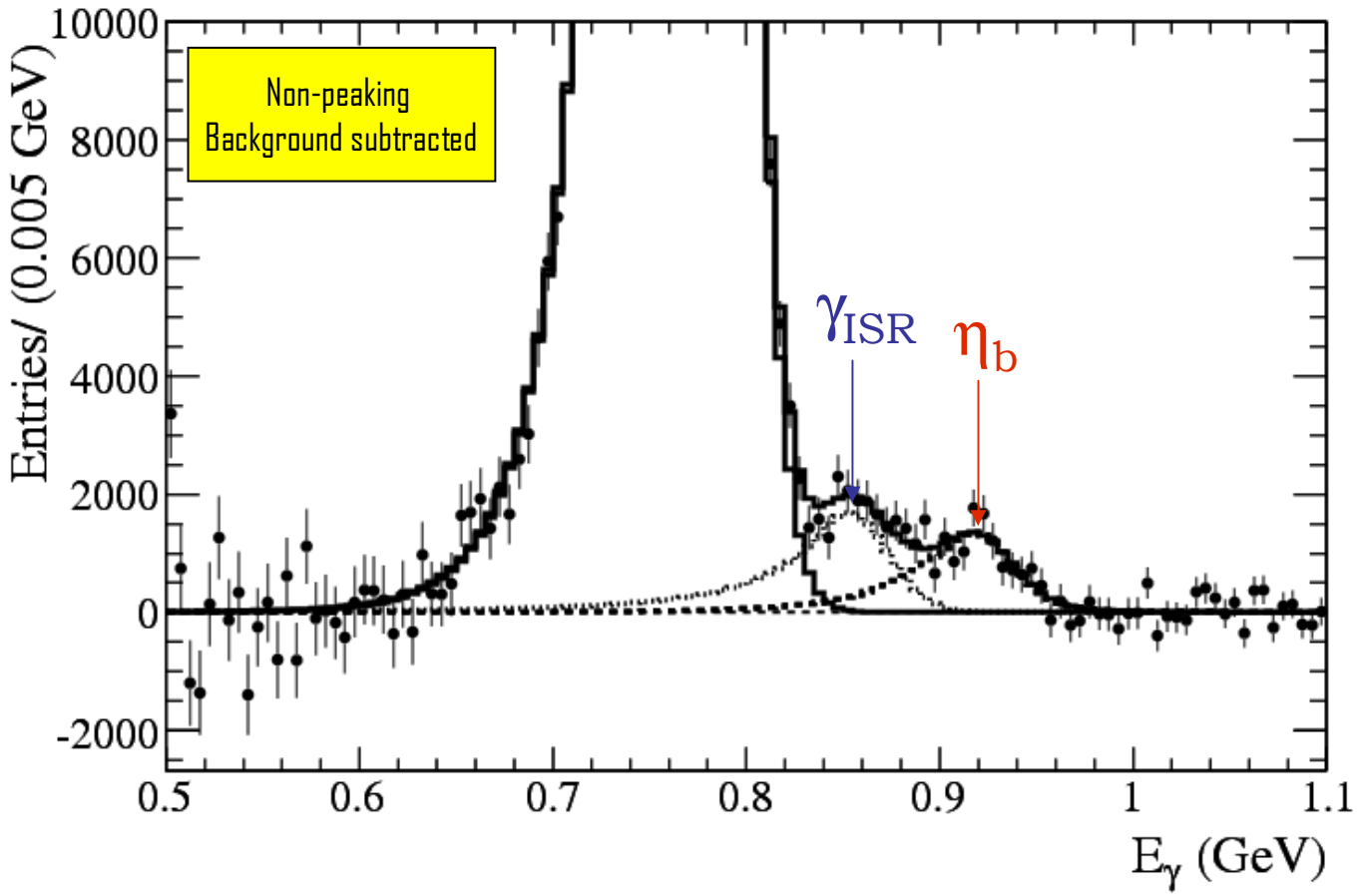
– Crystal Ball lineshape obtained from simulated events



Fit Result


×10^3
Events / (0.005 GeV)
500
400
300
200
100
0
0.5
0.6
0.7
0.8
0.9
1
1.1
E_γ (GeV)
L = 25.6 fb^-1
➔ (109 ± 1) x 10^6 Υ(3S) events
χ_bJ(2P) peak
γ_ISR Υ(1S)
η_b ?

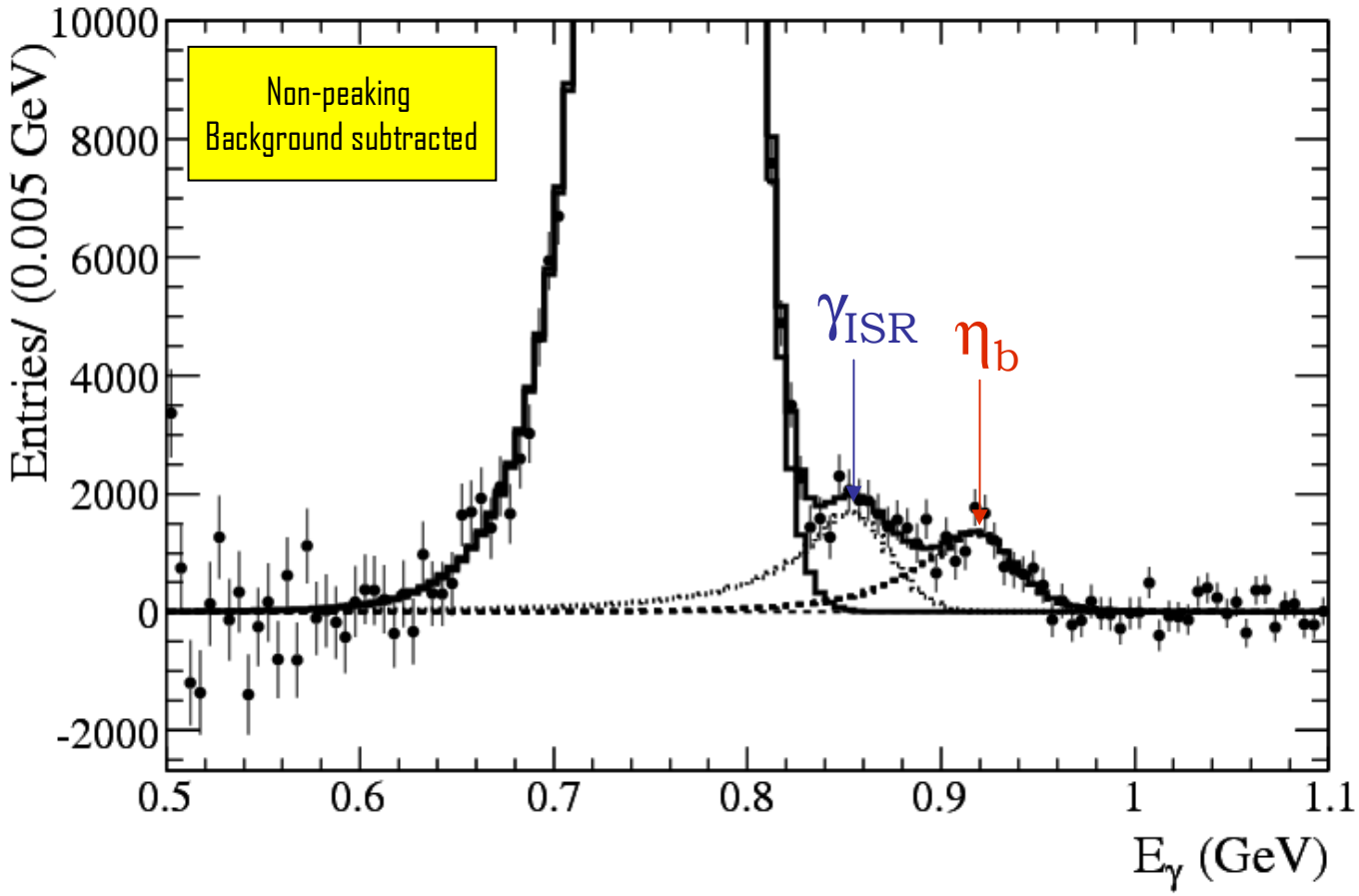
The Observation of the η_b



The Observation of the η_b

- χ_{bJ} Peak Yield : 821841 ± 2223
- γ_{ISR} Y(1S) Yield : 25153 (fixed)
- η_b Yield : 19152 ± 2010

➢ R(ISR/χ_{bJ}) ~ 1/33
➢ R(η_b/χ_{bJ}) ~ 1/43



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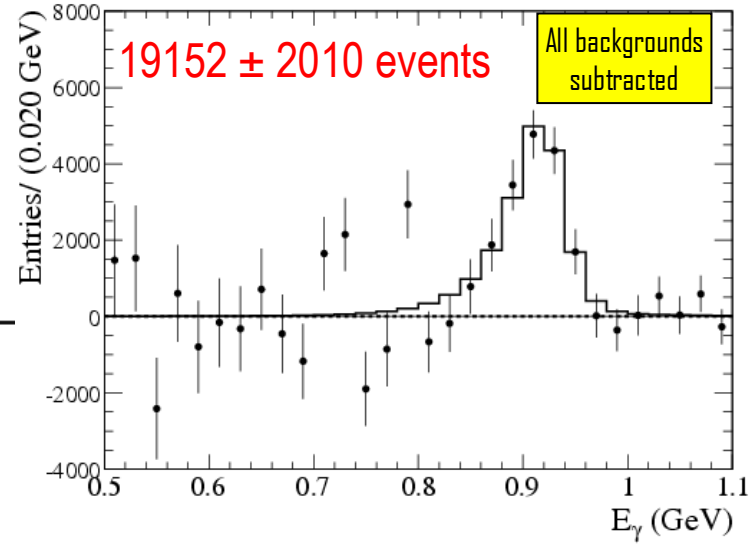
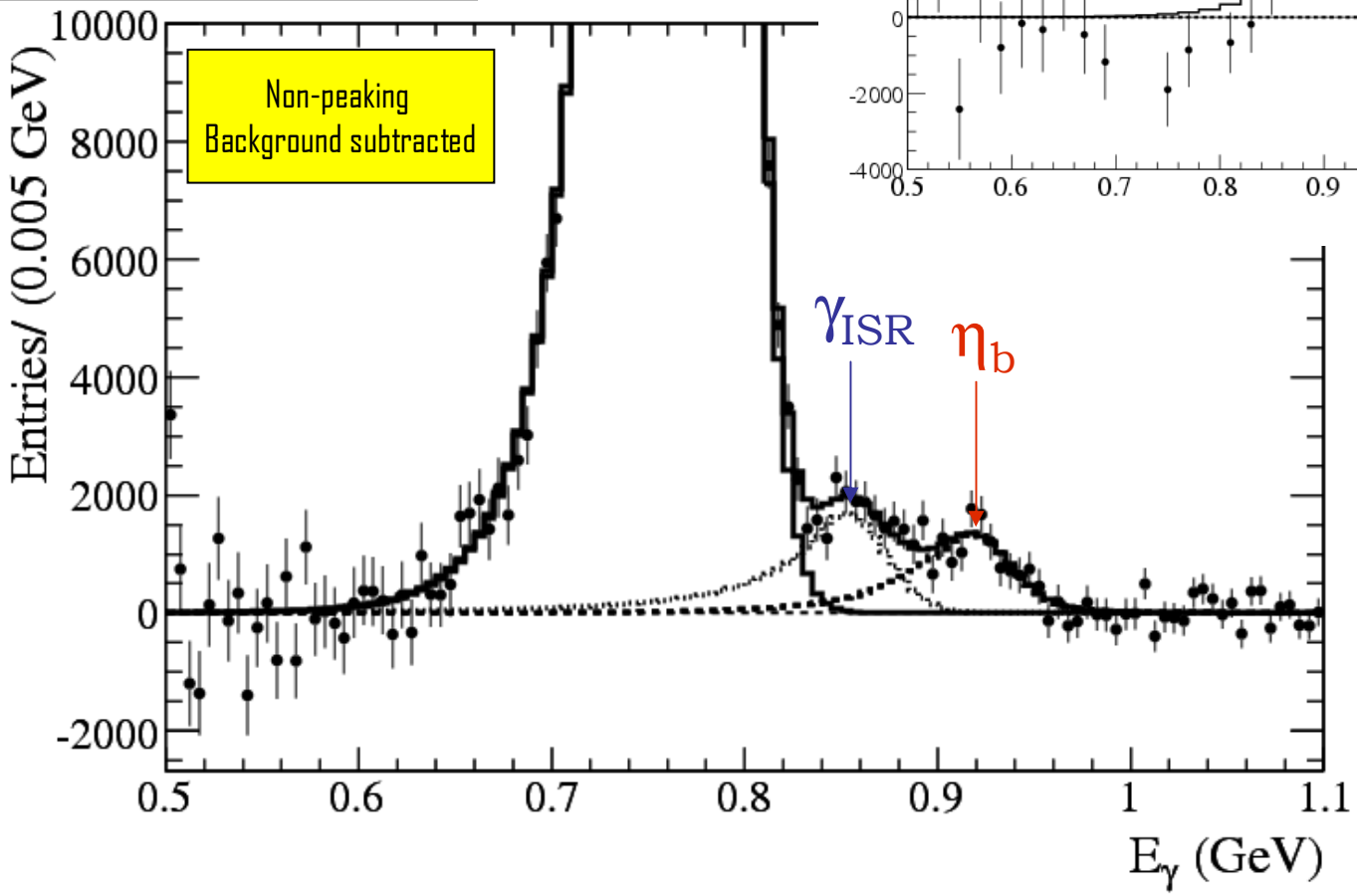




Summary of Results

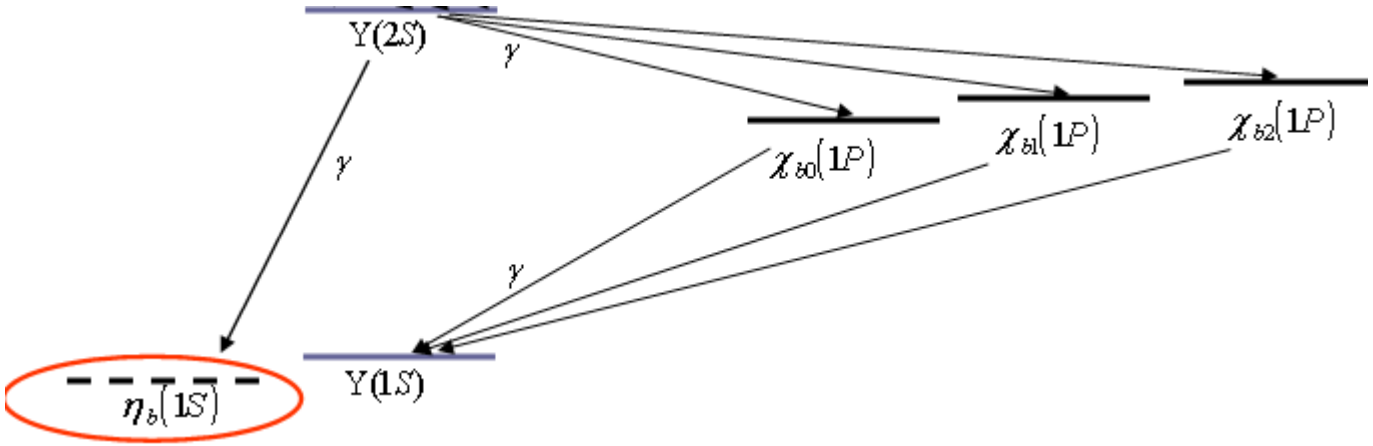
- Signal Yield :
  - Estimate of Branching Fraction (expected transition rate):

➔ BF ($\Upsilon(3S) \to \gamma\, \eta_b$) = (4.5 ± 0.5 [stat.] ± 1.2 [syst.]) x 10^{-4}

- Mass of the $\eta_b(1S)$:
  - Peak in γ energy spectrum at $E_\gamma = 921.2^{+2.1}_{-2.8}(\mathrm{stat})\,\mathrm{MeV}$
  - Corresponds to η_b mass $9388.9^{+3.1}_{-2.3}(\mathrm{stat})\,\mathrm{MeV}/c^2$
  - The hyperfine ($\Upsilon(1S)$-$\eta_b(1S)$) mass splitting is $71.4^{+2.3}_{-3.1}(\mathrm{stat})\,\mathrm{MeV}/c^2$

The Search for the η_b in $\Upsilon(3S) \rightarrow \gamma\,\eta_b(1S)$ Decay

The Search for the η_b in $\Upsilon(2S) \rightarrow \gamma\,\eta_b(1S)$ Decay



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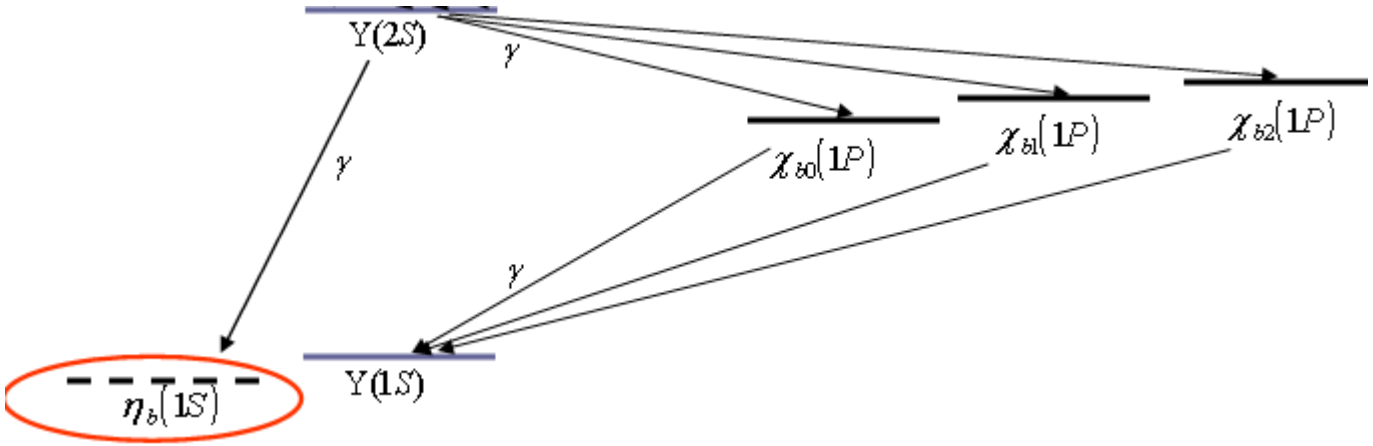

In c.m. frame: $E_\gamma = \dfrac{s - m^2}{2\sqrt{s}}$ $\sqrt{s}$ = c.m. energy
m = m(η_b)

– For η_b mass m = 9.4 GeV/c^2 ➔ monochromatic line in E_γ spectrum at 604 MeV, i.e. look for a bump near 600 MeV in inclusive photon energy spectrum from data taken at the $\Upsilon(2S)$

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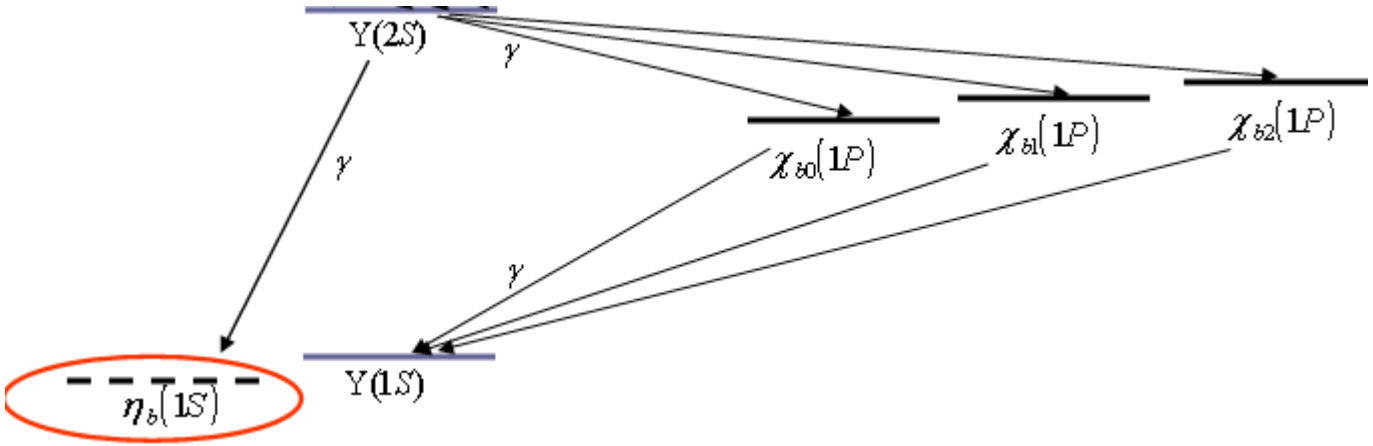

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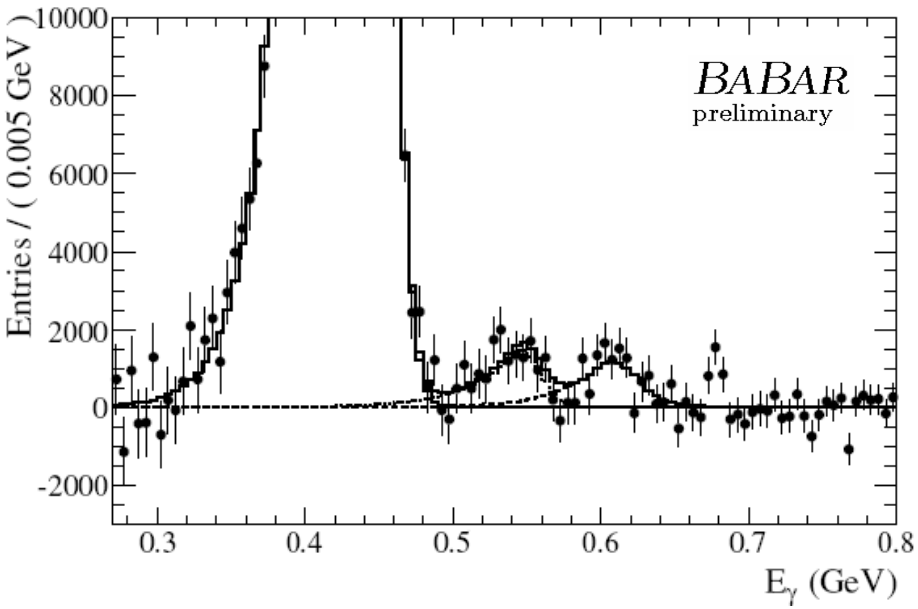
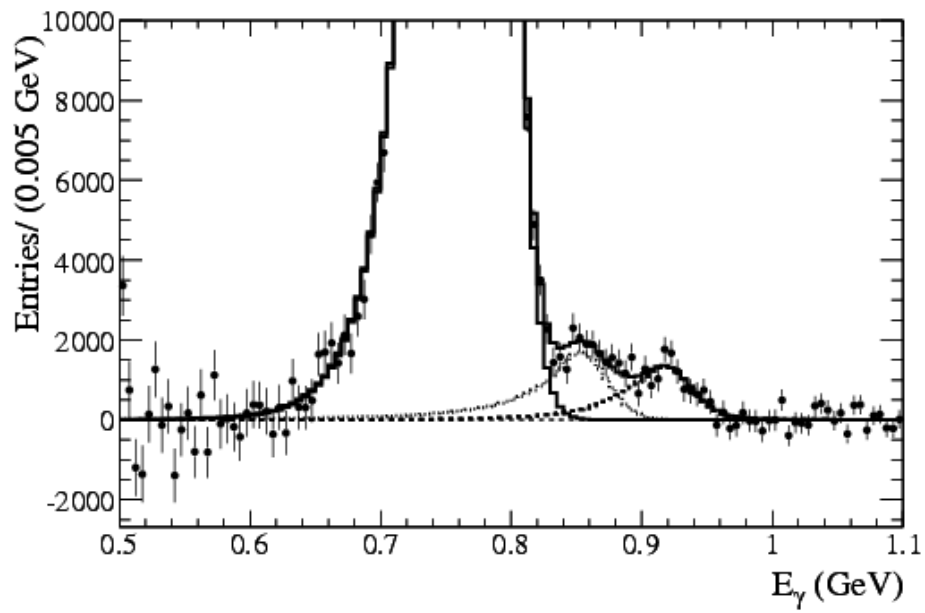
Data Sample ~ 100 x 10^6 $\Upsilon(2S)$ events

Similar analysis strategy in $\Upsilon(2S) \rightarrow \gamma\, \eta_b$ as for $\Upsilon(3S) \rightarrow \gamma\, \eta_b$

Comparison of Eγ Spectra



Υ(2S) spectrum



Υ(3S) spectrum

Results from Y(2S) and Y(3S) analyses are consistent!

Summary of η_b Results

- η_b mass:

$$Y(3S) \quad \text{analysis:} \qquad m(\eta_b) = 9388.9^{+3.1}_{-2.3} \pm 2.7 \ \text{MeV}/c^2$$

Phys.Rev.Lett.100;06200(2008)

$$Y(2S) \quad \text{analysis:} \qquad m(\eta_b) = 9392.9^{+4.6}_{-4.8} \pm 1.8 \ \text{MeV}/c^2$$

arXiv : 0903.1124 (submitted to PRL)

- Hyperfine splitting:

$$Y(3S) \quad \text{analysis:} \qquad m(\Upsilon(1S)) - m(\eta_b) = 71.4^{+2.3}_{-3.1} \pm 2.7 \ \text{MeV}/c^2$$

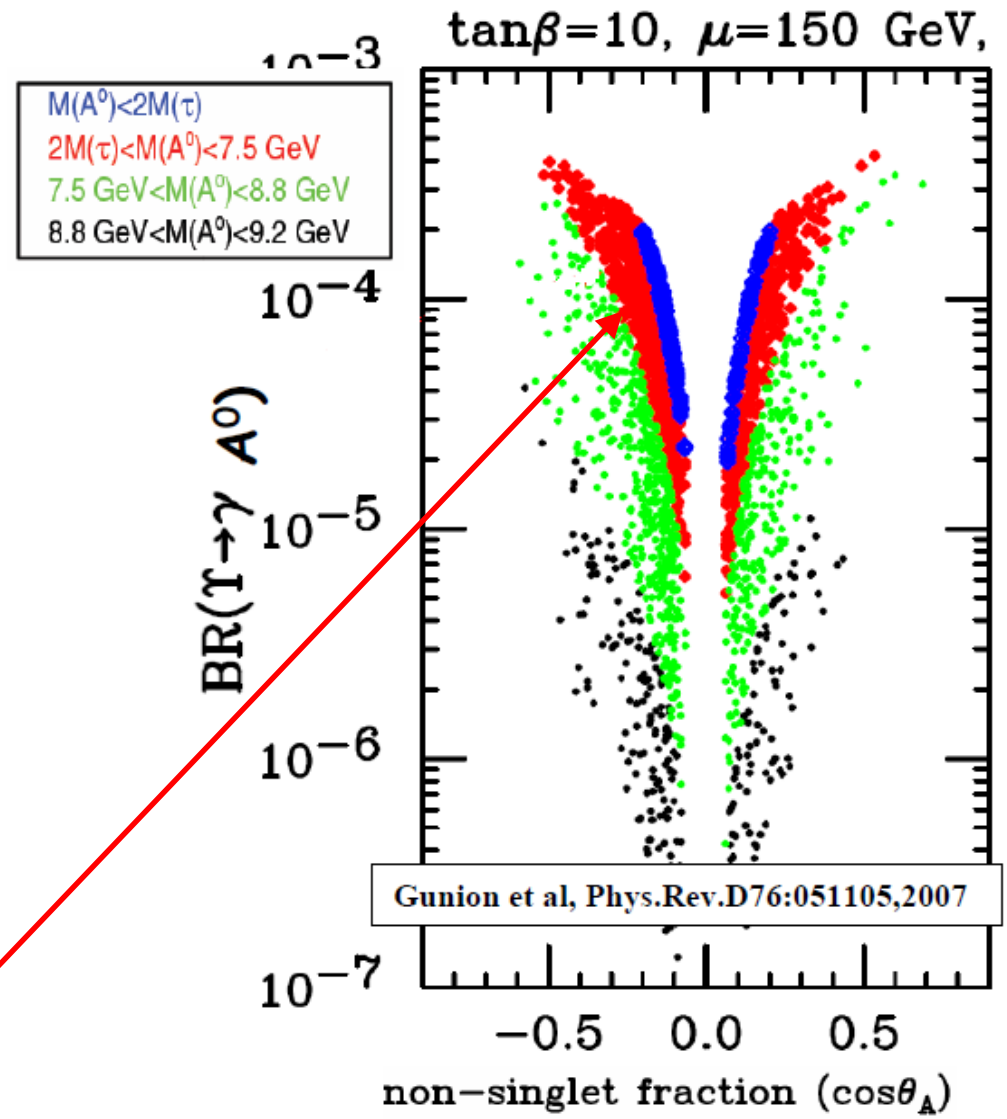
$$Y(2S) \quad \text{analysis:} \qquad m(\Upsilon(1S)) - m(\eta_b) = 67.4^{+4.8}_{-4.6} \pm 1.9 \ \text{MeV}/c^2$$

❖ Combined mass is $m(\eta_b(1S)) = 9390.4 \pm 3.1$ MeV/c^2 resulting in a hyperfine splitting of 69.9 ± 3.1 MeV/c^2

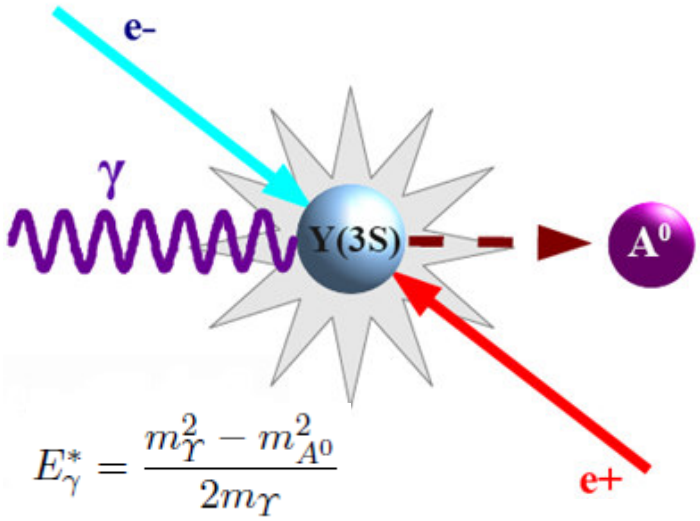
Searches for light *Higgs-like* particle in Υ(3S, 2S) decays

Light Higgs in NMSSM

- Next-to-Minimal Supersymmetric Standard Model (NMSSM) introduces a **singlet Higgs field**, which combines with electroweak doublet member to **produces a *light* CP-odd Higgs state A^0**, m(A0) < 2 m_b (accessible to decays of Y resonances).
- **NMSSM parameter search ⇨ BF(Y(3S) → γ A^0) ~10^{-4}**

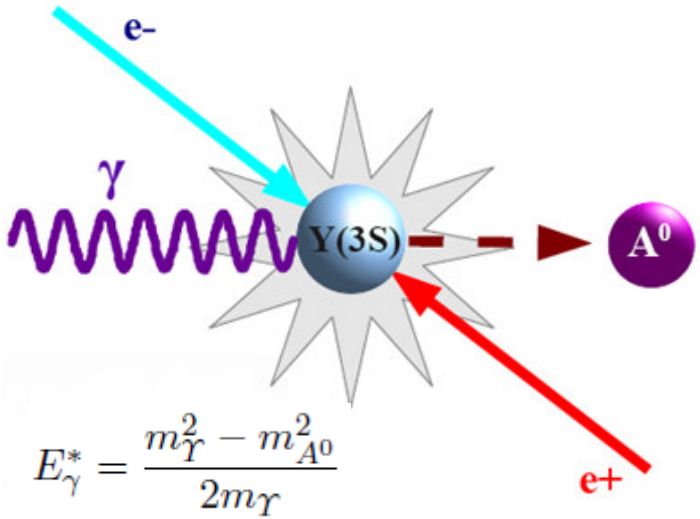


Search Strategies



- Search for an invisibly decaying particle recoiling against a single photon

Search Strategies

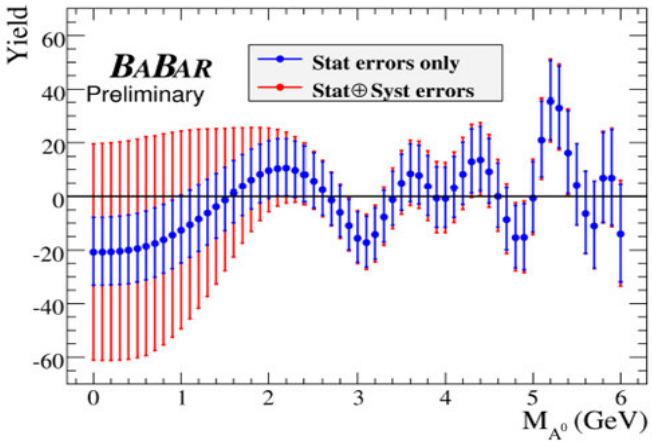


- Search for an invisibly decaying particle recoiling against a single photon

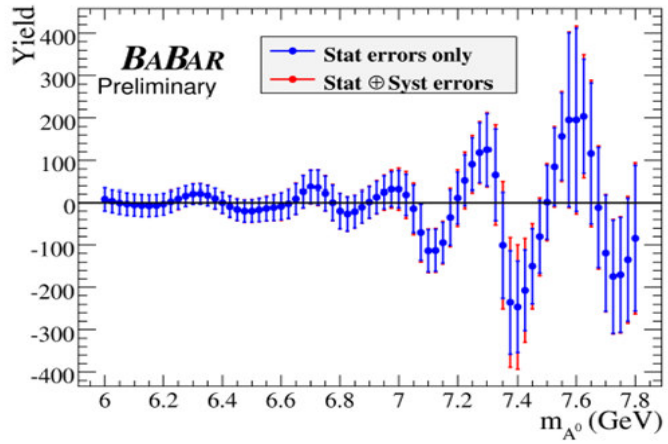
- Search in the radiative decays of the narrow Υ(2S) and Υ(3S) resonances: $\Upsilon(2S, 3S) \rightarrow \gamma A^0$, $A^0 \rightarrow \mu^+\mu^-$

Search in $\Upsilon(3S) \rightarrow \gamma A^0$, $A^0 \rightarrow$ *invisible*

Low mass region



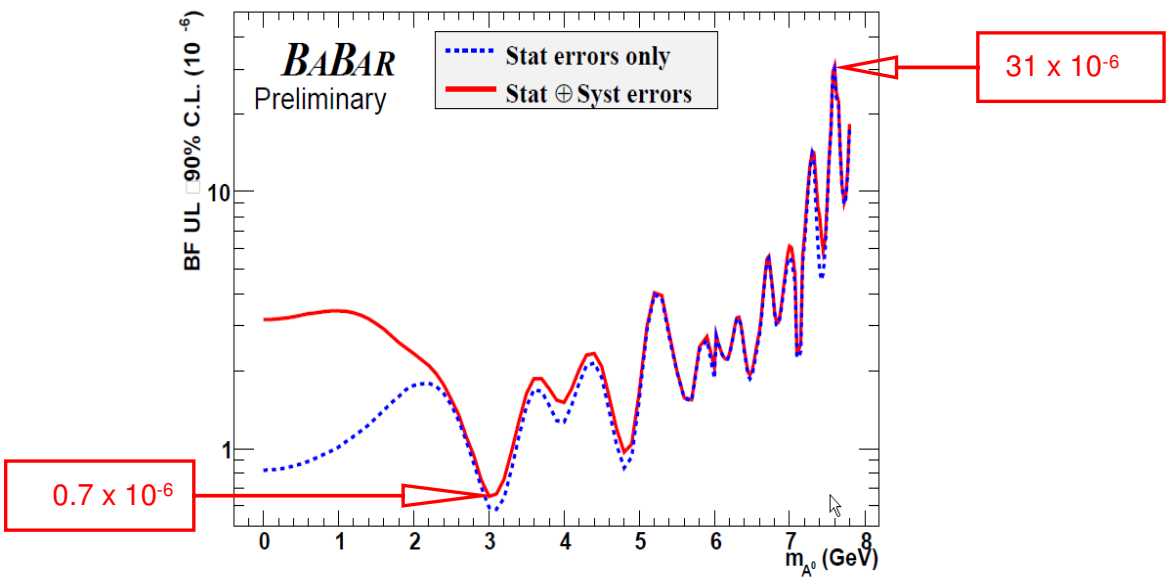
High mass region



Individual steps much finer than missing mass resolution, i.e. neighboring points highly correlated

No significant excess found; largest significance 2.6 σ at 5.2 GeV

Combine to extract upper limits on BF as a function of A^0 mass



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

No significant signal found

Upper limits (90% CL) range: $(0.25\text{-}5.2)\times10^{-6}$

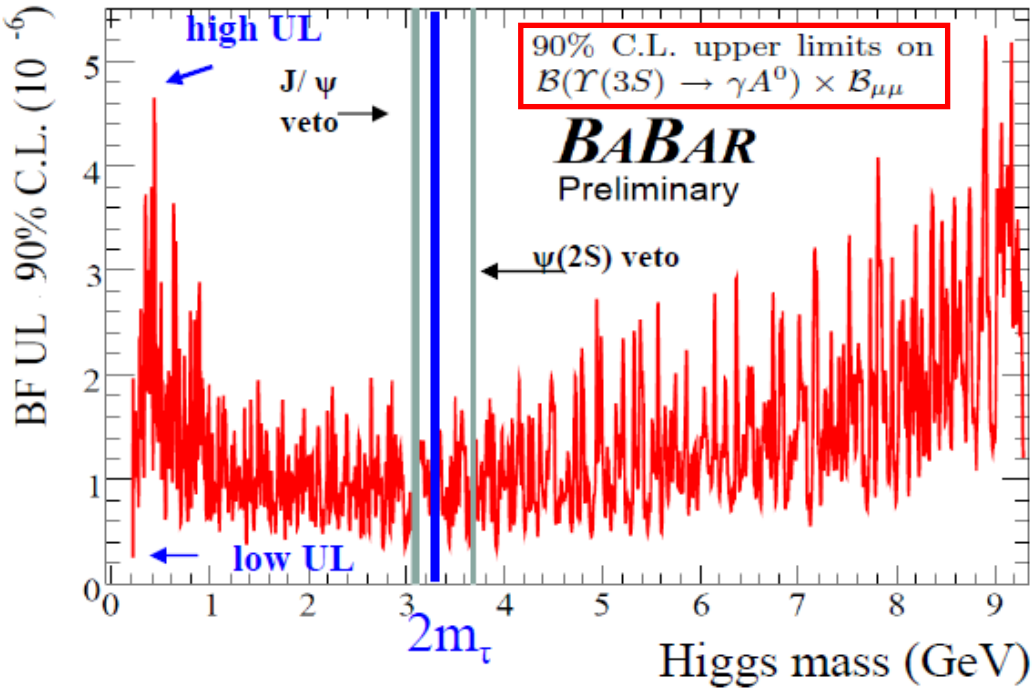
mass region $m_{\mu\mu} < 2m_\tau$:

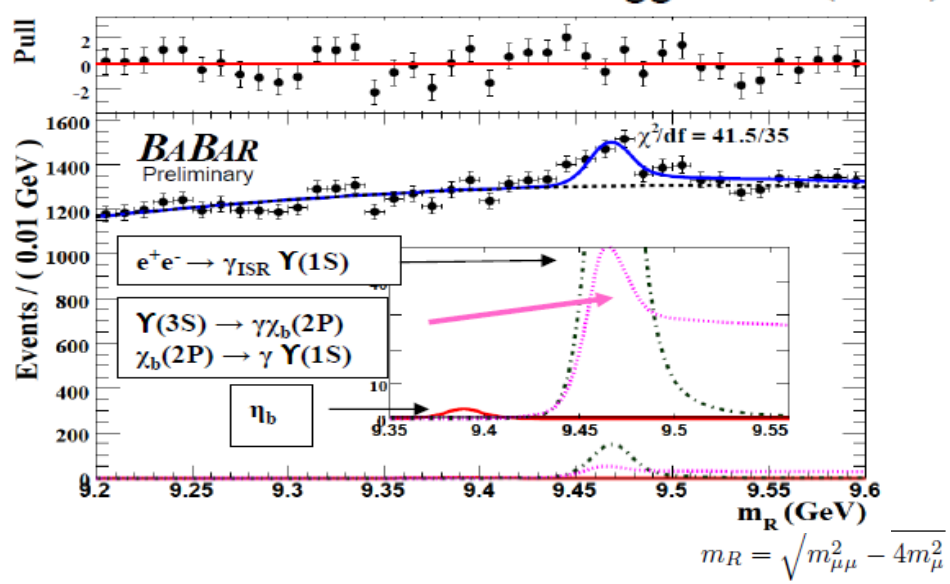
$BF \in (0.25-4.7)\times10^{-6}$

mass region $m_{\mu\mu} = 0.214\,\mathrm{GeV}/c^2$:

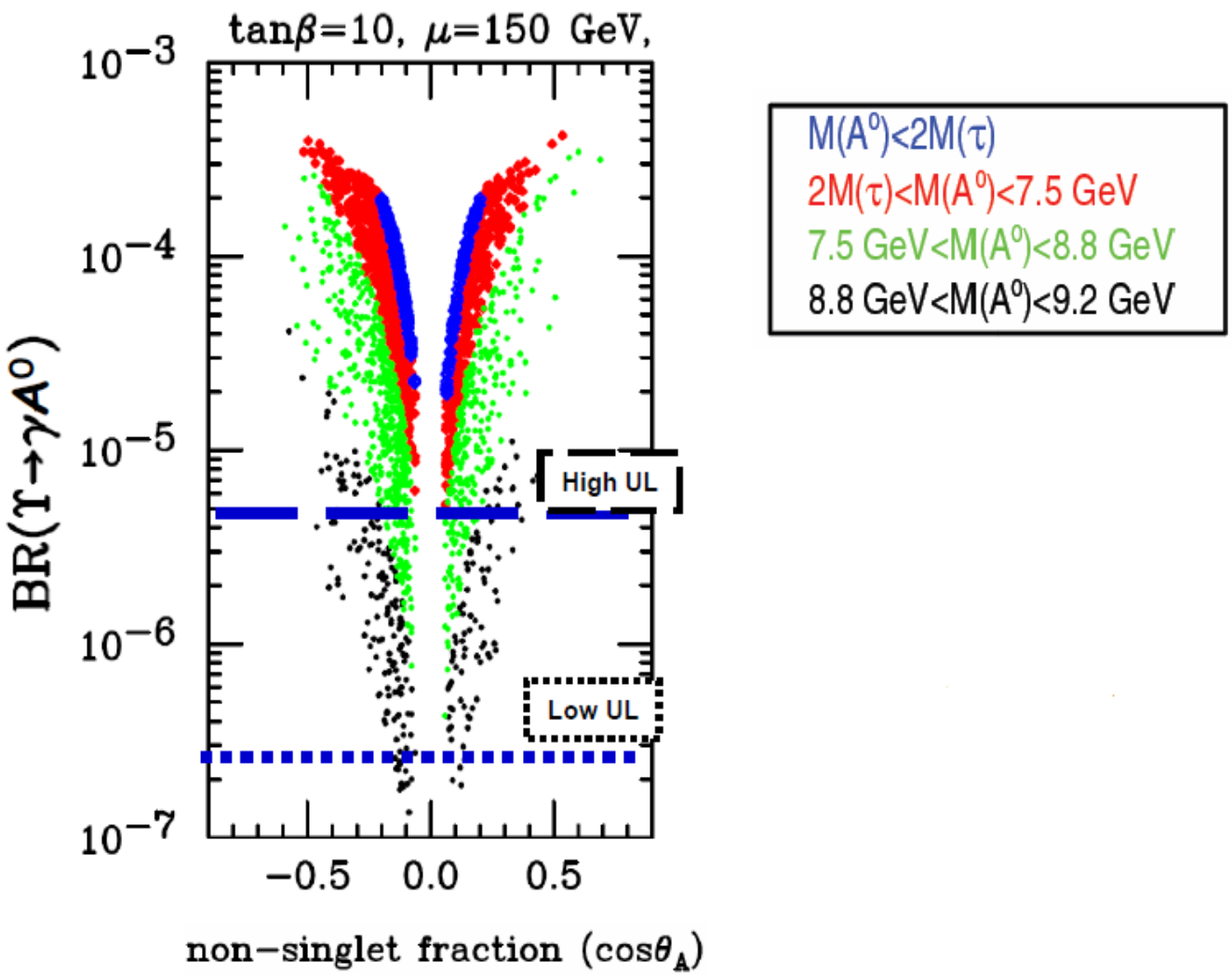
$\mathrm{BF} = (0.12^{+0.43}_{-0.41} \pm 0.17)\times10^{-6}$

$\mathrm{BF} < 0.8\times10^{-6}$ (90% CL)





Light Higgs Upper Limits



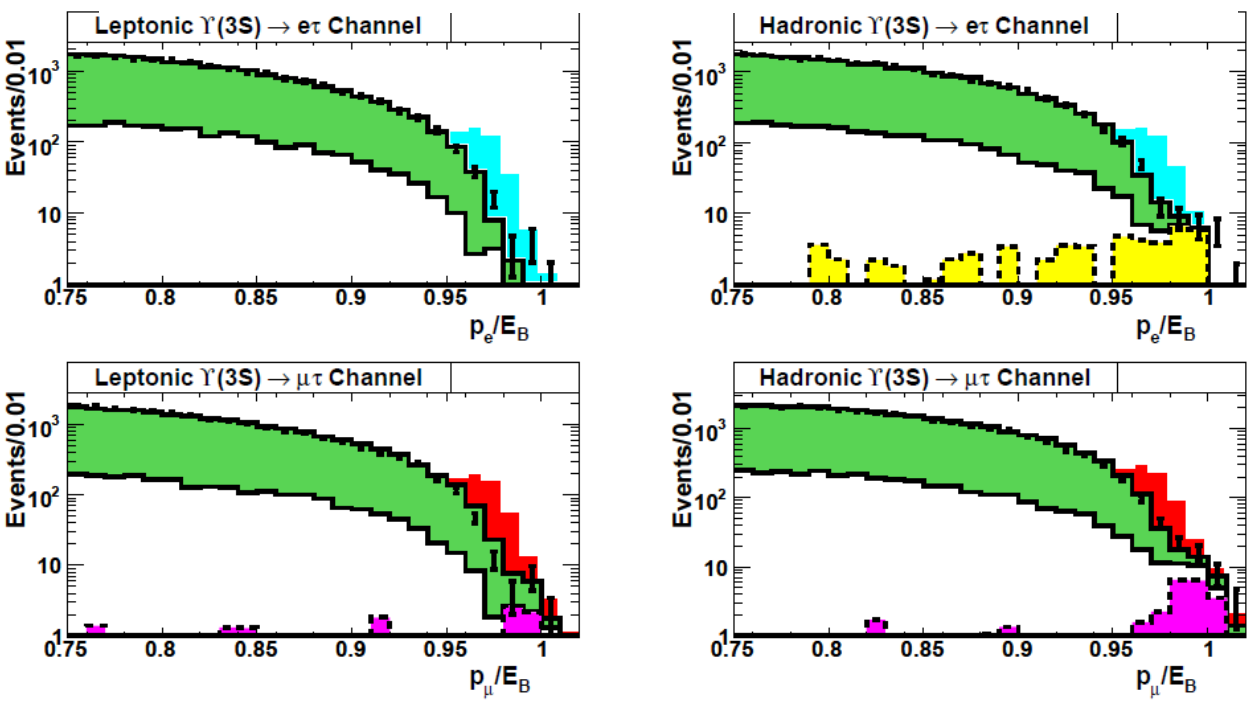
Upper limits rule out much of the parameter space allowed by the light Higgs models

The Search for the Lepton-Flavor Violating Decays $\Upsilon(3S) \to e^{\pm}\tau^{\mp}$ and $\Upsilon(3S) \to \mu^{\pm}\tau^{\mp}$

Search for the Lepton-Flavor Violating Decays $\Upsilon(3S) \to e^{\pm}\tau^{\mp}$ and $\Upsilon(3S) \to \mu^{\pm}\tau^{\mp}$

- If new particles contributing to charged lepton-flavor violation couple to b quarks,
- such processes may be observable in $\Upsilon(3S)$ Decays.
  - leptonic $e\tau$ channel: $\Upsilon(3S) \to e^{\pm}\tau^{\mp}$, $\tau^- \to \mu^-\nu_\tau\bar{\nu}_\mu$
  - hadronic $e\tau$ channel: $\Upsilon(3S) \to e^{\pm}\tau^{\mp}$, $\tau^- \to \pi^-\pi^0\nu_\tau/\pi^-\pi^0\pi^0\nu_\tau$
  - leptonic $\mu\tau$ channel: $\Upsilon(3S) \to \mu^{\pm}\tau^{\mp}$, $\tau^- \to e^-\nu_\tau\bar{\nu}_e$
  - hadronic $\mu\tau$ channel: $\Upsilon(3S) \to \mu^{\pm}\tau^{\mp}$, $\tau^- \to \pi^-\pi^0\nu_\tau/\pi^-\pi^0\pi^0\nu_\tau$

Strategy: unbinned extended maximum likelihood fit to x distribution



Primary discriminant variable **x**:
x = p_e/E_B for $\Upsilon(3S) \to e\tau$ channels
x = p_μ/E_B for $\Upsilon(3S) \to \mu\tau$ channels

Signal ($\mu\tau$ production)

Signal ($e\tau$ production)

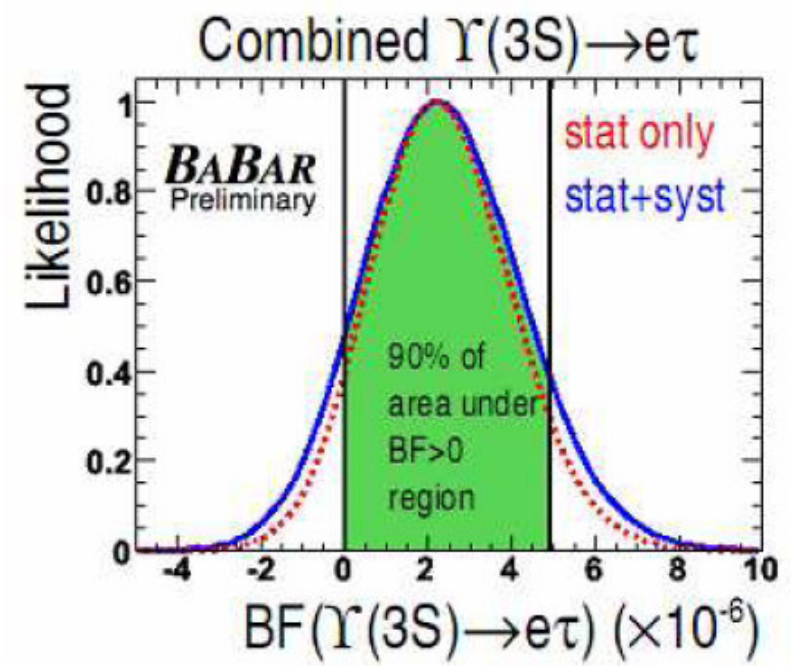
Continuum $\tau^+\tau^-$

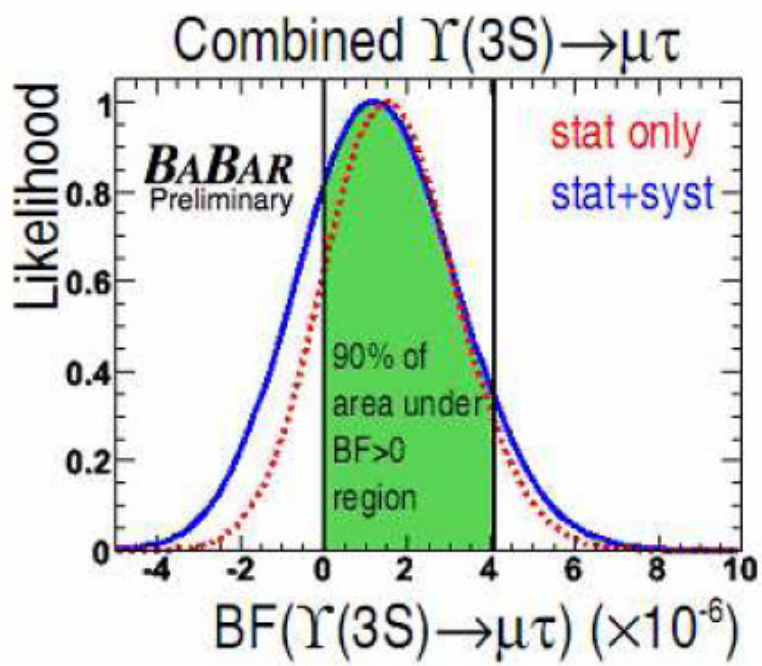
Resonant τ-pairs

Bhabha events

Continuum $\mu^+\mu^-$

$\Upsilon(3S) \to e^{\pm}\tau^{\mp}$ and $\Upsilon(3S) \to \mu^{\pm}\tau^{\mp}$ BF Measurements





$$BF(\Upsilon(3S) \to e\tau) < 5.0 \times 10^{-6}$$

(first upper limit)

$$BF(\Upsilon(3S) \to \mu\tau) < 4.1 \times 10^{-6}$$

(>4 times lower than previous upper limit)

The e^+e^- Cross Section Scan

Precision scan in E_{CM} from 10.54 GeV to 11.20 GeV

- 5 MeV steps with 25 pb^{-1} at each step ($\int \mathcal{L} \approx 3.3\, fb^{-1}$)
- 8 steps at Υ(6S) ($\int \mathcal{L} \approx 0.6\, fb^{-1}$)

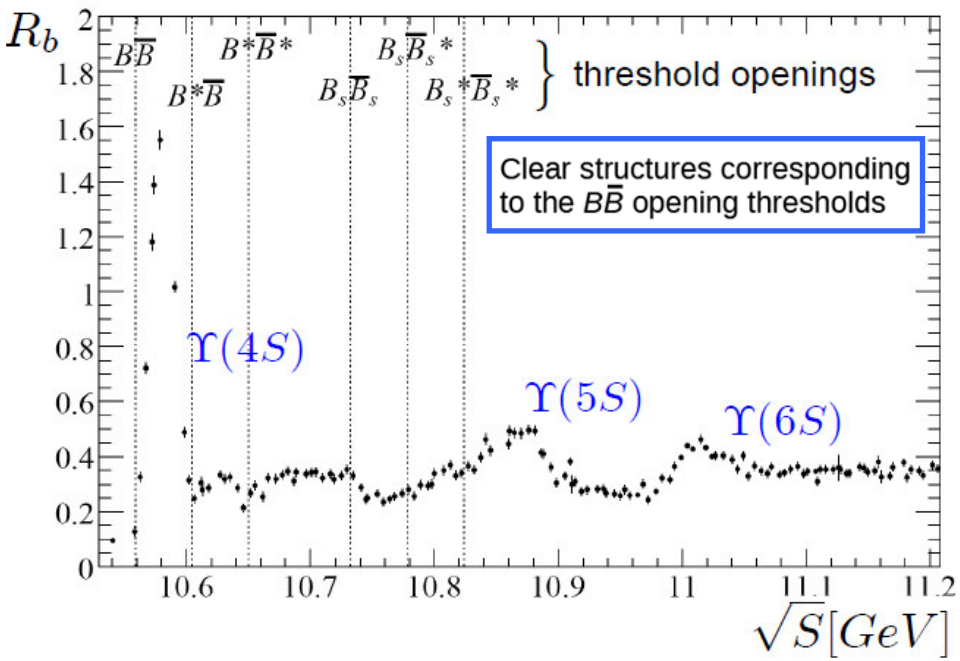
Inclusive approach

Search for unexpected structures in the inclusive hadronic cross section

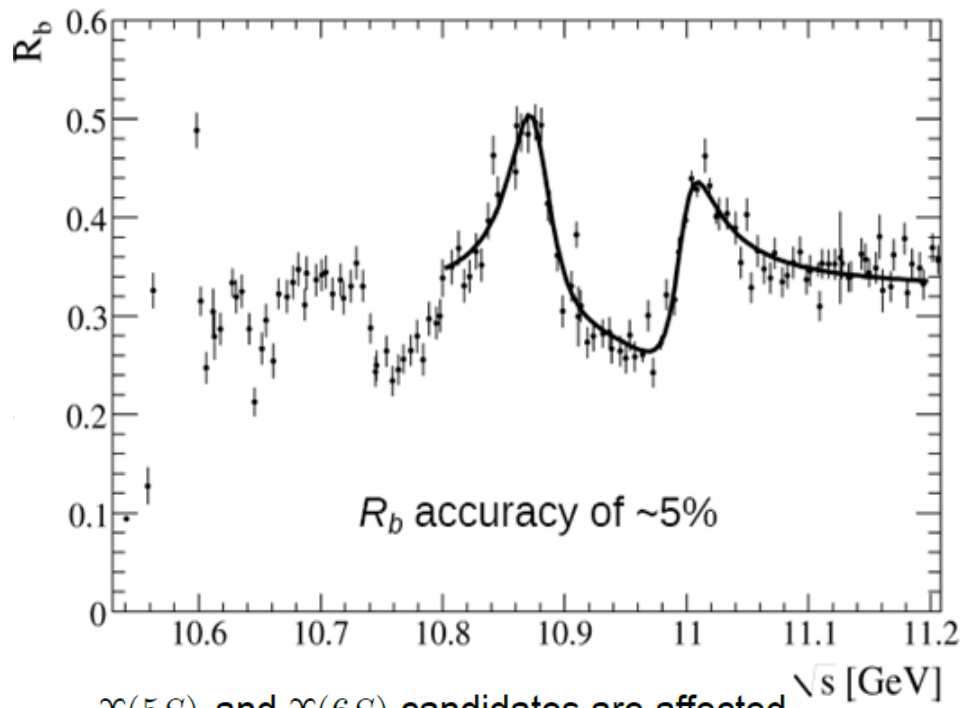
$$R_b(s) = \frac{\sigma_{bb(\gamma)}(s)}{\sigma^0_{\mu\mu}(s)}$$

$\sigma_{bb(\gamma)}$: cross section of $e^+e^- \to b\bar{b}(\gamma)$

$\sigma^0_{\mu\mu} = 4\pi\alpha^2/3s$: cross section of $e^+e^- \to \mu^+\mu^-$



PRL 102, 012001 (2009)



$\Upsilon(5S)$ and $\Upsilon(6S)$ candidates are affected by threshold effects and interference

Plateau above $\Upsilon(6S)$

Fit with flat component + two interfering relativistic Breit-Wigner functions

	$\Upsilon(5S)$	$\Upsilon(6S)$
$M[MeV]$	10876 ± 2	10960 ± 2
$\Gamma[MeV]$	43 ± 4	37 ± 3

SUMMARY

- First observation of the $\eta_b(1S)$ bottomonium ground state in the decay $\Upsilon(3S) \rightarrow \gamma\, \eta_b(1S)$

- Confirmation from $\Upsilon(2S) \rightarrow \gamma\, \eta_b(1S)$

- No significant $\Upsilon(3S) \rightarrow \gamma\, A^0$ observed
  - -- Upper limits (90% CL) range from (0.7-31) x 10^{-6} for $A^0 \rightarrow$invisible
  - -- Upper limits (90% CL) range from (0.25-5.2) x 10^{-6} for $A^0 \rightarrow \mu^+\mu^-$
  - ➔ limits rule out much of the parameter space allowed by the light Higgs models.

- No charged LFV observed

$$BR(\Upsilon(3S) \rightarrow e^{\pm}\tau^{\mp}) < 5\times10^{-6} \quad (90\%\ CL)$$
$$BR(\Upsilon(3S) \rightarrow e^{\pm}\tau^{\mp}) < 4.1\times10^{-6} \quad (90\%\ CL)$$

arXiv:0812.1021[hep-ex]

- Precision scan of R_b in the energy range of 10.54 GeV < $\sqrt{s}$ < 11.20 GeV yields parameters for $\Upsilon(5S)$ and $\Upsilon(6S)$, which differ from the PDG averages (also confirmed by BELLE 's exclusive studies)