Observation of the $\eta_b(1S)$ in $\Upsilon(3S)\to\gamma\eta_b(1S)$ and bottomonium physics at BaBar

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Bottomonium physics at BaBar:

- Hadronic transitions: $\Upsilon(4S)\to\pi\pi\Upsilon(1,2S)$, $\Upsilon(4S)\to\eta\Upsilon(1S)$
- $\Upsilon(3S)\to\gamma\eta_b(1S)$
- Scan above the $\Upsilon(4S)$

Search for CP-odd light Higgs in bottomonium decays

Bottomonium

$b\bar{b}$ bound states: spectroscopic notation: $n\,^{2S+1}L_J$

fermion-antifermion: $P = (-1)^{L+1}$ $C = (-1)^{L+S}$

$\Upsilon(nS) \equiv n^3S_1$ $\eta_b(nS) \equiv n^1S_0$

$\chi_{bJ}(nP) \equiv n^3P_J$ $h_b(nP) \equiv n^1P_1$

Heavy quarks ⇒ non relativistic

- relativistic corrections in $b\bar{b}$ smaller than in $c\bar{c}$

Potential models: "Cornell" (Coulomb +linear term)

but also

Lattice NRQCD, pNRQCD: α_s, m_b, lattice spacing, ...

See e.g.:
Brambilla et al, hep-ph/0412158
Eichten et al., hep-ph/0701208

Bottomonium physics

- Spectroscopy:

  fine and hyperfine splitting (spin-dependent terms)

  mass splitting between $\Upsilon(nS)$ and $\eta_b(nS)$ depend strongly on α_s

  singlet states conspicuously missing!

- Decay widths:

  below "open" $B\bar{B}$ threshold, $b\bar{b}$ annihilate to gluons (or virtual photon)

  "OZI-rule" ⇨ narrow states

  $\Upsilon(nS) \to ggg$, γgg [2.5%] or γ^* [$\ell^+\ell^-$ ~2%] Γ=20-50 keV

  other states decay to ggg or gg depending on J odd/even

  $$\left.\begin{array}{l}\eta_b(nS),\ \chi_{b0}(nP),\ \chi_{b2}(nP) \to gg \\ h_b(nP),\ \chi_{b1}(nP) \to ggg \text{ or } gq\bar{q}\end{array}\right\}\ \begin{array}{l}\text{in the MeV range} \\ \text{None measured}\end{array}$$

  very few exclusive hadronic modes observed

- Radiative and hadronic transitions

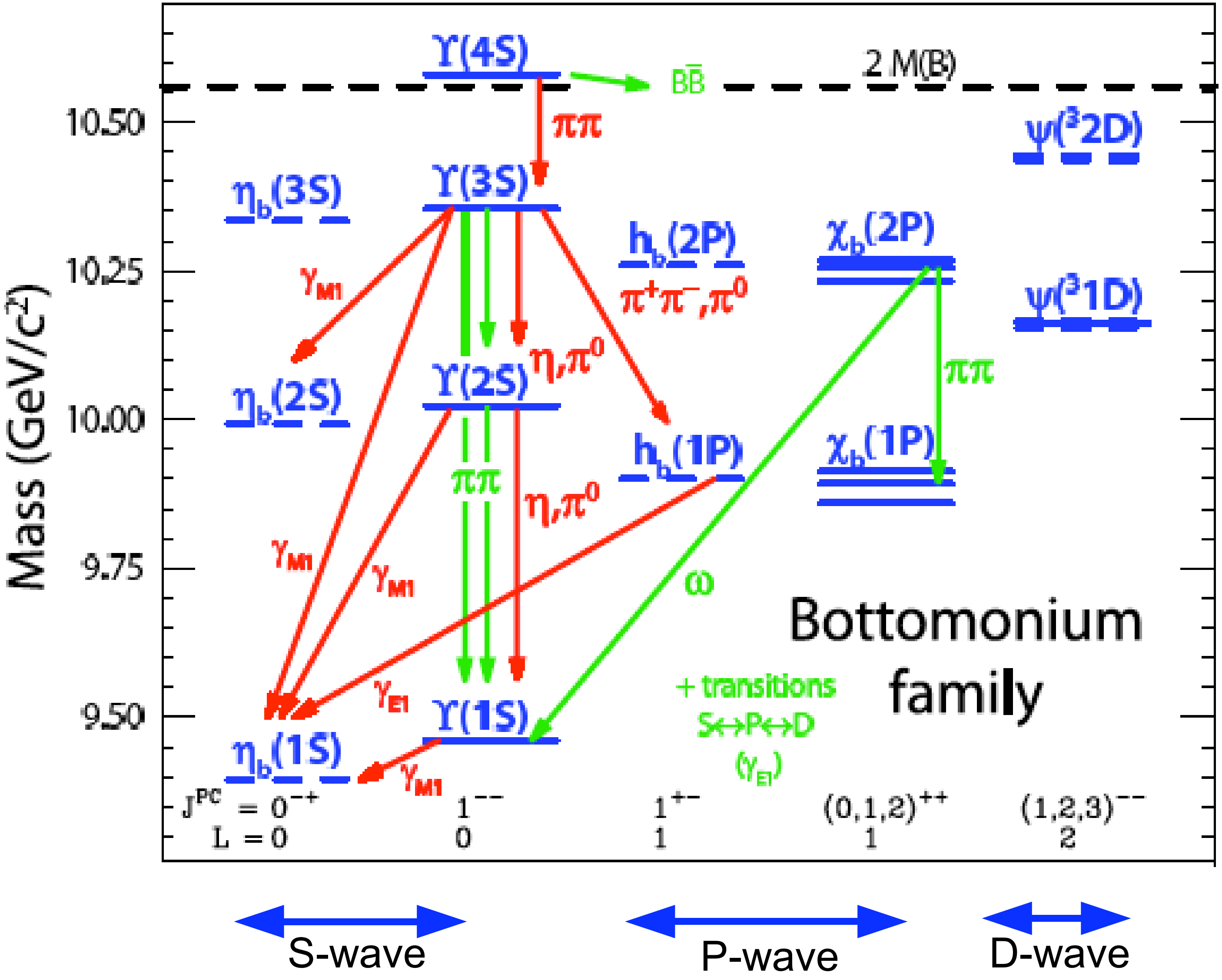
  photon or gluons radiation from $b\bar{b}$ state

  multipole expansion if radius ≪ wavelength

  many more allowed transitions in $b\bar{b}$ than in $c\bar{c}$

Bottomonium spectrum – before summer

From: Eichten,Godfrey,Mahlke,Rosner,hep-ph/0701208



Spectrum of spin triplets with L=0 and L=1 below $b\bar{b}$ threshold is complete

All spin singlet states missing:

$\eta_b(1S)$, $\eta_b(2S)$, $\eta_b(3S)$

$h_b(1P)$, $h_b(2P)$

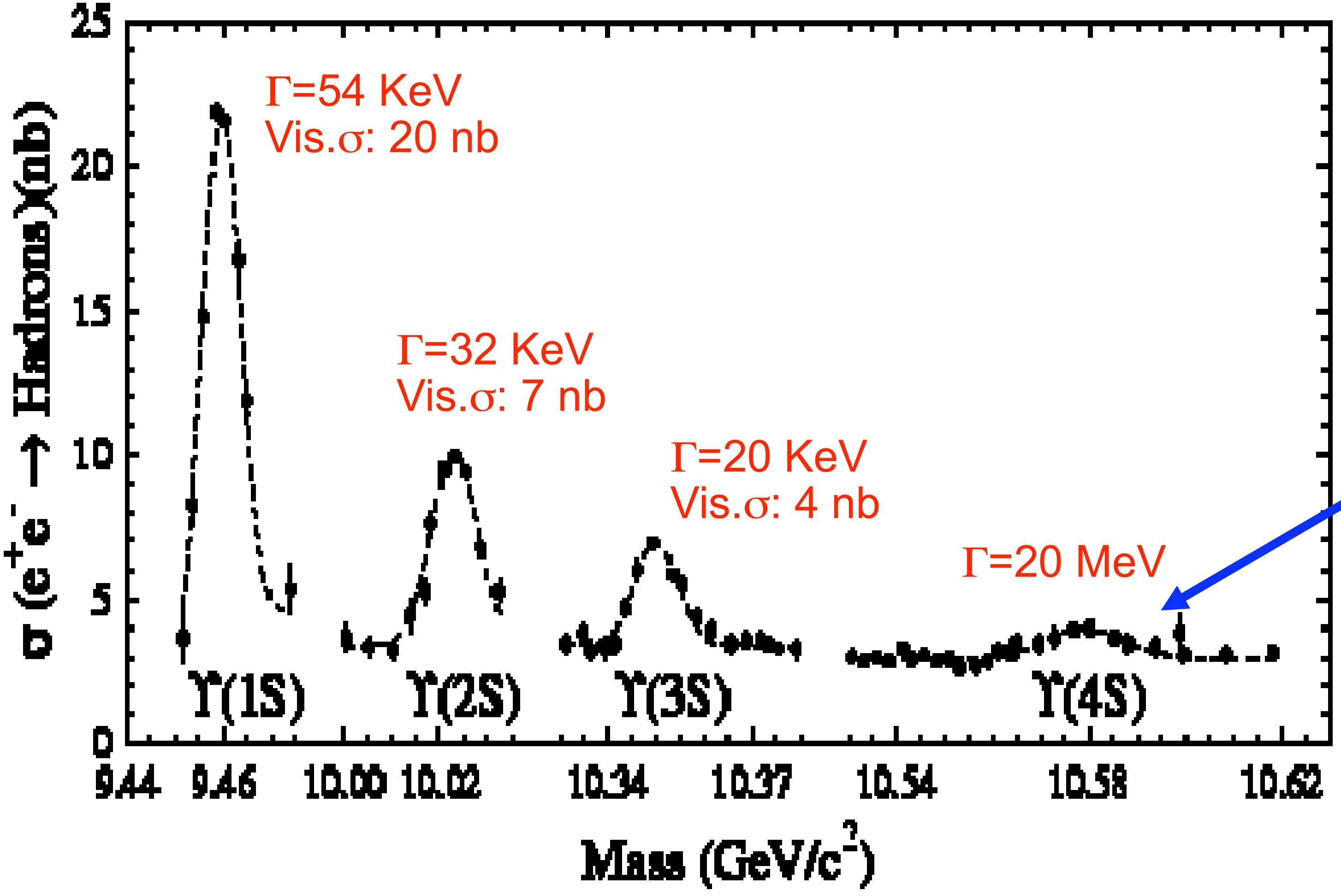
3 D states, [4 F states?]

Rich cascade structure from theϒ(3S) and ϒ(2S):

almost all states virtually accessible [$\mathcal{B}$'s]

Bottomonium production in e^+e^-

Copious production of 1^{--} in e^+e^- annihilations when $\sqrt{s} = M(\Upsilon)$



Initial State Radiation (ISR) yields large samples also when running at the ϒ(4S)

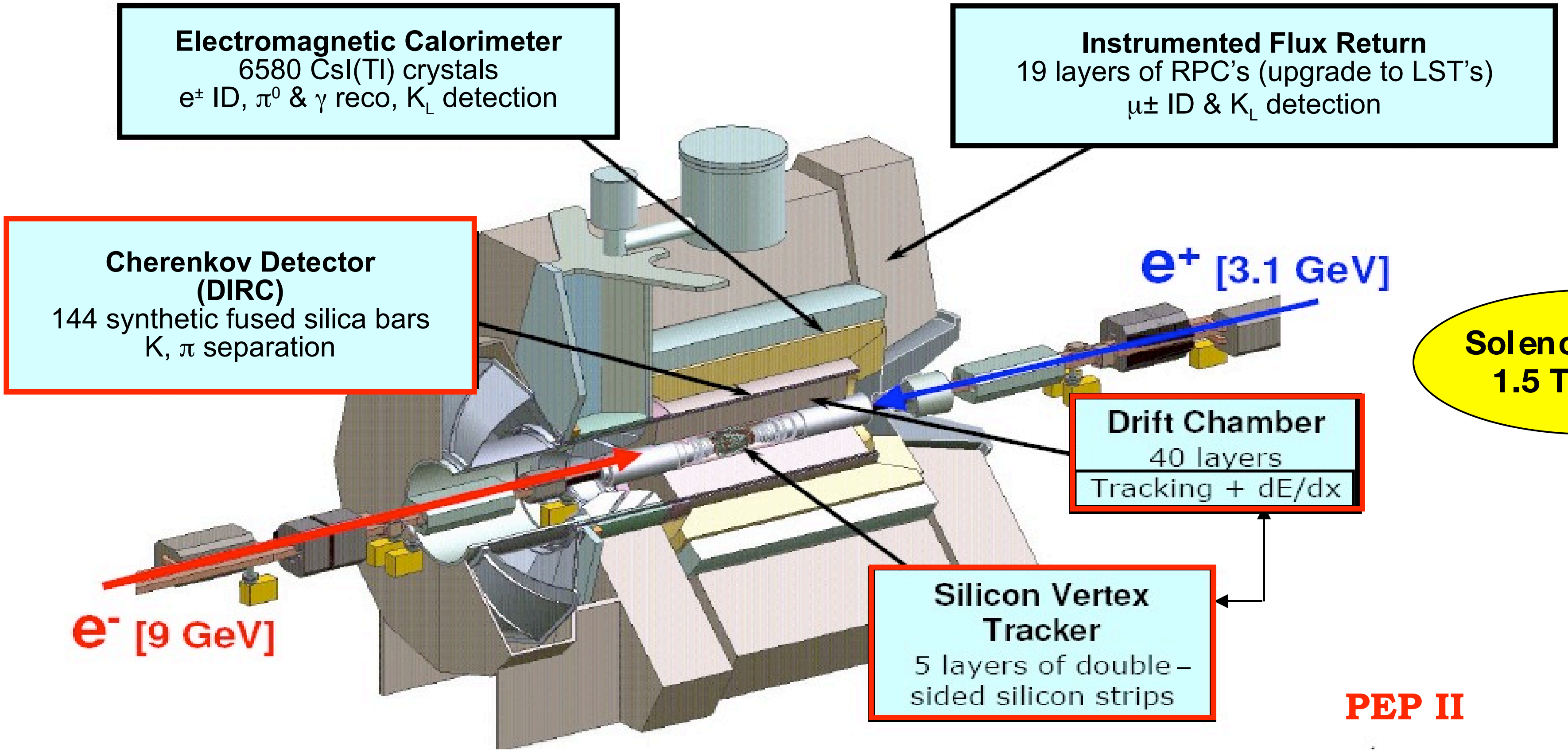
$\sigma(e^+e^- \rightarrow \Upsilon(3S)\gamma_{ISR}) \sim 29$ pb
$\sigma(e^+e^- \rightarrow \Upsilon(2S)\gamma_{ISR}) \sim 17$ pb
$\sigma(e^+e^- \rightarrow \Upsilon(1S)\gamma_{ISR}) \sim 19$ pb

few M events for "free" while running at the ϒ(4S)

can be used to study ϒ(nS) in fully reconstructed final states

inclusive searches or final states with missing particles require on-peak running

The BaBar detector and PEP-II



Electromagnetic Calorimeter
6580 CsI(Tl) crystals
$e^{\pm}$ ID, π^0 & γ reco, K_L detection

Instrumented Flux Return
19 layers of RPC's (upgrade to LST's)
$\mu\pm$ ID & K_L detection

Cherenkov Detector (DIRC)
144 synthetic fused silica bars
K, π separation

Solenoidal Coil
1.5 T B-field

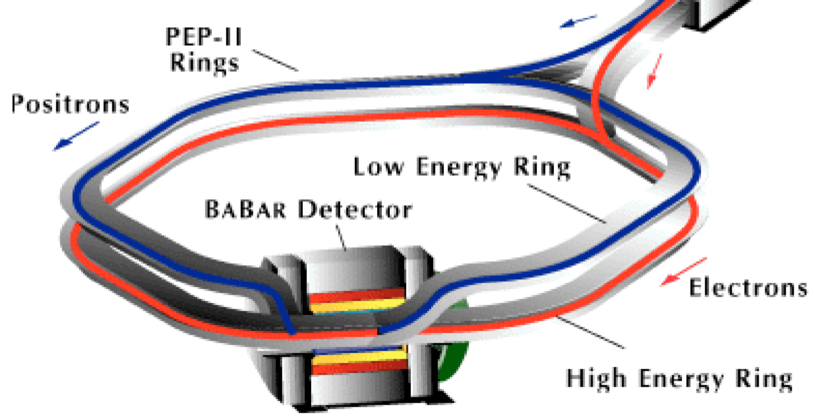
Drift Chamber
40 layers
Tracking + dE/dx

Silicon Vertex Tracker
5 layers of double – sided silicon strips

Excellent tracking and particle ID
CM boost crucial for BB time dependent measurement

Designed to study CP violation yet gave a flood of exciting new results on many diverse topics

PEP II



Bottomonium physics at the $\Upsilon(4S)$: non-$B\overline{B}$ decays of the $\Upsilon(4S)$

- It is usually assumed that $\mathcal{B}(\Upsilon(4S)\rightarrow B\overline{B})=100\%$

non-$B\overline{B}$ decays <4% [PDG]

[B-factories] ... several 10^8 $\Upsilon(4S)$ to search for rare B decays...
can search for rare $\Upsilon(4S)$ decays as well!

- First non-$B\overline{B}$ decays observed by BaBar with 211 fb^{-1} PRL 96, 232001(2006)

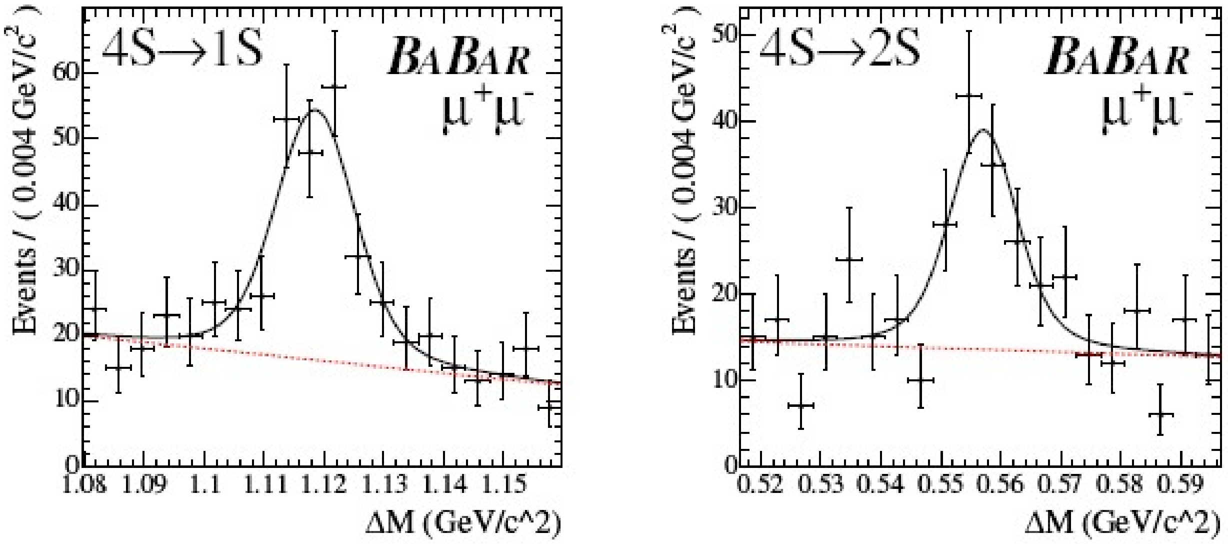
$\Upsilon(4S)\rightarrow\pi^+\pi^-\Upsilon(1S)$ also by Belle: PRD 75,071103 (2007).

$\Upsilon(4S)\rightarrow\pi^+\pi^-\Upsilon(1S)$ and $\Upsilon(4S)\rightarrow\pi^+\pi^-\Upsilon(2S)$

Selecting $\Upsilon(nS)\rightarrow\mu^+\mu^-$

1D-fit to

$\Delta M=M(\pi^+\pi^-\mu^+\mu^-)-M(\mu+\mu^-)$



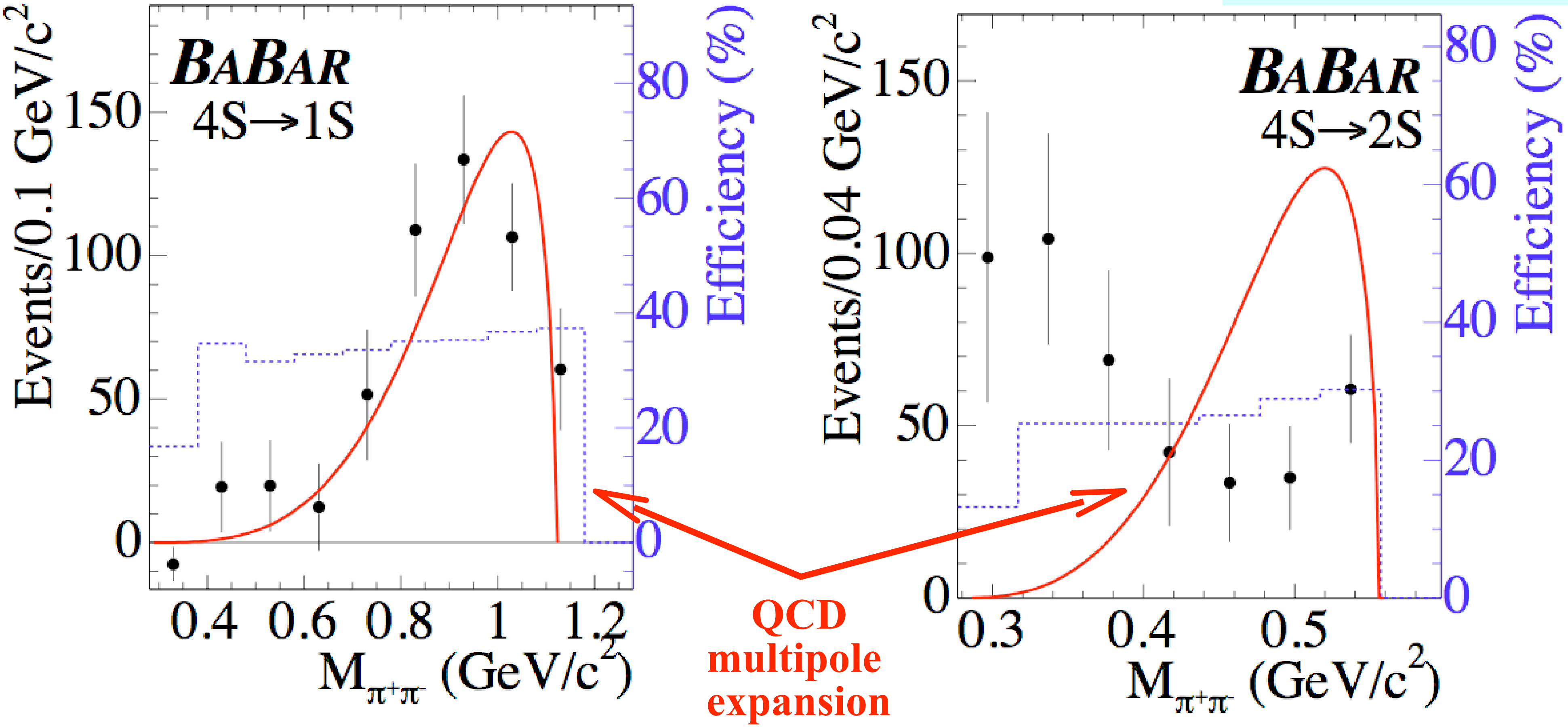
167±19 evts

97±15 evts

[... not really a surprise...]

$M(\pi^+\pi^-)$ in $\Upsilon(4S)\rightarrow\pi^+\pi^-\Upsilon(1S,2S)$

PRL 96, 232001(2006)

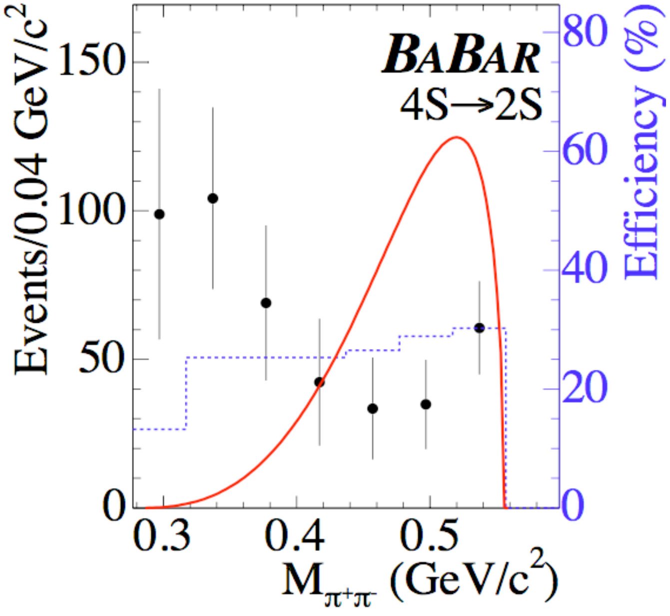


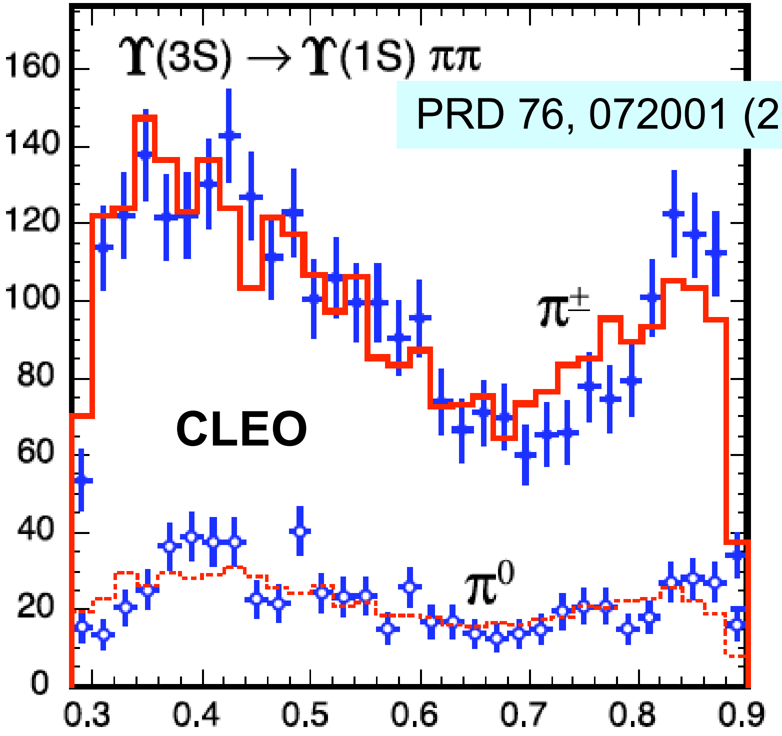
QCD multipole expansion

THIS is a surprise.!

“Double bump” structure?

Similar to $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(1S)$?





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long standing puzzle

ϒ(4S) hadronic decays

arXiv:0807.2014[hep-ex]
(submitted to PRD)

- Updated measurement with 347 fb^{-1}:

  ϒ(4S) and also ϒ(3S) and ϒ(2S) from ISR

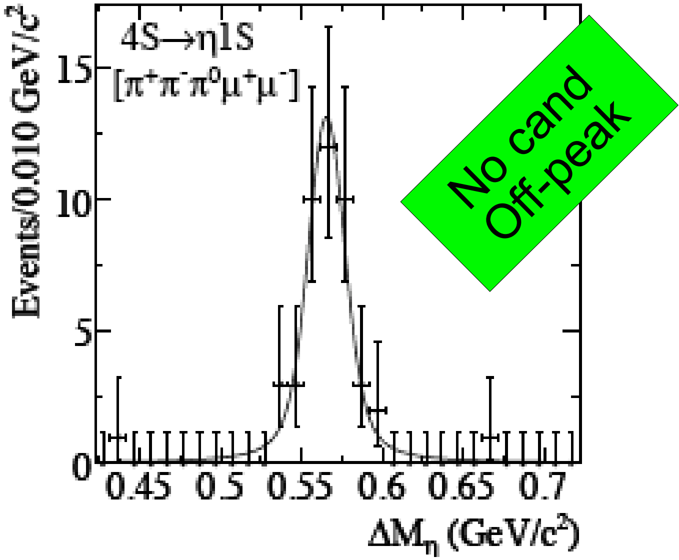
reconstruct $\Upsilon(mS)\to\pi^+\pi^-\Upsilon(nS)$ and $\Upsilon(mS)\to\eta\Upsilon(1S)$

[m=4,3,2 n=2,1]

with $\Upsilon(nS)\to\mu^+\mu^-/e^+e^-$ and $\eta\to\pi^+\pi^-\pi^0$

$$\mathcal{B}(\Upsilon(4S)\to\pi^+\pi^-\Upsilon(1S)) = (0.800\pm0.064\pm0.027)\times10^{-4}$$

$$\mathcal{B}(\Upsilon(4S)\to\pi^+\pi^-\Upsilon(2S)) = (0.86\pm0.11\pm0.07)\times10^{-4}$$

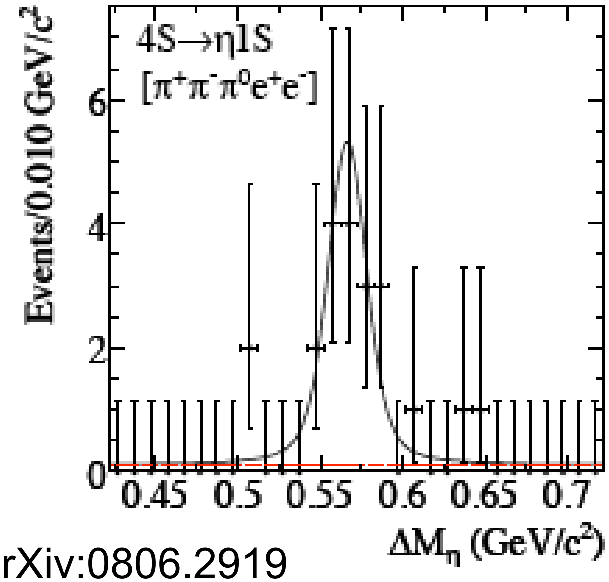


No cand
Off-peak

- Observation of $\Upsilon(4S)\to\eta\Upsilon(1S)$:

$$\mathcal{B}(\Upsilon(4S)\to\Upsilon(1S)\eta) = (1.96\pm0.06\pm0.09)\times10^{-4}$$

$$\frac{\mathcal{B}(\Upsilon(4S)\to\eta\,\Upsilon(1S))}{\mathcal{B}(\Upsilon(4S)\to\pi^+\pi^-\Upsilon(1S))} = 2.41\pm0.40\pm0.12$$



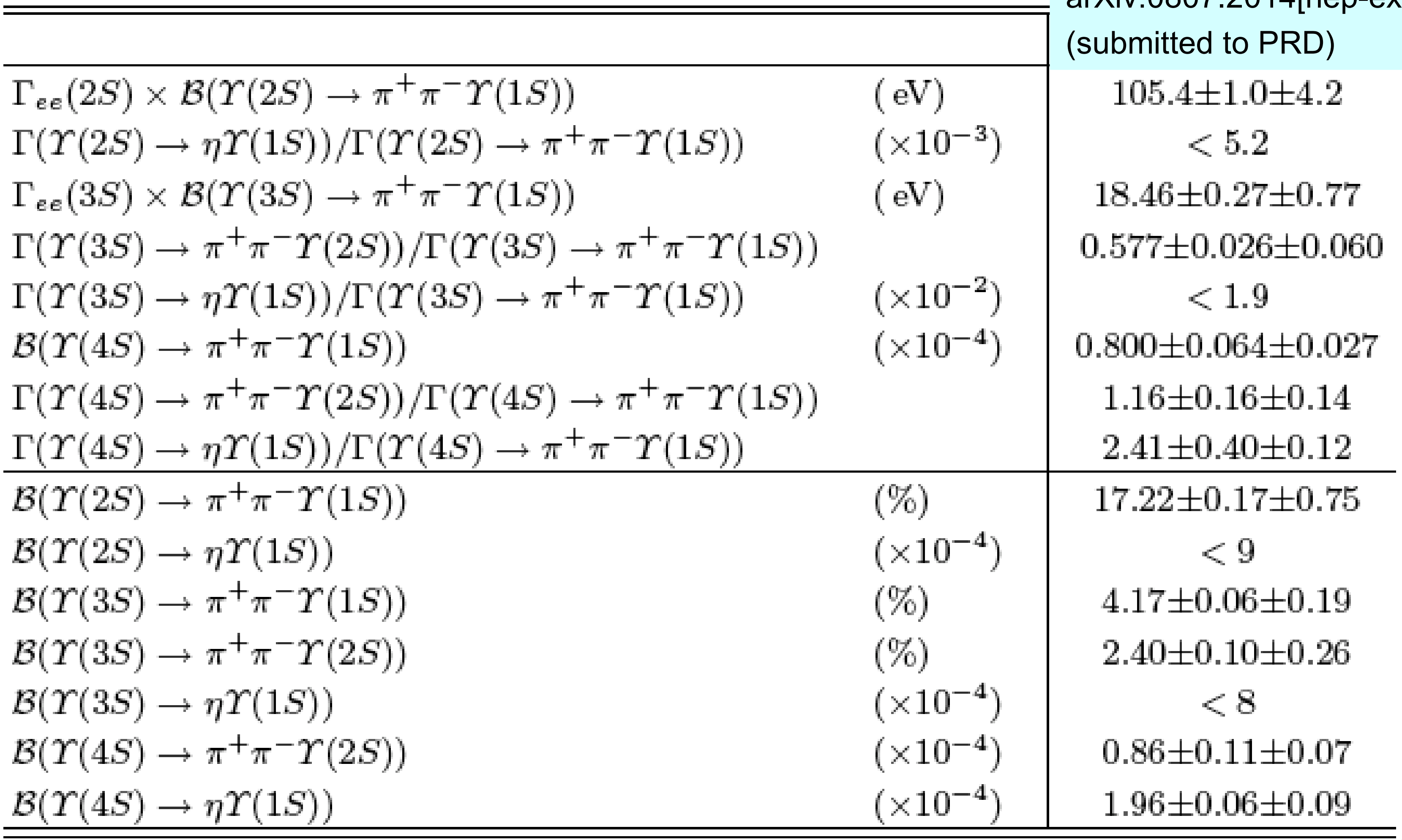
QCD multipole expansion: $\frac{\text{E1- M2}}{\text{E1- E1}}$

unexpectedly large ratio!

Other mechanisms? Simonov,Veselov arXiv:0806.2919
Meng,Chao,arXiv0806:3259

Υ(nS) hadronic transitions in the Υ(4S) sample

arXiv:0807.2014[hep-ex]
(submitted to PRD)



$\Gamma_{ee}(2S) \times \mathcal{B}(\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S))$	(eV)	105.4±1.0±4.2
$\Gamma(\Upsilon(2S) \to \eta\Upsilon(1S))/\Gamma(\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S))$	$(\times 10^{-3})$	< 5.2
$\Gamma_{ee}(3S) \times \mathcal{B}(\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S))$	(eV)	18.46±0.27±0.77
$\Gamma(\Upsilon(3S) \to \pi^+\pi^-\Upsilon(2S))/\Gamma(\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S))$		0.577±0.026±0.060
$\Gamma(\Upsilon(3S) \to \eta\Upsilon(1S))/\Gamma(\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S))$	$(\times 10^{-2})$	< 1.9
$\mathcal{B}(\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S))$	$(\times 10^{-4})$	0.800±0.064±0.027
$\Gamma(\Upsilon(4S) \to \pi^+\pi^-\Upsilon(2S))/\Gamma(\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S))$		1.16±0.16±0.14
$\Gamma(\Upsilon(4S) \to \eta\Upsilon(1S))/\Gamma(\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S))$		2.41±0.40±0.12
$\mathcal{B}(\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S))$	(%)	17.22±0.17±0.75
$\mathcal{B}(\Upsilon(2S) \to \eta\Upsilon(1S))$	$(\times 10^{-4})$	< 9
$\mathcal{B}(\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S))$	(%)	4.17±0.06±0.19
$\mathcal{B}(\Upsilon(3S) \to \pi^+\pi^-\Upsilon(2S))$	(%)	2.40±0.10±0.26
$\mathcal{B}(\Upsilon(3S) \to \eta\Upsilon(1S))$	$(\times 10^{-4})$	< 8
$\mathcal{B}(\Upsilon(4S) \to \pi^+\pi^-\Upsilon(2S))$	$(\times 10^{-4})$	0.86±0.11±0.07
$\mathcal{B}(\Upsilon(4S) \to \eta\Upsilon(1S))$	$(\times 10^{-4})$	1.96±0.06±0.09

had just started considering
physics reach of a SMALL bottomonium program
in BaBar

Run 7 at BaBar

- Dec. 15th: first collisions at Υ(4S) energy
- Dec. 19th: FY08 Budget Disaster

  faced with immediate shutdown of PEP-II

  BaBar proposed to run at Υ(3S) energy by reducing the HER(e-) energy
- Dec. 21st,1:30PM: PEPII-BaBar mtg.

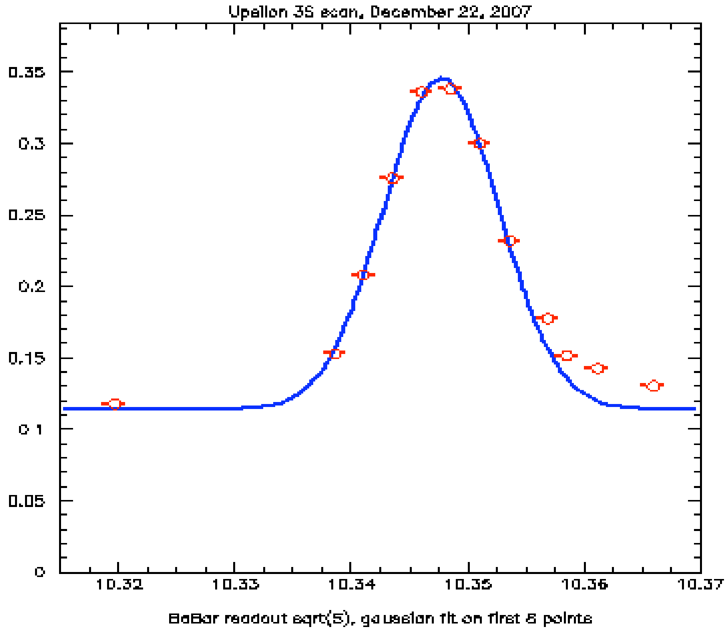
  Decision to move to Υ(3S)
- Dec. 22nd ,7:00 PM :

  Υ(3S) scan completed!
  - moved to Υ(3S) peak
  - initial luminosity at 3.5 x 10^{33}
- Move to Υ(2S) energy in March (in 10 hrs)
- Scan above Υ(4S) for 10 days

- Last data taken on Apr. 7, 2008

The goal was to double the integrated luminosity at the Υ(4S)

Changes to machine operation, trigger, reconstruction and simulation software implemented over Xmas



Physics goals of Run 7 at the $\Upsilon(3S)$ and $\Upsilon(2S)$

Explore bottomonium physics with unprecedented statistics:

	CLEO III	**BaBar**	**BELLE**
$\Upsilon(1S)$	**20 M**	**--**	**100 M** (June, 2008)
$\Upsilon(2S)$	**9 M**	**110 M**	
$\Upsilon(3S)$	**6 M**	**120 M**	**11 M**

- "New physics":
  search for light Higgs, light Dark Matter

- Bottomonium physics:
  search for $b\bar{b}$ singlet states: $\boxed{\eta_b(1S)}$, $\eta_b(2S)$, $h_b(1P)$

  first priority

  precision measurements
  of radiative and hadronic transitions...

Previous searches for $\eta_b(1S)$

- Inclusive search in radiative transitions

[CLEO III, PRL 94, 0322002, 2005]

$\mathcal{B}(\Upsilon(2S) \rightarrow \gamma\, \eta_b) < 5.1 \times 10^{-4}$

$\mathcal{B}(\Upsilon(3S) \rightarrow \gamma\, \eta_b) < 4.3 \times 10^{-4}$

- Double transitions

$\Upsilon(3S) \rightarrow \pi^0\, h_b(1P)$ or $\pi^+\pi^- h_b(1P)$ with $h_b(1P) \rightarrow \gamma\, \eta_b$

$\mathcal{B} < 1.8 \times 10^{-3}$ (CLEO)

$\Upsilon(3S) \rightarrow \gamma\chi_{b0}(2P)$; with $\chi_{b0}(2P) \rightarrow \gamma\, \eta_b$

$\mathcal{B} < 2.5 \times 10^{-4}$ (CLEO III)

- Exclusive searches

$\eta_b \rightarrow$ 4- and 6-prong Final States in 2-photon Production

ALEPH at LEP II (2002)

One 6-prong candidate around M=9300 MeV

1 expected background event

$\eta_b \rightarrow$ 4-, 6-, 8-prong Final States in 2-photon Production

DELPHI at LEP II (2006)

$\eta_b \rightarrow J/\psi\, J/\psi \rightarrow \mu^+\mu^-\mu^+\mu^-$ CDF II at Tevatron (2006)

Expected properties of $\eta_b(1S)$

- Spin-0 partner of $\Upsilon(1S)$

  hyperfine splitting: 35 to 100 MeV (potential models, LQCD)

- Decay rates:

$$\frac{\Gamma_{\gamma\gamma}(\eta_b)}{\Gamma_{gg}(\eta_b)} = \frac{9}{2} Q_b^4 \frac{\alpha_{em}^2}{\alpha_s^2} \left(1 - 7.8 \frac{\alpha_s}{\pi}\right)$$

Kwong, Mackenzie, Rosenfeld, Rosner, PRD 37, 3210 (1988)

  using estimates of $\Gamma_{\gamma\gamma}(\eta_b(1S))$=(0.2-0.7) keV

$\Gamma(\eta_b(1S))$=5-15 MeV

- Radiative transitions $\Upsilon(nS)\rightarrow\gamma\eta_b(1S)$

  magnetic dipole (M1)
  k=60,600,900 MeV
  [for 1S,2S,3S]

$$\Gamma_{M1} \propto \frac{k^3}{m_Q^2} \cdot |<f|j_0(\frac{kr}{2})|i>|^2$$

"hindered" (n≠ n') transitions strongly suppressed

- $h_b(1P)\rightarrow\gamma\eta_b(1S)$ dominant [but need to produce $h_b(1P)$]
- $\mathcal{B}$'s of hadronic $\chi_b(2P)\rightarrow\eta_b(1S)$ transitions?

Predictions for $\Upsilon(mS)\to\gamma\eta_b(nS)$

CLEO III, PRL 94, 0322002, 2005

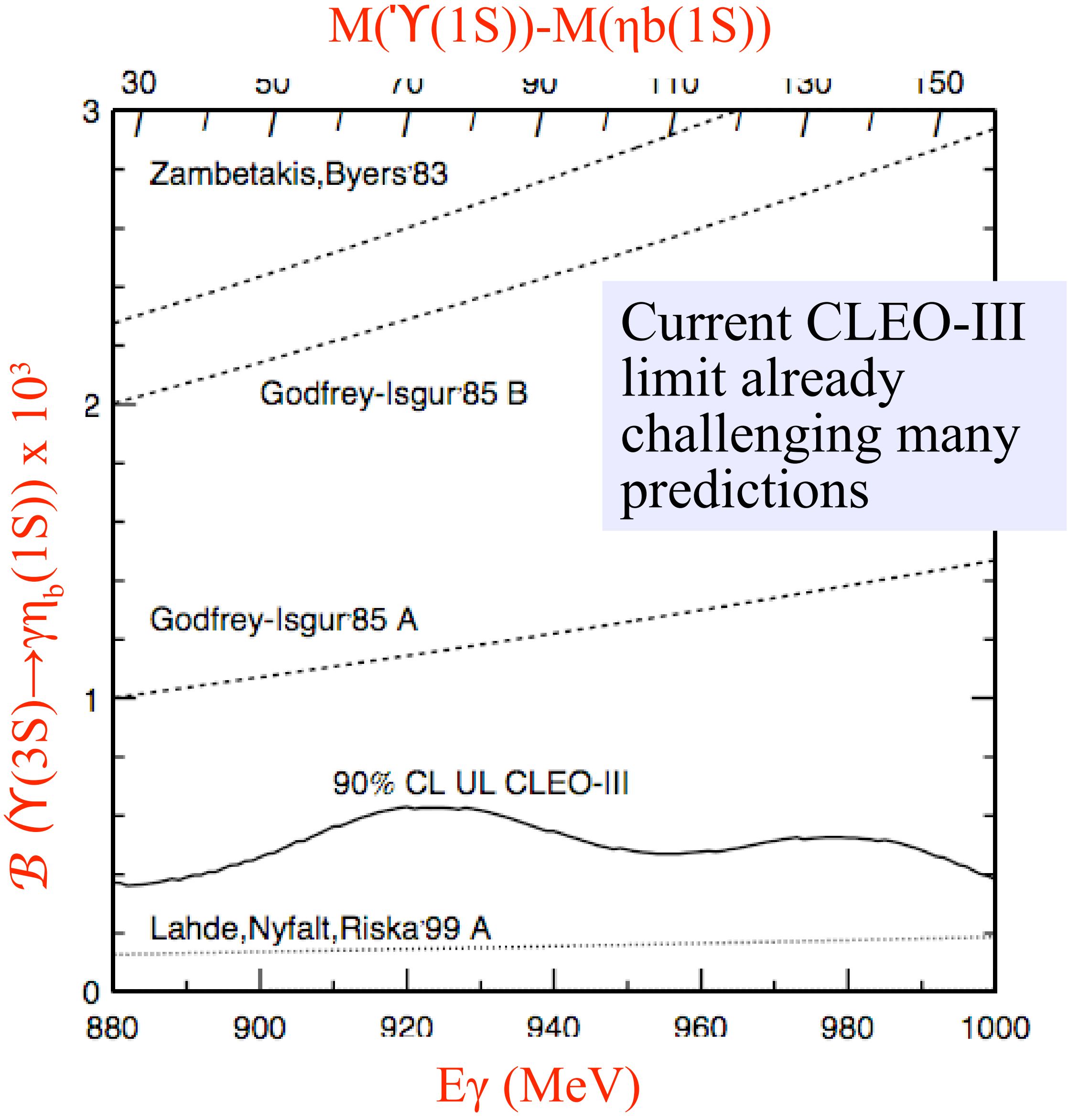
Predictions for M1 $\mathcal{B}$'s depend on wave-functions (potential, relativistic corrections, etc....)

Strong dependence from η_b mass

$\mathcal{B}(\Upsilon(3S)\to\gamma\eta_b(2S)) = (1.4\text{-}7)\ 10^{-4}$

$\mathcal{B}(\Upsilon(2S)\to\gamma\eta_b(1S)) = (3\text{-}5)\ 10^{-4}$

$\mathcal{B}(\Upsilon(3S)\to\gamma\eta_b(1S)) = (1\text{-}20)\ 10^{-4}$



Current CLEO-III limit already challenging many predictions

The search for the $\eta_b(1S)$ at BaBar

- Decays of η_b not known

  ⮡ **inclusive search**

  - **Search for the radiative transition $\Upsilon(3S) \to \gamma\eta_b(1S)$**

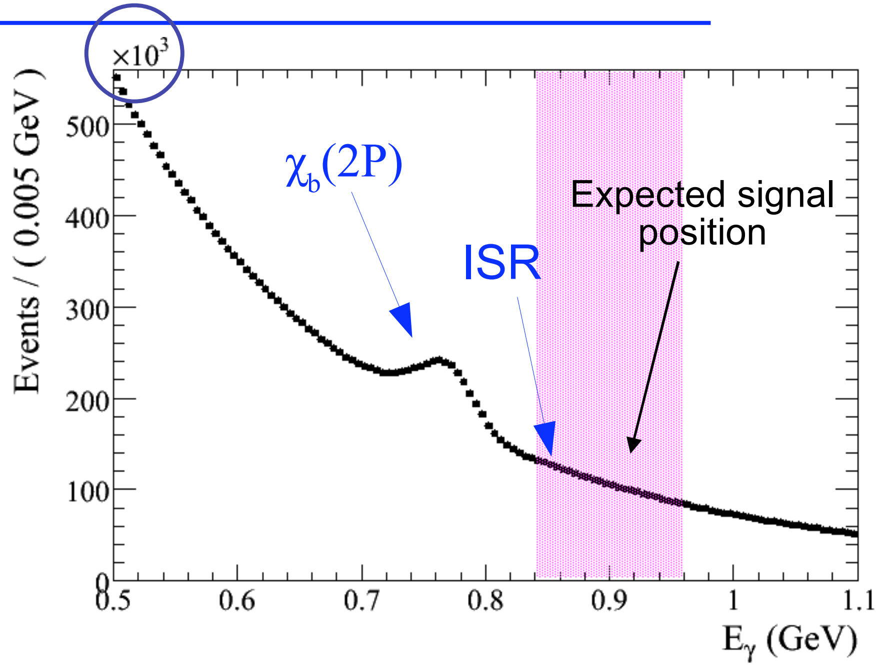
- In c.m. frame: $E_\gamma = \dfrac{s - m^2}{2\sqrt{s}}$

  - For η_b mass m = 9.4 GeV/c^2 E_γ ~911 MeV

    ⮡ look for a bump near 900 MeV in inclusive photon energy spectrum from data taken at the Y(3S)

BLIND ANALYSIS

Search for $\eta_b(1S)$ in the $\Upsilon(3S)$ inclusive γ spectrum



Very high background rate

- Smooth background from many sources

  Photons from hadrons decays: π^0, η, ω, η', φ, ...

  Direct photons from bottomonium decays:

  ***e.g.*, $\mathcal{B}(\Upsilon(1S) \rightarrow \gamma\, g\, g) = 2.5\ \%$**

  ISR photons from e+e- → γ_{ISR} $q\bar{q}$ events

  → Not reliably modeled by MC

- Large "peaking-backgrounds" close to signal region

  $\chi_b(2P) \rightarrow \gamma\Upsilon(1S)$ from $\Upsilon(3S) \rightarrow \gamma\chi_b(2P)$ $E_{\gamma 2}$ = 743-777 MeV

  $\Upsilon(1S)$ ISR production : $e^+e^- \rightarrow \gamma_{ISR}\ \Upsilon(1S)$ $E_{\gamma ISR}$ = 856 MeV

  Accurate modeling crucial to extract the signal

Estimated sensitivity:

if $\mathcal{B}(\Upsilon(1S) \rightarrow \gamma\eta_b) = (1\text{x}10^{-4})$

with 100 M $\Upsilon(3S)$ and ε = ~40 %

expected background (after selection/optimization cuts) in the signal region: 4 M

→ Signal Yield = (4000 +/- 2000) Events

Selection optimization

"Optimal" cuts selected by maximizing the $S/\sqrt{B}$

$\Upsilon(3S) \to \gamma\eta_b$ (Signal) MC simulation

$1+\cos^2\theta$ distribution relative to beam axis

JETSET is used for hadronization of quarks/gluons
Detector Simulations via GEANT

- Inclusive properties of $\eta_b \to gg$ not known:

  Use $\chi_b(2P)$ to validate MC efficiency

Cannot rely on MC to model smooth background: use data...

- Use ~ 9% of the data sample for optimization [signal region blind]

  $2.5 fb^{-1}$ a sample larger than the prevoious largest sample...

- Perform the measurement on the remaining 91% of the sample

$25.6\ fb^{-1}$ → **109±1 M $\Upsilon(3S)$**

Preliminary event selection

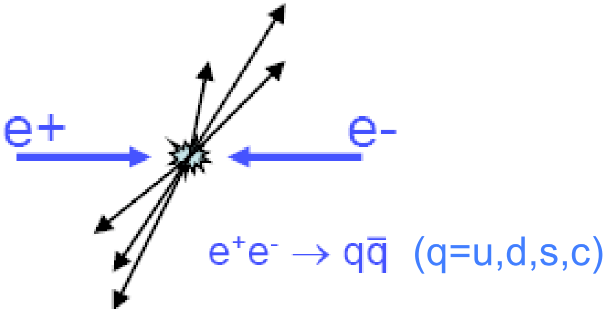
- Hadronic event selection
  - Track multipliciy of the event > 3
  - R2 (ratio of 2nd to 0th Fox-Wolfram moment) <0.98 to suppress QED background

- Photon Selection
  - Neutral clusters in EMC; Isolated from charged tracks
  - Shower shape consistent with EM shower profile
  - central barrel section of the CsI Calorimeter

    $-0.762 < \cos(\theta_{\gamma,\mathrm{lab}}) < 0.890$

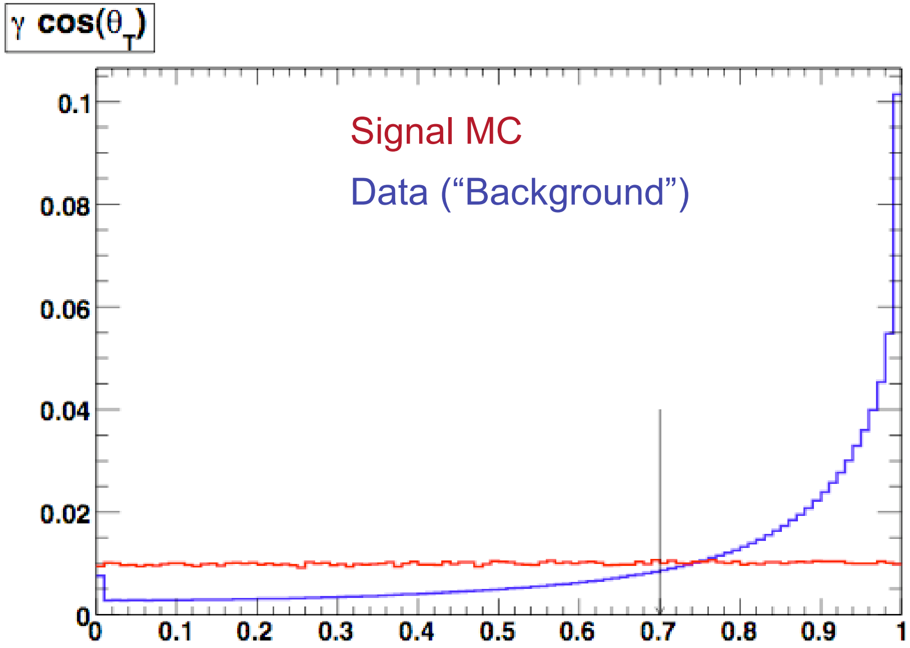
    ⇨ Better energy resolution & reduced ISR photon background

Event shape



Strong correlation between the candidate photon and event jet axis (thrust axis of the rest of the event)

Signal photon has little correlation with the η_b (spin-0) decay



$|\cos\theta(\text{Thrust})| < 0.7$

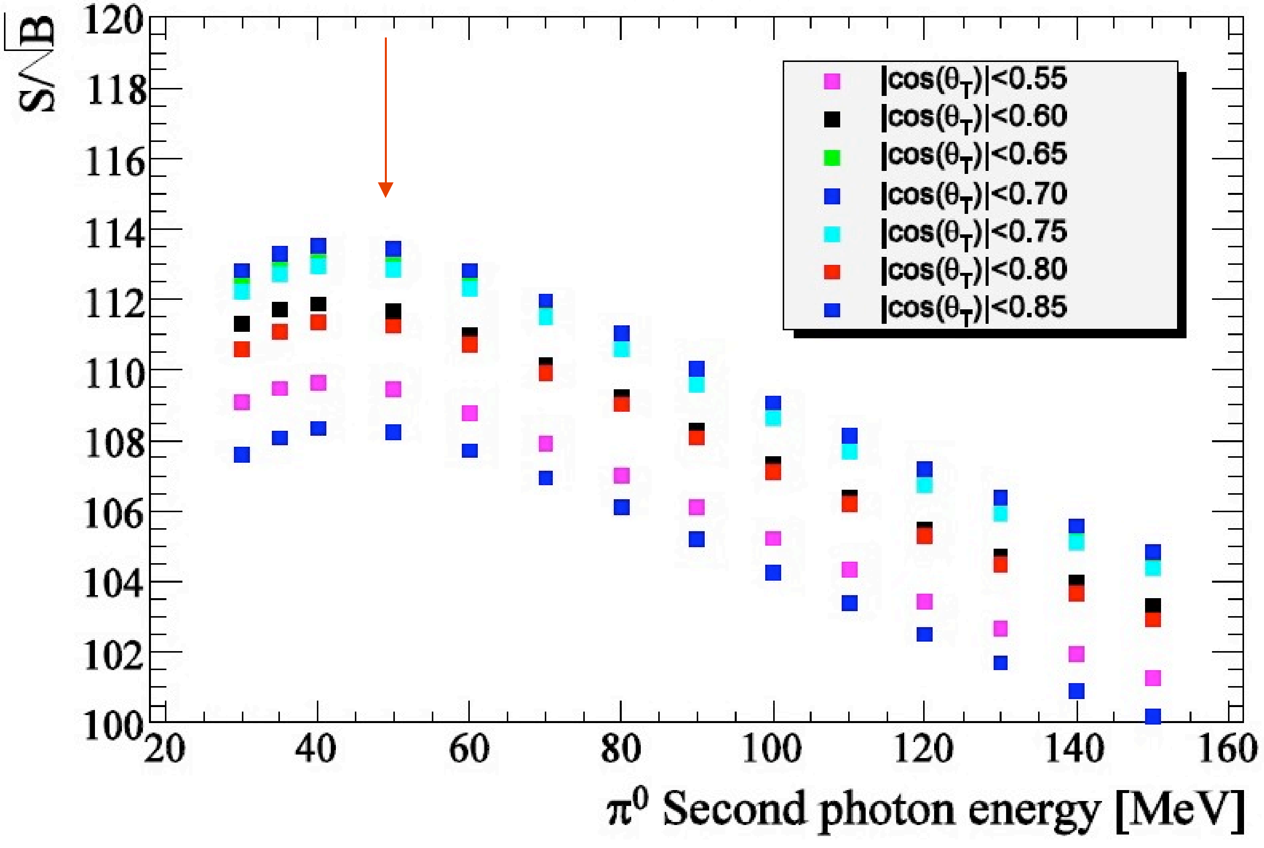
No other useful event shape variables found…

More isotropic distribution for the photon background from bottomonium decays (3-gluon,γ gg, gg)

π^0 veto

Reject photon candidate if $|M(\gamma\gamma_2) - M(\pi^0)| < 15\ \mathrm{MeV}/c^2$

$E(\gamma_2) > 50$ MeV

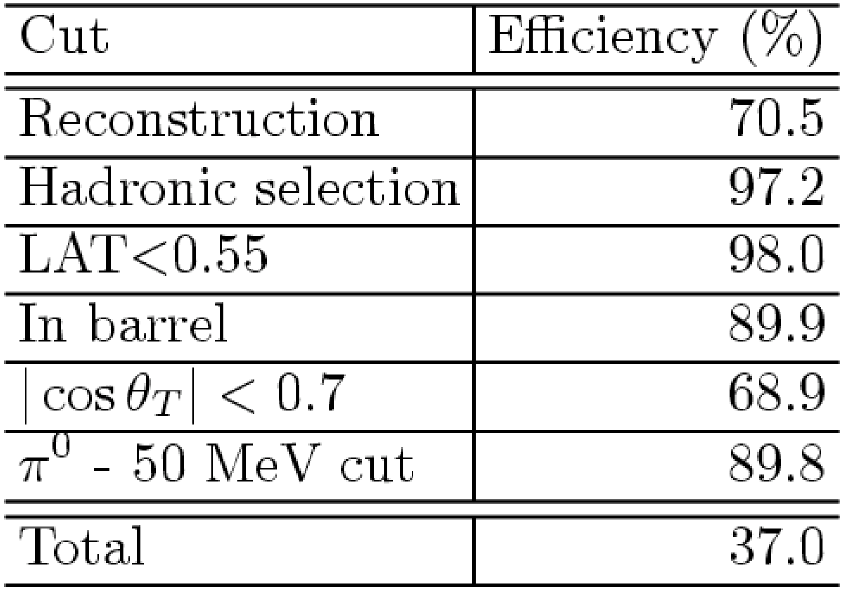


Same optimization criteria obtained from χ_b signal yield in test sample

Similar $\eta \to \gamma\gamma$ veto does not improve S/B ratio…

Selection efficiency

Efficiency determined on MC



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

Net efficiencies:

ε(signal) = 37%

ε(bkgr.) = 6%

30 % of Background from continuum processes

Fit to the E_γ spectrum

- binned Maximum likelihood Fit with 4 components

    1) Smooth non-peaking background
    2) $e^+e^- \to \gamma_{ISR}\Upsilon(1S)$ Peak (850 MeV)
    3) $\chi_b(2P) \to \gamma\Upsilon(1S)$ Peak (750 MeV)
    4) $\Upsilon(3S) \to \gamma\eta_b(1S)$ Signal (920 MeV)

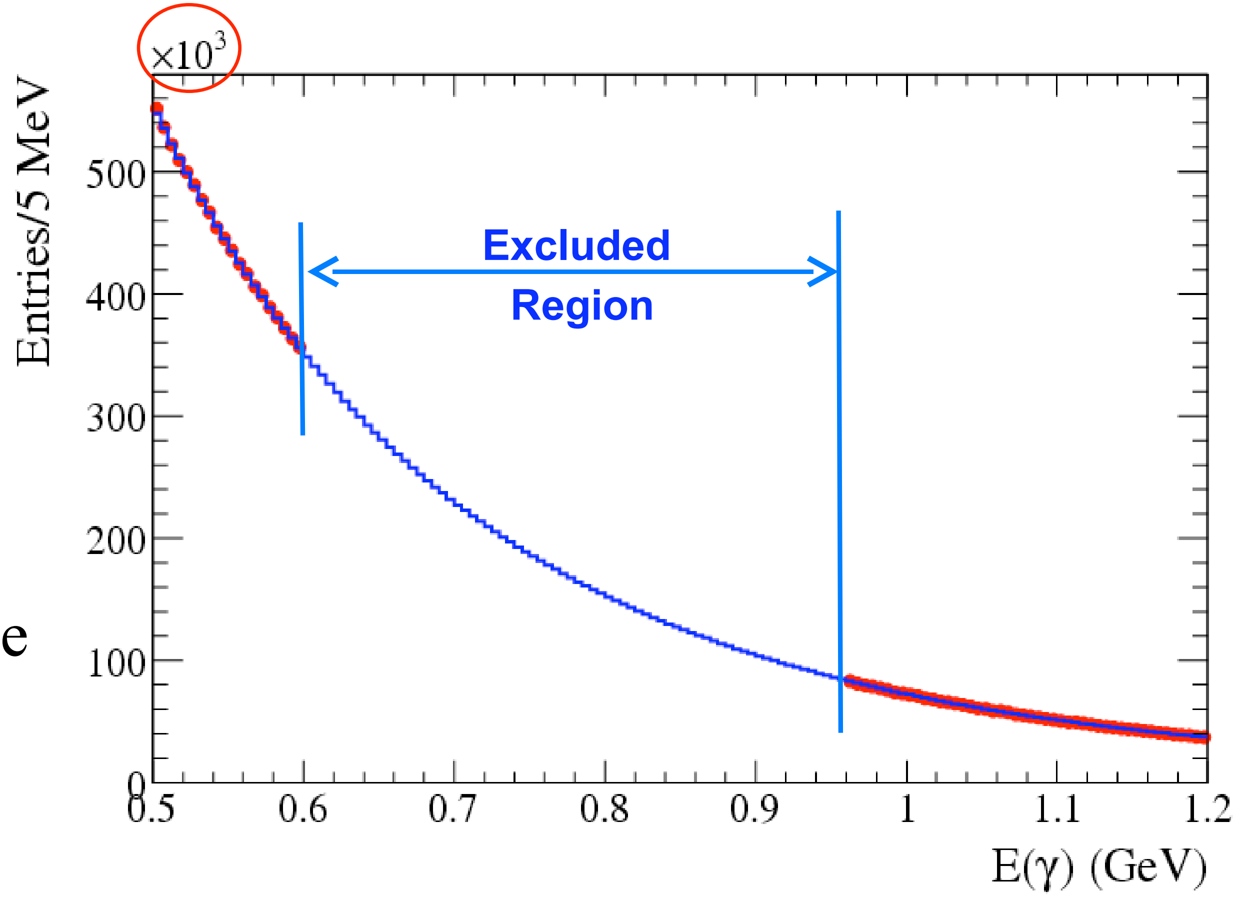
- PDF shape of each component studied in advance on MC and/or test samples
- PDF parameters estimated before the final fit

1) Non-peaking Background

Empirical function used to parameterize the smooth non-peaking background

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

Fit parameters C, α, β, and γ determined here are used as the starting values in the final fit



2) Peaking Background : $e^+e^- \to \gamma_{ISR}\Upsilon(1S)$

Shape/Rate determined using the sample collected at $\sqrt{s} \sim 40$ MeV below the $\Upsilon(4S)$

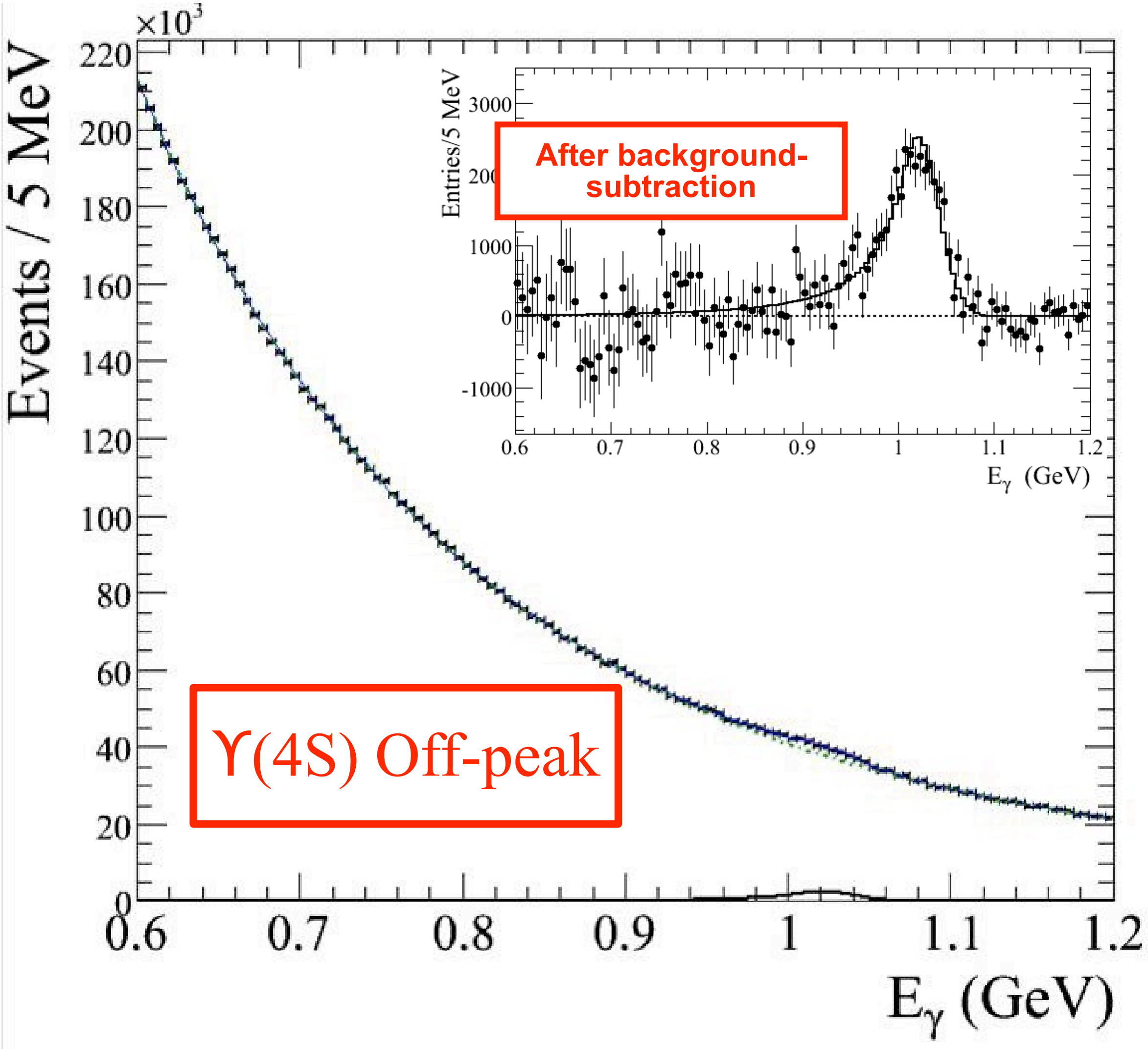
"$\Upsilon(4S)$ Off-peak"

ISR Peak at $E_\gamma = 1.025$ GeV

Crystal Ball function with power law, transition point and width parameters obtained from the fit

$N_{ISR}(\Upsilon(4S)$ Off-peak$) =$

35800 ± 1600 evt

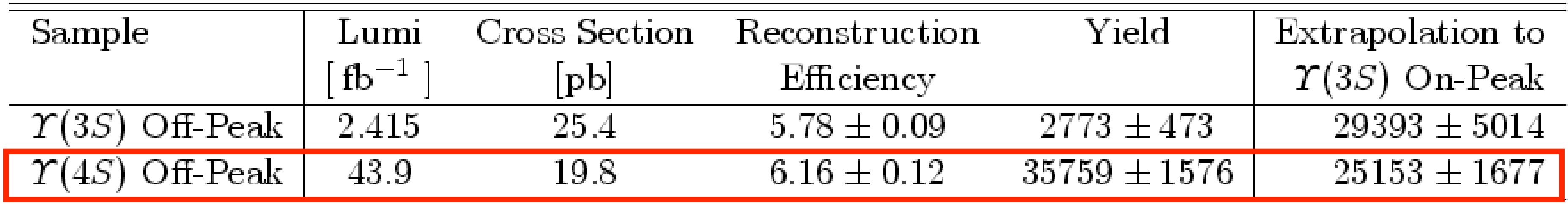


Extrapolate ISR yield and PDF from $\Upsilon(4S)$ Off-peak to $\Upsilon(3S)$ →

Extrapolated yield (25153) and PDF fixed in the final fit

Cross check: use Υ(3S) Off-peak for ISR extrapolation

Repeat the exercise with the sample collected ~ 40 MeV below the Υ(3S)
" Υ(3S) Off-peak"



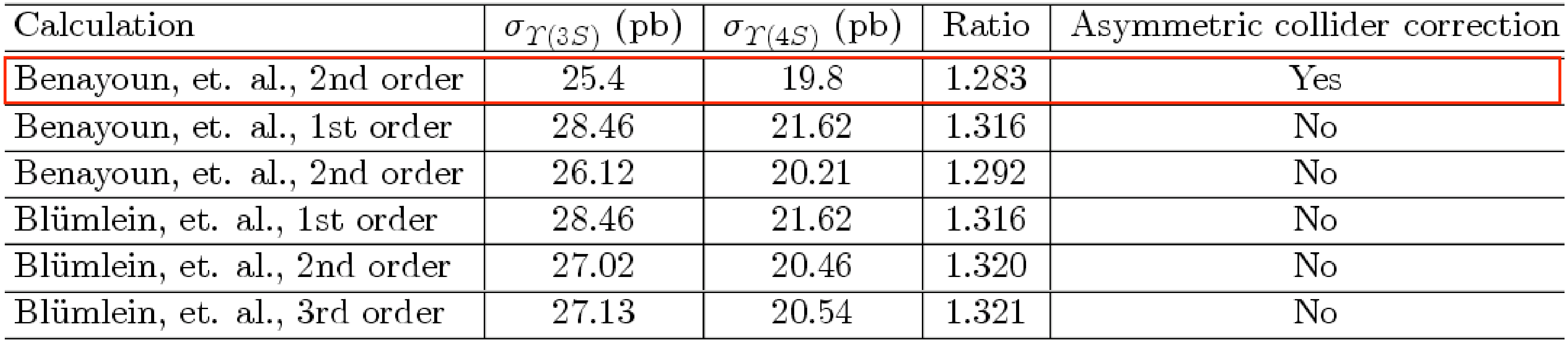
Sample	Lumi [fb^{-1}]	Cross Section [pb]	Reconstruction Efficiency	Yield	Extrapolation to $\Upsilon(3S)$ On-Peak
$\Upsilon(3S)$ Off-Peak	2.415	25.4	5.78 ± 0.09	2773 ± 473	29393 ± 5014
$\Upsilon(4S)$ Off-Peak	43.9	19.8	6.16 ± 0.12	35759 ± 1576	25153 ± 1677

Stat. Error

- ISR yields extrapolated from Υ(4S) Off-peak and Υ(3S) Off-peak samples in good agreement

  ✓ ISR Yield varied by ±1 σ as part of the study of the systematic uncertainties on the η_b peak position and yield.

- Systematic error on extrapolation (5%)



Calculation	$\sigma_{\Upsilon(3S)}$ (pb)	$\sigma_{\Upsilon(4S)}$ (pb)	Ratio	Asymmetric collider correction
Benayoun, et. al., 2nd order	25.4	19.8	1.283	Yes
Benayoun, et. al., 1st order	28.46	21.62	1.316	No
Benayoun, et. al., 2nd order	26.12	20.21	1.292	No
Blümlein, et. al., 1st order	28.46	21.62	1.316	No
Blümlein, et. al., 2nd order	27.02	20.46	1.320	No
Blümlein, et. al., 3rd order	27.13	20.54	1.321	No

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

- Model each transition by a Crystal Ball function

  Transition point and power law tail parameter fixed to same value for each peak

- Peak positions fixed to PDG values shifted by a common offset:
  - Offset: **3.8 MeV** in data

    (shift in γ energy calibration)

    used to correct energy scale of other peaks

- Ratio of yields taken from PDG

  -- $R(\chi_{b1}/\chi_{b2}) = 1.2$

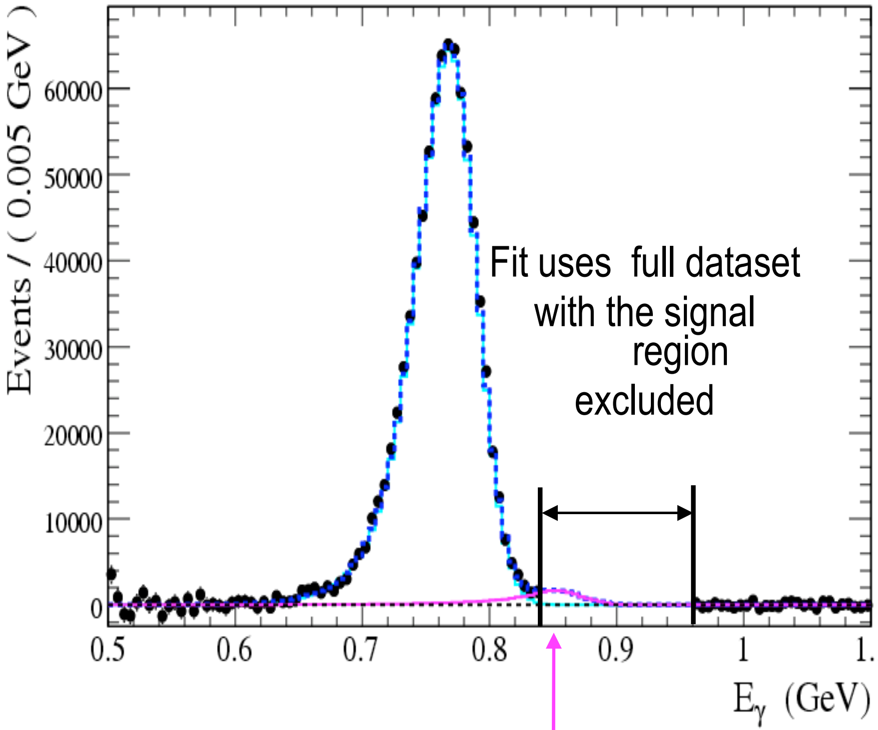
  consistent with the value measured using soft $\Upsilon(3S)\rightarrow\gamma\chi_{b1,2}(2P)$ transition photons

  -- $R(\chi_{b1}/\chi_{b0}) = 21$

  $\chi_{b0}(2P)$ contrib. very small

Peaks of the 3 χ_{bJ}(2P) transitions merged

- photon energy resolution (~20 MeV)
- Broadening due to Lorentz boost of χ_b in the CM-frame

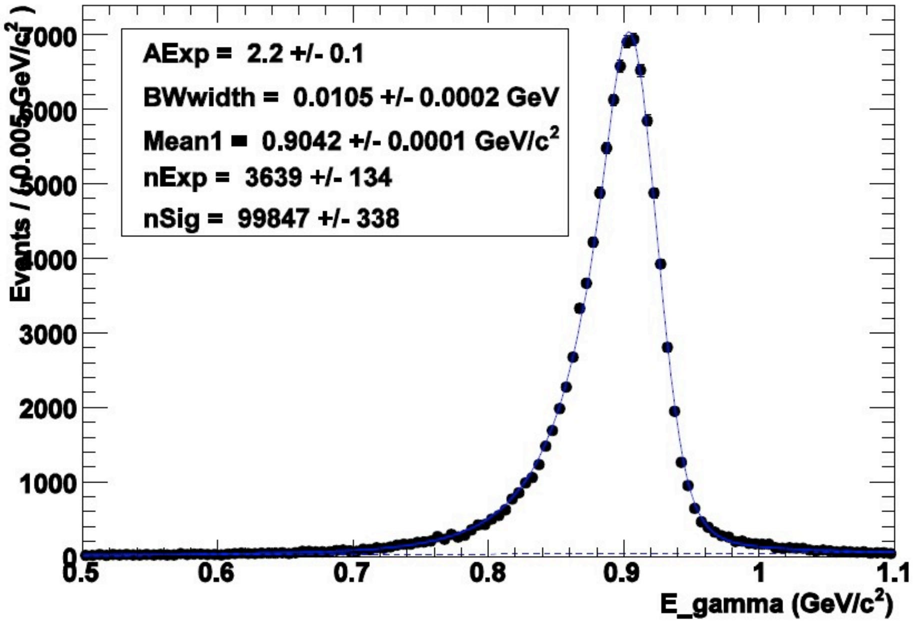


Fit uses full dataset with the signal region excluded

Incorporate ISR peak contribution to model tail of γ peak from $\chi_b(2P)$ properly

4) η_b Signal PDF

Signal Shape
from
MC Simulations

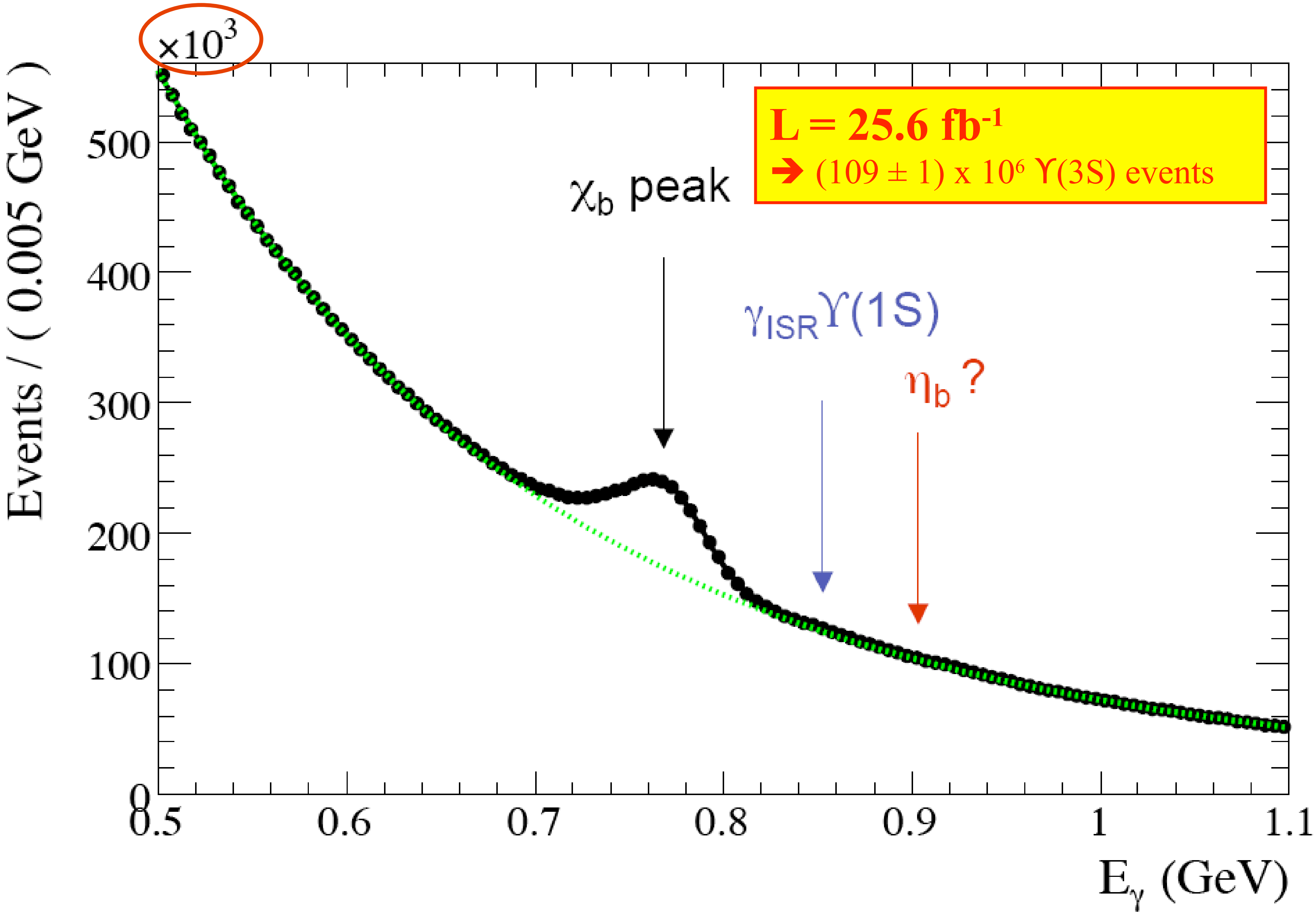


Signal PDF: Crystal Ball ⊗ Breit-Wigner Function

- Fix signal Crystal Ball parameters from zero-width MC
- Fix the S-wave Breit-Wigner width to 10 MeV

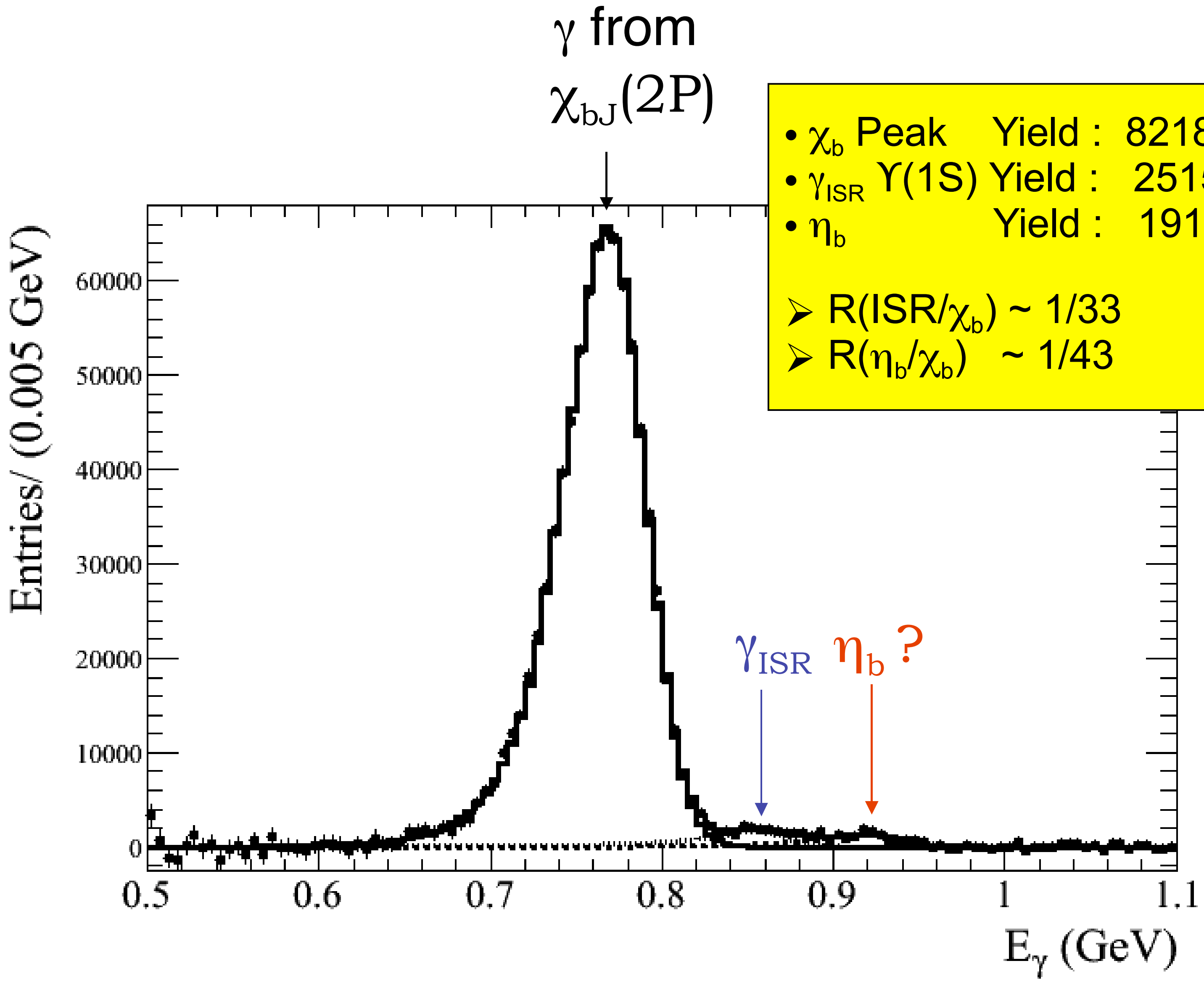
Fit the data with 5, 15, 20 MeV widths to study systematic errors

Fit result



L = 25.6 fb^{-1}
➔ (109 ± 1) x 10^6 $\Upsilon(3S)$ events

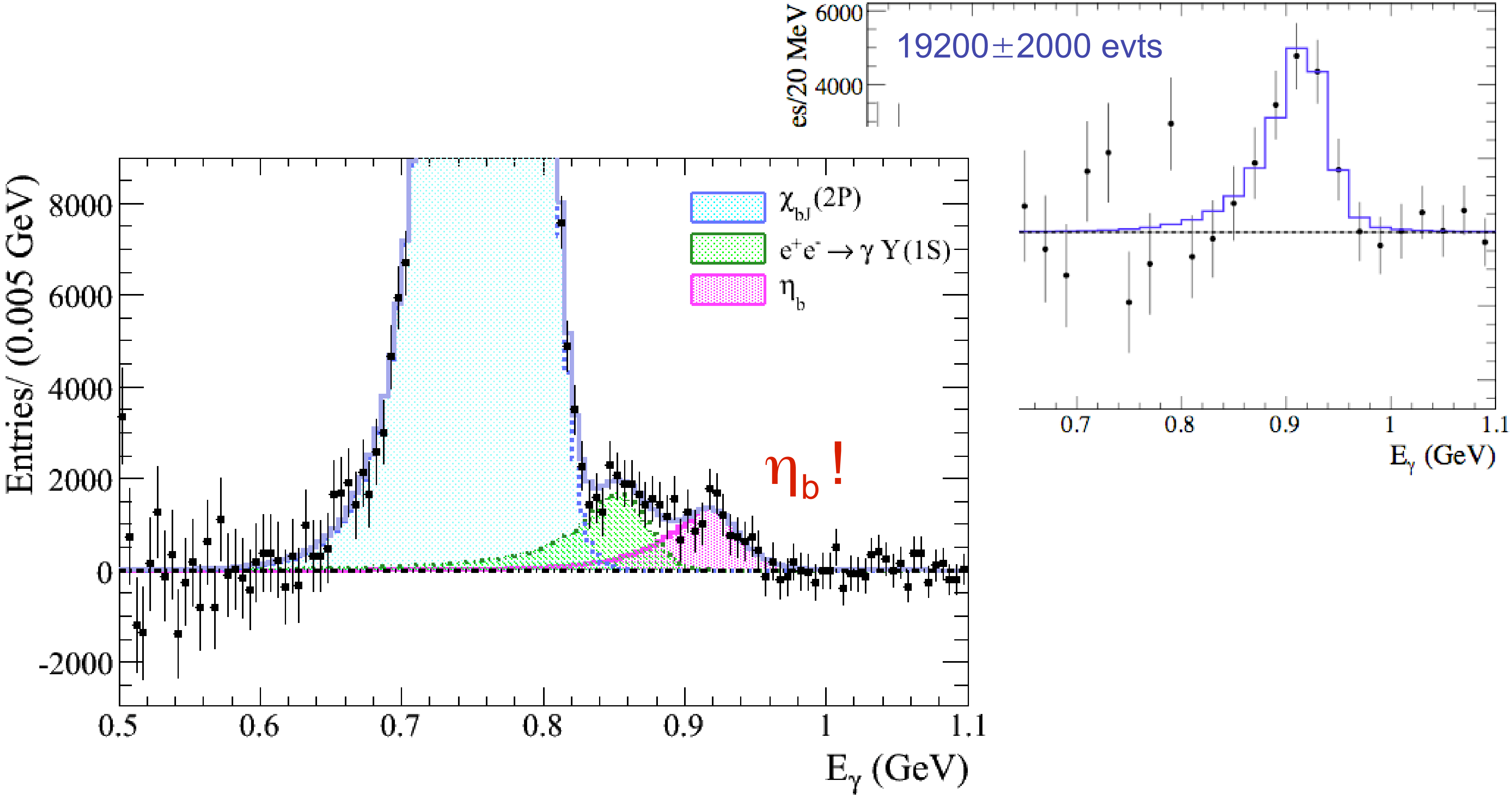
Non-peaking background subtracted



- χ_b Peak Yield : 821841 ± 2223
- γ_{ISR} $\Upsilon(1S)$ Yield : 25153 (fixed)
- η_b Yield : 19152 ± 2010

- ➢ $R(ISR/\chi_b) \sim 1/33$
- ➢ $R(\eta_b/\chi_b) \sim 1/43$

Observation of the $\eta_b(1S)$



η_b !

η_b signal observed with a statistical significance of 10 σ

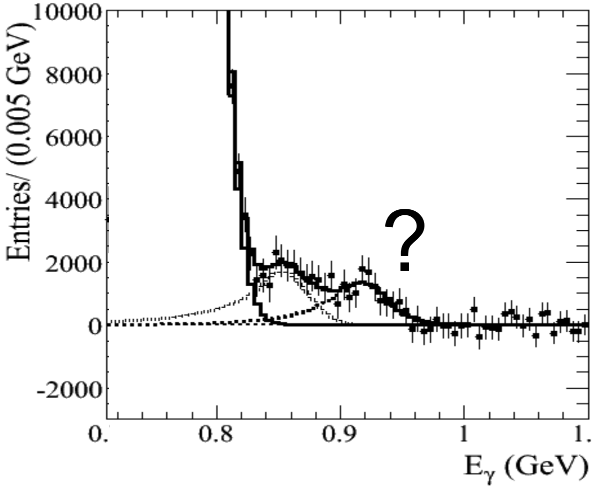
Peak position: $921.2^{+2.1}_{-2.8}$ (stat only) MeV

Could this be a fake signal?

- detector effects?

  (hot channels in the electromagnetic calorimeter (EMC), crystal defects, etc…)

  - Noisy channels in the EMC would have been detected by our online data monitoring
  - Check of the angular distribution of inclusive photons reveals that there are no *hot* spots
    - A tighter Lateral Moment criterion would eliminate such problems
      - η_b signal remains after tighter Lateral Moment requirement



- Artifacts?
  - Random overlap of photons with γ from $\chi_b(2P)$?
    - tight Lateral Moment cut reduces also the potential overlap of random photons
  - Check of fit quality in the signal region floating the ISR $\Upsilon(1S)$ yield:
    - ISR fitted yield (24799) consistent with expected yield from extrapolation (25153) background parameterization in the signal region is good

How do we know this is the η_b?

... alternatives? glueball, Higgs...

below the $\Upsilon(1S)$ – only candidate is the η_b

Systematic uncertainties

- Systematic uncertainties associated with the η_b mass
    - Vary ISR yield by ± 1σ (stat ⊗ 5% syst) → $\delta N =$ 180, $\delta E\gamma =$0.7 MeV
    - Vary ISR PDF parameters by ± 1σ → $\delta N =$ 50, $\delta E\gamma =$0.3 MeV
    - Vary Signal PDF parameters by ± 1σ → $\delta N =$ 98, $\delta E\gamma =$0.1 MeV
    - Vary χ_b peak PDF parameters by ± 1σ → $\delta N =$ 642, $\delta E\gamma =$0.3 MeV
- Systematic uncertainties associated with the η_b yield
    - Includes systematic uncertainties associated with the η_b mass
    - Fit with BW width fixed to 5, 15, 20 MeV → $\delta N =$ 2010, $\delta E\gamma$=0.8 MeV
    - efficiency [data/MC comparison on χ_b(2P)] → $\delta N/N =$12.6%
    - χb(2P) $\mathcal{B}$'s [fixed in fit, from PDG] → $\delta N/N =$18.2%
- Study of Significance
    - Vary BW width
    - Vary all parameters independently
    - Vary all parameters in the direction resulting in lowest significance

→ No significant change !

Summary of measurements

$$\mathrm{M}(\eta_b) = 9388.9^{+3.1}_{-2.3} \pm 2.7\ \mathrm{MeV}/c^2$$

$$\mathrm{M}(\Upsilon(1S))\text{-}\mathrm{M}(\eta_b) = 71.4^{+2.3}_{-3.1} \pm 2.7\ \mathrm{MeV}/c^2$$

PRL 101,071801(2008)

A. Gray et al., Phys. Rev. D 72, 094507(2005) (L. QCD)

ΔM = 61 +/- 14 MeV/c^2

- lattice spacing: +/- 4 MeV/c^2
- QCD radiative corrections: +/- 12 MeV/c^2
- relativistic corrections: +/- 6 MeV/c^2

S. Godfrey and N. Isgur, Phys. Rev. D 32, 189(1985)

ΔM = 60 MeV/c^2

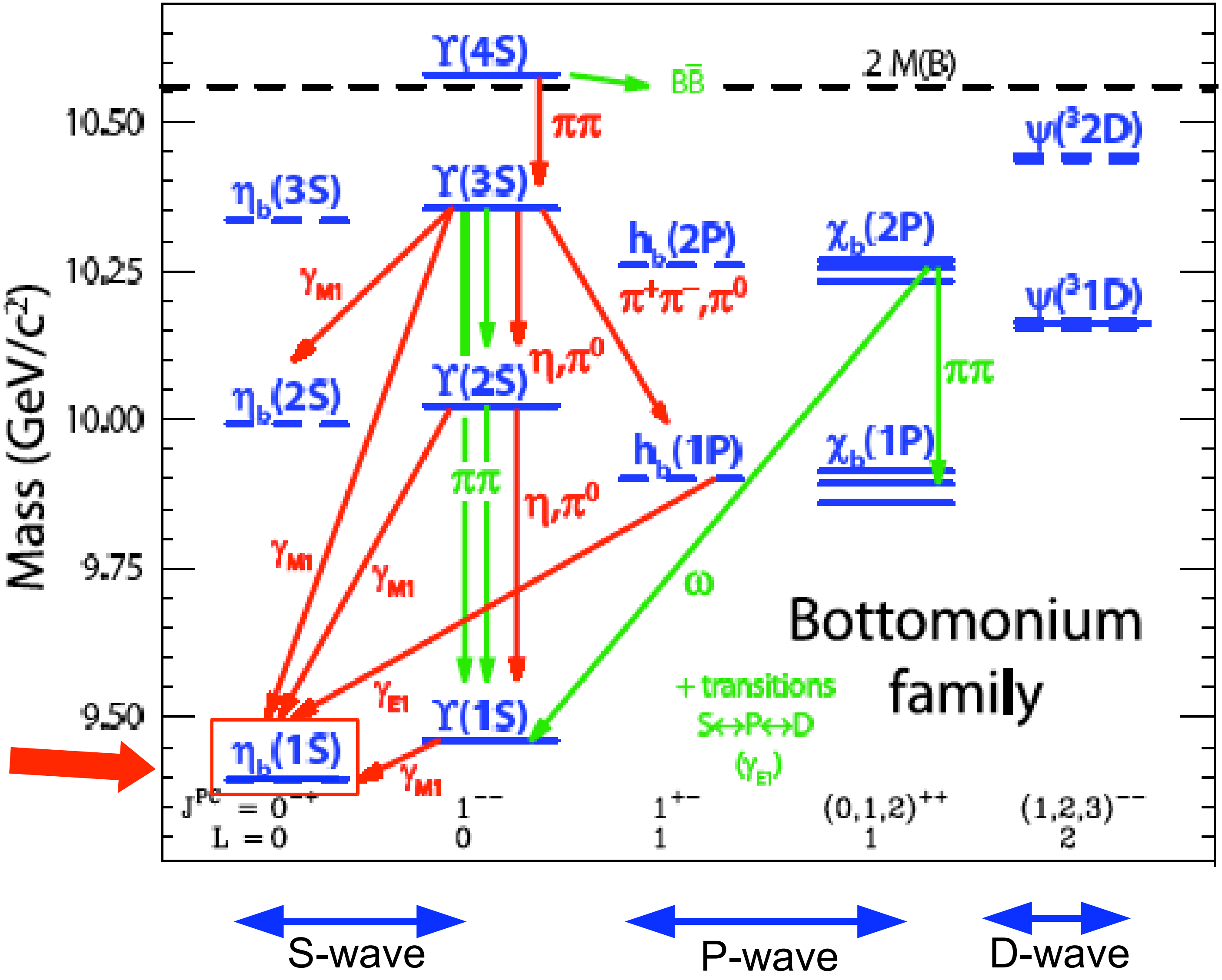
(Relativized Quark Model with Chromodynamics)

$$\mathcal{B}(\Upsilon(3S)\rightarrow\gamma\eta_b(1S)) = (4.5 \pm 0.5 \pm 1.2) \times 10^{-4}$$

cf. upper limit: $\mathcal{B}(\Upsilon(3S)\rightarrow\gamma\eta_b(1S))$. $<4.3\mathrm{x}10^{-4}$ @ 90% [CLEO III]

Bottomonium spectrum - UPDATE

From: Eichten,Godfrey,Mahlke,Rosner,hep-ph/0701208



~~All~~ spin singlet states missing:

~~$\eta_b(1S)$,~~ $\eta_b(2S)$, $\eta_b(3S)$

$h_b(1P)$, $h_b(2P)$

3 D states, [4 F states?]

Other inclusive searches for η_b at BaBar

- $\Upsilon(2S) \to \gamma\eta_b(1S)$

  100 M Υ(2S) events, $\mathcal{B}(\Upsilon(2S) \to \gamma\eta_b(1S))$ =3-5 10^{-4}

  Eγ Signal : 611 MeV
  $\chi_b(1P) \to \gamma\, \Upsilon(1S)$ 455MeV
  ISR-ϒ(1S) peak 544 MeV STAY TUNED

- $\Upsilon(1S) \to \gamma\eta_b(1S)$

  Use 18 M tagged ϒ(1S) in the $\pi^+\pi^-$ recoil mas of $\Upsilon(2S) \to \pi^+\pi^-\, \Upsilon(1S)$

  Eγ signal 74 MeV
  no $\chi_b(1P)$ or ISR-ϒ(S) peaking background

- $\Upsilon(3S) \to \gamma\eta_b(2S)$

  Eγ signal = 360 MeV Difficult region !

- $\Upsilon(3S) \to \pi^0\, h_b(1P)$ or $\Upsilon(3S) \to \pi^+\pi^- h_b(1P)$ where $h_b(1P) \to \gamma\eta_b(1S)$

  "requires" to observe also the singlet P state $h_b(1P)$

Scan above the ϒ(4S)

The charmonium spectrum has many states above open $c\bar{c}$ threshold that are not well-understood (molecules?, 4-quark state?, hybrids? etc….)

[large widths for ϒ(5S)→$\pi^+\pi^-$ϒ(nS) observed by Belle]

⇨ **look for analogues in bottomonium spectrum!**

Last detailed scan ~25 yrs ago (CUSB)

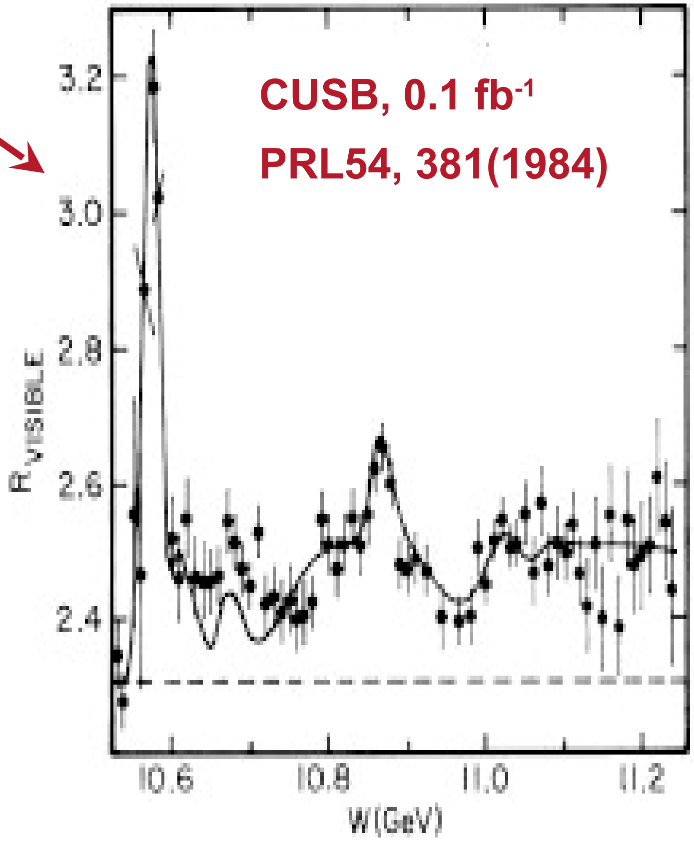
BaBar:

$\sqrt{s}$ = 10.54 GeV → 11.20 GeV

5 MeV steps, ~25 pb^{-1}/step ⇨ 3.3 fb^{-1}

$\sqrt{s}$ = 10.96 GeV → 11.10 GeV

additional 600 pb^{-1} in the ϒ(6S) region

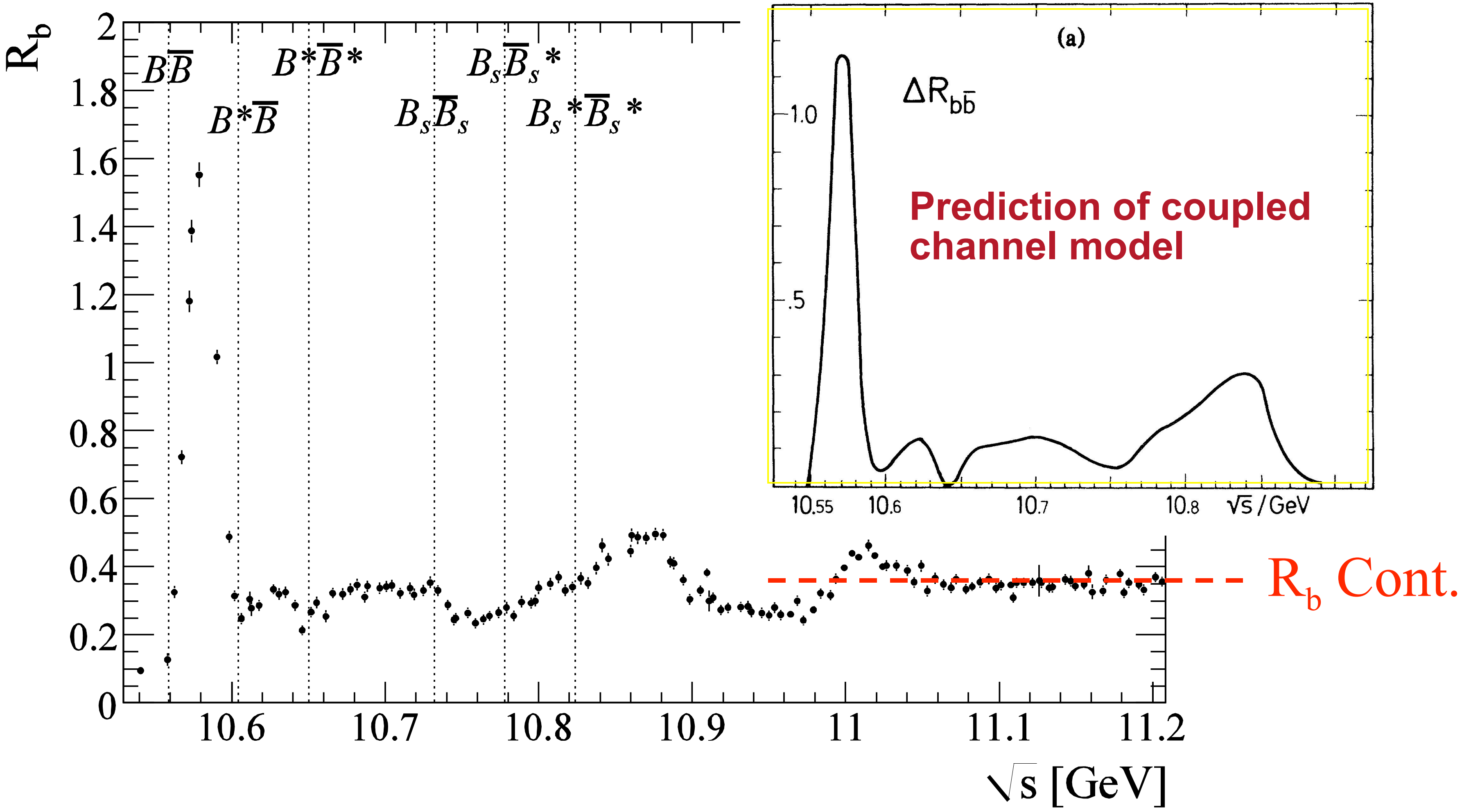


BaBar measurement of R_b

- $R_b(s) = \sigma_b(s)/\sigma_\mu(s)$, where $\sqrt{s} = E_{cm}$
  - σ_b is the total cross section for $e^+e^- \rightarrow b\bar{b}(\gamma)$ including $b\bar{b}$ states produced in initial state radiation (ISR) below open beauty threshold
  - σ_μ is the tree-level X-section for $e^+e^- \rightarrow \mu^+\mu^-$

- b-enriched sample selected for R_b measurement
- Off-peak ϒ(4S) data ($\sqrt{s}$ = 10.54 GeV) used as reference sample.

BaBar measurement of R_b



Prediction of coupled channel model

- Distribution indicates significant features above Υ(4S).
- Interpretation of structure at ~10.62 & ~10.7 GeV dependent on threshold openings

Searching for Higgs...

PRL 95:041801,2005
PRD 76:051105,2007

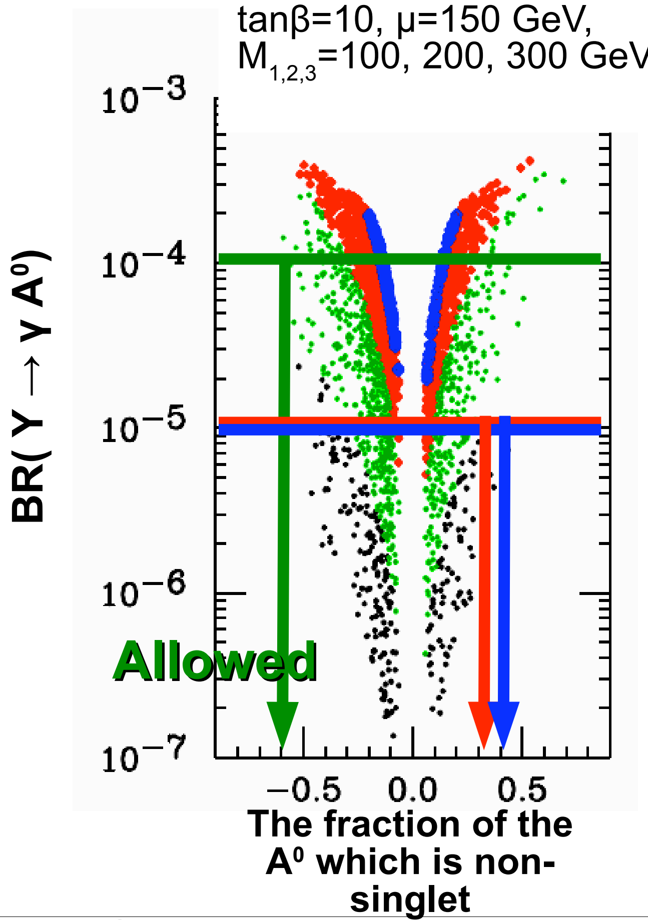
Additional extensions to the MSSM (NMSSM) allow for a light CP-odd Higgs (A^0)

In such picture the SM Higgs decays to A^0A^0

Depending on the mass

$A^0 \to \tau^+\tau^-$, $\mu^+\mu^-$, $\gamma\gamma$ or even invisible!
(Dark Matter)

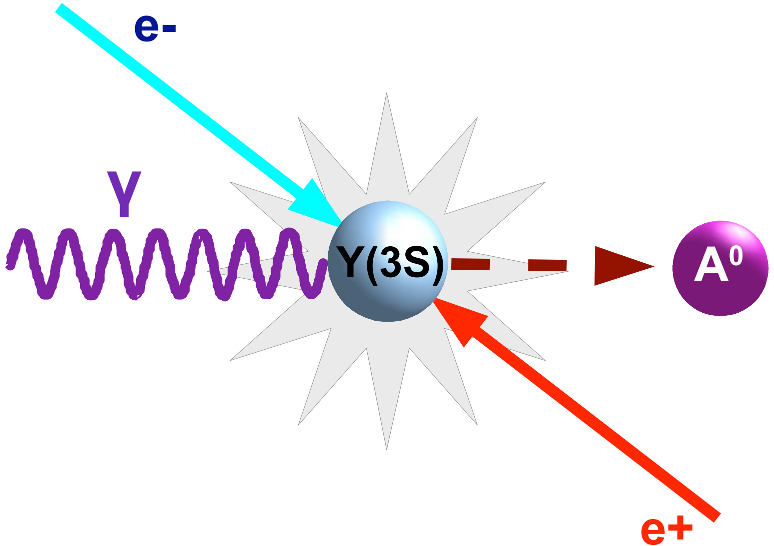
and the SM Higgs would end in final states to which LEP limits do not apply



... even best : Υ radiative decays to A^0 could be as large as 10^{-4}

Parameter Scan
blue points: $m_{A0} < 2m_\tau$
red points: $2m_\tau < m_{A0} < 7.5$ GeV
green points: 7.5 GeV $< m_{A0} <$ 8.8 GeV
black points: 8.8 GeV $< m_{A0} <$ 9.2 GeV

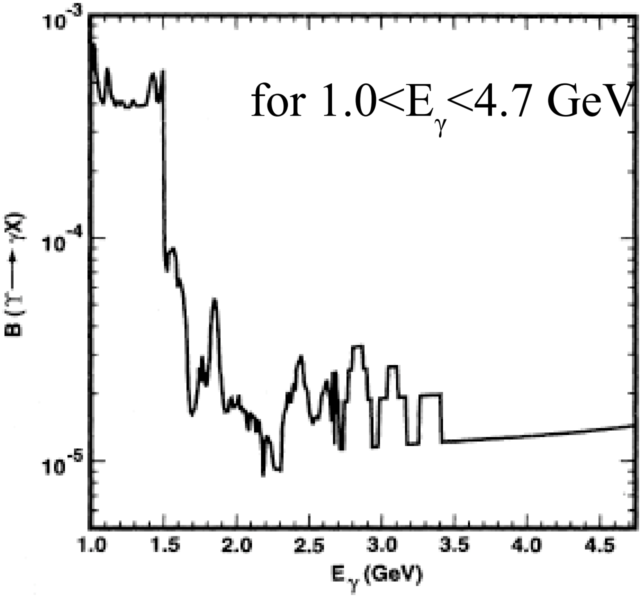
Search for invisible decay of light CP-odd Higgs



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

Best limits from CLEO
$\mathcal{B}(\Upsilon(1S)\rightarrow\gamma + \text{invisible}) < 10^{-5}–6\ 10^{-4}$

[No limits at Υ(2S) or Υ(3S)]



for $1.0<E_\gamma<4.7$ GeV

Need dedicated trigger:

γ + missing energy

More and more difficult with lower γ energy:

.

- “Isolated γ” [HE]: $E_\gamma^*>2$GeV
  (no additional constraints)
- “Single-γ” [LE]: $E_\gamma^*>1$GeV
  no additional tracks from IP

20 fb^{-1}
82M Υ(3S)

Event Selection

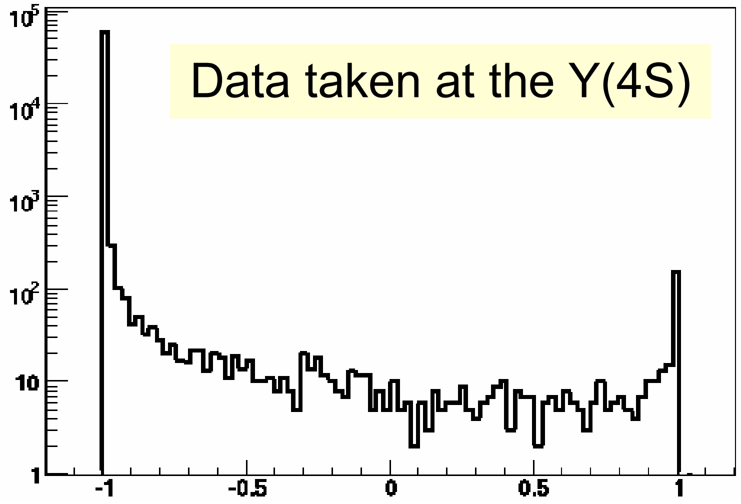
Variable	$3.2 < E^*_\gamma < 5.5$ GeV	$2.2 < E^*_\gamma < 3.7$ GeV
Number of crystals in EMC cluster	$20 < N_{\rm crys} < 48$	$12 < N_{\rm crys} < 36$
LAT shower shape	$0.24 < LAT < 0.51$	$0.15 < LAT < 0.49$
a_{42} shower shape	$a_{42} < 0.07$	$a_{42} < 0.07$
Polar angle acceptance	$-0.31 < \cos\theta^*_\gamma < 0.6$	$-0.46 < \cos\theta^*_\gamma < 0.46$
2nd highest cluster energy (CMS)	$E^*_2 < 0.2$ GeV	$E^*_2 < 0.14$ GeV
Extra photon correlation	$\cos(\phi^*_2 - \phi^*_1) > -0.95$	$\cos(\phi^*_2 - \phi^*_1) > -0.95$
Extra EMC energy (Lab)	$E_{\rm extra} < 0.1$ GeV	$E_{\rm extra} < 0.22$ GeV
IFR veto	$\cos(\Delta\phi^*_{\rm NH}) > -0.9$	$\cos(\Delta\phi^*_{\rm NH}) > -0.95$
IFR fiducial	$\cos(6\phi^*_\gamma) < 0.96$	...

Efficiency:

High Energy Region: 10-11%

Low Energy Region: 20%

Selection of high-quality photons, with tighter criteria for lower photon energies (increasing backgrounds)



Angle of IFR cluster relative to photon

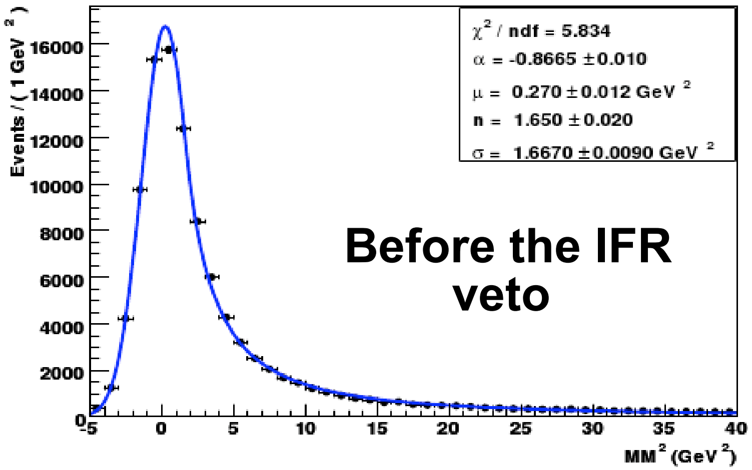
Veto $e^+e^- \to \gamma\gamma$ where one of the photons ends up in a dead EMC region

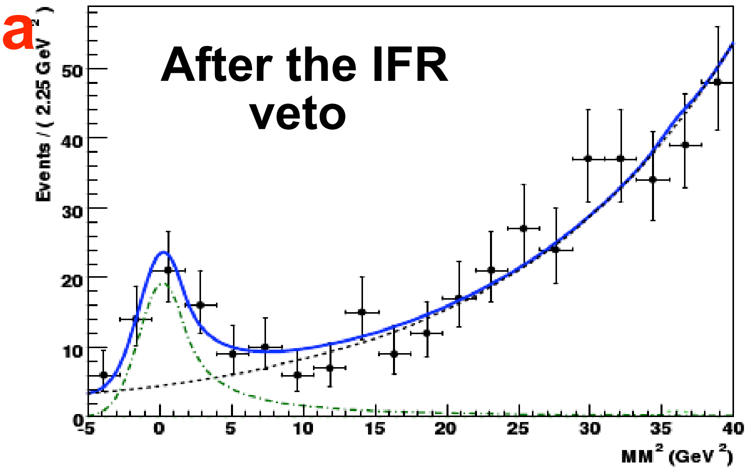
Maximum Likelihood Fit

- 1-D fit to the missing mass-squared: $m_X^2 = M_{\Upsilon(3S)}^2 - 2E_\gamma^* M_{\Upsilon(3S)}$
- Signal model
  - parameterized as a single "Crystal Ball" Function
  - parameters vary with assumed Higgs mass, due to EMC response
- Background models
  - determined from control samples and a small test-sample of the on-resonance Y(3S) data
  - Major backgrounds: $e^+e^- \rightarrow \gamma\gamma$ (HE,LE), $\gamma\gamma\gamma$ (LE), $e^+e^-\gamma$ (LE),

Off-Resonance Y(3S) Data

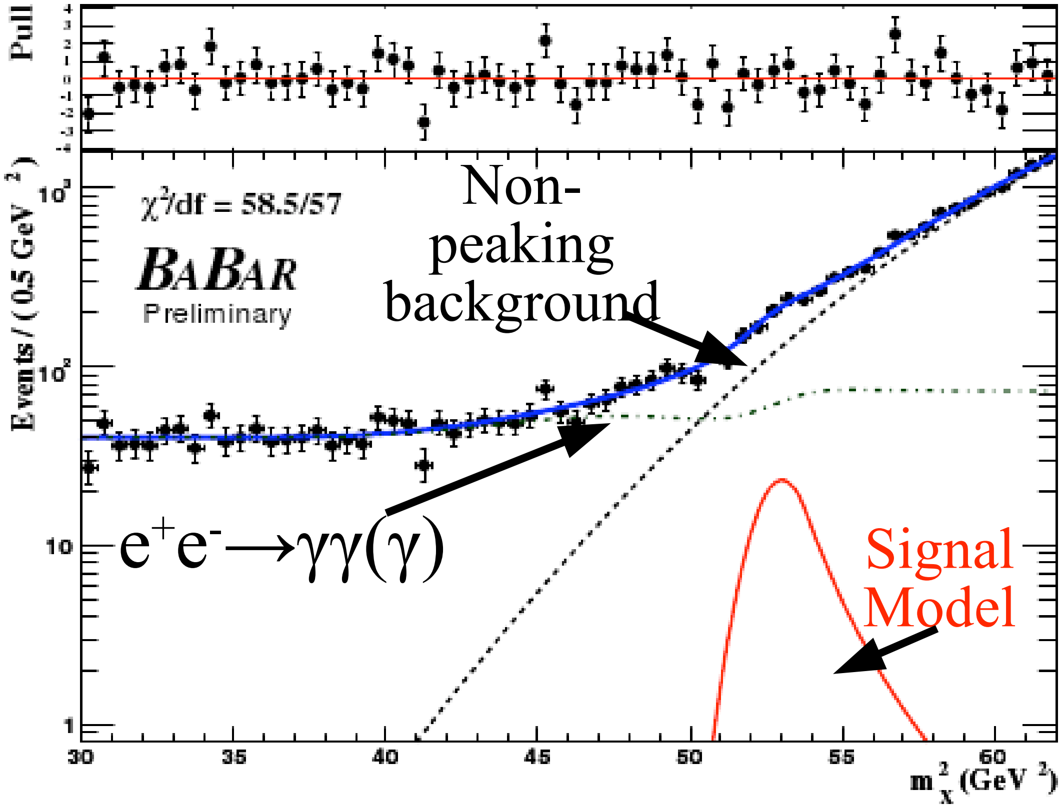
γγ background PDF modeled on data before the IFR veto.





Fits to the Spectrum

arXiv:0808.0017 [hep-ex]



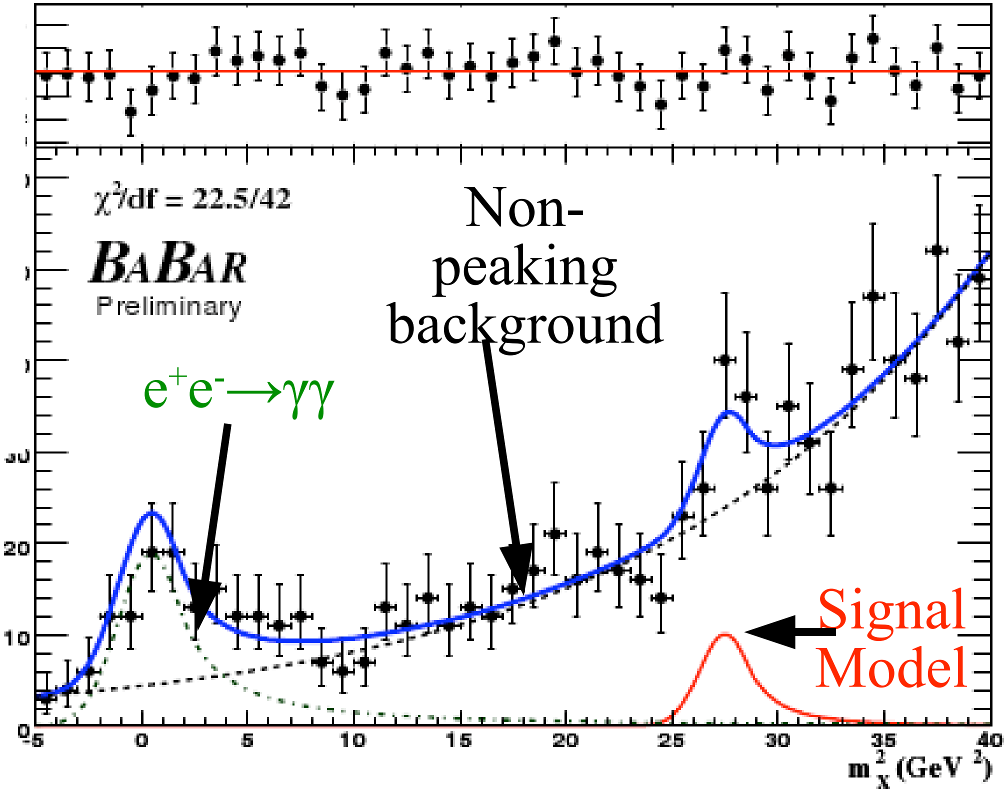
Non-peaking background

$e^+e^-\rightarrow\gamma\gamma(\gamma)$

Signal Model

Low-Energy region

High-Energy region

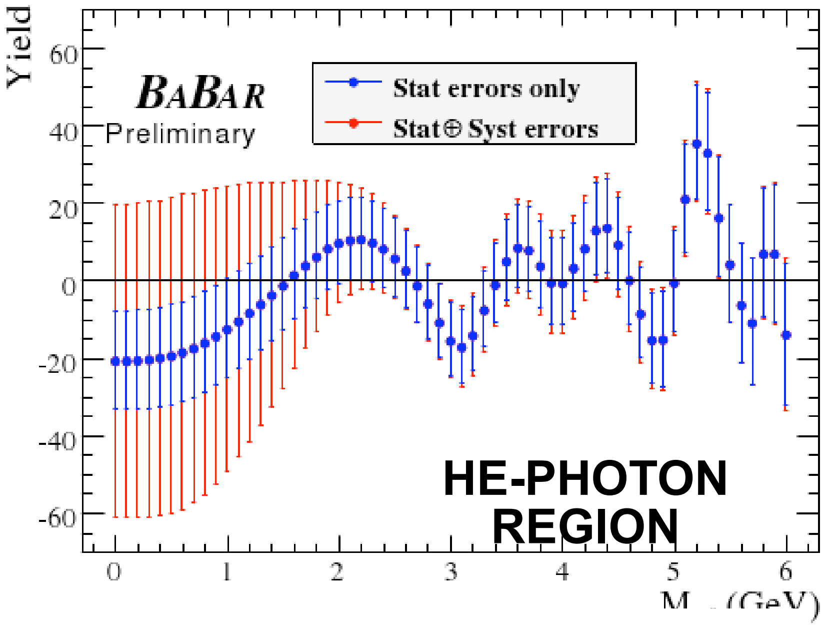


Non-peaking background

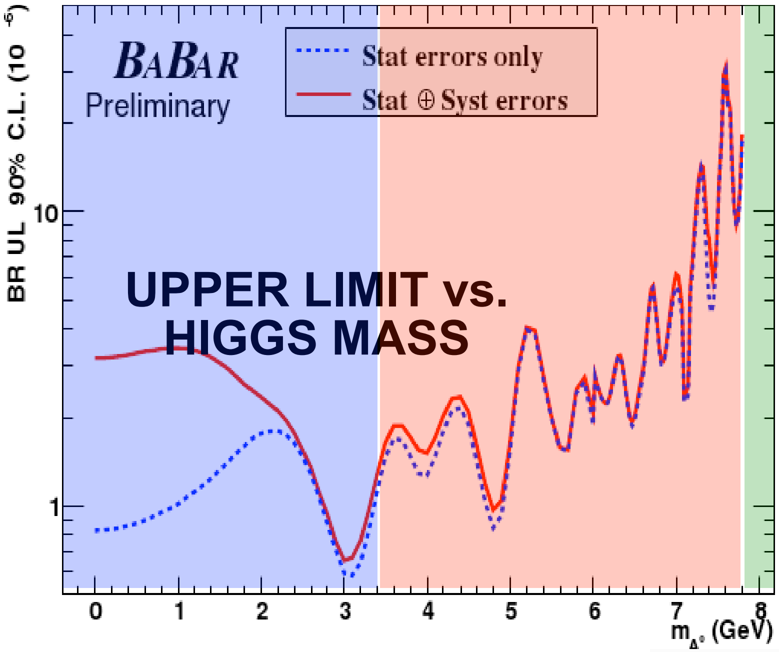
$e^+e^-\rightarrow\gamma\gamma$

Signal Model

Results

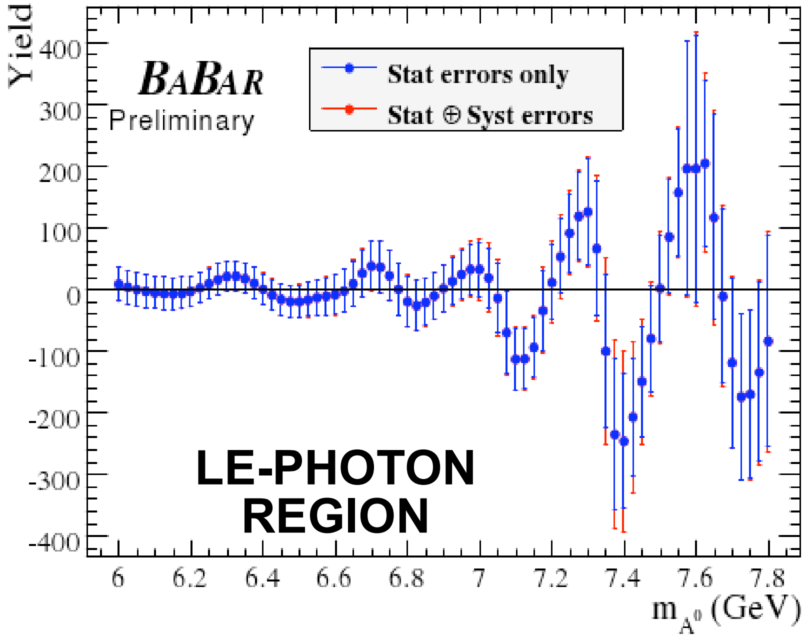


HE-PHOTON REGION



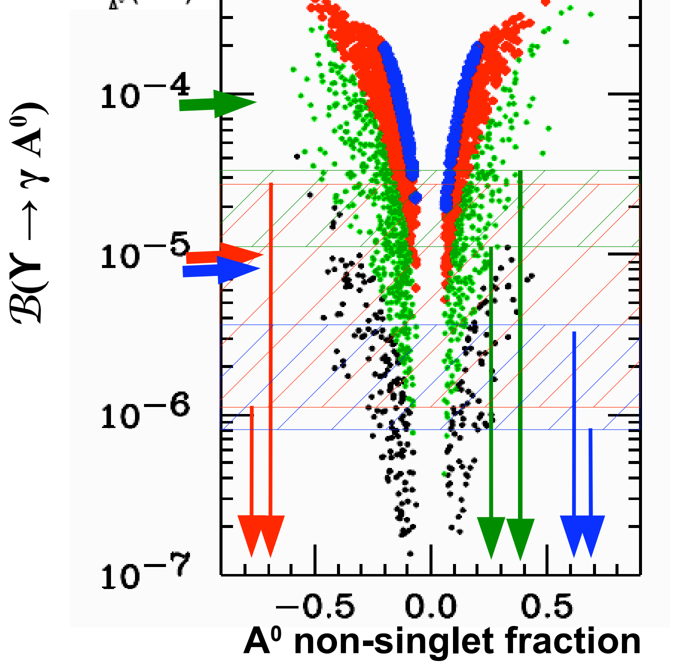
UPPER LIMIT vs. HIGGS MASS

arXiv:0808.0017 [hep-ex]



LE-PHOTON REGION

tanβ=10, μ=150 GeV, $M_{1,2,3}$=100, 200, 300 GeV

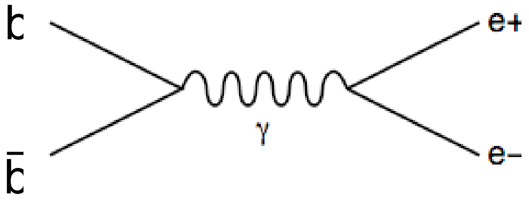


Conclusions

- After a long successful run at the Υ(4S) primarily devoted to CP violation and CKM measurements, BaBar managed to reshape its physics program almost overnight in response to the budget crisis
- Still mining our $B\overline{B}$ sample [$\tau^+\tau^-$, $D\overline{D}$,...]
- the bottomonium harvest just started:
  - The observation of $\eta_b(1S)$ thirty years after the discovery of the narrow Υ resonances is the first great result from the Run7
  - The region above the Υ(4S) scanned in fine steps
  - New physics searches extended to Υ(3S) and Υ(2S) as well

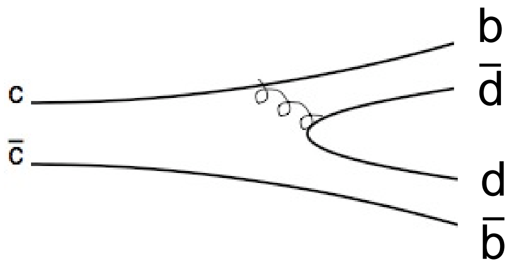
backup slides

Bottomonium decays

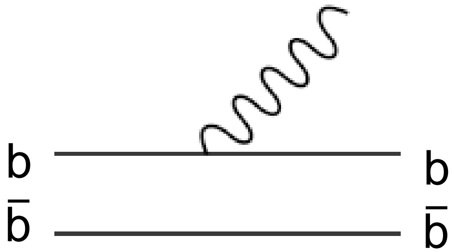


only $J^{PC}=1$

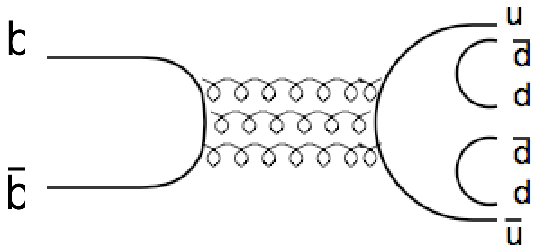
Experimentally clean



Dominant above $B\bar{B}$

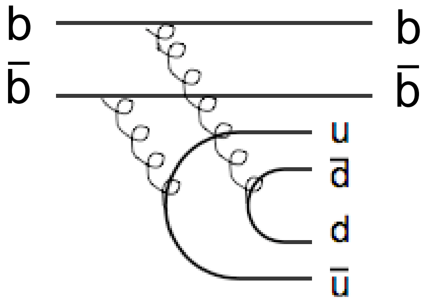


Radiative transitions



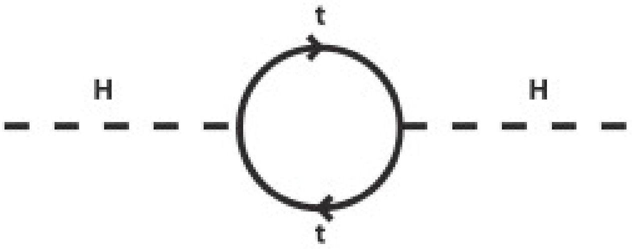
2 [3] gluons J odd[even]

α_{ss}suppressed



Hadronic transitions

Next to Minimal Supersymmetric Standard Model (NMSSM)

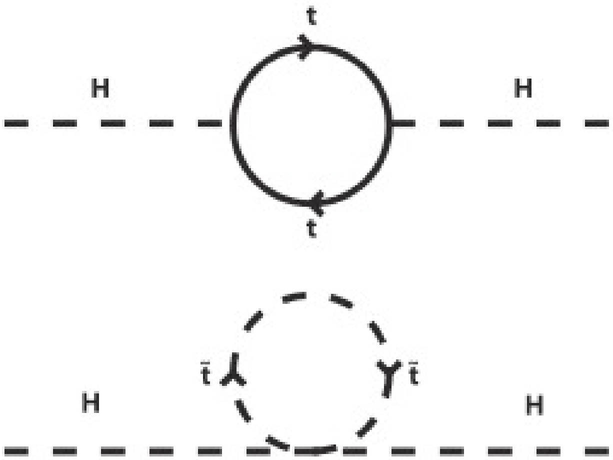


Higgs self-coupling diverges in the Standard Model at high energies

$$\mu H_u H_d$$

gives the two Higgs doublets non-zero vacuum-expectation values

μ expected to have a value of order the weak scale, much smaller than the next natural scale (Planck scale, “



Loops involving superpartners cancel divergences

One Solution: NMSSM
Next-to-Minimal Supersymmetric Standard Model

$$\mu H_u H_d \Rightarrow \lambda N H_u H_d$$

Add an additional Higgs singlet field, effectively promoting μ to a gauge singlet, chiral superfield

Adding a CP-odd Higgs (A^0) can change the phenomenology of the Higgs sector

Radiative transitions

- QED multipole expansion

E1 transitions:

$$\Gamma(n^{2S+1}L_{iJ_i} \to n'^{2S+1}L_{fJ_f} + \gamma) = \frac{4\alpha e_Q^2 k^3}{3}(2J_f+1)\mathcal{S}_{if}|\langle f|r|i\rangle|^2$$

M1 transitions: (spin flip)

$$\left\{\begin{array}{l} \Gamma(n^3S_1 \to n'^1S_0 + \gamma) \\ \Gamma(n^1S_0 \to n'^3S_1 + \gamma) \end{array}\right\} = 4\alpha e_Q^2 k^3 (2J_f+1)|\langle f|j_0(kr/2)|i\rangle|^2/3m_Q^2$$

Estimate of branching fraction

With **$N(\Upsilon(3S)) = (109 \pm 1) \times 10^6$** $\varepsilon = 37\%$

$$\mathcal{B}(\Upsilon(3S) \to \gamma\eta_b(1S)) = \frac{N(\eta_b(1S))}{\varepsilon N(\Upsilon(3S))} = (4.5 \pm 0.5[stat]) \times 10^{-4}$$

- Systematic Uncertainties:
  - Uncertainty on Signal efficiency → 12.6%
    - Obtained by comparing χ_b efficiency in data (39.4%) and MC (35.0%)
    - Uncertainty from $\chi_b(2P)$ BF (PDG) → 18.2%
      - Focus on Observation not BF measurement
      - Will be improved in the future ….

    22%
  - Uncertainty on BW width → 11%
  - **Total Systematic Uncertainty** → **25%**

$\mathcal{B}(\Upsilon(3S) \to \gamma\eta_b(1S)) = (4.5 \pm 0.5 \text{ [stat.]} \pm 1.2 \text{ [syst.]}) \times 10^{-4}$