Observation of the Bottomonium Ground State, $\eta_b(1S)$, in the Decay $\Upsilon(3S) \rightarrow \gamma\,\eta_b$

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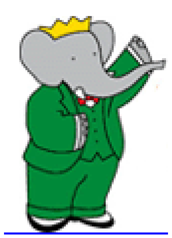
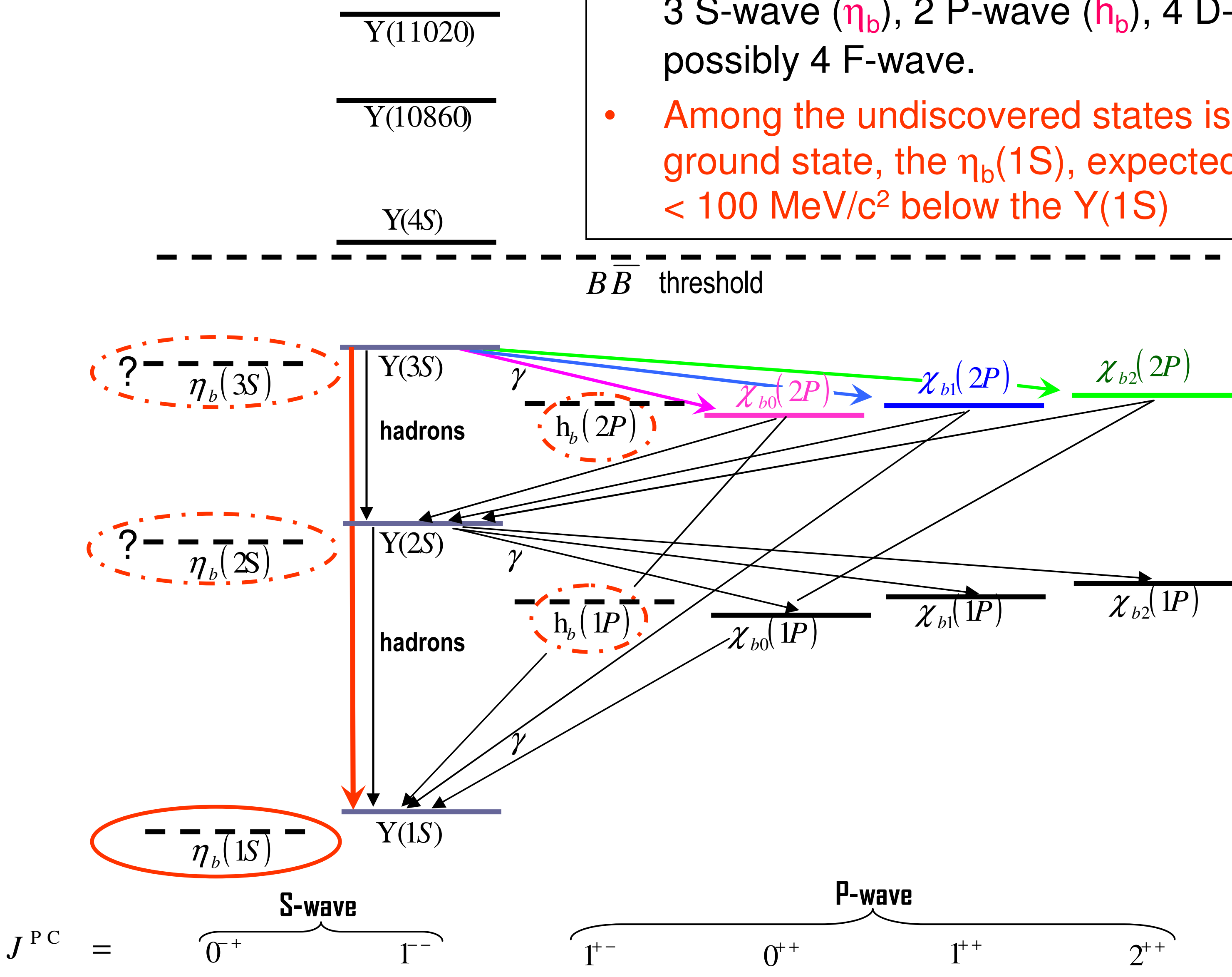
Representing the BaBar Collaboration

BNL Seminar, Oct. 1, 2008

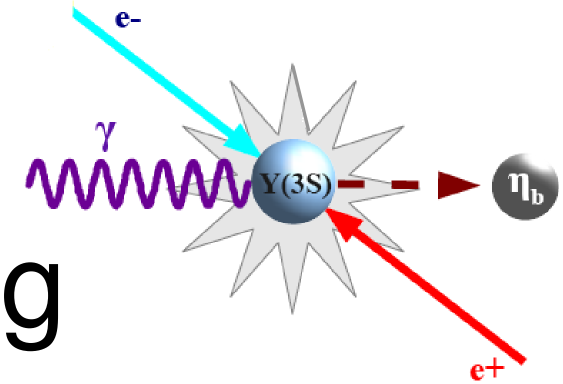


Current Picture of the Bottomonium Spectrum

- $b\bar{b}$ states below Υ(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 $\eta_b(1S)$, expected to be < 100 MeV/c² below the Υ(1S)



Expected Mass Splitting



- **Bottomonium systems are described by QCD-motivated potential models.**
- The spin-triplet S-wave $\Upsilon(nS)$ states are produced in hadronic interactions or by virtual photons e^+e^- interactions
- Spin-dependent interactions give rise to splittings within multiplets

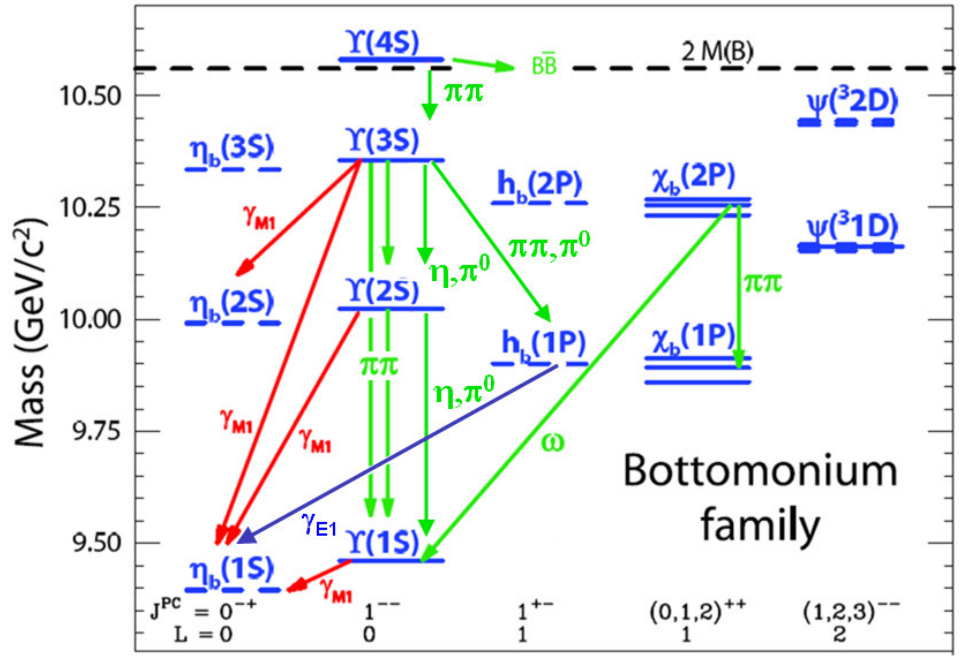
→ can predict $\Upsilon\!-\!\eta_b$ splittings (analogous to hyperfine splittings in positronium).

⅄ Spin-spin splitting between the singlet and triplet *S*-wave $b\bar{b}$ states is predicted to be small.

⅄ $\Upsilon\!-\!\eta_b$ mass splitting → key test of the applicability of perturbative quantum chromodynamics (pQCD) to the bottomonium system & useful check of lattice QCD results.

Expected Mass Splitting

- Υ(nS) resonances undergo:
  - Hadronic transitions via π^0, η, ω, $\pi\pi$ emission
  - Electric dipole transitions [E1: between states with the same total spin]
  - Magnetic dipole transitions [M1: between states of opposite quark spin configurations and same orbital angular momentum].



  - Electromagnetic transitions between the levels can be calculated in the quark model → important tool in understanding the bottomonium internal structure

- Hyperfine splitting of bottomonium ground state very sensitive to α_s
  ➔ experimental measurement of $M(\eta_b)$ with a few MeV error sufficient to improve $\alpha_s(M_Z)$ accuracy.
- $Y(1S)-\eta_b$ mass splitting varies from 35-100 MeV (Lattice-QCD, pQCD, quark potential models)

Expected Transition Rates

- Singlet S-state, η_b, may be produced in the decay of the Υ through the M1 transition $\Upsilon(nS) \rightarrow \eta_b(n'S)\,\gamma$ $(n' \leq n)$.

- In the non-relativistic approximation:

$$\Gamma[\Upsilon(nS) \rightarrow \eta_b(n'S)\gamma] = \frac{4}{3}\alpha\frac{e_b^2}{m_b^2} I^2 k^3$$

S. Godfrey and J.L. Rosner, Phys. Rev. D 64, 074011 (2001).

$$I = \langle f \,|\, j_0(kr/2) \,|\, i \rangle, \;\; \alpha = 1/137.036, \;\; e_b = -1/3|e|, \;\; m_b \approx 4.8\,\mathrm{GeV}/c^2$$

- For hindered† transitions $(n \neq n')$:

† In the non-relativistic limit the spatial overlap integrals for M1 transitions equal one between *S*-wave states within the same multiplet and zero for transitions between states with different radial quantum numbers

Relativistic corrections ➔ small overlaps (I); can be compensated by large phase space factor k^3 ☞ rates expected to be observable

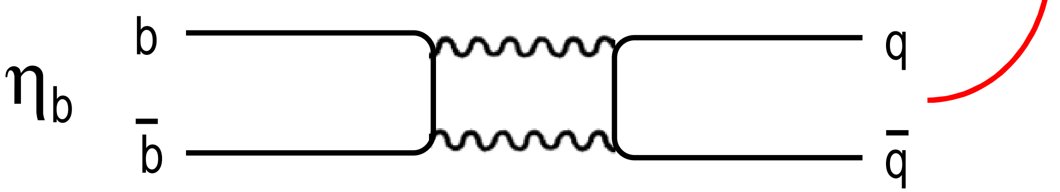
☛Essential to measure rate to test relativistic correction factors

- Transition rate: BF($\Upsilon(3S) \rightarrow \gamma\,\eta_b$) ~ 1×10^{-4} - 2×10^{-3}

- Upper limit on B.F.($\Upsilon(3S) \rightarrow \gamma\,\eta_b$) < 4.3×10^{-4} @ 90% [CLEO]

Expected η_b Decay Properties

- η_b expected to decay almost entirely through 2 gluons (OZI-suppressed decay)



hadronization → large multiplicities expected, difficult to identify exclusive decay modes

→ inclusive search

- Width expected to be smaller than for the η_c [Γ = 26.5 MeV]

- smaller relativistic correction & smaller strong coupling constant at the b mass than at the c mass.

- Predictions for $\Gamma[\eta_b \rightarrow gg]$: [5 – 20] MeV

The study of bottomonium began with …

Evidence for the bottom quark

VOLUME 39, NUMBER 5 PHYSICAL REVIEW LETTERS 1 AUGUST 1977

Observation of a Dimuon Resonance at 9.5 GeV in 400-GeV Proton-Nucleus Collisions

S. W. Herb, D. C. Hom, L. M. Lederman, J. C. Sens,[a] H. D. Snyder, and J. K. Yoh
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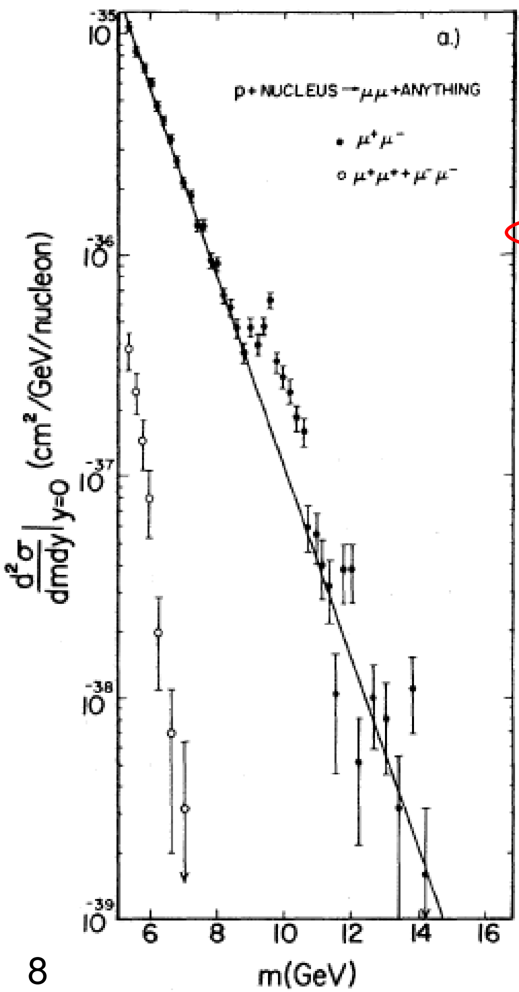
(Received 1 July 1977)

Accepted without review at the request of Edwin L. Goldwasser under policy announced 26 April 1976

Dimuon production is studied in 400-GeV proton-nucleus collisions. A strong enhancement is observed at 9.5 GeV mass in a sample of 9000 dimuon events with a mass $m_{\mu^+\mu^-} > 5$ GeV.



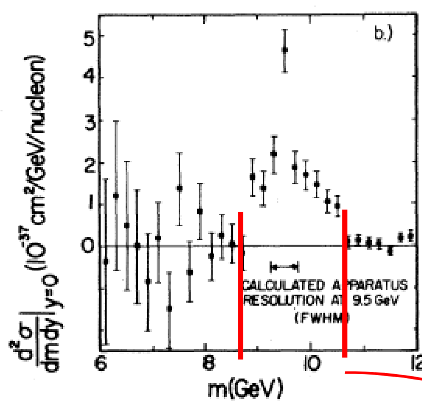
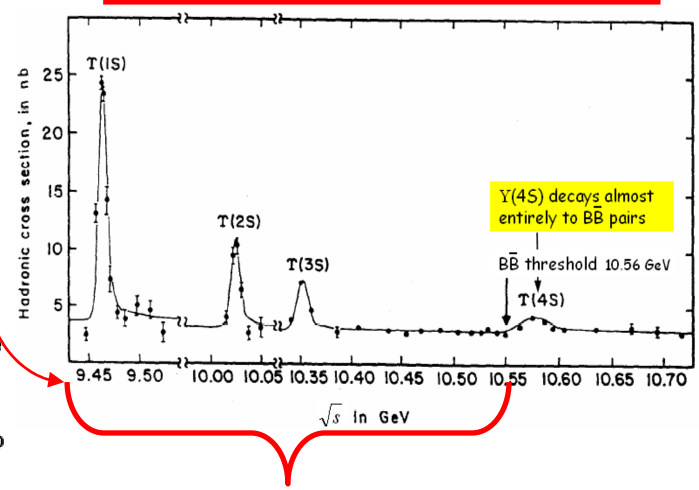
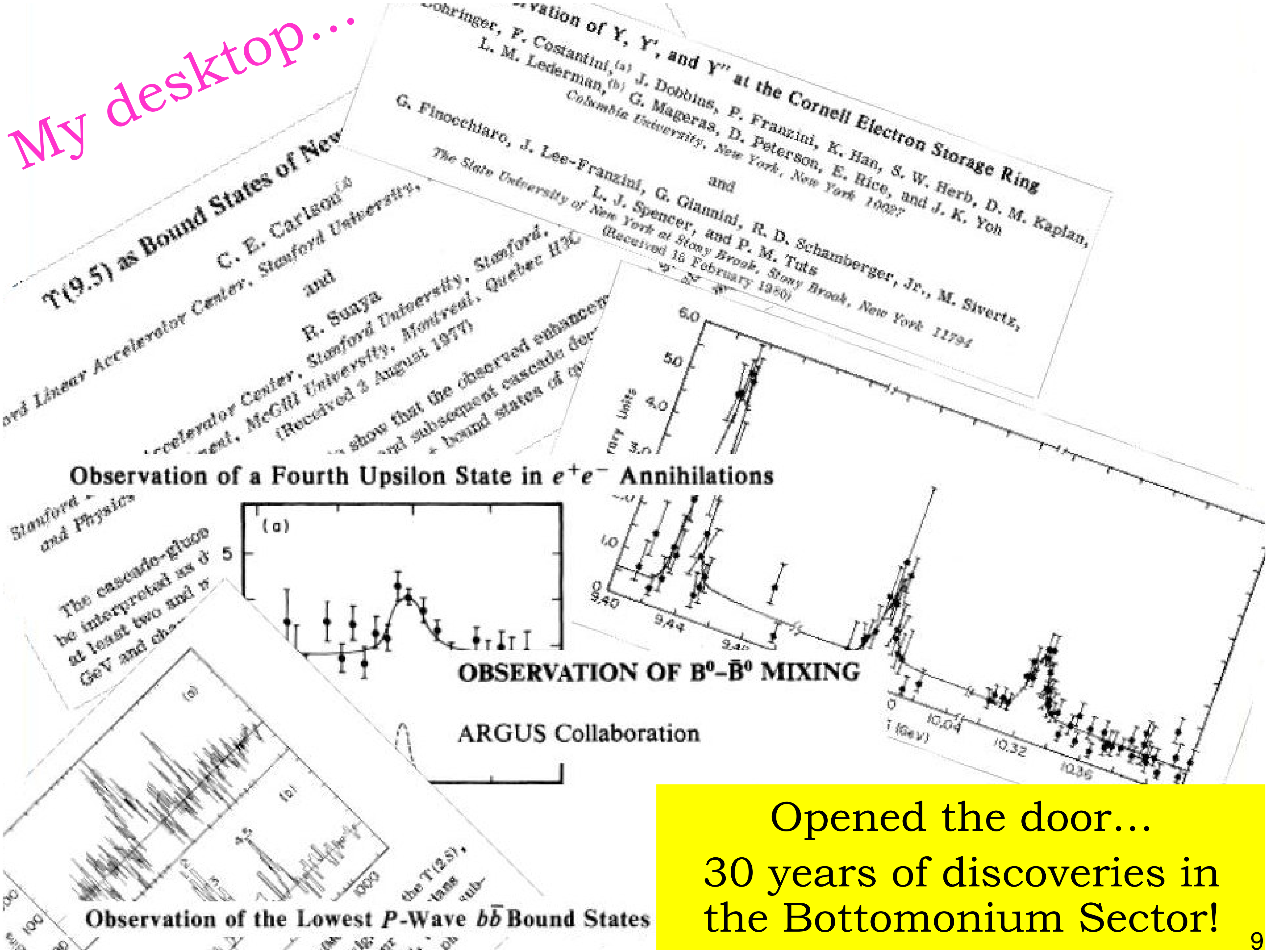


FIG. 3. (a) Measured dimuon production cross sections as a function of the invariant mass of the muon pair. The solid line is the continuum fit outlined in the text. The equal-sign–dimuon cross section is also shown. (b) The same cross sections as in (a) with the smooth exponential continuum fit subtracted in order to reveal the 9–10-GeV region in more detail.

Discovery of $b\bar{b}$ pairs
↓
Bottomonium



My desktop…



Opened the door…

30 years of discoveries in the Bottomonium Sector!

PEP-II Running at the Υ(3S)…

Dec. 12th -17th: Start-up after upgrade aimed at $\mathcal{L}$=2 x 10^{34} cm^2s^{-1}

Dec. 15th : first collisions at Υ(4S) energies

Dec. 17th : first delivery to BaBar

BaBaR Run 7

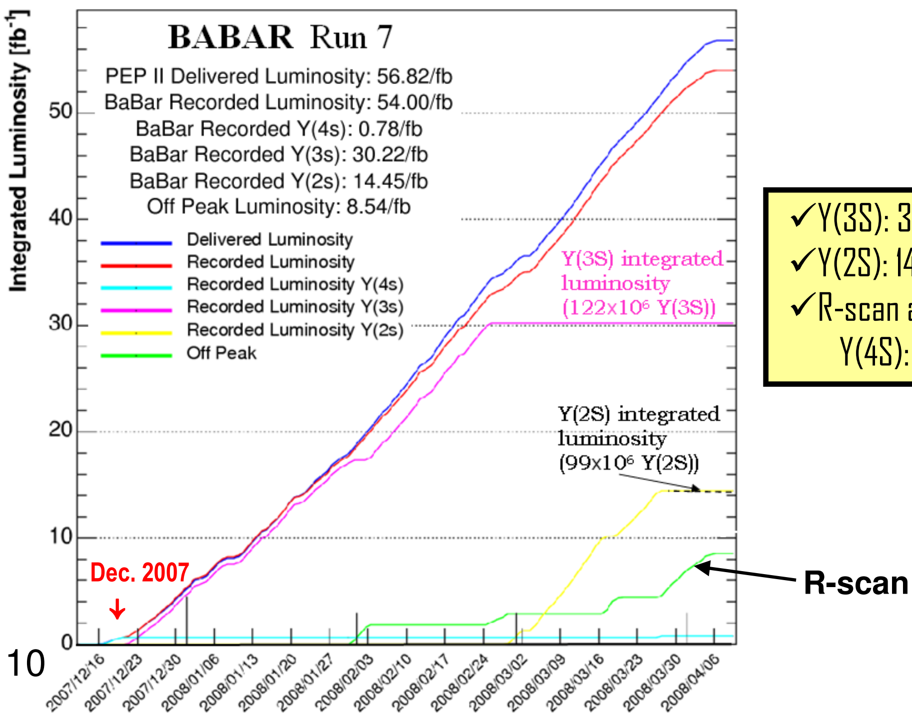
Dec. 19th : Budget gloom and doom ☹

Dec. 20th – 21st : Discussions about immediate move to Υ(3S)

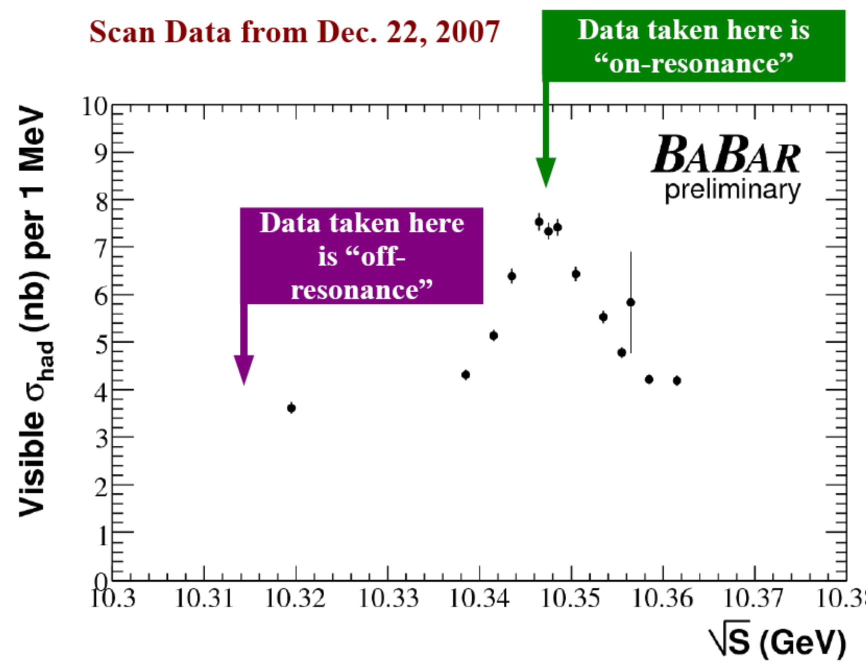
Dec. 21st, 3:00 p.m.: Start to lower the energy of the e^- beam for Υ(3S) running

Dec. 22nd : LINAC & PEP-II problems related to start-up blues sorted out…

Υ(3S) scan completed – **moved to Υ(3S) peak,** began data-taking …



✓Υ(3S): 33 fb^{-1}
✓Υ(2S): 14 fb^{-1}
✓R-scan above Υ(4S): 4 fb^{-1}



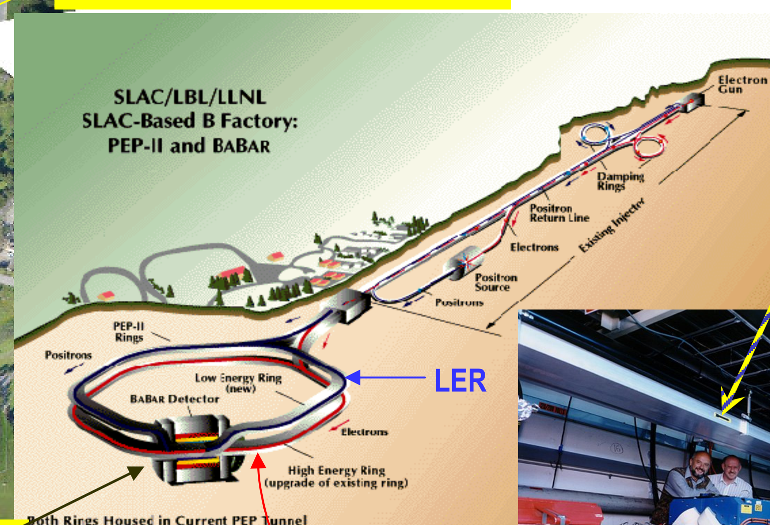
THE PEP-II STORAGE RINGS AT SLAC

~~Proton~~ – Electron Project (original idea)

Positron – Electron Project — Symmetric-energy collider- single ring

Positron – Electron Project II — Asymmetric-energy collider-
- **HER**: old PEP ring
- **LER**: new ring built on top of HER

* Steve Williams piloting from Bldg 750 (bottom of picture)
* World Models Super Frontier 80" span
* Sony U30 2 MP looking straight down
* e-switch by www.rc-cam.com
* electric brushless motor
* altitude 1500'
* Picture-It software
* Feb 28, 2004
* more pix at www.pam-rc.org



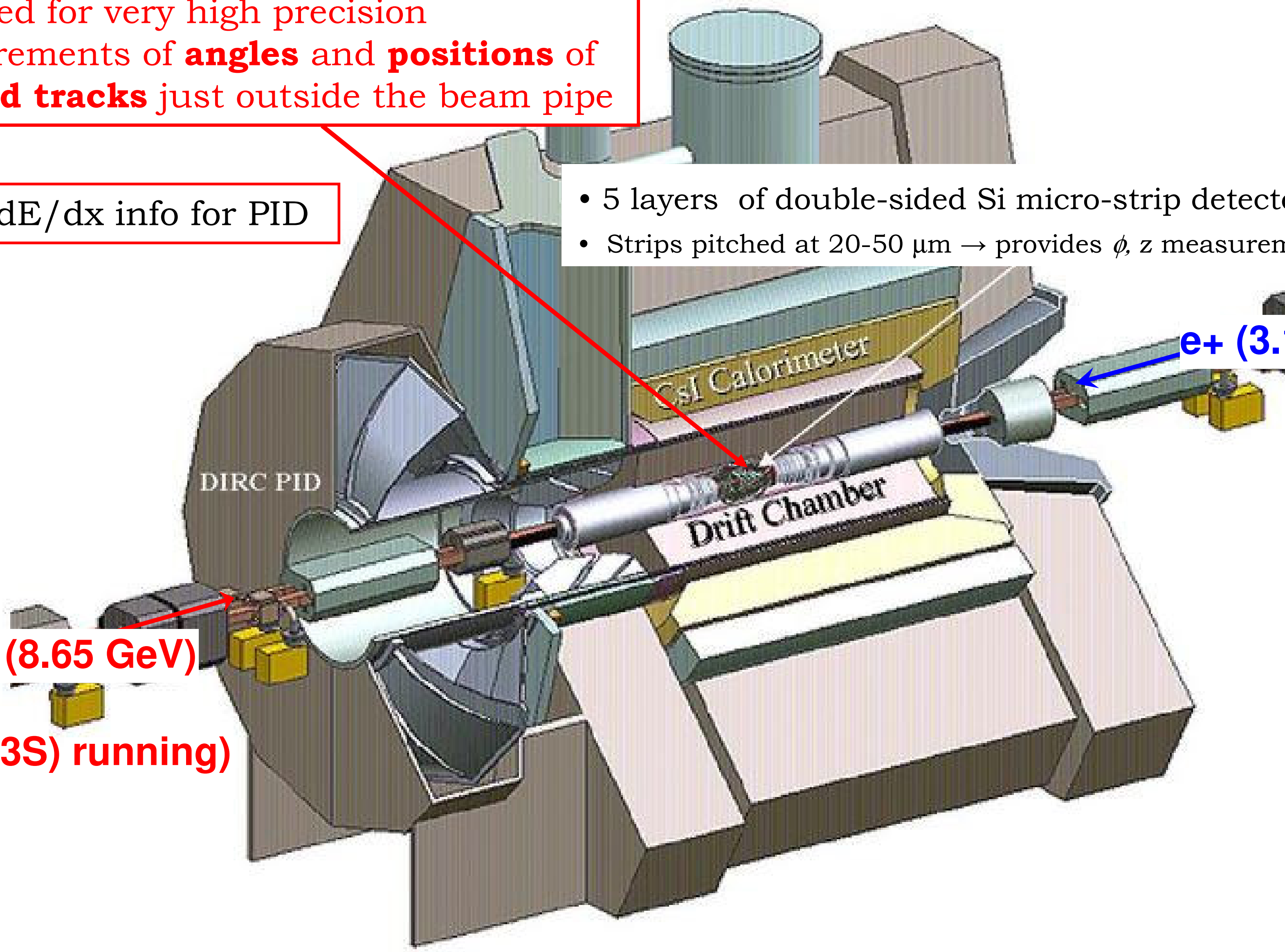
PEP II AND THE BABAR DETECTOR

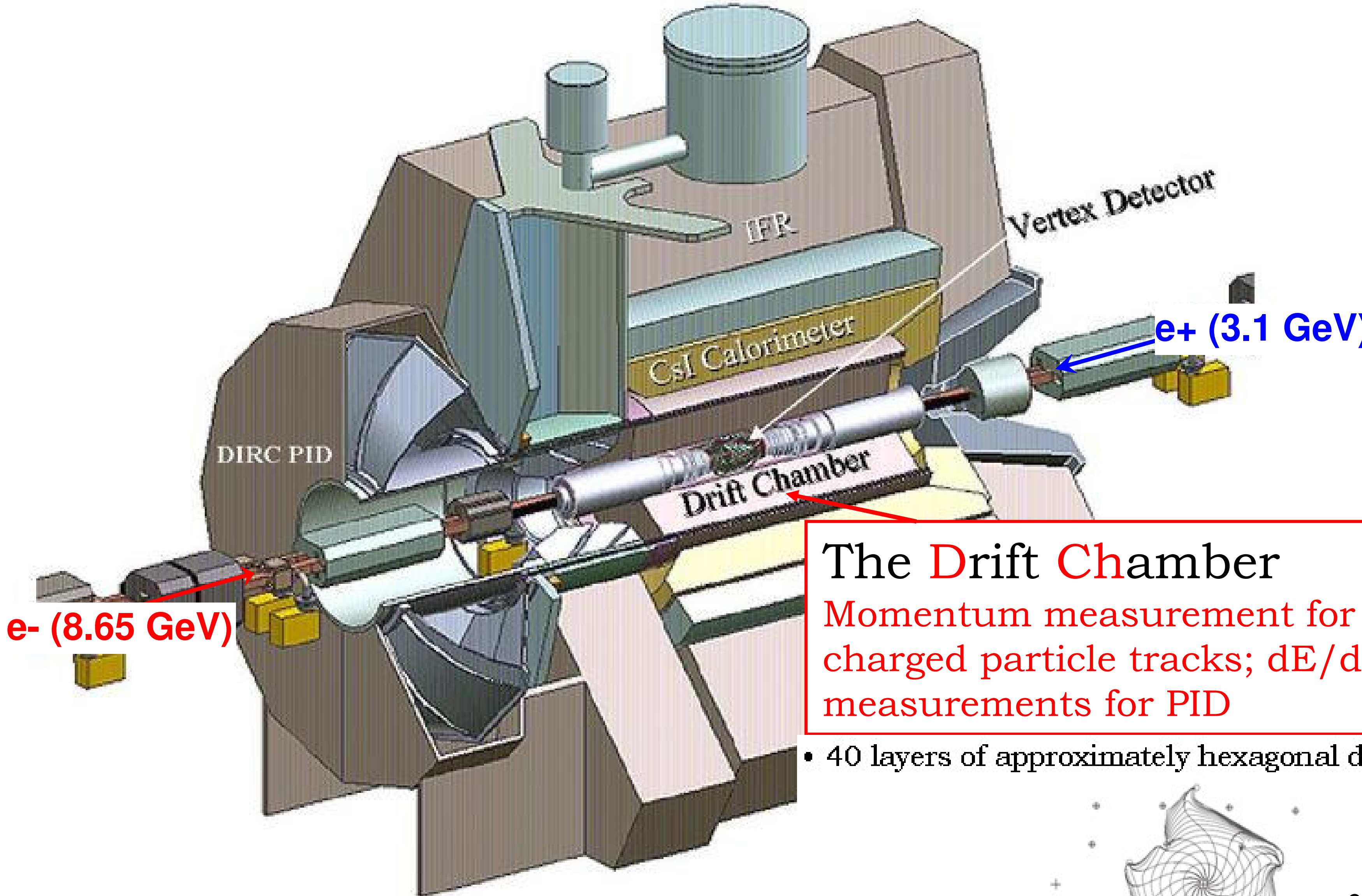
The Silicon Vertex Tracker

Designed for very high precision measurements of **angles** and **positions** of **charged tracks** just outside the beam pipe

Some dE/dx info for PID

- 5 layers of double-sided Si micro-strip detectors
- Strips pitched at 20-50 μm → provides ϕ, z measurements





The Drift Chamber

Momentum measurement for charged particle tracks; dE/dx measurements for PID

- 40 layers of approximately hexagonal drift cells

Courtesy of GARFIELD

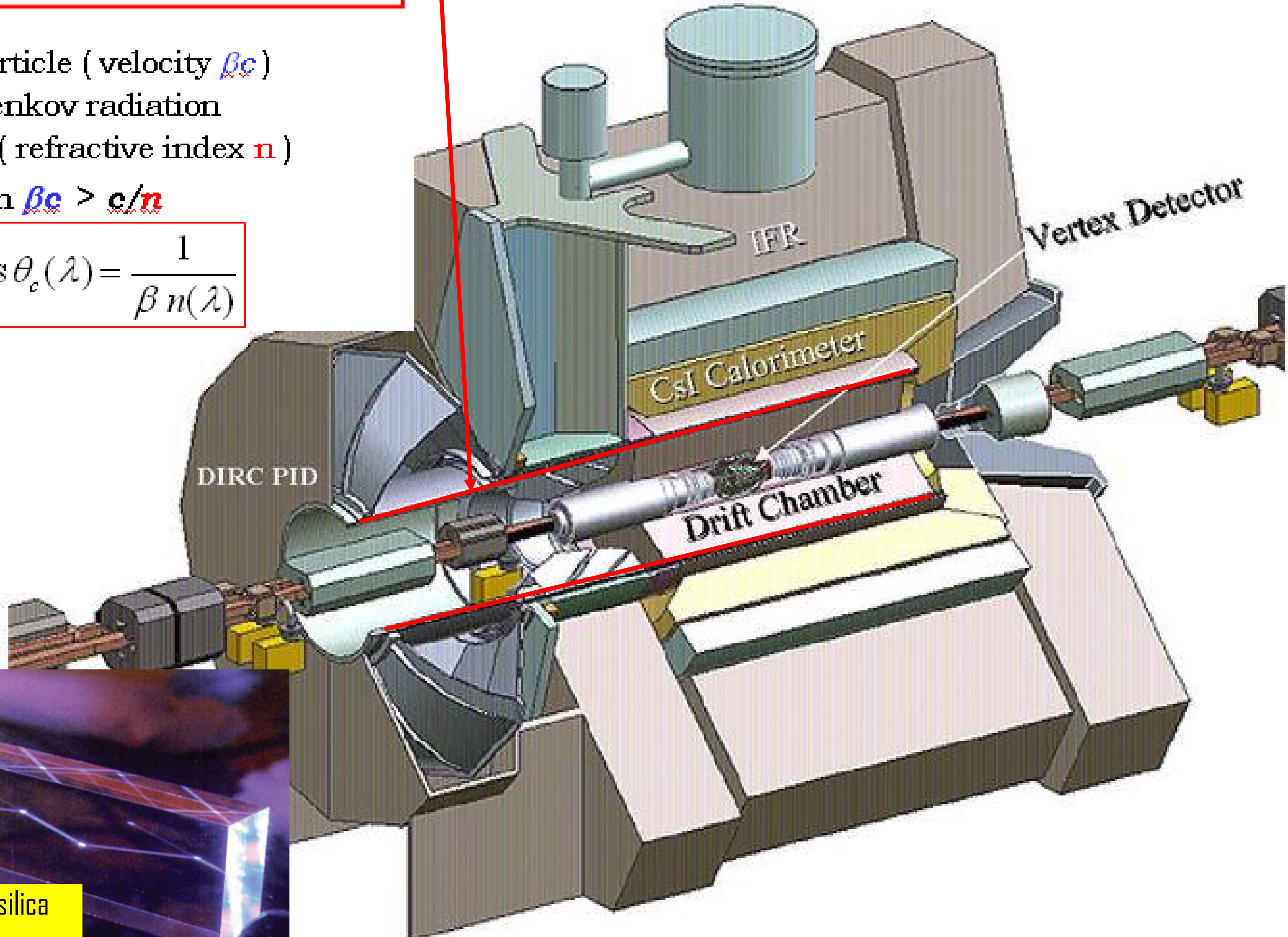
The Detector of Internally Reflected Cherenkov Radiation

Charged particle identification by means of velocity measurement

Charged particle (velocity βc)
emits Cherenkov radiation
in medium (refractive index n)

when $\beta c > c/n$

So that $$\cos\theta_c(\lambda) = \frac{1}{\beta\, n(\lambda)}$$



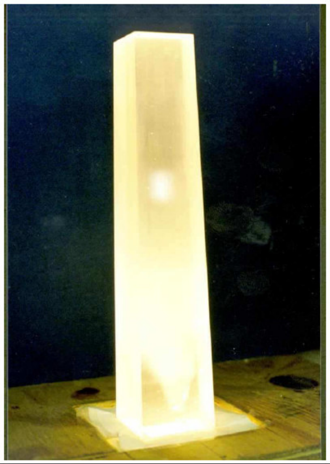
long synthetic fused silica (quartz) bar acts as light guide (preserves θ_c)

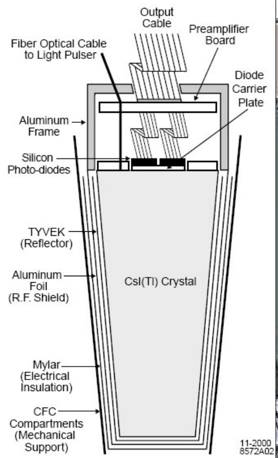
The ElectroMagnetic Calorimeter

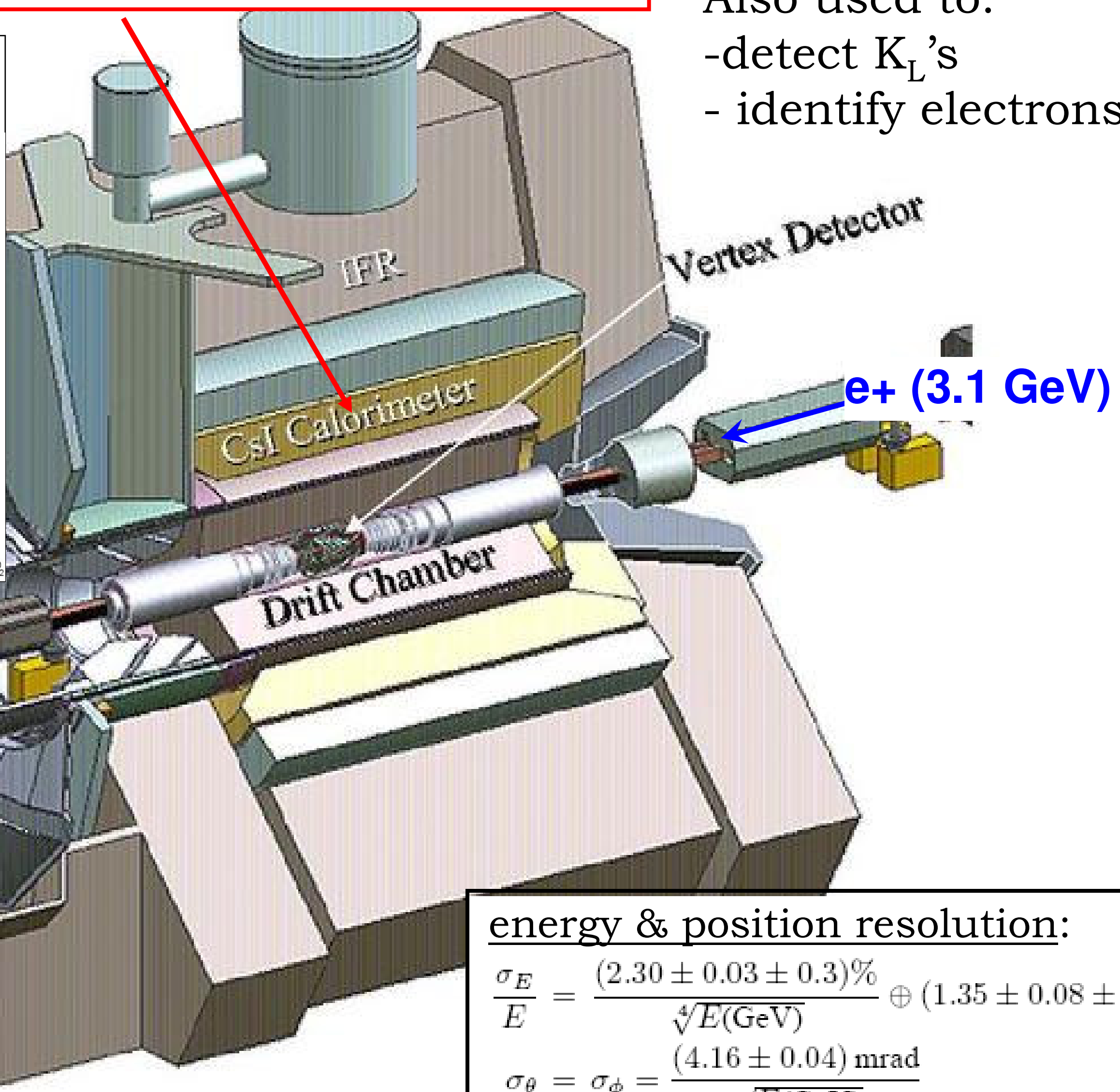
Designed to detect electromagnetic showers over the energy range from 20 MeV to 4GeV

Also used to:
- detect K_L's
- identify electrons

Segmented array of 6580 Thallium-doped CsI crystals 16 to 17.5 radiation lengths deep (Rad. L. >1.85 cm)







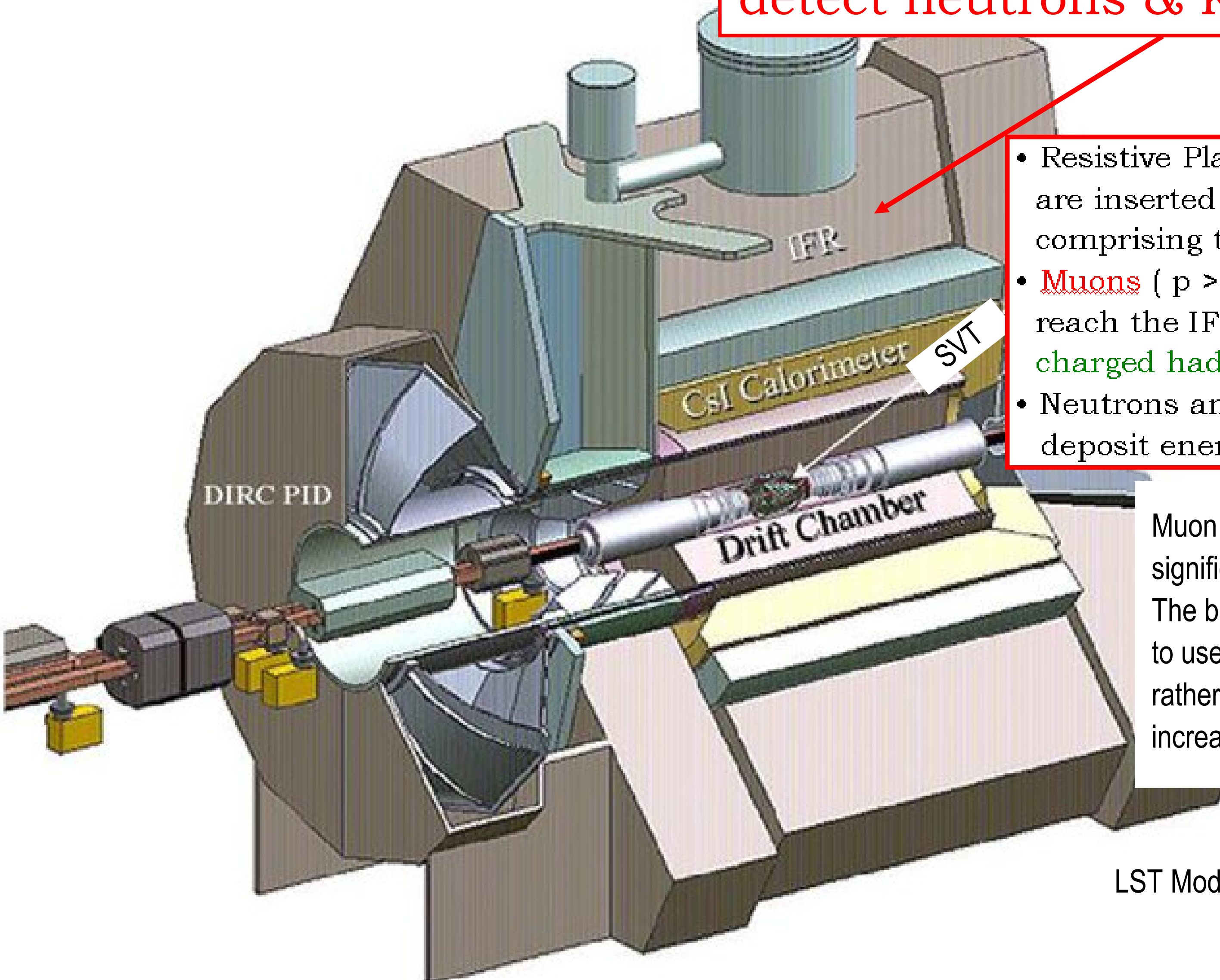
energy & position resolution:

$$\frac{\sigma_E}{E} = \frac{(2.30 \pm 0.03 \pm 0.3)\%}{\sqrt[4]{E(\mathrm{GeV})}} \oplus (1.35 \pm 0.08 \pm 0.2)\%$$

$$\sigma_\theta = \sigma_\phi = \frac{(4.16 \pm 0.04)\,\mathrm{mrad}}{\sqrt{E(\mathrm{GeV})}}$$

The Instrumented Flux Return

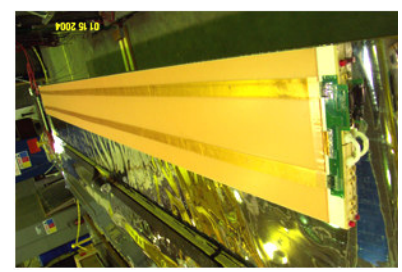
Designed to identify muons and detect neutrons & K_Ls



- Resistive Plate Chambers (RPC's) are inserted between the iron plates comprising the magnet flux return
- Muons (p > ~ 1 GeV/c) should reach the IFR and be detected; charged hadrons should not
- Neutrons and K_L mesons can also deposit energy in the IFR

Muon detection efficiency degraded significantly over the years.
The barrel IFR was upgraded to use Limited Streamer Tubes (LST's) rather than RPC's with a significant increase in efficiency.

LST Module →



The Search for the η_b at BaBar

- 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 915 MeV, i.e. look for a bump near 900 MeV in inclusive photon energy spectrum from data taken at the Υ(3S)

BLIND ANALYSIS

ANALYSIS STRATEGY

1. **Look for a bump near 900 MeV in the inclusive photon spectrum**
    - Large background
        - Non-peaking components
        - Peaking components
2. **Reduce the background**
    - Selection Criteria
    - Optimization of Criteria
    - Optimization Check (using data)
3. **Fitting Procedure**
    - One-dimensional fit to the $E\gamma$ distribution
        - Obtain lineshapes of the various components
        - Binned Maximum Likelihood Fit

DATA SETS

- Υ(3S) On-peak data

{ L = Integrated Luminosity }

- Full data sample: **L = 28.6 fb^{-1}**
  - ↳122 x 10^6 Υ(3S) events
- Analysis sample: **L = 25.6 fb^{-1}**
  - ↳109 x 10^6 Υ(3S) events
  - ↳expect ~ 20 x 10^3 Υ(3S)→ $\gamma\,\eta_b$ events
- Test sample: **L = 2.6 fb^{-1}**
  (used for optimization of selection criteria)
  - ↳11 x 10^6 Υ(3S) events
  - ↳expect ~ 2 x 10^3 Υ(3S)→ $\gamma\,\eta_b$ events
  { much smaller than expected background }

❖ Use since no reliable event generator for Υ(3S) background photon simulation

- **Υ(3S) & Υ(4S) Off-peak data: L = 2.4 & 43.9 fb^{-1}**
  (used for background studies)

1. Look for a bump near 900 MeV in the inclusive photon spectrum

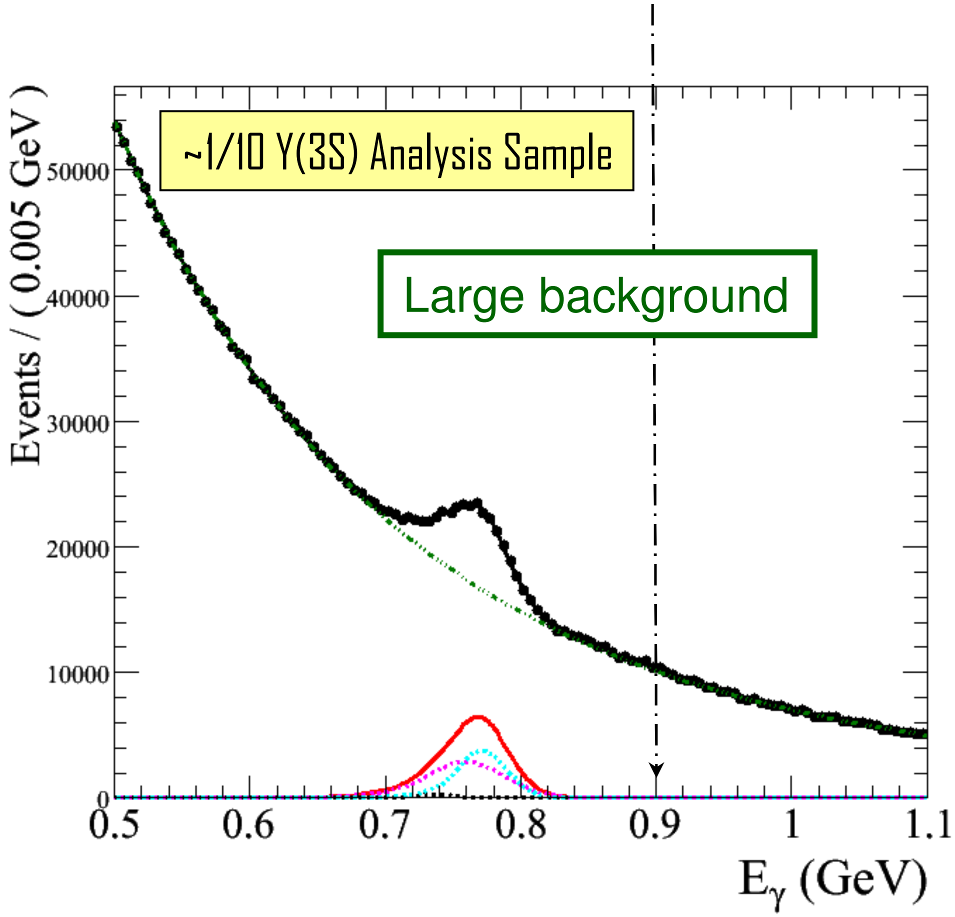
The Inclusive Photon Spectrum

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

Look for a bump near 900 MeV in the inclusive photon spectrum

Non-Peaking background components:

- continuum $q\bar{q}$(udsc) events
- generic Initial State Radiation events
- Υ(3S) cascade decays
- Υ(1S) decays to γgg, ggg with final state π^0's, η's, etc…



The Inclusive Photon Spectrum

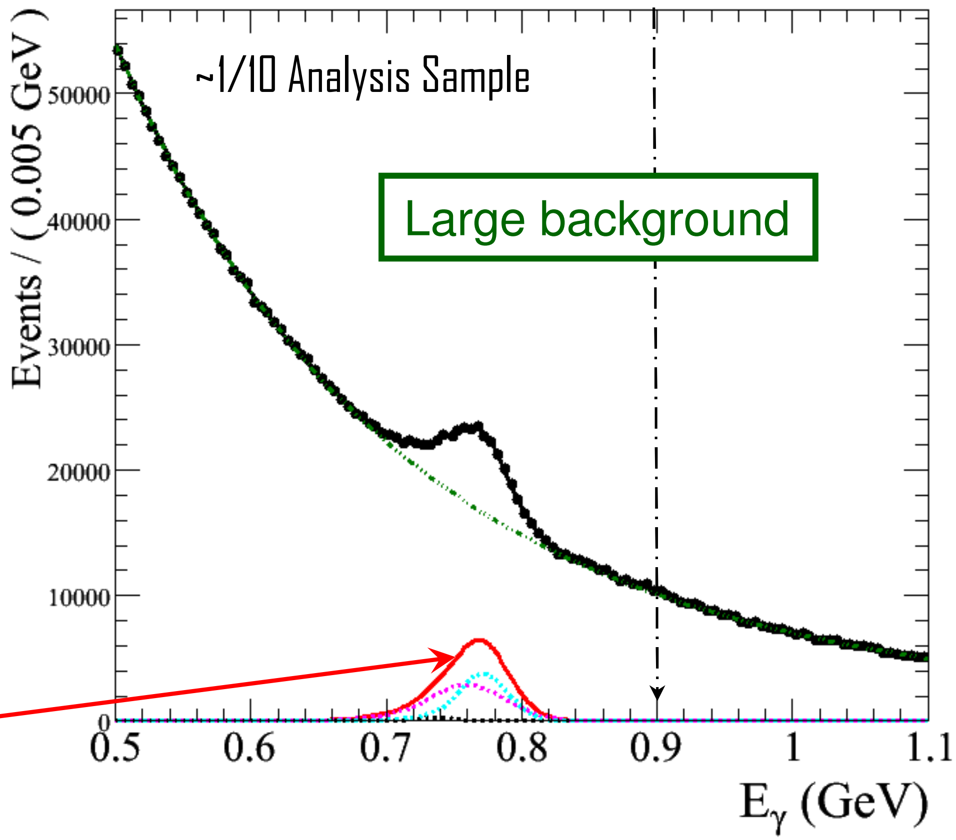
Look for a bump near 900 MeV in the inclusive photon spectrum

Peaking background components:

$\Upsilon(3S) \rightarrow \chi_{b0}(2P)\,\gamma^{soft}$ $E(\gamma^{soft}) = 122$ MeV
$\hookrightarrow \Upsilon(1S)\,\gamma^{hard}$ $E(\gamma^{hard}) = 743$ MeV

$\Upsilon(3S) \rightarrow \chi_{b1}(2P)\,\gamma^{soft}$ $E(\gamma^{soft}) = 99$ MeV
$\hookrightarrow \Upsilon(1S)\,\gamma^{hard}$ $E(\gamma^{hard}) = 764$ MeV

$\Upsilon(3S) \rightarrow \chi_{b2}(2P)\,\gamma^{soft}$ $E(\gamma^{soft}) = 86$ MeV
$\hookrightarrow \Upsilon(1S)\,\gamma^{hard}$ $E(\gamma^{hard}) = 777$ MeV

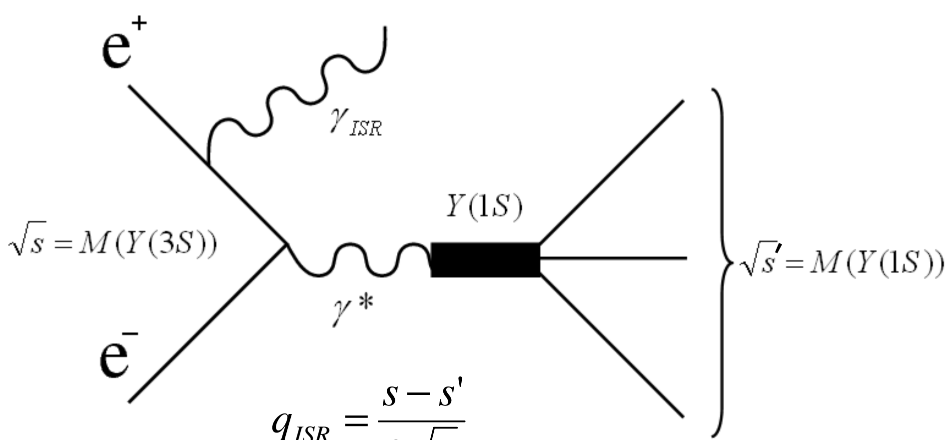


$\Upsilon(3S) \rightarrow \chi_{bJ}(2P)\,\gamma^{soft}$
(J=0,1,2) $\hookrightarrow \Upsilon(1S)\,\gamma^{hard}$

The Inclusive Photon Spectrum

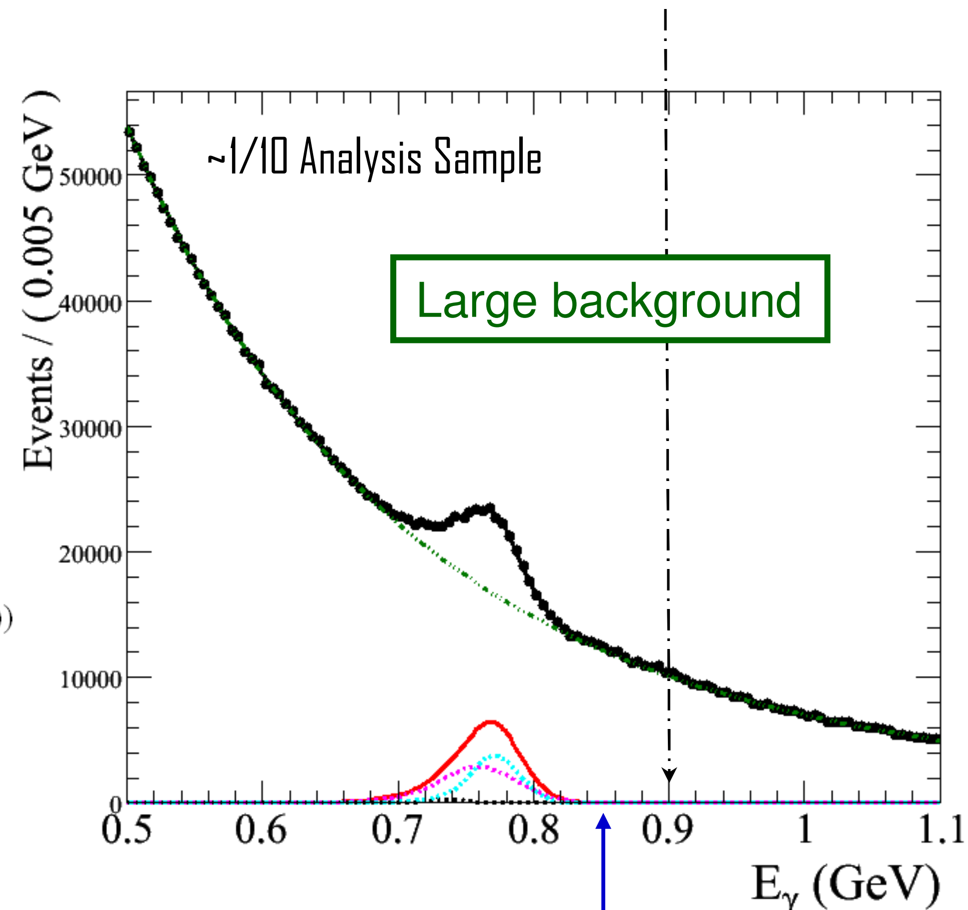
Peaking background component:

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



$$q_{ISR} = \frac{s - s'}{2\sqrt{s}}$$

Look for a bump near 900 MeV in the inclusive photon spectrum



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

2. Reduce the background

Selection Criteria

- Selection Criteria aimed at reducing background while retaining high efficiency

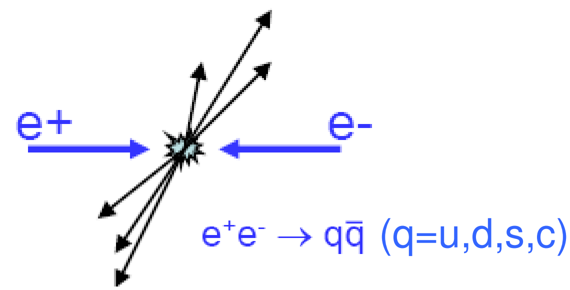
- Optimization done using S/sqrt(B):

  - S from Signal MC
  - B from 2.6 fb^{-1} On-peak data (Test sample ~ 9%of full statistics sample)

    - Test sample not used in final fit (avoid any bias)

Event Selection

- **Hadronic event selection:**
  - η_b decays mostly via 2 gluons → high track multiplicity
  - ⇨ require ≥ 4 Charged Tracks / Event
  - ⇨ R2 (ratio of 2^{nd} to 0^{th} Fox-Wolfram moment)<0.98 [Sphericity criterion: suppresses QED background]



- **Candidate photon:**
  - Isolated from charged tracks (i.e. energy deposit in the EMC not matched with any track)
  - Shape consistent with electromagnetic shower (i.e. Lateral moment < 0.55)
  - Photon required to be in EMC barrel
    → $-0.762<\cos(\theta_{\gamma,\,lab})<0.890$
    - Ensures good energy resolution & high efficiency
    - Reduces contribution from $e+e- \to \gamma_{ISR} Y(1S)$ [peaks @ $|\cos\theta^*|\sim1$]
  - Strong correlation between thrust axis and photon direction for continuum events ($e^+e^- \to q\,\bar{q}$), weak correlation for spin 0 η_b → photon satisfies $|\cos\theta_{thrust}| < 0.7$
  - π^0 Veto ($|M(\gamma\gamma_2) - M(\pi^0)| < 15$ MeV/c^2), $E_{\gamma_2} > 50$ MeV

Criterion	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 - Veto	89.8
Total	37.0

Net efficiencies:

ε(signal) = 37%
ε(bkgr.) = 6%

Checking the Optimization

- Can we trust our η_b signal MC? [$\eta_b \rightarrow gg$ generated using JETSET]

- Use of exclusive decay: $\Upsilon(3S) \rightarrow \chi_{bJ}(2P)\,\gamma^{soft}$ [J = 0,1,2]
  E(γ^{hard}) close to E(γ) for $\Upsilon(3S) \rightarrow \gamma\,\eta_b$ $\hookrightarrow \Upsilon(1S)\,\gamma^{hard}$

- Data from ~2.5 fb^{-1} Test Sample

  - Very reasonable agreement between efficiencies in η_b signal MC

Criterion	Efficiency estimates: Eff. (from χ_b peak)	Efficiency estimates: 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- Veto	0.849	0.899

3. Fitting Procedure

Modeling of the Non-Peaking Background Components

- **Large background** (dominated by $q\bar{q}$(udsc), generic ISR events, Υ(3S) cascade decays, Υ(1S) decays)
- Small amount of off-Υ(3S)-peak data (2.4 fb^{-1}) compared to on-Υ(3S)-peak data (25.6 fb^{-1}) makes direct subtraction imprecise
- Model each component with a separate Probability Density Function (PDF), or model all components with the same PDF?
  - Examined both options carefully; chose to **fit using one PDF to describe the combined background**

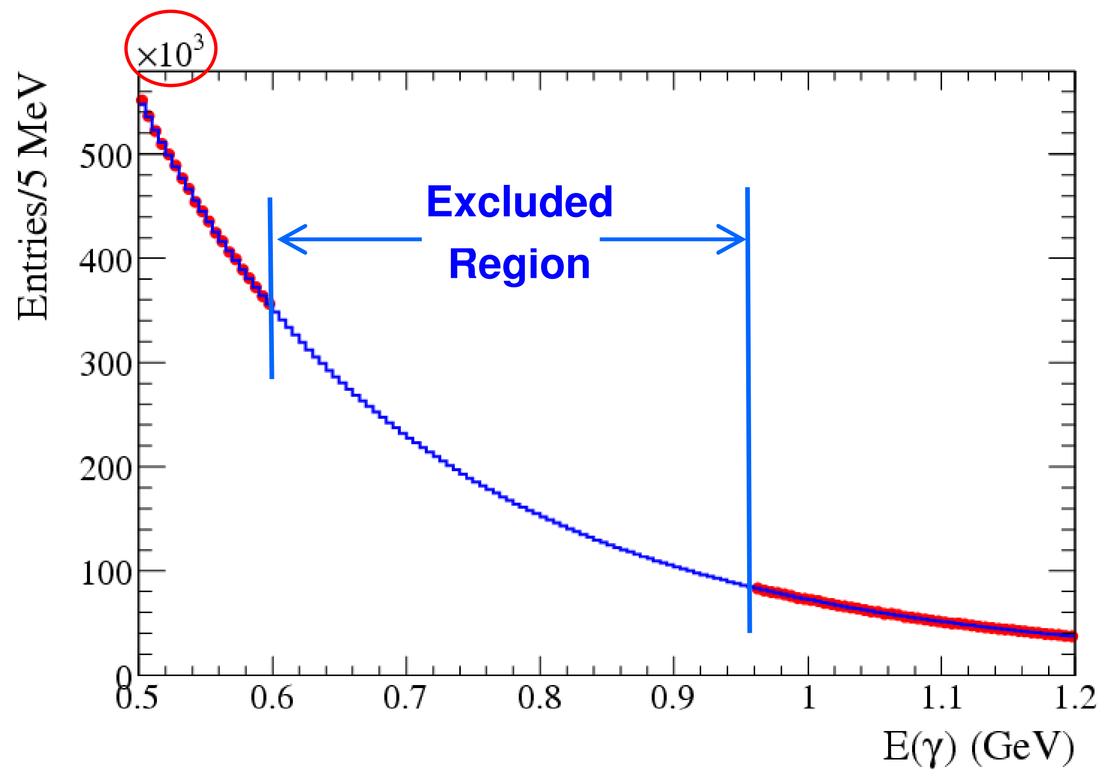
Non-Peaking Background Parametrization

- Fit combined non-peaking background with a single PDF:
  - Empirical function used to parameterize this background:

$$A\left(C + e^{-\alpha E_\gamma - \beta E_\gamma^2}\right) \rightarrow \text{4 free parameters}$$

Fit to the Full Dataset, but with Peaking Bg + Signal Region Excluded

Fit parameters ***C***, α, β, then used as <u>starting</u> values in the final fit.



Understanding the Various Peaking Background Components

- Accurate parametrization of **dominant** $\chi_{bJ}(2P)$ contributions essential
  - Monochromatic lines from $\chi_{bJ}(2P) \rightarrow \gamma\,\Upsilon(1S)$ close to η_b signal
    ➔ correct modeling of γ from $\chi_{bJ}(2P)$ lineshape very important!
  - Use χ_{bJ} transitions to determine absolute photon energy scale
  - Use γ from χ_{bJ} peak to validate signal reconstruction efficiency

- Radiative return to the Y(1S) produces a peak near 860 MeV in the photon spectrum
  - Crucial to model the lineshape correctly as the ***signal*** γ associated with the η_b is expected to sit on the high-energy tail of the ISR peak
  - Essential to estimate the ISR yield because of this expected overlap (due to energy resolution)

Peaking Background Components Modeled with Crystal Ball Functions

Crystal Ball Function*: Gaussian **with transition** to a Low-side Power-law Tail

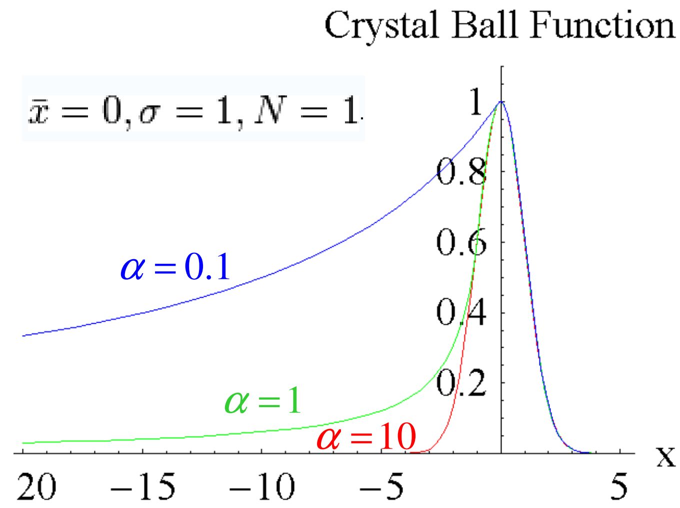
$$f(x;\alpha,n,\bar{x},\sigma) = N \cdot \begin{cases} \exp(-\frac{(x-\bar{x})^2}{2\sigma^2}), & \text{for } \frac{x-\bar{x}}{\sigma} > -\alpha \\ A \cdot (B - \frac{x-\bar{x}}{\sigma})^{-n}, & \text{for } \frac{x-\bar{x}}{\sigma} \leqslant -\alpha \end{cases}$$

where

$$A = \left(\frac{n}{|\alpha|}\right)^n \cdot \exp\left(-\frac{|\alpha|^2}{2}\right),$$

$$B = \frac{n}{|\alpha|} - |\alpha| .$$

N is a normalization factor and α, n, $\bar{x}$ and σ are parameters which are fitted with the data.

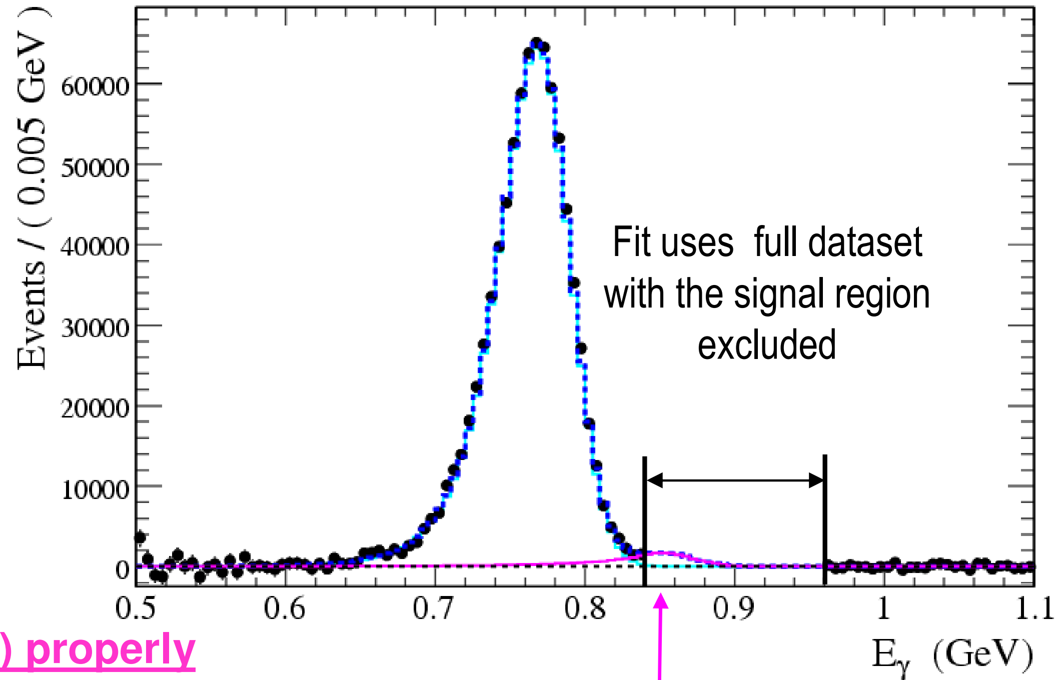


* Refs: M. Oreglia, SLAC-236 (1980); J.E. Gaiser, SLAC-255 (1982).

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

- Model each transition using 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 parameter
  - Offset (γ energy calibration shift) of **+3.8 MeV** in data
    ➔used to correct energy scale of other peaks
- Ratio of yields taken from PDG
  -- $R(\chi_{b1}/\chi_{b2}) = 1.2$ (consistent with value we measure using soft $\Upsilon(3S) \rightarrow \chi_{b1,2}(2P)$ transition photons)
  -- $R(\chi_{b1}/\chi_{b0}) = 21$ ➔ $\chi_{b0}(2P)$ contrib. very small
- **Incorporate ISR peak contribution**
  - **Model tail of γ peak from $\chi_b(2P)$ properly**

Peak ➔ 3 $\chi_{bJ}(2P)$ transitions merge
- photon energy resolution (~20 MeV)
- Broadening due to Lorentz boost from the χ_{bJ} rest-frame to the CM-frame



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

Photon c.m. energy for $\Upsilon(3S) \to \gamma_{ISR}\,\Upsilon(1S)$: 856.4 MeV

➔Very important to determine both **lineshape** and **yield**

- ➢ Depending on η_b mass, the peaks may overlap!

➔Estimate the expected lineshape using Signal MC

➔Estimate the expected yield: Several options Investigated

- Use of $e^+e^- \to \gamma_{ISR}\,\Upsilon(1S) \to \mu^+\mu^-$ decay: no sign of ISR peak, too much $\gamma\mu\mu$ radiative QED background ....
- Use of Υ(3S) Off-Peak data: ~2.4 fb^{-1} → large stat. error [σ^{ISR}_{3SOff} (Υ(1S)) =25.4 pb]
- **Use of Υ(4S) Off-Peak data: 43.9 fb^{-1} → high statistics, smaller error [σ^{ISR}_{4SOff} Υ(1S)) =19.8 pb]**

➢Use Υ(4S) Off-Peak data, and extrapolate yield to Υ(3S) On-Peak data using proper cross sections, efficiencies, and integrated luminosities

➢In good agreement with yield extrapolated from Υ(3S) Off-Peak data to Υ(3S) On-peak data

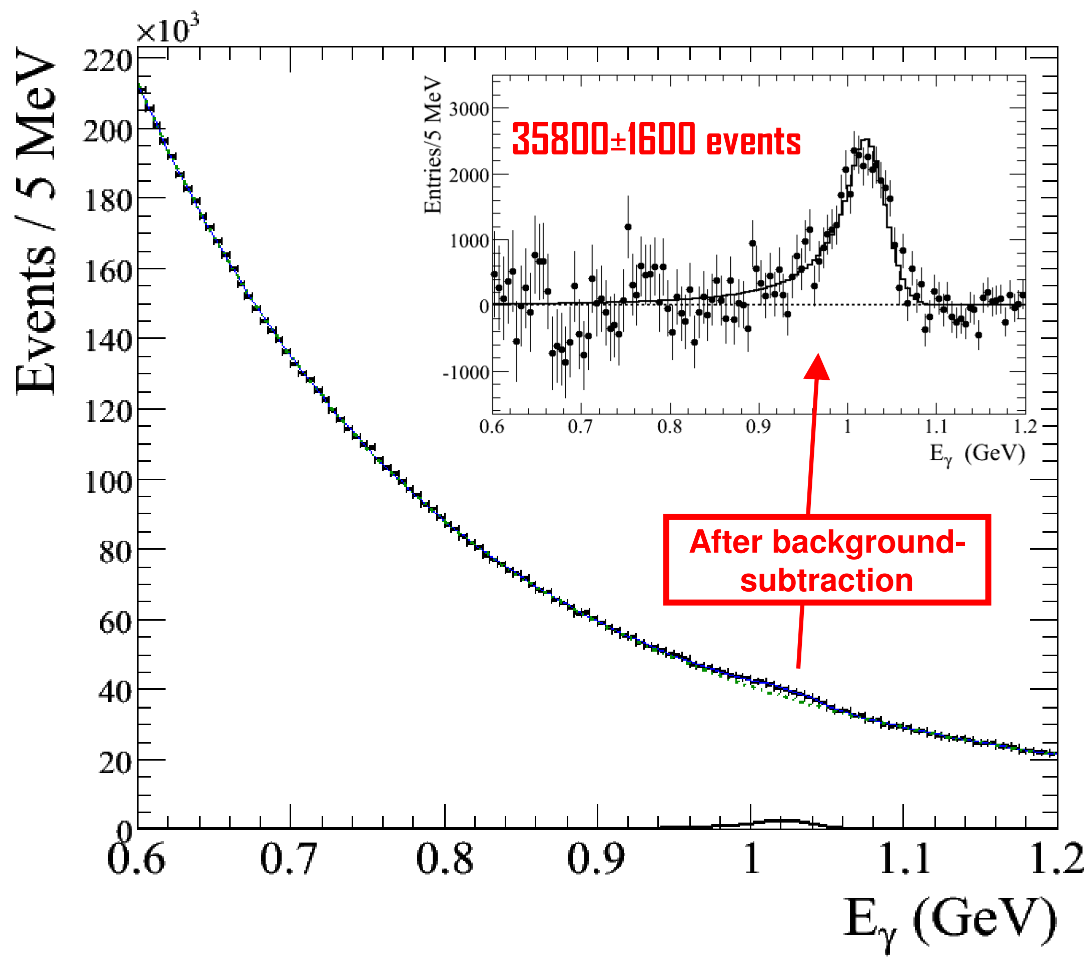
Peaking Background from $e^+e^- \rightarrow \gamma_{ISR}\Upsilon(1S)$

- **Use Y(4S) Off-peak Data**

- **Fit γ energy spectrum with:**
  - Non-Peaking Background PDF proportional to:

    $$(C+\exp[-\alpha\, E_\gamma - \beta\, E_\gamma^2])$$

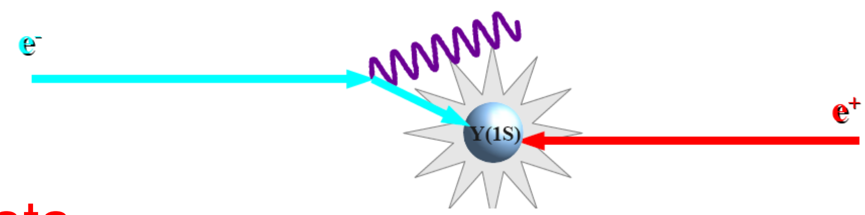
  - ISR Signal Component
    - Crystal Ball function with power law, transition point, and width parameters obtained from a fit to $e+e- \rightarrow \gamma_{ISR}Y(1S)$ (@ Y(4S) off-peak c.m. energy) Signal MC E_γ distribution.



- Fitted Yield: 35800 ± 1600 events

Yield for $e^+e^- \to \gamma_{ISR}\Upsilon(1S)$ at Y(3S)

Estimated using Y(4S) Off-Peak Data



The cross section for ISR production of a narrow vector meson is given by

$$\sigma_V(s) = \frac{12\pi^2\Gamma_{ee}}{m_V s} \cdot W(s, x_v)$$

where Γ_{ee} is the di-electron width of the vector meson, m_V is the mass of the vector meson, s is the center of mass energy, $x_v = 2E_\gamma/\sqrt{s}$, and $W(s, x_v)$ is the probability function of photon emission. $W(s, x_v)$ is often referred to as the "radiator function".

Extrapolation ➔ $$N_{\sqrt{s}=M_{\Upsilon(3S)}} = N_{\sqrt{s'}} \frac{\sigma_{\sqrt{s}=M_{\Upsilon(3S)}}\, \varepsilon_{\sqrt{s}=M_{\Upsilon(3S)}}}{\sigma_{\sqrt{s'}}\, \varepsilon_{\sqrt{s'}}}$$

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

Stat. Error

- Extrapolated numbers from Y(3S/4S) Off-peak samples **consistent**
- Systematic error on extrapolation (5%)
- Y(3S) ISR Yield (25153) fixed in the final fit
  - ✓ ISR Yield varied by $\pm 1\sigma$ in the study of systematic uncertainty in the η_b peak position and yield.

FIT STRATEGY

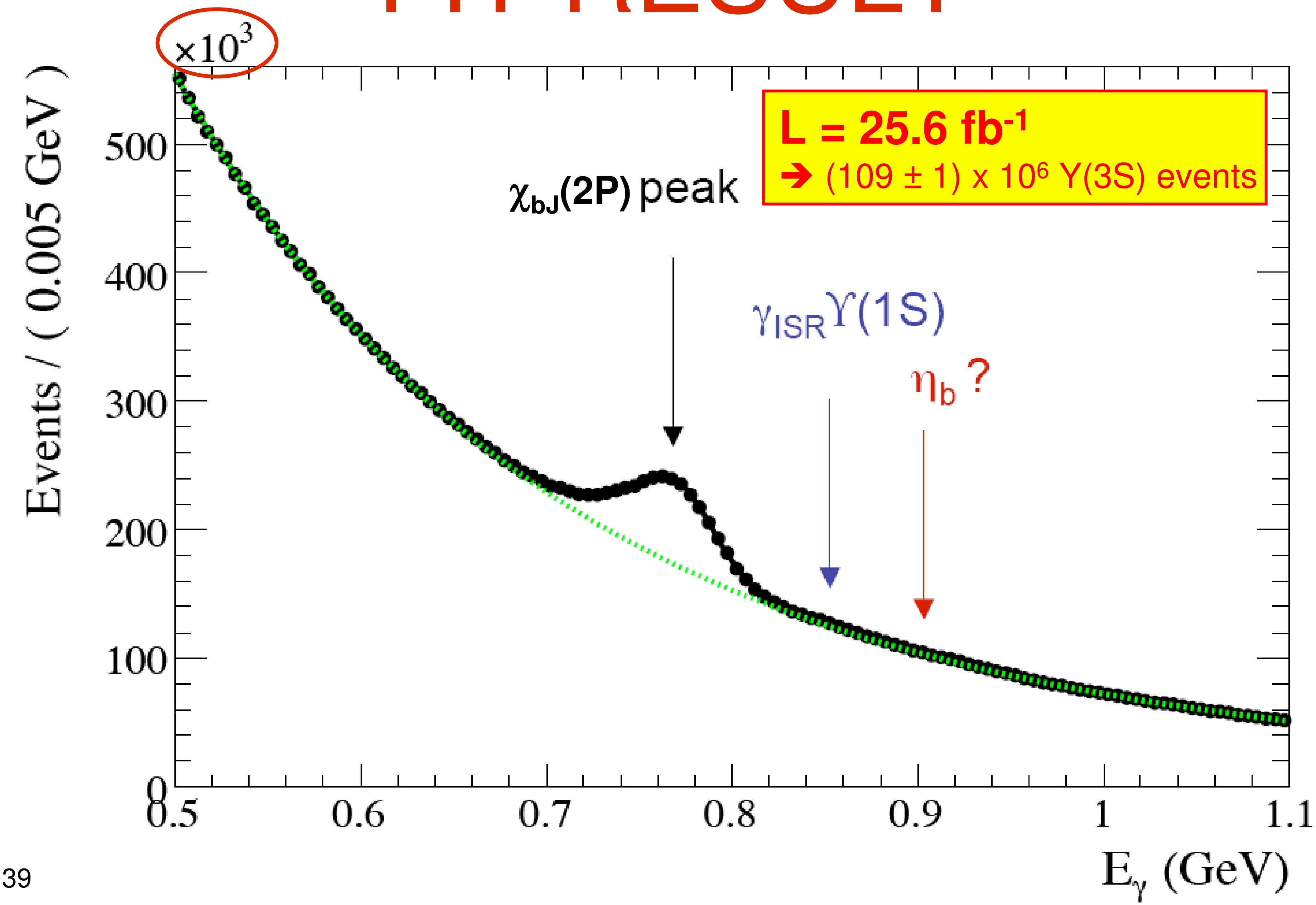
- Allow non-peaking-background parameters to vary
  - A (C + exp[$-\alpha E_\gamma - \beta E_\gamma^2$])
- Fix lineshape parameters for γ from χ_{bJ} transitions
  - 3 CB functions describing $\gamma\, \chi_{b0,1,2}(2P)$ (≠ widths, common energy scale shift → obtained from fit with ISR Υ(1S) and signal excluded)
- Fix ISR Υ(1S) yield from Υ(4S) off-peak analysis
  - CB lineshape from Υ(3S) on-peak MC; yield fixed to value obtained from Υ(4S) off-peak to Υ(3S) on-peak extrapolation
- Signal PDF: Crystal Ball function convolved with BW 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 Validation

✓MC simulation studies (toys)
- Events simulated according to fit component PDFs
- To test the fitting procedure, we generate 500 MC samples for all combinations of
  - Yield: 15000, 20000, 30000 events
  - Peak position: 890, 895, 900, 910, 920 MeV
- No bias seen in fitted peak position, even near ISR peak

✓Fit Procedure checked on 2.6 fb^{-1} Test Sample

FIT RESULT



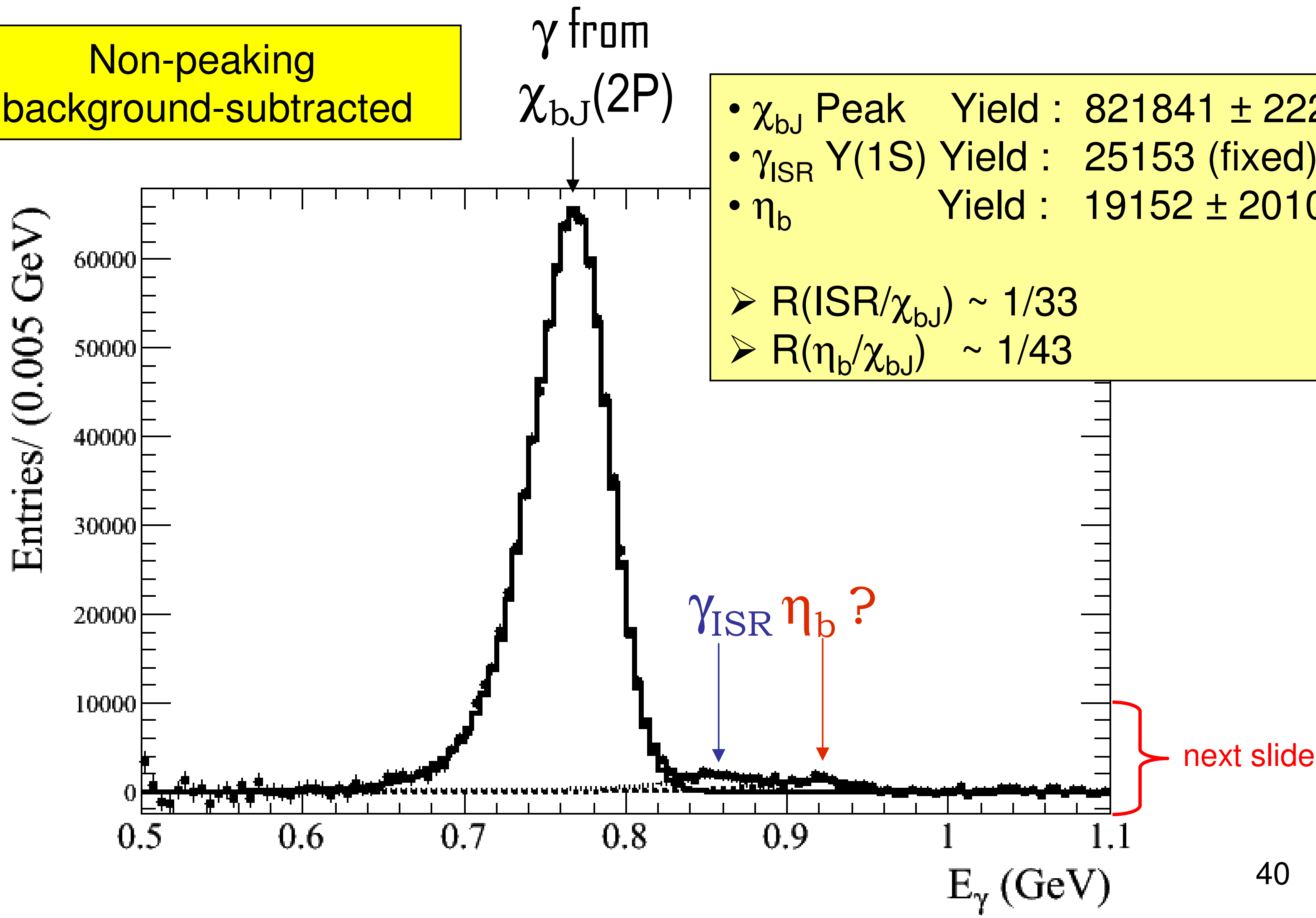
×10^3
Events / (0.005 GeV)
500
400
300
200
100
0
0.5
0.6
0.7
0.8
0.9
1
1.1
E_γ (GeV)
L = 25.6 fb^-1
➔ (109 ± 1) x 10^6 ϒ(3S) events
χ_bJ(2P) peak
γ_ISR ϒ(1S)
η_b ?

FIT RESULT

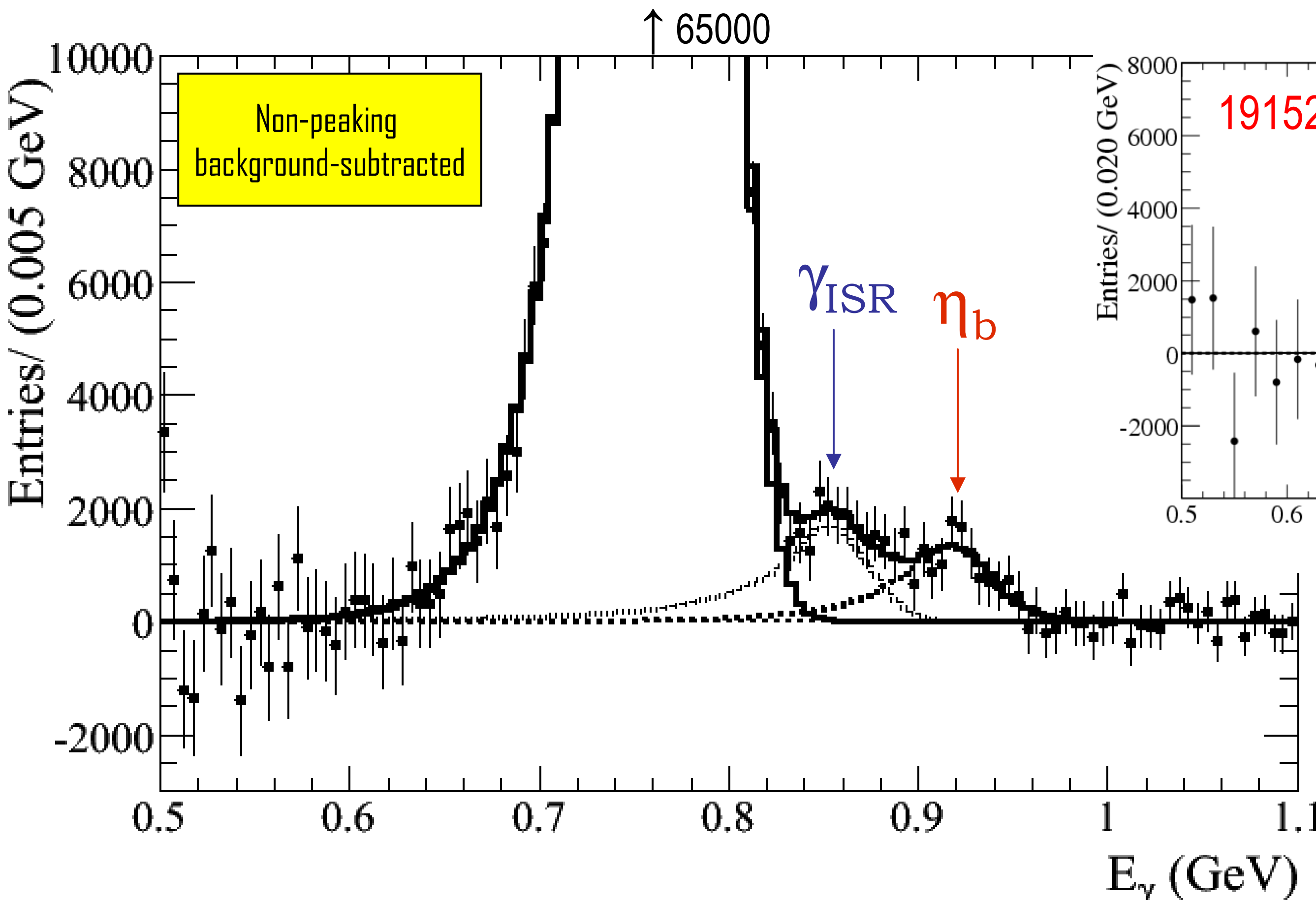
Non-peaking background-subtracted

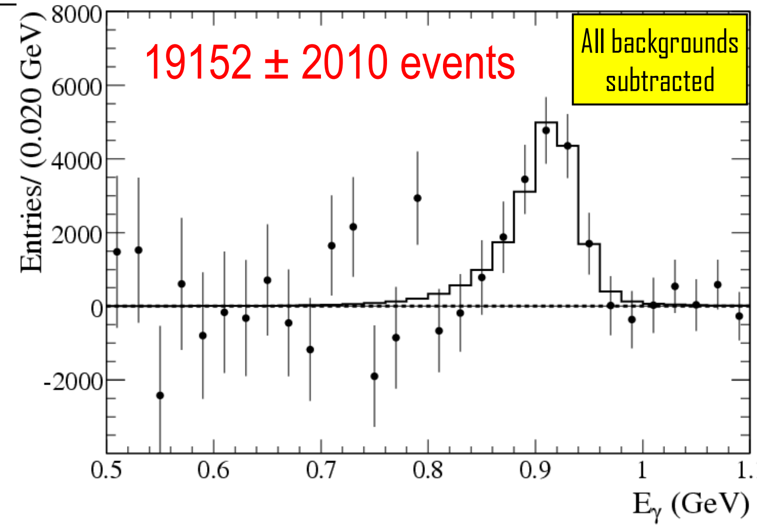
- χ_{bJ} Peak Yield : 821841 ± 2223
- γ_{ISR} Υ(1S) Yield : 25153 (fixed)
- η_b Yield : 19152 ± 2010

➢ $R(ISR/\chi_{bJ})$ ~ 1/33
➢ $R(\eta_b/\chi_{bJ})$ ~ 1/43



The Observation of the η_b

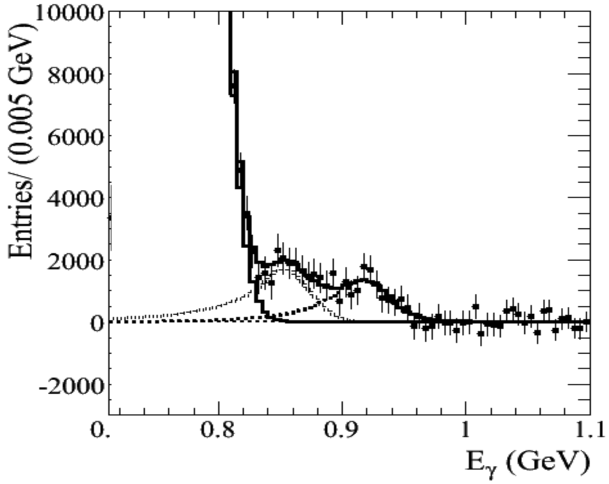




Histogram: Integral of fit function over each energy interval

- η_b signal observed with a statistical significance of 10 σ ($S = \sqrt{2\log(L_{max}/L_0)}$)
- Peak position(*) of $921.2^{+2.1}_{-2.8}$ MeV

(*) after γ energy calib. shift of + 3.8 MeV



Is this signal real?

- Could it result from detector effects, e.g. hot channels in the 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
  - Could this signal result from random overlap of photons with γ from $\chi_{bJ}(2P)$?
    - Similarly tight Lateral Moment requirement reduces the potential overlap of random photons
  - Check of fit quality in the signal region is provided by the ISR Y(1S) yield
    - Floating the ISR Y(1S) yield → fitted yield (24799±2500) consistent with 25153, from extrapolation; assurance that the background parametrization near the signal region is good
- How do we know this is the η_b?

  Peak γ energy ➔ State has mass < m(Y(1S)) – only expected candidate is the η_b

  - But if light Higgs, glueball…? ➔New physics ! We'll take it !!

SUMMARY OF FIT RESULTS

- Signal Yield :
  - Fitted Yield (with BW width of 10 MeV)
    ~19200 ± 2000 (stat)
  - Signal Significance of 10 standard deviations

- Mass of the η_b:
  - 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 $71.4^{+2.3}_{-3.1}(\mathrm{stat})\ \mathrm{MeV}/c^2$

STUDY OF SYSTEMATIC UNCERTAINTIES

- Vary ISR yield by $\pm 1\sigma$ (stat $\otimes$ 5% syst) → δN = 180, $\delta E\gamma$ =0.7 MeV
- Vary ISR PDF parameters by $\pm 1\sigma$ → δN = 50, $\delta E\gamma$ =0.3 MeV
- Vary Signal PDF parameters by $\pm 1\sigma$ → δN = 98, $\delta E\gamma$ =0.1 MeV
- Vary χ_{bJ} peak PDF parameters by $\pm 1\sigma$ → δN = 642, $\delta E\gamma$ =0.3 MeV
- Fit with BW width fixed to 5, 15, 20 MeV → δN = 2010, $\delta E\gamma$=0.8 MeV
  ↳ main source of systematic uncertainty in the η_b yield
- Systematic uncertainty in the η_b mass associated with the γ energy calibration shift obtained from the fit to the χ_b peak → $\delta E\gamma$=2.0 MeV

* Study of Significance

- Vary BW width
- Vary all parameters independently
- Vary all parameters in the direction resulting in lowest significance

} → No significant change !

Estimate of Branching Fraction

- **With N(Y(3S)) = (109 ± 1) x 10^6**

  BF (Y(3S)$\rightarrow \gamma\, \eta_b$) = N($\eta_b$)/[N(Y(3S))x Eff.] = (4.5 ± 0.5 [stat.]) x 10^{-4}

  - Signal Efficiency = 37%

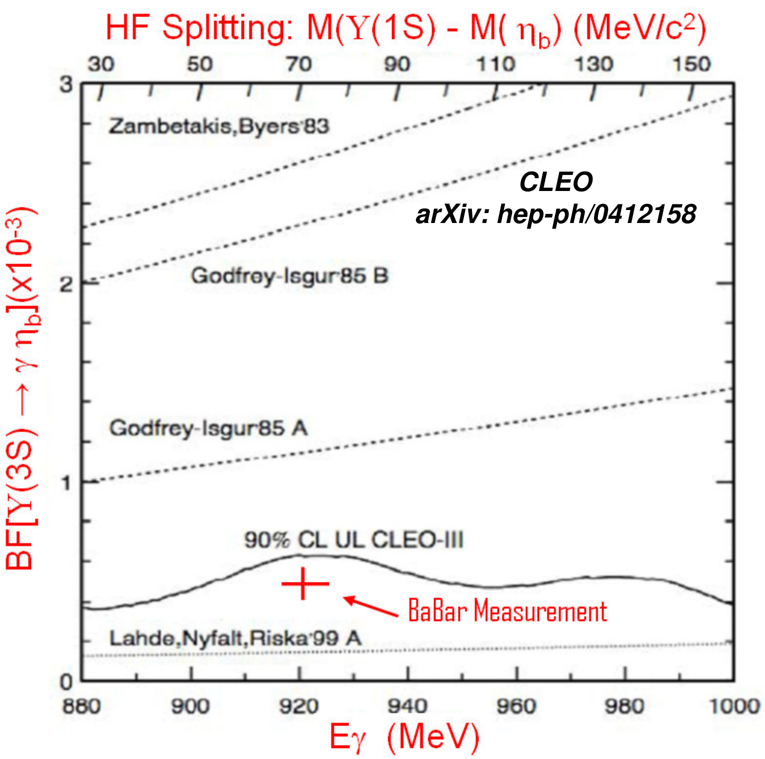
- Systematic Uncertainties:
  - Uncertainty in Signal efficiency (don't trust MC ε) → 12.6%
    - Obtained by comparing χ_{bJ} efficiency in data (39.4%) and MC (35.0%)
    - Uncertainty from χ_b(2P) BF (PDG) → 18.2%
      - Focus on Observation not BF measurement
      - Will be improved in the future ….

  (combined: 22%)

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

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

SUMMARY OF MEASUREMENTS



$$\text{Mass}: \quad \eta_b = 9388.9^{+3.1}_{-2.3} \pm 2.7\ \text{MeV}/c^2$$

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

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)

$$\text{Estimated BF}(\Upsilon(3S) \to \gamma\eta_b) = (4.8 \pm 0.5 \pm 1.2) \times 10^{-4}$$

cf. upper limit on B.F. **< 4.3 x 10^{-4} @ 90%** [CLEO III]

CONCLUDING REMARKS

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 $(4.8 \pm 0.5 \pm 1.2) \times 10^{-4}$.

Phys.Rev.Lett.100:06200, 2008

- Charged-track multiplicity studies indicate a pattern consistent with $\eta_b \to g\,g$
- Confirmation from $\Upsilon(2S) \to \gamma\,\eta_b(1S)$; analysis is ongoing …

- Observation of $\Upsilon(1S) \to \gamma\,\eta_b(1S)$ (although favored *n=n'* decay) – hard to observe due to ***very soft photon*** transition; very large background

- Observation of $\Upsilon(3S) \to \gamma\,\eta_b(2S)$ nearly impossible to obtain due to overlap of $\Upsilon(3S) \to \gamma\,\eta_b(2S)$ monochromatic photon peak with peaks in photon energy spectrum due to transitions from decays to and from $\chi_{bJ}(1P)$ states

BACK-UP SLIDES

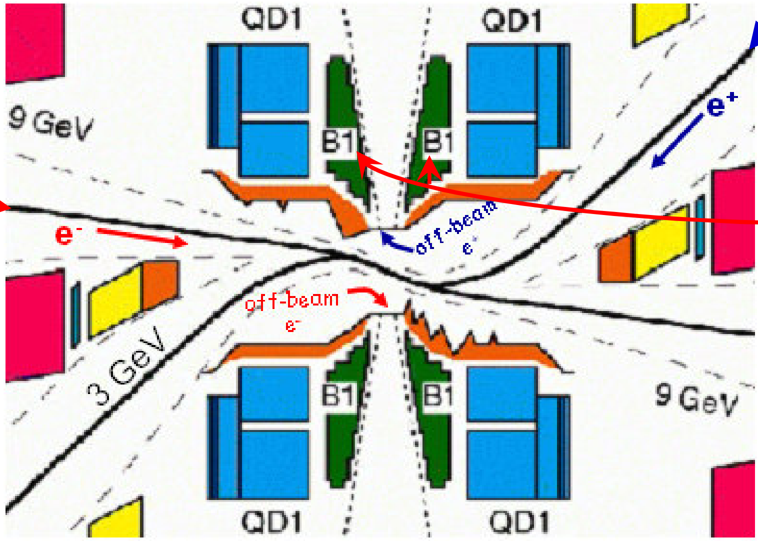
The B-Factory Collision Region (IR-2)

Ring circumference = 2.2 km
# of stored bunches / ring = 1728

Bunch separation = 1.27 m
⇨ ~ 4 ns between collisions

3.1 GeV
8.0 x 10^{10} **e^+** / bunch
Equivalent current 3.0 Amps

9.0 GeV
4.8 x 10^{10} **e^-** / bunch
Equivalent current 1.8 Amps



Dipole Permanent Magnets:
(Samarium Cobalt)
Bend beams into head-on collision

✓best shift: 339 pb^{-1}
✓best day: 911 pb^{-1}
✓best week: 5.4 fb^{-1}
✓best month: 19.7 fb^{-1}
✓Peak L: $12.1 \times 10^{33} cm^{-2} s^{-1}$

Bunch Dimensions:
(Gaussian ellipsoid)
$\sigma(z)$ = 11 mm
$\sigma(x)$ = 120 μm
$\sigma(y)$ = 5 μm } i.e. "flat" beams

$\rightarrow H_20$

Be beampipe

$\leftarrow$ Cooling H_20

y, z, x

Collision Region Dimensions:
- $\sigma(z)$ = 7.5 mm
- $\sigma(x)$ = 85.0 μm
- $\sigma(y)$ = 3.5 μm

HOW THIS ALL CAME ABOUT…

December Start-Up

Dec. 12th : first beam stored in HER
Dec. 14th : first positrons in LER
Dec. 15th : first collisions
Dec. 17th : first delivery to BaBar

} at Υ(4S) energies

Dec. 19th : Budget gloom and doom ☹

Dec. 20th – 21st : Discussions about immediate move to Υ(3S); had run there briefly and scanned the peak in Nov. 2002; Mike Sullivan indicated that could reduce HER energy to get there.

Dec. 21st,1:30PM: PEPII-BaBar meeting: decision to move to Υ(3S) immediately

3:00PM : Start to lower the HER energy

December Start-Up (continued)

Dec. 21st, 3:00PM + : Began by following procedure for c.m. energy shift to off-peak value (10.54 GeV). This is done with the beam in the HER in order to check that everything is O.K.
Found a a problem as lowered the energy further; quadrupole magnets in the transport line from LINAC to HER were not changing with the dipoles (not noticeable for small change to off-peak running); messes up the injection!
Mike Sullivan and Uli Wienands calculated necessary quadrupole strengths & changed the quad. power supplies by hand to keep them in line with the dipole magnets.

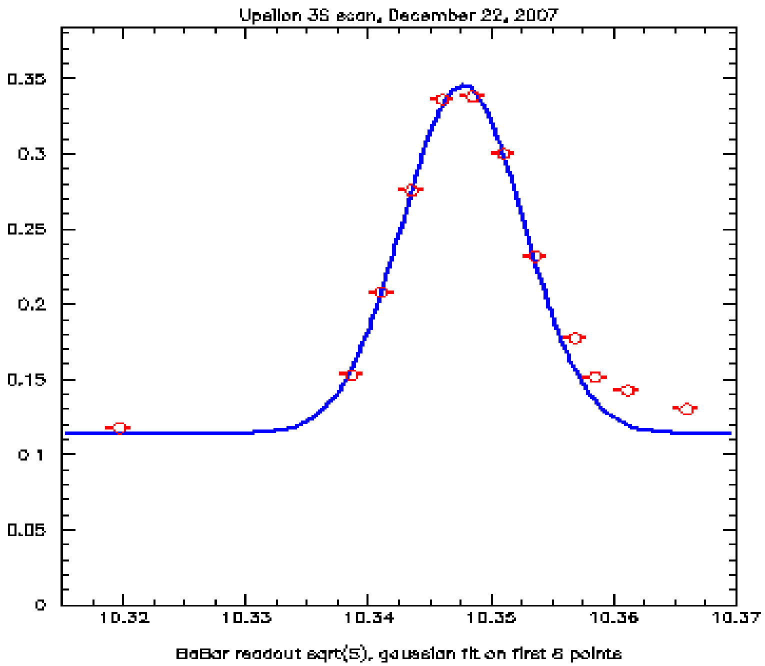
Swing Shift : LINAC & PEP-II problems related to start-up blues

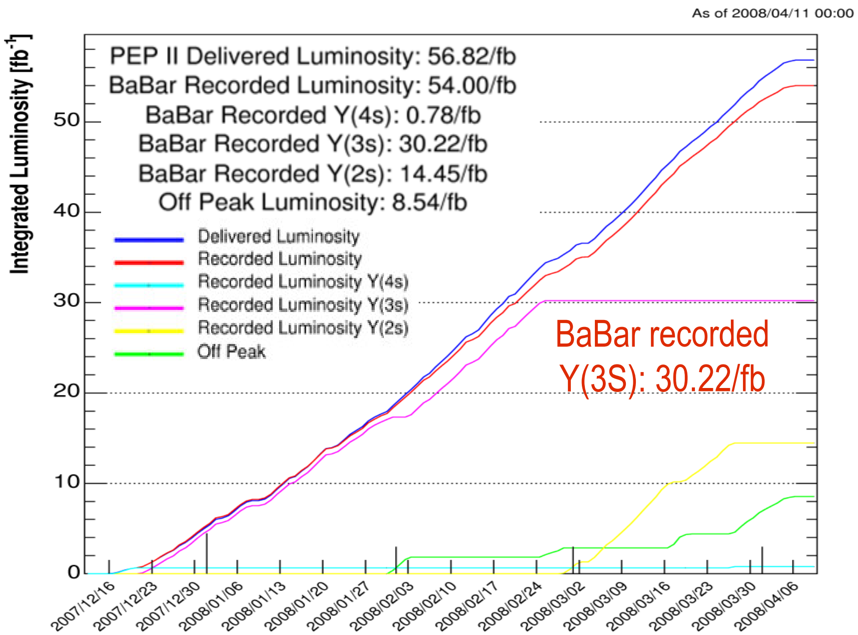
Midnight : Reached first scan point – but beam injection & storage problems during OWL shift

Dec. 22nd , 9:00 AM : Problems sorted out; scan over Υ(3S) begun [Mike Sullivan quote: " lumi was only ~3.5 x 10^{33} ", which is actually slightly over the design value!!]
Injection backgrounds bad – beams coasted for data taking - filled with BaBar turned down

7:00 PM : Υ(3S) scan completed – moved to Υ(3S) peak

December Start-Up (continued)

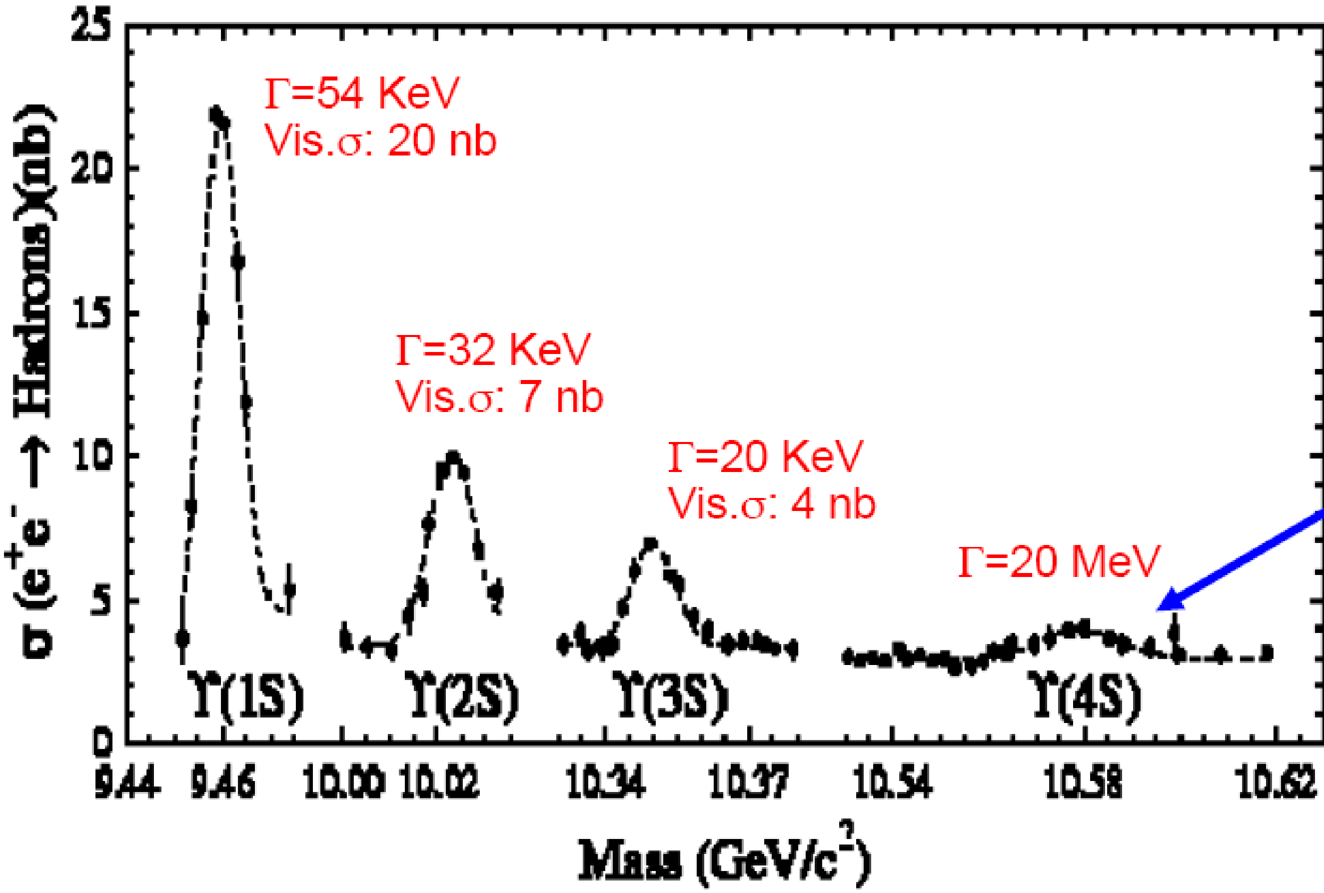




- However, beam energy drifted – required manual intervention in order to remain on the peak.
- Great job of doing this by our BaBar run coordinators
- Stabilized by the 3rd week of January
- After a month of running, tunnel temperature stabilized & ring geometry stopped changing
- This learning experience made the subsequent change to the Y(2S) much more smooth – accomplished in ~ 10 hrs
- Moving to the Y(1S) would require changing both HER & LER energy; fortunately we did not have to worry about that ☺

	M(PDG) (GeV/c²)	Transition	BF	E*(γ) (GeV)		Transition	BF	E*(γ) (GeV)			BF	E*(γ) (GeV)
Y(3S)	10.3552					Y(3S)->Y(2S)	10.60%					
Y(2S)	10.0233	ee(@Y3S) → γ Y(2S)	0.001%	0.3266								
Y(1S)	9.4603	ee(@Y3S) → γ Y(1S)		0.8562								
χ_{b2}(2P)	10.2687	Y(3S) → γ χ_{b2}(2P)	13.1%	0.0862	➔	χ_{b2}(2P) → γ Y(2S)	0.0212%	0.2425	➔	Y(2S) → γ χ_{b2}(1P)	0.758%	0.1104
χ_{b1}(2P)	10.2555	Y(3S) → γ χ_{b1}(2P)	12.6%	0.0993	➔	χ_{b1}(2P) → γ Y(2S)	0.0204%	0.2296	➔	Y(2S) → γ χ_{b1}(1P)	0.731%	0.1296
χ_{b0}(2P)	10.2325	Y(3S) → γ χ_{b0}(2P)	5.9%	0.1220	➔	χ_{b0}(2P) → γ Y(2S)	0.0096%	0.2071	➔	Y(2S) → γ χ_{b0}(1P)	0.403%	0.1625
χ_{b2}(1P)	9.9122	Y(3S) → γ χ_{b2}(1P)		0.4335	➔	χ_{b2}(1P) → γ Y(1S)	0.0005%	0.4416				
χ_{b1}(1P)	9.8928	Y(3S) → γ χ_{b1}(1P)		0.4521	➔	χ_{b1}(1P) → γ Y(1S)	0.0005%	0.4230				
χ_{b0}(1P)	9.8594	Y(3S) → γ χ_{b0}(1P)	0.003%	0.4839	➔	χ_{b0}(1P) → γ Y(1S)	0.0004%	0.3911				
η_b(1S)	9.3889	Y(3S) → γ η_b(1S)		0.9212								
η_b(2S)	9.9633	Y(3S) → γ η_b(2S)		0.3845	➔	η_b(2S) → γ Y(1S)		0.4903				

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 $\Upsilon(4S)$

$\sigma(e^+e^- \rightarrow \Upsilon(3S)\gamma_{ISR}) \sim 29$ 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" whle running at the $\Upsilon(4S)$

can be used to study $\Upsilon(nS)$ in fully reconstructed final states

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

QCD Calculations of the η_b mass and branching fraction

- Recksiegel and Sumino, Phys. Lett. B 578, 369 (2004) [hep-ph/0305178]
- Kniehl et al., PRL 92 242001 (2004) [hep-ph/0312086]
- Godfrey and Isgur, PRD 32, 189 (1985)
- Fulcher, PRD 44, 2079 (1991)
- Eichten and Quigg, PRD 49, 5845 (1994) [hep-ph/9402210]
- Gupta and Johnson, PRD 53, 312 (1996) [hep-ph/9511267]
- Ebert et al., PRD 67, 014027 (2003) [hep-ph/0210381]
- Zeng et al., PRD 52, 5229 (1995) [hep-ph/9412269]

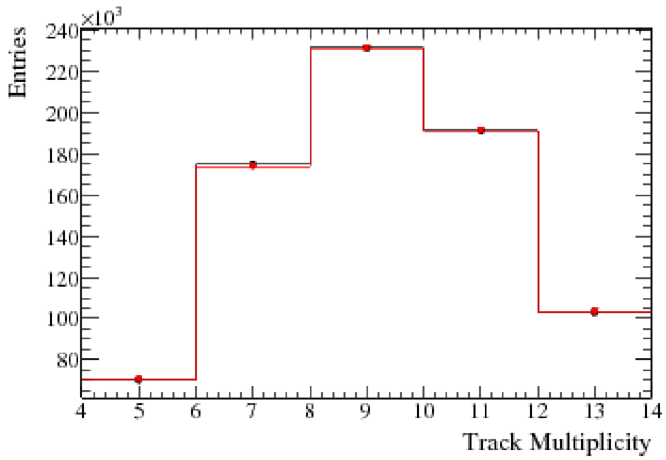
$e^+e^- \to \gamma_{ISR}\Upsilon(1S)$ Calculations

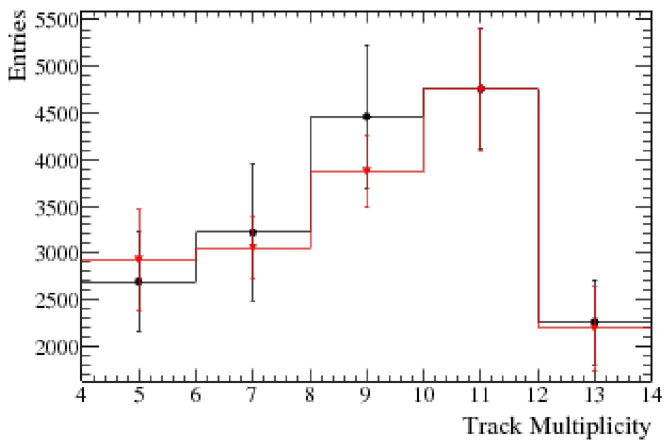
Calculation	$\sigma_{\Upsilon(3S)}$ (pb)	$\sigma_{\Upsilon(4S)}$ (pb)	Ratio	Asymmetric collider correction
Benayoun, et. al., 2nd order	25.4	19.8	1.283	Yes
Benayoun, et. al., 1st order	28.46	21.62	1.316	No
Benayoun, et. al., 2nd order	26.12	20.21	1.292	No
Blümlein, et. al., 1st order	28.46	21.62	1.316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

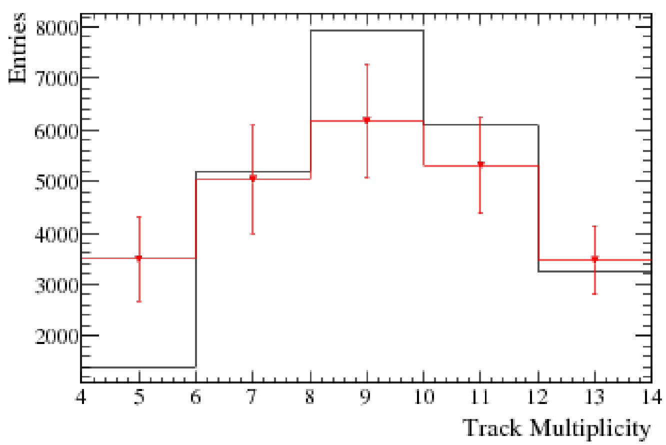
$$\sigma_V(s) = \frac{12\pi^2\Gamma_{ee}}{m_V s} \cdot W(s, x_v)$$

$$x_v = 2E_\gamma/\sqrt{s}$$

➔ Production cross section for $e^+e^- \to \gamma_{ISR}\Upsilon(1S)$ at $\sqrt{s} = 10.3252\,\text{GeV}$ ($\sigma_{\Upsilon(3S)}$), production cross section for $e^+e^- \to \gamma_{ISR}\Upsilon(1S)$ at $\sqrt{s} = 10.55\,\text{GeV}$ ($\sigma_{\Upsilon(4S)}$), and their ratio for various theoretical calculations. The assumed di-electron width of the $\Upsilon(1S)$ is 1.340 MeV.







Charged Track Multiplicity

+ ISR Yield/Multiplicity Interval fixed to value obtained from MC

+ ISR Yield/Multiplicity Interval floated

Calculation of photon energy range limits in the $\Upsilon(3S)$ rest-frame for net $\Upsilon(3S) \to \Upsilon(1S)$ transitions

Consider the transition $\Upsilon(3S) \to \gamma_X X$, where X represents some χ_b state, and where X further decays to photon, γ_R, and a recoil system, R. The boost to the $\Upsilon(3S)$ rest-frame produces a spread in photon γ_R energy distribution; in this frame this change in photon frequency as a result of the boost is somtimes called a Doppler shift. Here we calculate the spread in energy for certain χ_b transitions.

- In the $\Upsilon(3S)$ rest-frame

$$m_{\Upsilon(3S)} = p^*_\gamma + E^*_X,$$

where p^*_γ and E^*_X are the energies of the photon and of the χ_b state in the $\Upsilon(3S)$ frame, respectively. In that frame,

$$p^*_\gamma = \frac{m^2_{\Upsilon(3S)} - m^2_X}{2m_{\Upsilon(3S)}}$$

$$E^*_X = \frac{m^2_{\Upsilon(3S)} + m^2_X}{2m_{\Upsilon(3S)}}$$

- In the X rest-frame

Consider the case where $X \to \gamma_R R$, where R is now the recoil system. The energy of the photon, γ_R, in the X rest-frame is:

$$E^{(X)}_{\gamma_R} = \frac{m^2_X - m^2_R}{2m_X}.$$

- Boosting to the $\Upsilon(3S)$ rest-frame gives

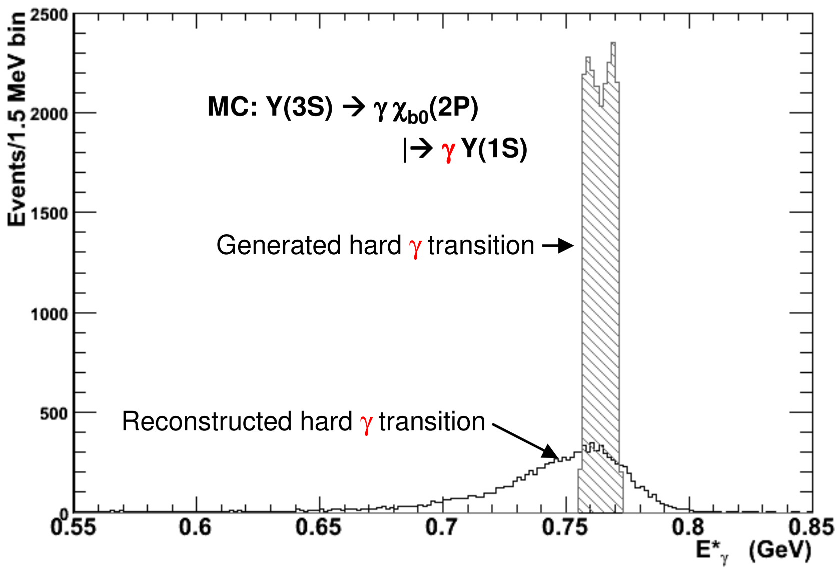
$$\gamma_X = \frac{E^*_{\gamma_X}}{m_X} = \frac{m^2_{\Upsilon(3S)} + m^2_X}{2m_{\Upsilon(3S)}m_X}$$

$$(\gamma_X\beta_X) = \frac{p^*_{\gamma_X}}{m_X} = \frac{m^2_{\Upsilon(3S)} - m^2_X}{2m_{\Upsilon(3S)}m_X},$$

where β_X is the velocity of X and $\gamma_X = (1-\beta^2_X)^{-1/2}$.
The momentum of the photon, γ_R, in the $\Upsilon(3S)$ rest-frame is then

$$p^*_{\gamma_R} = \gamma_X \left[cos\theta E^{(X)}_{\gamma_R} + (\gamma_X\beta_X)\, E^{(X)}_{\gamma_R}\right],$$

where θ is the angle between the direction of γ_R w.r.t. X.



In the case where γ_R and X are collinear, the momentum range of γ_R, in the $\Upsilon(3S)$ rest-frame is

$$p^*_{\gamma_R} = \gamma_X \left[\pm E^{(X)}_{\gamma_R} + (\gamma_X\beta_X)\, E^{(X)}_{\gamma_R}\right]$$

$$= E^{(X)}_{\gamma_R}\left(\frac{m^2_{\Upsilon(3S)} + m^2_X}{2m_{\Upsilon(3S)}m_X}\right)\left[\frac{m^2_{\Upsilon(3S)} - m^2_X}{m^2_{\Upsilon(3S)} + m^2_X} \pm 1\right],$$

so that

$$p^*_{\gamma_R} \in E^{(X)}_{\gamma_R}\left[-\frac{m_X}{m_{\Upsilon(3S)}}, \frac{m_{\Upsilon(3S)}}{m_X}\right],$$

where

$$\frac{m_X}{m_{\Upsilon(3S)}} > \frac{m_{\Upsilon(1S)}}{m_{\Upsilon(3S)}} \sim 0.914.$$

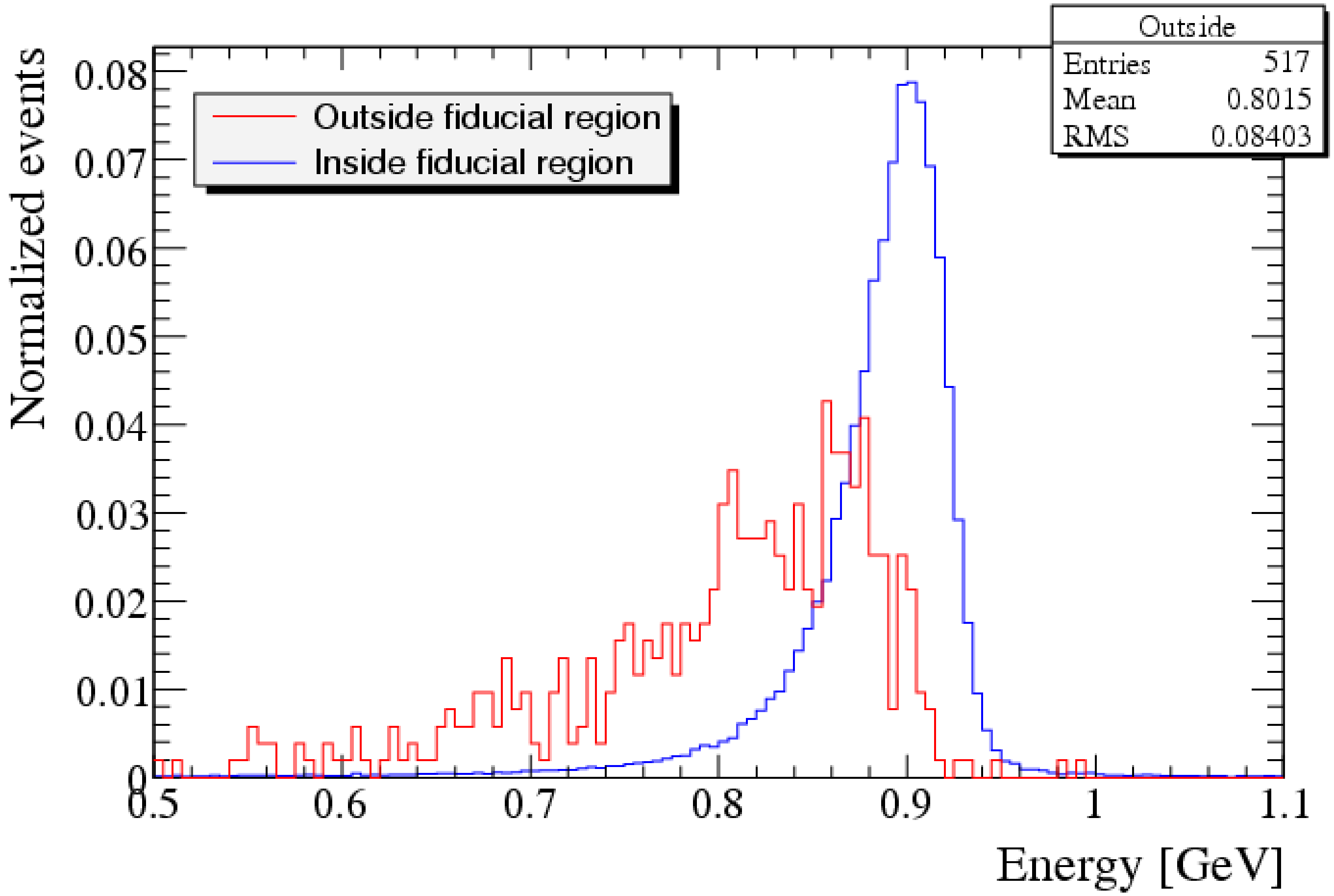
Then the effect on the photon from $X \to \gamma\Upsilon(1S)$ is

– For $X = \chi_{b2}(2P)$:

$$m_X = 10.26865GeV \Rightarrow \frac{m_X}{m_{\Upsilon(3S)}} = 0.992, \frac{m_{\Upsilon(3S)}}{m_X} = 1.008 \Rightarrow \pm 0.8\% \text{ energy spread}$$

- spread on 777 MeV peak = ± 6.2 MeV

Candidate photons are required to be within calorimeter barrel



Optimization of Selection Criteria

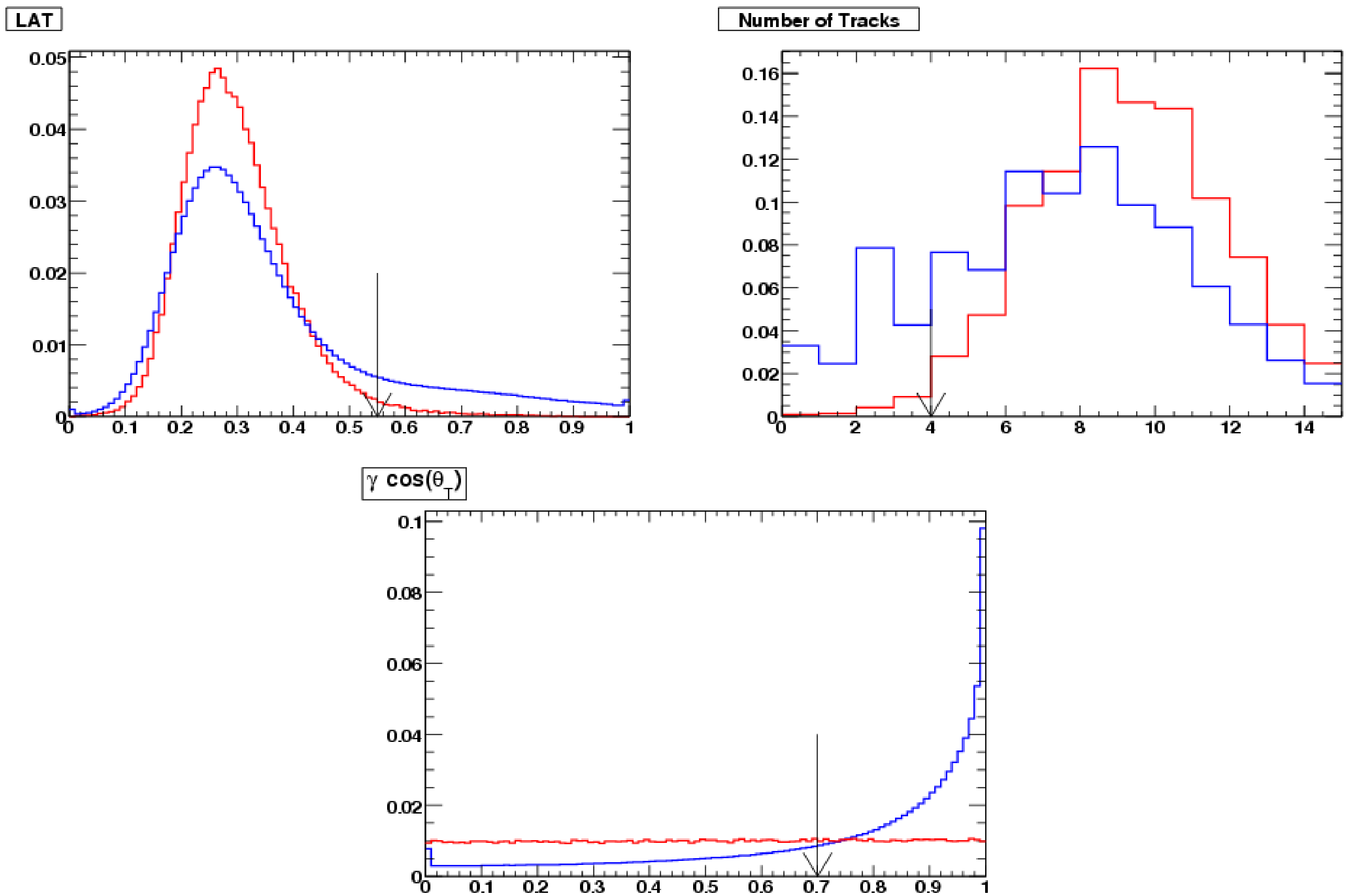
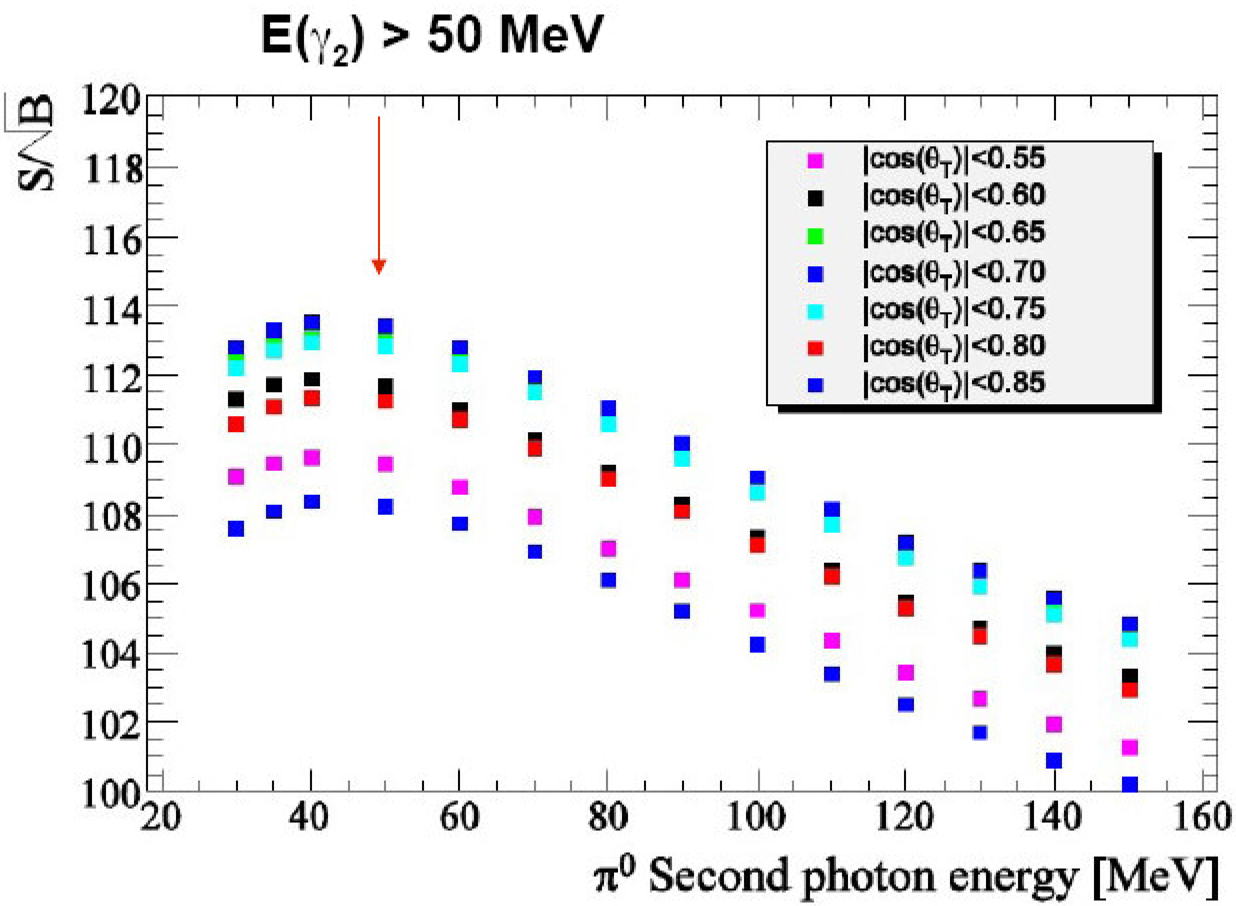


Figure 4: Cluster lateral moment (left), number of ChargedTracks in event (right), cosine of photon momentum direction with the thrust axis of the rest of the event (bottom), for truth-matched signal (red) and data (blue). The distributions are prior to any cuts except except a preliminary energy cut of $0.85 < E_{\gamma,CM} < 0.95$. The arrows show the cut values.

π^0 veto

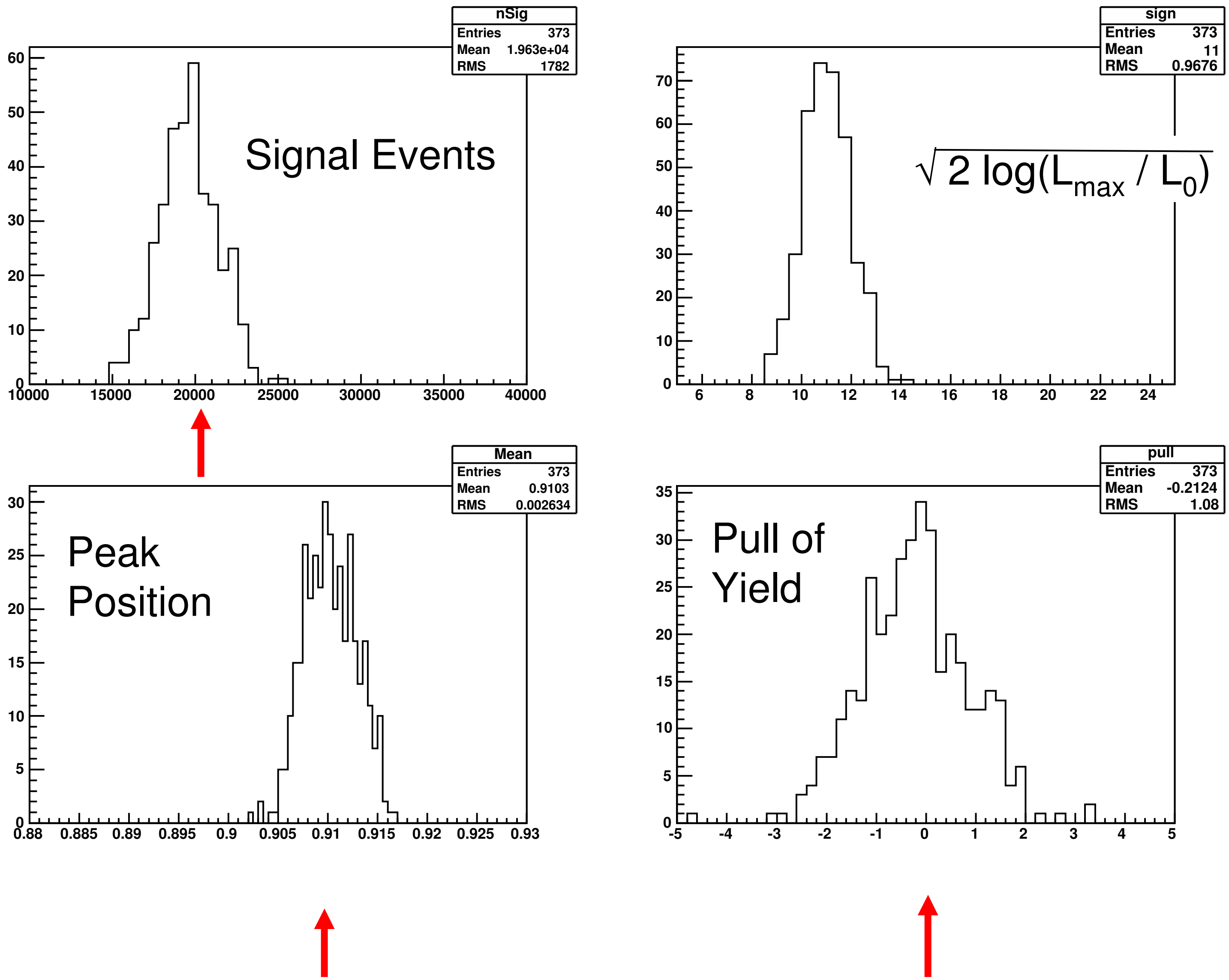
Reject photon candidate if $|M(\gamma\gamma_2) - M(\pi^0)| < 15$ MeV/c^2



Same optimization criteria obtained from χ_b signal yield in test sample

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

Example of MC Validation Study



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 $\pi^+\pi^- h_b(1P)$; $h_b(1P) \rightarrow \gamma\, \eta_b$

$BF < 1.8 \times 10^{-3}$ **(CLEO)**

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

$BF <$ **2.5 x 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 in the signal region, M=9300 MeV

1 expected background event

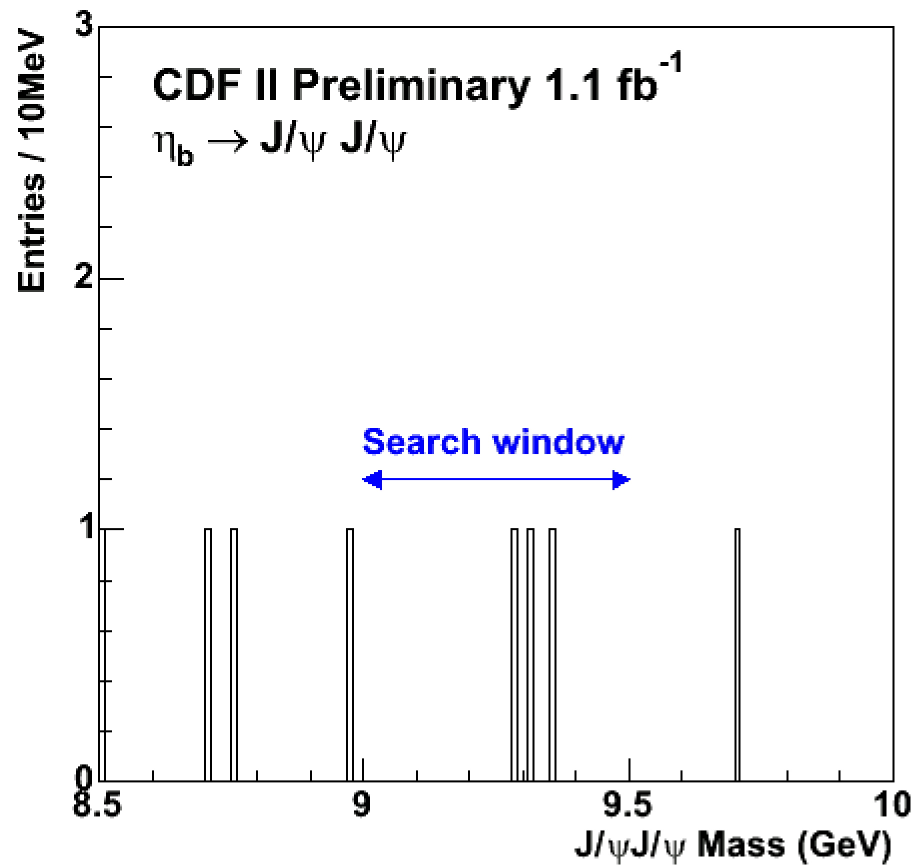
$\eta_b \rightarrow$ **4-, 6-, 8-prong Final States in 2-photon Production**

DELPHI at LEP II (2006)

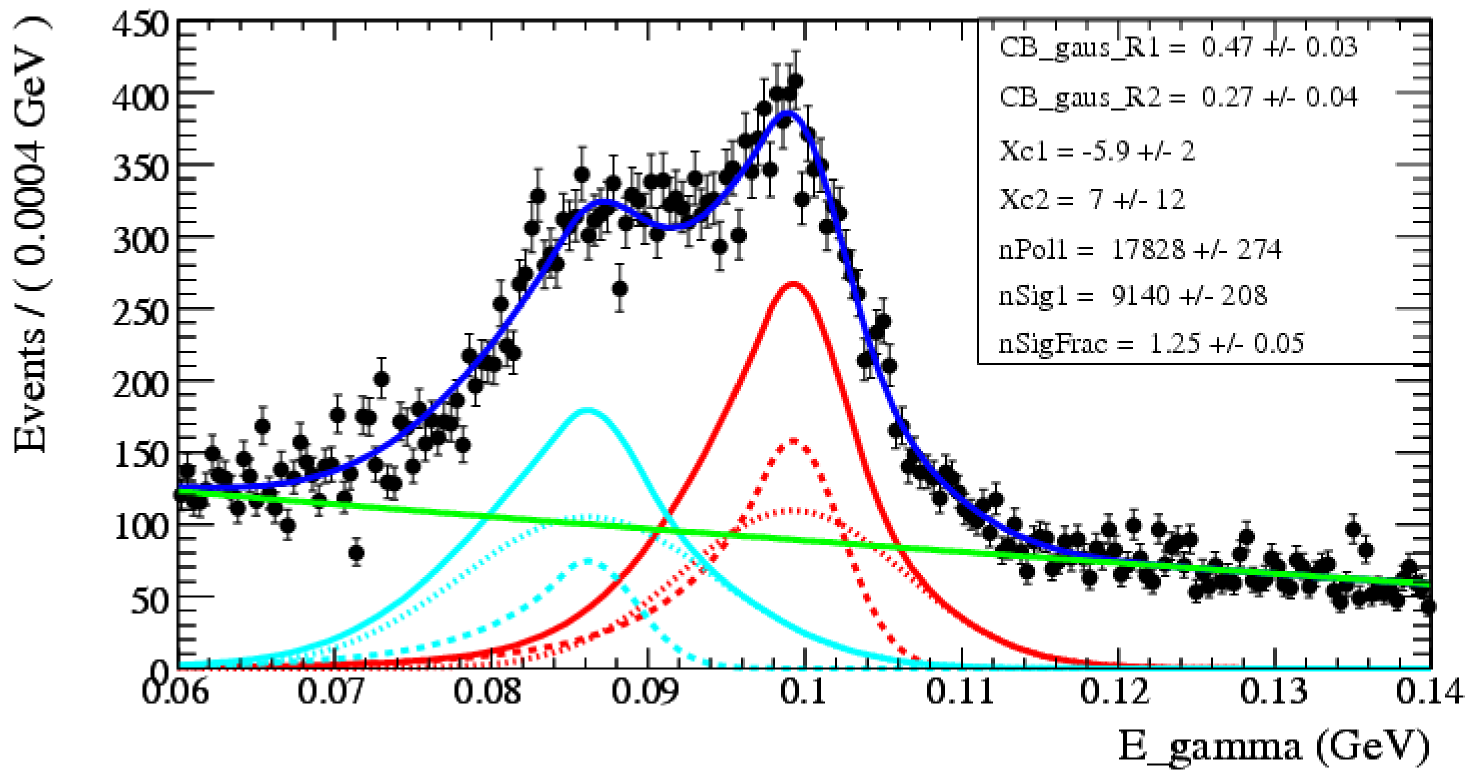
$\eta_b \rightarrow J/\psi\, J/\psi \rightarrow \mu^+\mu^-\mu^+\mu^-$ **CDF II at Tevatron (2006)**

Search for η_b decay into J/ψ J/ψ at CDF

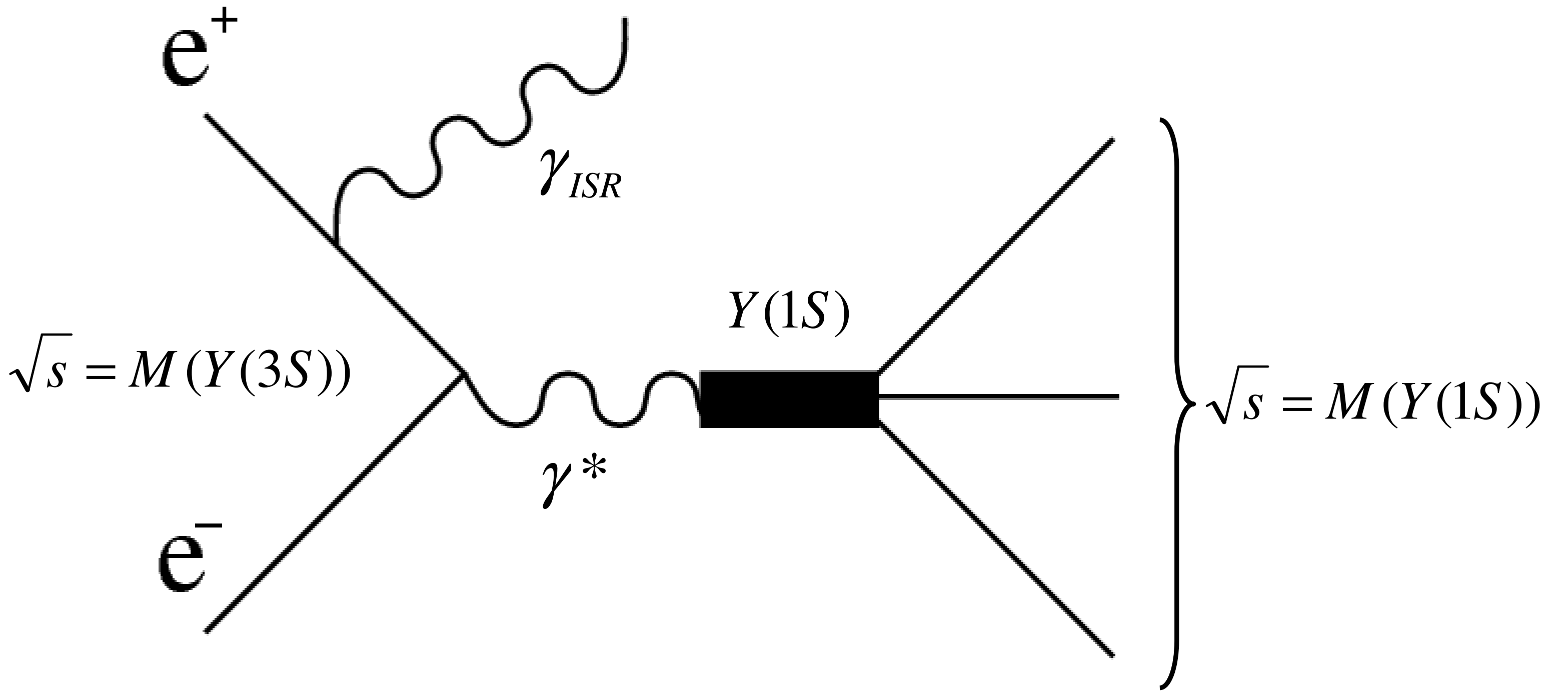
$$\frac{\sigma(p\bar{p} \to \eta_b X; |y(\eta_b)| < 0.6, p_T(\eta_b) > 3.0GeV) \cdot Br(\eta_b \to J/\psi J/\psi)}{\sigma(p\bar{p} \to H_b \to J/\psi X); |y(J/\psi)| < 0.6, p_T(J/\psi) > 3.0GeV)} < 5.0 \times 10^{-3}$$



Fit to soft photon transitions c.m. energy distribution

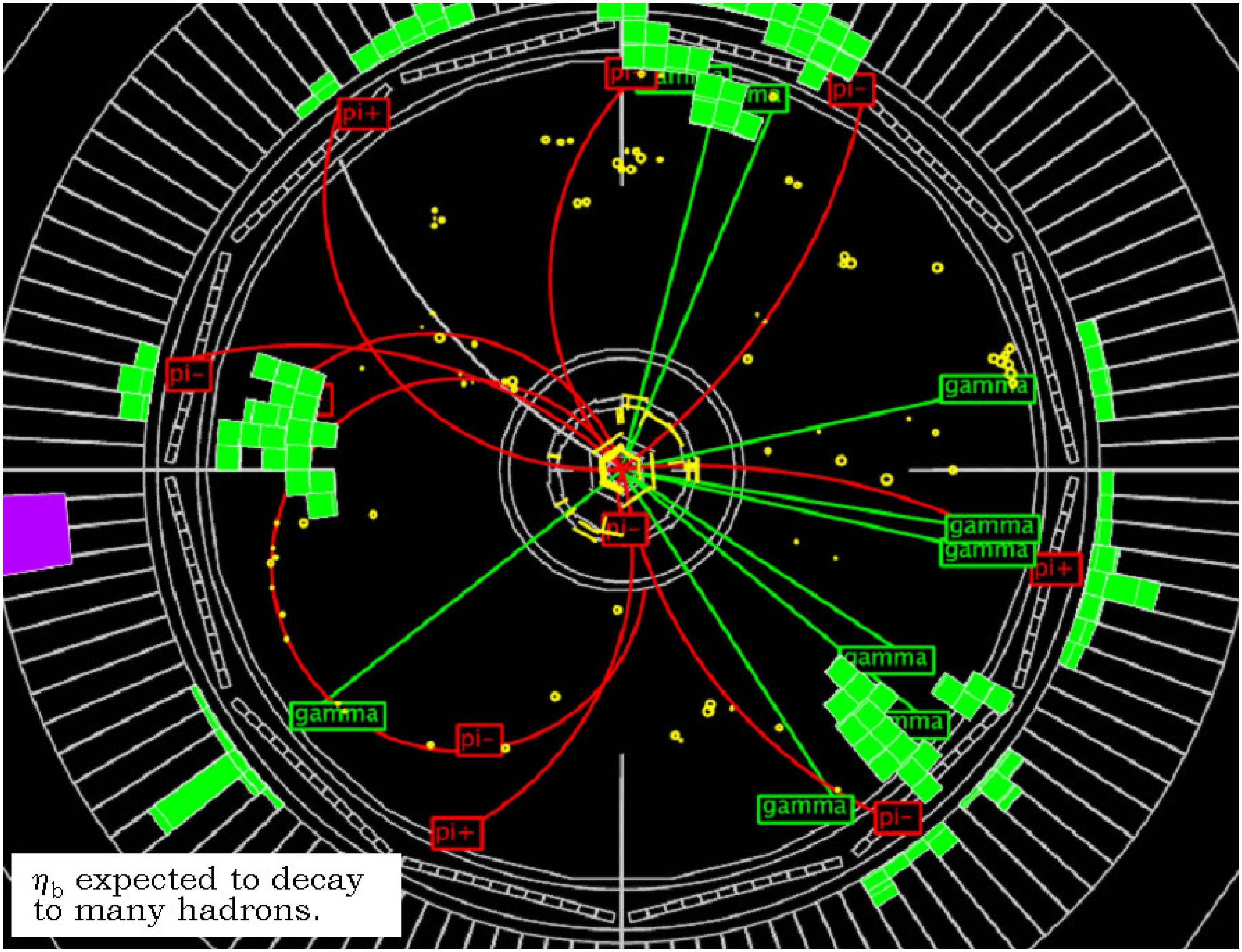


$$R = \frac{BF(\Upsilon(3S) \to \gamma\chi_{b1}) \times BF(\chi_{b1} \to \gamma\Upsilon(1S))}{BF(\Upsilon(3S) \to \gamma\chi_{b2}) \times BF(\chi_{b2} \to \gamma\Upsilon(1S))} = 1.2$$

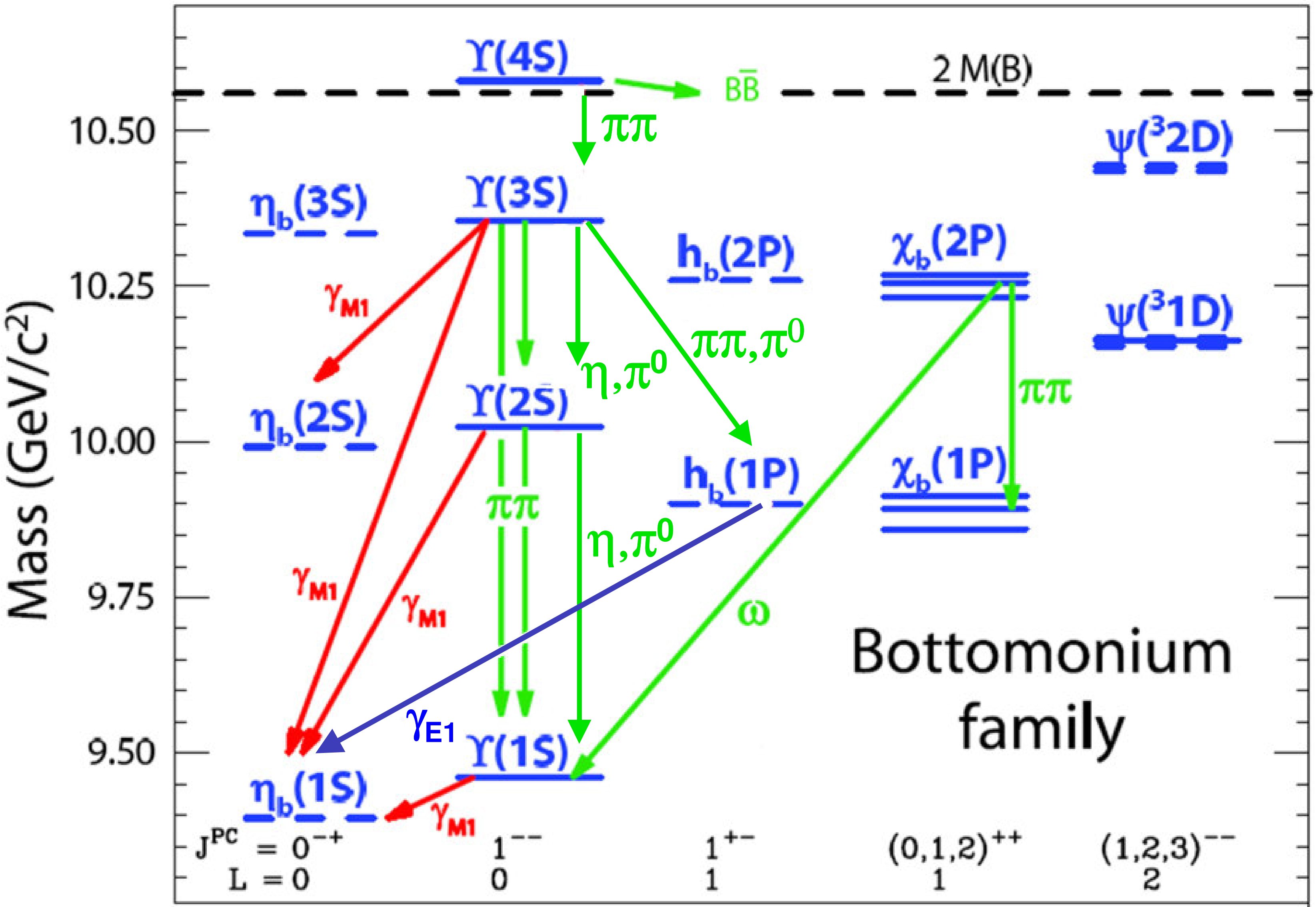


The diagram for the $e^+e^- \to \gamma_{ISR}\, Y(1S)$ process.

Simulation of a Signal event in the BaBar Detector



η_b expected to decay to many hadrons.



Mass (GeV/c²)
10.50
10.25
10.00
9.75
9.50
Υ(4S)
BB̄
2 M(B)
ππ
Υ(3S)
Υ(2S)
Υ(1S)
η_b(3S)
η_b(2S)
η_b(1S)
h_b(2P)
h_b(1P)
χ_b(2P)
χ_b(1P)
ψ(³2D)
ψ(³1D)
γM1
γM1
γM1
γM1
γE1
η,π0
ππ,π0
ππ
η,π0
ω
ππ
Bottomonium
family
JPC = 0−+
1−−
1+−
(0,1,2)++
(1,2,3)−−
L = 0
0
1
1
2