Stephen Sekula
The Ohio State University

Presented at
the University of California - Davis
October 21, 2008
Programme

- The bottomonium system: prospects for discovery
- The BaBar/PEP-II B-factory
- A matter of QCD – the $\eta_b$
- A matter of new physics – the light Higgs
- Prospects for further discovery
The Bottomonium System: Prospects for Discovery
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, H. D. Snyder, and J. K. Yoh
Columbia University, New York, New York 10027

and

Fermi National Accelerator Laboratory, Batavia, Illinois 60510

and

A. S. Ito, H. Jöstlein, D. M. Kaplan, and R. D. Kephart
State University of New York at Stony Brook, Stony Brook, New York 11974
(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 8000 dimuon events with a mass $m_{\mu^+\mu^-} > 5$ GeV.
The Upsilon is discovered, and identified as the first resonance of a new quark – the bottom quark.
The floodgates opened, ushering in 30 years of discovery!
The RPP 2006 summary tables for the Upsilon states below $\bar{B}B$ threshold take up 4 pages – less than 50% of the allowed decays are known.
By contrast, just the $B^0$ meson summary tables fill 10 pages of the RPP 2006.
The case for BaBar taking data at one of the narrow Upsilon resonances built over time, and involved the whole collaboration. Here are just a few snapshots . . .

June Collaboration Meeting, 2007

I ideas for searching for a low-mass Higgs (pdf) (ppt) (video)

October, 2007

Higgs and Exotics 2007 Workshop
Workshop on Higgs and other Exotic particles

Higgs Workshop, Monday October 29, 2007

December Collaboration Meeting, 2007

Run Strategy

<table>
<thead>
<tr>
<th>Time</th>
<th>Topic</th>
<th>(pdf)</th>
<th>(ppt)</th>
<th>(video)</th>
</tr>
</thead>
<tbody>
<tr>
<td>17:30-17:40</td>
<td>Upsilon (3S) SM Physics</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17:40-17:50</td>
<td>Upsilon (3S) non-SM Physics</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17:50-18:10</td>
<td>Upsilon (5S) Physics</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18:10-18:25</td>
<td>Off-resonance data</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

After December 17, 2007:

The Physics Case for Running the B-factory at the \( \Upsilon(3S') \) Resonance

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The BaBar/PEP-II b-Factory
Instrumented Flux Return for muon and neutral hadron identification

Electromagnetic calorimeter: ~6500 CsI crystals

5-layer, double-sided silicon strip vertex tracker

Drift chamber

Stephen Sekula - OSU
Scan Data from Dec. 22, 2007

Data taken here is “on-resonance”

Data taken here is “off-resonance”

$\sqrt{S}$ (GeV)
BaBar
Run 7

PEP II Delivered Luminosity: 56.82/ fb
BaBar Recorded Luminosity: 54.00/ fb
BaBar Recorded Y(4s): 0.78/ fb
BaBar Recorded Y(3s): 30.22/ fb
BaBar Recorded Y(2s): 14.45/ fb
Off Peak Luminosity: 8.54/ fb

Y(3S) Integrated Luminosity (122M Y(3S))

Belle: 11M
CLEO: 6M

Y(2S) Integrated Luminosity (99M Y(2S))

Above-the-4S Scan

CLEO: 9M

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A matter of QCD: The search for the $\eta_b$
Remember your Quantum Mechanics

What are the allowed states of a pair of spin-1/2 particles?

**SPIN:** \(\uparrow\), \(\downarrow\), \(\uparrow\uparrow\), \(\uparrow\downarrow\), \(\downarrow\uparrow\), \(\downarrow\downarrow\) \(S_{bb} = 0, 1\)

**ORBITAL:** \(L=0, 1, 2, \ldots\) (S, P, D, \ldots)

**TOTAL ANGULAR MOMENTUM (J):**
\[|L - S| < J < L + S\]

**THE FIRST FEW STATES:**

<table>
<thead>
<tr>
<th>L</th>
<th>S</th>
<th>J</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>(\eta_b(1S, 2S, \ldots))</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
<td>(\Upsilon(1S, 2S, \ldots))</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>(h_b(1P, 2P, \ldots))</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0,1,2</td>
<td>(\chi_{bb}(1P, 2P, \ldots))</td>
</tr>
</tbody>
</table>
Spectroscopy:
Find the bottomonium ground state

QCD is assumed to be the dominant factor in defining the spectrum of states. Predictions proceed from this . . .

Hyperfine splitting predictions (1^3S_1 – 1^1S_0)
- pNRQCD: (39-44) MeV (~25% uncertainty)
- Potential models: (46-87) MeV
- Lattice QCD: (40-71) MeV (10-25% uncertainty)
What were the best existing experimental constraints?

\[ Y(nS) \rightarrow \gamma \eta_b \]

Published CLEO limits
PRL 94 032001 (2005)

\[ e^+ e^- \rightarrow e^+ e^- \gamma \gamma \gamma (\rightarrow \eta_b) \]

<table>
<thead>
<tr>
<th>Expt</th>
<th>final state</th>
<th>( \Gamma_{\gamma \gamma} \times B ) (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALEPH</td>
<td>4 charged</td>
<td>&lt; 0.048</td>
</tr>
<tr>
<td></td>
<td>6 charged</td>
<td>&lt; 0.132</td>
</tr>
<tr>
<td>L3</td>
<td>( K^+ K^- \pi^0 )</td>
<td>&lt; 2.83</td>
</tr>
<tr>
<td></td>
<td>4 charged</td>
<td>&lt; 0.21</td>
</tr>
<tr>
<td></td>
<td>4 charged ( \pi^0 )</td>
<td>&lt; 0.50</td>
</tr>
<tr>
<td></td>
<td>6 charged</td>
<td>&lt; 0.33</td>
</tr>
<tr>
<td></td>
<td>6 charged ( \pi^0 )</td>
<td>&lt; 5.50</td>
</tr>
<tr>
<td></td>
<td>( \pi^+ \pi^- \eta' )</td>
<td>&lt; 3.00</td>
</tr>
<tr>
<td>DELPHI</td>
<td>4 charged</td>
<td>&lt; 0.093</td>
</tr>
<tr>
<td></td>
<td>6 charged</td>
<td>&lt; 0.270</td>
</tr>
<tr>
<td></td>
<td>8 charged</td>
<td>&lt; 0.780</td>
</tr>
</tbody>
</table>

30 years after the discovery of the Upsilon, the ground state of bottomonium had eluded detection
Monte Carlo Simulations
used for modeling signal and specific backgrounds
tune selection criteria

Full dataset: 122M Y(3S) mesons
use a small sample (9%) for tuning the selection
use $(109 \pm 1) \times 10^6$ Y(3S) for final result

Blind Analysis
We never look at the signal region in the final data set until the analysis method is finalized.

Search for a “bump” in the photon spectrum
use maximum likelihood fit, including backgrounds and a possible signal

Analysis Strategy

$E_\gamma^* = \frac{m_{Y(3S)}^2 - m_{\eta_b}^2}{2 m_{Y(3S)}^2}$

Monte Carlo Simulations
used for modeling signal and specific backgrounds
tune selection criteria
Signal photon required to be reconstructed with high quality, be well within the calorimeter acceptance, and be inconsistent with originating from a $\pi^0$.

$\eta_b$ expected to decay into many hadrons (through two gluons), and have uniform distribution of final state particles.

Signal Efficiency: 37%
The Single Photon Challenge: Backgrounds

Non-peaking shape is parameterized by: \( A(C+\exp[-\alpha E_{\gamma} - \beta E_{\gamma}^2]) \)

The shape is determined by a fit excluding the \( \chi_b \) and signal regions ("peaking regions")

\[ e^+ e^- \rightarrow \gamma Y(1S) \]

Anticipated \( \eta_b \) signal region blinded until analysis finalized
$e^+e^- \rightarrow \gamma_{\text{ISR}} Y(1S): \text{Expectation}$

The fitted ISR shape is shifted down to the expected peak position for the $Y(3S)$ CM energy. The yield is scaled using the ratio of cross-sections (computed from theory).

$\sqrt{s} = 10.54 \text{ GeV} \rightarrow \sqrt{s} = 10.3552 \text{ GeV}: \ 25153 \pm 1677$

$\sqrt{s} = 10.31 \text{ GeV} \rightarrow \sqrt{s} = 10.3552 \text{ GeV}: \ 29393 \pm 5014$
The $\chi_{bj}(2P)$ – background, calibration

The peak position is shifted by 3.8 MeV below the expectation – this is used to calibrate the photon energy.

The data are shown after subtracting the non-peaking background.

ISR Background Expectation
The $\eta_b$ Signal Model

Use a Monte Carlo simulation of signal events. Set $\eta_b$ width to zero to study detector resolution effects.

- Convolute resolution model with a Breit-Wigner, which represents the resonance.
- Floating the BW width in the final fit failed to converge. Fix to 10 MeV and vary from 5-20 MeV.
Strategy to search for a “bump”

The $\chi_{bJ}^{(2P)}$ peak is fixed from the fit with the signal region blinded.

ISR background shape taken from simulation, yield taken from extrapolation, peak fixed to 851.4 MeV

Signal shape taken from simulation, peak position allowed to vary, nominal width is 10 MeV

Events / (0.5 GeV)
Results

Fitted Mean: $E_\gamma = 921.2^{+2.1}_{-2.8} \pm 2.4 \text{ MeV}$

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

Hyperfine Splitting: $71.4^{+2.3}_{-3.1} \pm 2.7 \text{ MeV}/c^2$

Consistent with predictions of the $\eta_b$ properties

Fitted signal yield: $19200 \pm 2000 \text{ (stat.)} \pm 2100 \text{ (syst.)}$

Branching Fraction: $(4.8 \pm 0.5 \pm 1.2) \times 10^{-4}$
Is this really the ground state?

- photon angular distribution can tell us the spin
- are the dominant decay modes to hadrons?
- do we see the “same” state in $\Upsilon(2S) \rightarrow \gamma \eta_b$?

PRL 101, 071801 (2008)
A Matter of New Physics: Search for a Light CP-Odd Higgs
Can we solve the dark matter puzzle and illuminate the Higgs sector at the same time?
Higgs self-coupling diverges in the Standard Model at high energies.

Loops involving superpartners cancel divergences!
The above term in the superpotential gives the two Higgs doublets non-zero vacuum-expectation values, so that the Higgses can then give mass to the matter particles.

μ is then expected to have a value of order the weak scale, far from the next natural scale: the Planck scale. Why is μ so small?

One Solution: The Next-to-Minimal Supersymmetric Standard Model (NMSSM)

$$\mu \, H_u \, H_d$$

$$\lambda \, N \, H_u \, H_d$$

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

This adds a CP-odd Higgs, which I will denote the $A^0$, that can radically change the phenomenology of the Higgs sector.
New Physics: A Light Higgs Boson

For a light $A^0$, the dominant SM Higgs decay will be $h \rightarrow A^0 A^0$

Depending on the $A^0$ mass, the dominant decay could be:

$A^0 \rightarrow \tau^+ \tau^-$

Leading to 4-$\tau$ final states at LEP, which were never explored.

Best limits come from recent CLEO search for $A^0 \rightarrow \mu\mu$, $\tau\tau$ hep/ex arXiv:0807.1427

Parameter Scan

- blue points: $m_{A^0} < 2m_\tau$
- red points: $2m_\tau < m_{A^0} < 7.5$ GeV
- green points: $7.5$ GeV < $m_{A^0}$ < 8.8 GeV
- black points: 8.8 GeV < $m_{A^0}$ < 9.2 GeV


$\tan\beta=10$, $\mu=150$ GeV, $M_{1,2,3}=100, 200, 300$ GeV

The fraction of the $A^0$ which is non-singlet
This isn't simple . . .

Why should this be any simpler?

A low-mass dark matter component might be the dominant CP-odd Higgs decay mode, leading to an invisible Higgs signature.
Experimental Signature

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

Interpret as invisible pseudoscalar

\[ E^*_\gamma = \frac{m_T^2 - m_{A^0}^2}{2m_T} \]

There are no limits from the Y(3S) or the Y(2S).

PRD 51, no. 5 2053 (1995)
An illustrative signal candidate event...

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

Require very little additional detector activity either in tracking or in the calorimeter

One catch: this event is a data event from a problematic background: $e^+ e^- \rightarrow \gamma \gamma$

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We reject this background by vetoing correlations between our signal photon and activity in the muon system.

**Total Signal Efficiency:**

- High Energy Region: 10-11%
- Low Energy Region: 20%
Maximum Likelihood Fit

- 1-D fit to the missing mass-squared:
  \[ m_X^2 = M_{Y(3S)}^2 - 2 E_y^* M_{Y(3S)} \]

- Signal model
  - parameterized using same detector resolution function as \( \eta_b \) search (zero-width Higgs)
  - parameters vary with assumed Higgs mass, due to calorimeter response

- Background models
  - determined from data control samples
  - Major backgrounds: \( e^+e^- \rightarrow \gamma \gamma, \gamma \gamma \gamma, e^+e^-\gamma \)
$\text{e}^+\text{e}^- \rightarrow \gamma\gamma$ background

Off-Resonance $\Upsilon(3S)$ Data

The $\gamma\gamma$ background model is taken from data before the IFR veto.

The tail of this function extends into the high-mass region, and is treated as part of the background there.

The remaining non-peaking background in the low-mass region is empirically modeled as a single exponential function.
A Snapshot: Fits to the Spectrum Low-Mass Region

\[ e^+ e^- \rightarrow \gamma \gamma \]

Non-peaking background

Signal Model
A Snapshot: Fits to the Spectrum
High-Mass Region

\[ e^+e^- \rightarrow \gamma\gamma(\gamma) \]

Non-peaking background

Signal Model
Results

Most significant yields:
- low-mass region: $37 \pm 15$ (2.6σ, stat. only)
- high-mass region: $119 \pm 71$ (1.7σ, stat. only)
The fraction of the $A_0^0$ which is non-singlet

$\tan\beta=10$, $\mu=150$ GeV, $M_{1,2,3}=100, 200, 300$ GeV

Results (continued)

BaBar Preliminary Result:

arXiv:0808.0017 [hep-ex]
Concluding Thoughts:
Prospects for Further Discovery
First Results from BaBar Upsilon Sample

- Unmatched samples of Upsilon mesons below threshold open up new doors of exploration
  - Standard Model – discovery and further study of the $\eta_b$

  \[
  \begin{align*}
  \text{Mass:} & \quad 9388.9^{+3.1}_{-2.3} \pm 2.7 \text{ MeV}/c^2 \\
  \text{Hyperfine Splitting:} & \quad 71.4^{+2.3}_{-3.1} \pm 2.7 \text{ MeV}/c^2 \\
  \text{Branching Fraction:} & \quad BR(Y(3S) \rightarrow \gamma \eta_b) = (4.8 \pm 0.5 \pm 1.2) \times 10^{-4}
  \end{align*}
  \]

- New Physics – searches for low-mass Higgs and light dark matter

  - We exclude an invisibly decaying light Higgs up to 7.8 GeV/c$^2$
    at the 90% CL at the level of $10^{-5} -- 10^{-6}$
What is the white elephant?

It is the legacy left by our overwhelming success in understanding 5% of the universe.

Exhilarating in the receiving, it has proven hard to shed in order to make sense of the rest.
Backup Slides:
Reference and Details
QCD Calculations of the $\eta_b$ mass and branching fraction

Godfrey and Isgur, PRD 32, 189 (1985)
Fulcher, PRD 44, 2079 (1991)

Spectroscopy


$\eta_b$ Event Pre-selection

- Selection chosen to have high signal efficiency
  - Dominant $\eta_b$ decay expected to be $\eta_b \rightarrow gg$
    - require $\geq 4$ charged tracks in an event
    - exclude “jetty” events (e.g. $e^+e^- \rightarrow qq$) using Fox-Wolfram moment ratio, $H_2/H_0 < 0.98$
  - Select high-quality photons:
    - lateral moment of EMC shower < 0.55
    - EMC barrel-only photons (-0.762 < $\cos \theta_\gamma$ < 0.890)
    - Spin-0 $\eta_b$ leaves a small correlation between the photon and event thrust axis, in contrast to $e^+e^- \rightarrow qq$: $|\cos \theta_T| < 0.7$
    - Veto photons consistent with a $\pi^0$ decay

Signal Efficiency: 37%
\( \eta_b - \text{track multiplicity} \)

Track multiplicity after all other cuts, compared between signal MC (BLUE) and the test data (RED).

According to MC simulation, the \( \geq 4 \) track multiplicity is 99.5\% efficient on signal events: check signal simulation against \( \chi_{bJ}(2P) \) data!

Despite the expected higher multiplicity of the \( \chi_{bJ}(2P) \rightarrow \gamma Y(1S) \) events (due to \( Y(1S) \rightarrow gg \)), the difference in the efficiencies due to the track multiplicity cut is only about 10\%. We conservatively assign this as part of the selection efficiency systematic.

<table>
<thead>
<tr>
<th>Cut</th>
<th>( S/\sqrt{B} )</th>
<th>Eff. (from ( \eta_b ) peak)</th>
<th>Eff. (signal MC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No cut</td>
<td>101.5</td>
<td>-</td>
<td>0.629</td>
</tr>
<tr>
<td>RGFMultiHadron</td>
<td>109.8</td>
<td>0.973</td>
<td>0.977</td>
</tr>
<tr>
<td>( \geq 4 ) ChargedTracks</td>
<td>107.2</td>
<td>0.903</td>
<td>0.995</td>
</tr>
<tr>
<td>LAT&lt;0.55</td>
<td>113.2</td>
<td>0.997</td>
<td>0.991</td>
</tr>
<tr>
<td>(-0.762 &lt; \cos(\theta_{\gamma_LAB}) &lt; 0.890)</td>
<td>109.6</td>
<td>0.928</td>
<td>0.901</td>
</tr>
<tr>
<td>(</td>
<td>\cos(\theta_T)</td>
<td>&lt; 0.7 )</td>
<td>135.2</td>
</tr>
<tr>
<td>( \pi^0 )-50 MeV cut</td>
<td>164.7</td>
<td>0.849</td>
<td>0.899</td>
</tr>
</tbody>
</table>
The $\eta_b$ width

• **Predictions of the width:**
  - based on the ratio of $\Gamma(\eta_b \rightarrow \gamma\gamma)$ and $\Gamma(\eta_b \rightarrow gg)$, predictions range from 4-20 MeV/$c^2$

• **Systematic variations:**
  - fit with width floated won't converge
  - variations from 5-20 MeV/$c^2$ lead to largest single systematic uncertainty on yield (10%)
The Details of the $\eta_b$ Fit

- The fit is done using a maximum likelihood function on the binned data, $0.5 < E_\gamma < 1.1$ GeV
- bin size: 5 MeV
- Fit models
  - non-peaking parameters floated, with initial values set from the peaking-region-blinded fit
  - $\chi_{bj}(2P)$ shape fixed, yield floated
  - ISR shape fixed, yield fixed
  - signal shape fixed, except the peak position; yield floated
$e^+e^- \rightarrow \gamma_{\text{ISR}} Y(1S)$: Expectation

\[
\sigma(e^+e^- \rightarrow \gamma_{\text{ISR}} Y(1S)) = \frac{\pi \Gamma_{ee}}{M_{Y(1S)} s} \cdot W(s, 2E_\gamma / \sqrt{s})
\]

Use the ratio of cross-sections and efficiencies to cancel most of the uncertainties from either source.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Lumi [fb$^{-1}$]</th>
<th>Cross-Section [pb]</th>
<th>Reconstruction Efficiency</th>
<th>Yield</th>
<th>Extrapolation to $Y(3S)$ On-Peak</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Y(3S)$ Off-Peak</td>
<td>2.415</td>
<td>25.4</td>
<td>$5.78 \pm 0.09$</td>
<td>$2773 \pm 473$</td>
<td>$29393 \pm 5014$</td>
</tr>
<tr>
<td>$Y(4S)$ Off-Peak</td>
<td>43.9</td>
<td>19.8</td>
<td>$6.16 \pm 0.12$</td>
<td>$35759 \pm 1576$</td>
<td>$25153 \pm 1677$</td>
</tr>
</tbody>
</table>
We use 40/fb of data taken 40 MeV below the $\Upsilon(4S)$ resonance to study ISR production of the $\Upsilon(1S)$. The data are fitted with the same non-peaking model and a Gaussian + Power-Law Tail (ISR peak).

The fitted ISR shape is shifted down to the expected peak position for the $\Upsilon(3S)$ CM energy.

Data shown are from the $\Upsilon(4S)$ off-resonance sample.

Binned ISR PDF taken from MC simulation.
Systematic Uncertainties - $\eta_b$

**Signal Yield:**

ISR Background:

- fit with ISR yield floated – consistent with the fixed yield of ISR, and has no effect on $\eta_b$ yield or peak position
- fixed value varied by $\pm 1\sigma$ to get systematic on signal yield

$\eta_b$ width varied in fit (5, 15, 20 MeV), yielding largest single systematic effect: 10%

PDF parameters – varied by $\pm 1\sigma$

**TOTAL UNCERTAINTY: 11%**

**Mass:**

$\chi_{bj}(2P)$ peak shift: $(3.8 \pm 2.0)$ MeV

**Branching Fraction:**

Selection efficiency: compare data yield to expectation from PDG branching fractions (18%) and MC efficiency – 22% uncertainty

**TOTAL UNCERTAINTY: 25%**
Data Samples

- **Data with single-photon triggers:**
  - 28 fb\(^{-1}\) taken at the Y(3S)
    - signal analysis sample
  - 4.7 fb\(^{-1}\) taken at the Y(4S)
    - used HE trigger, can be used to tune cuts on photons
  - “Off-resonance” data
    - 2.6 fb\(^{-1}\) taken 40 MeV below the Y(3S)
    - 0.97 fb\(^{-1}\) taken 30 MeV below the Y(2S)
    - 4.5 fb\(^{-1}\) taken in a scan above the Y(4S)
The plot below is taken from arXiv:hep-ph/0312114v2 and is meant to illustrate the $e^+e^- \rightarrow \text{hadrons}$ spectrum between 9.1 GeV and 11.2 GeV.

Data taken away from resonances or above the $\Upsilon(4S)$ – background studies.

122M $\Upsilon(3S)$

$\Upsilon(4S)$ data for tuning photon selection.
Triggering on Single Photons + $E_{\not}^\gamma$

The ability to trigger on events with a single photon and significant missing energy is critical to this analysis

- Dedicated online triggered and filtering were developed
  - Level 1 (hardware trigger): require at least one EMC cluster with energy $> 800$ MeV (lab frame)
  - Level 3 (software trigger): two lines developed
    - High-energy (HE) line: require isolated EMC cluster with CM-frame energy $> 2$ GeV
    - Low-energy (LE) line: developed later (only 82 million $Y(3S)$ taken), requires cluster energy $> 1$ GeV and no tracks from the IP

$100$ Hz
**Event Selection**

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

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

Data taken at the Y(4S)

**Total Efficiency:**

- High Energy Region: 10-11%
- Low Energy Region: 20%
Systematic Uncertainties - Higgs

**e^+ e^- → γγ background (dominant effect)**

varying the yield gives a ±38 event uncertainty for m_{A0} = 0 GeV/c^2,

with a decreasing effect for larger masses.

varying the shape gives a ±70 event uncertainty at m_{A0} = 7.4 GeV/c^2

**Signal PDF**

corrected using data vs. simulation comparison of e^+ e^- → γγ events,

  taking half the correction as the systematic uncertainty

  – The largest impact is at m_{A0} = 7.4 GeV/c^2, where the signal yield

  varies by ±64 events

**Signal Efficiency**

trigger/event filter efficiency checked with e^+ e^- → γγ and e^+ e^- γ (0.4%)

Photon selection checked using e^+ e^- → μμγ, ττγ, and ωγ (2%)

Neutral reconstruction: 2%
$p + (\text{Cu, Pt}) \rightarrow \mu^+ + \mu^- + \text{anything}$
T. Bohringer et al., PRL 44, 1111 (1980)