Confronting the White Elephant: Upsilon Physics at the BaBar B-factory

flickr.com/photos/shoshannabauer/2215305114/

Stephen Sekula
The Ohio State University

Presented at Southern Methodist University
December 8, 2008

BABAR

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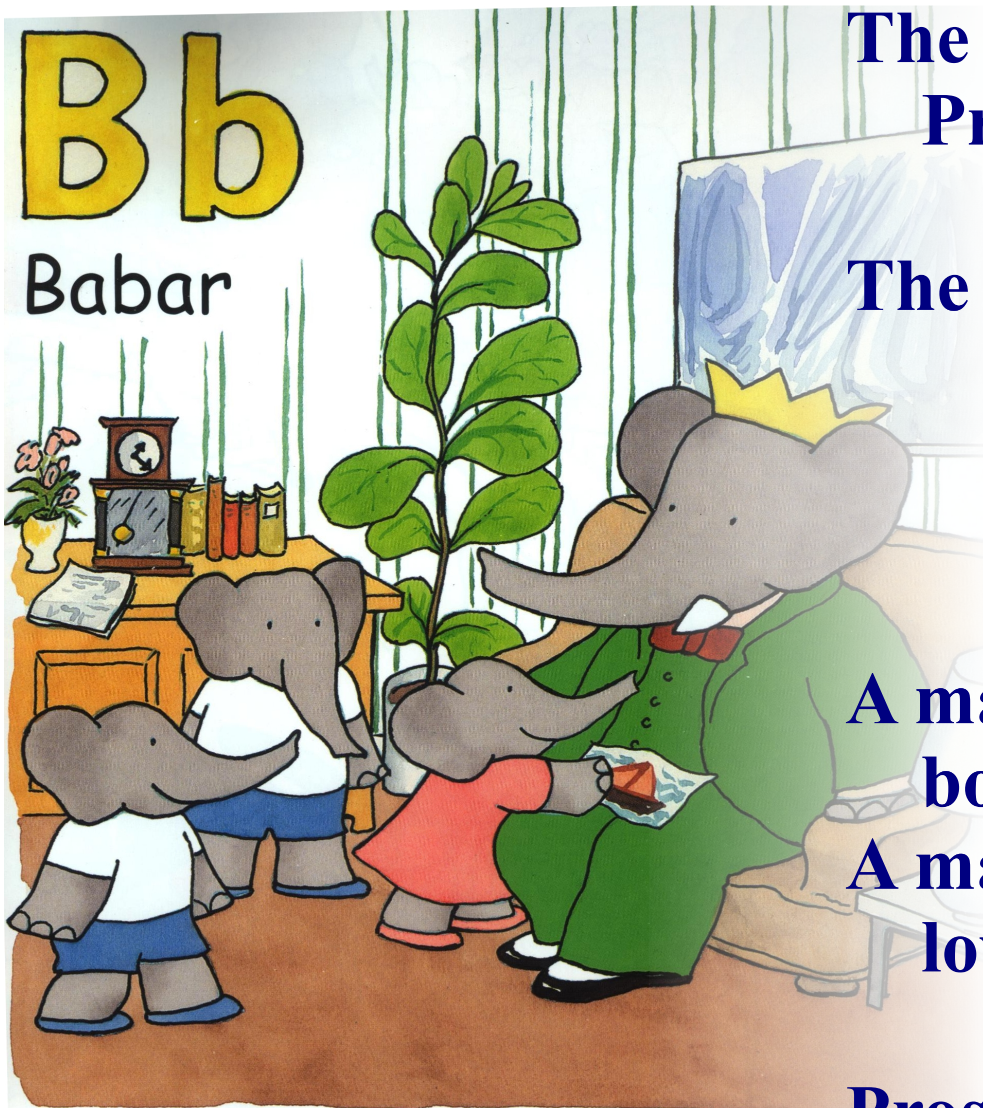
Programme



The Bottomonium System – Prospects for Discovery

The PEP-II/BaBar ~~B~~ b-Factory

$B^0 = (\bar{b}\, d)$

$B^+ = (\bar{b}\, u)$

$\Upsilon = (\bar{b}\, b)$

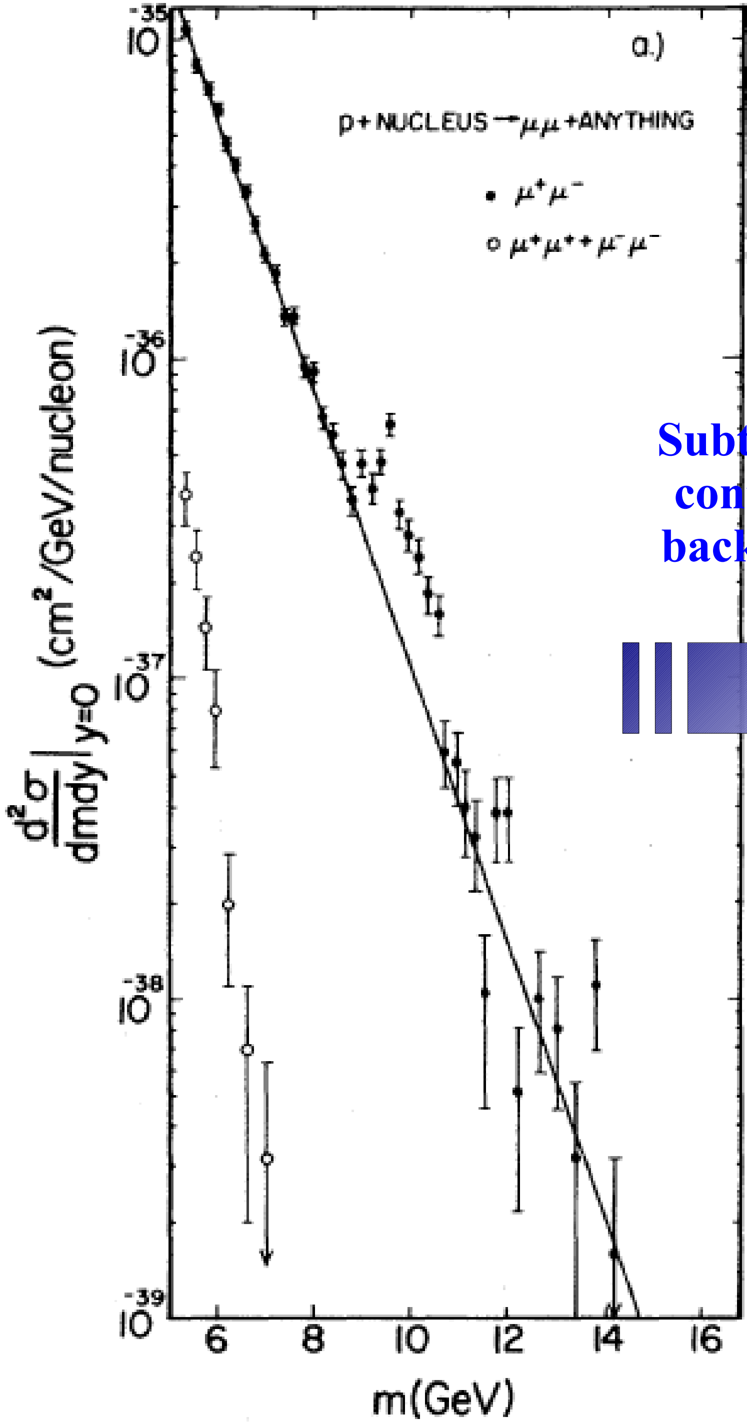
A matter of QCD – the bottomonium ground state

A matter of new physics – the low-mass Higgs

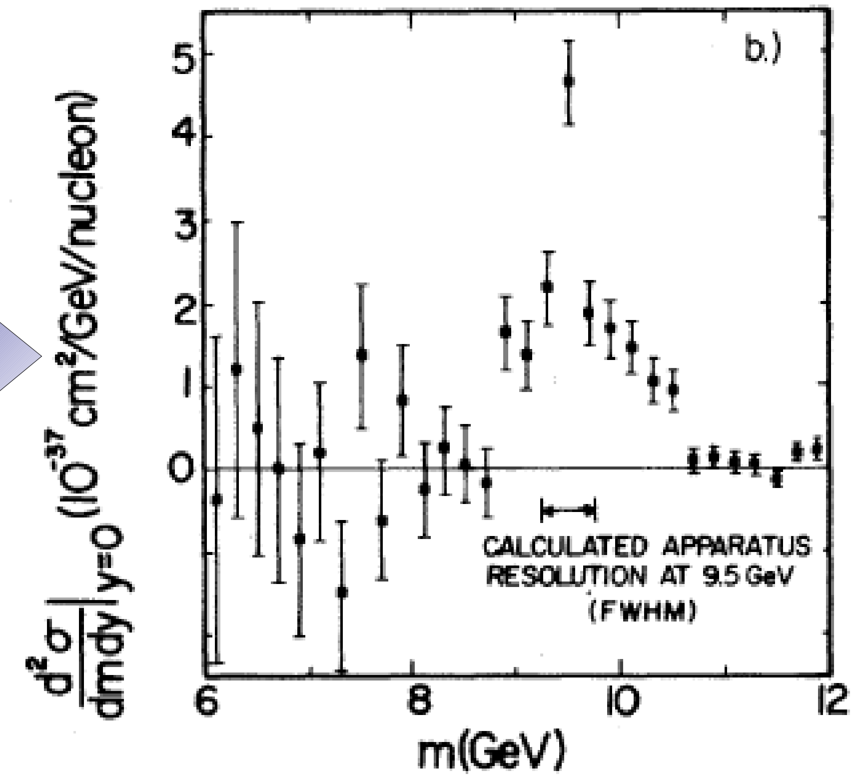
Prospects for further discovery

The Bottomonium System: Prospects for Discovery

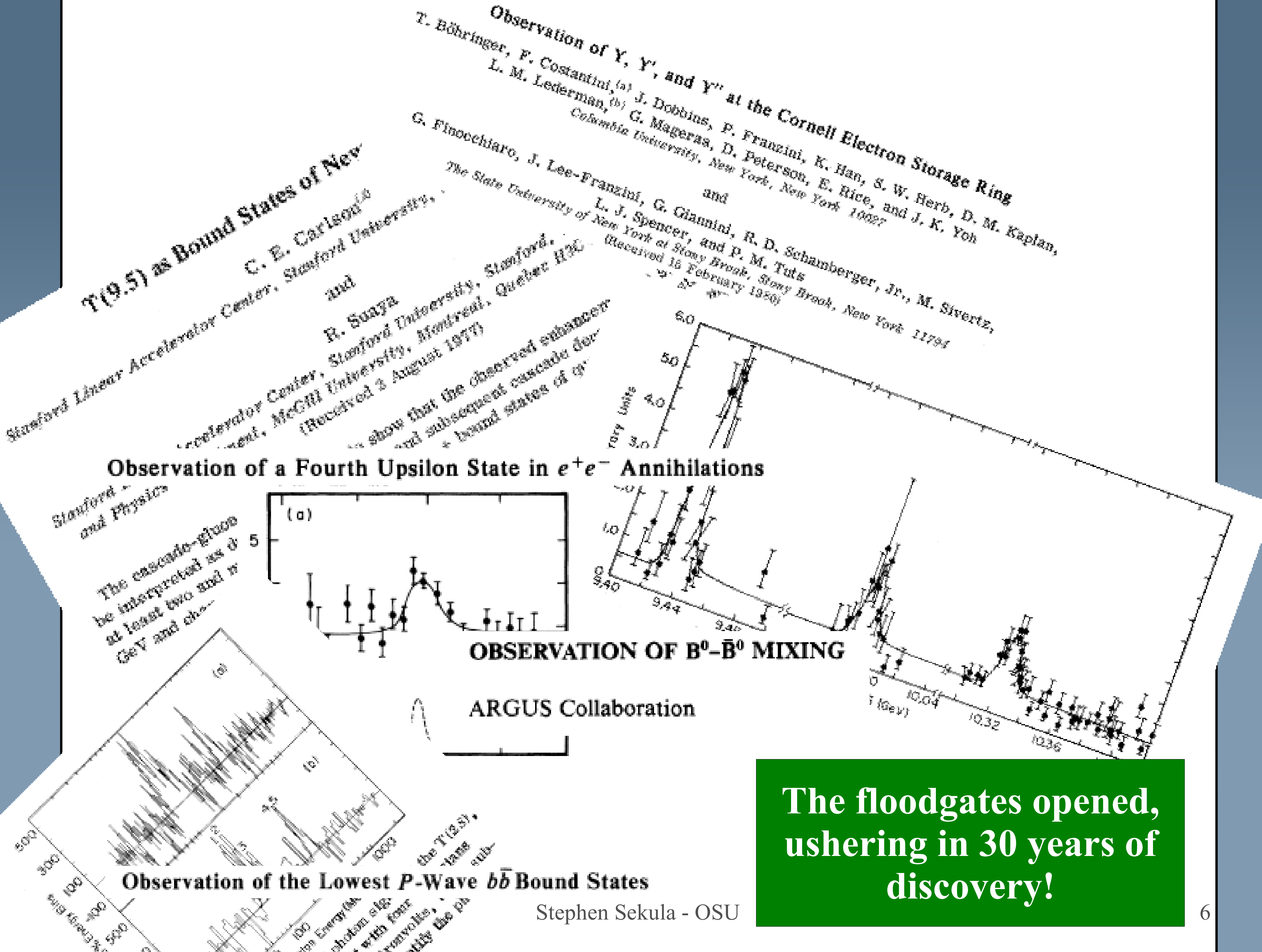
1977



Subtract the continuum background



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!

2007

Citation: C. Amsler *et al.* (Particle Data Group), PL B667, 1 (2008) (URL: http://pdg.lbl.gov)

$\Upsilon(3S)$

$I^G(J^{PC}) = 0^-(1^{--})$

$\Upsilon(3S)$ MASS

VALUE (GeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
10.3552±0.0005	[1] ARTAMONOV 00	MD1	$e^+e^- \to$ hadrons
• • • We do not use the following data for averages, fits, limits, etc. • • •			
10.3553±0.0005	[2,3] BARU 86B	REDE	$e^+e^- \to$ hadrons

[1] Reanalysis of BARU 86B using new electron mass (COHEN 87).
[2] Reanalysis of ARTAMONOV 84.
[3] Superseded by ARTAMONOV 00.

$\Upsilon(3S)$ WIDTH

VALUE (keV)	*DOCUMENT ID*
20.32±1.85 OUR EVALUATION	See the Note on "Width Determinations of the Υ States"

$\Upsilon(3S)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	$\Upsilon(2S)$ anything	(10.6 ±0.8) %	
Γ_2	$\Upsilon(2S)\pi^+\pi^-$	(2.8 ±0.6) %	S=2.2
Γ_3	$\Upsilon(2S)\pi^0\pi^0$	(2.00±0.32) %	
Γ_4	$\Upsilon(2S)\gamma\gamma$	(5.0 ±0.7) %	
Γ_5	$\Upsilon(1S)\pi^+\pi^-$	(4.48±0.21) %	
Γ_6	$\Upsilon(1S)\pi^0\pi^0$	(2.06±0.28) %	
Γ_7	$\Upsilon(1S)\eta$	< 2.2 × 10^{-3}	CL=90%
Γ_8	$\tau^+\tau^-$	(2.29±0.30) %	
Γ_9	$\mu^+\mu^-$	(2.18±0.21) %	S=2.1
Γ_{10}	e^+e^-	seen	
	Radiative decays		
Γ_{11}	$\gamma\chi_{b2}(2P)$	(13.1 ±1.6) %	S=3.4
Γ_{12}	$\gamma\chi_{b1}(2P)$	(12.6 ±1.2) %	S=2.4
Γ_{13}	$\gamma\chi_{b0}(2P)$	(5.9 ±0.6) %	S=1.4
Γ_{14}	$\gamma\chi_{b0}(1P)$	(3.0 ±1.1) × 10^{-3}	
Γ_{15}	$\gamma\eta_b(2S)$	< 6.2 × 10^{-4}	CL=90%
Γ_{16}	$\gamma\eta_b(1S)$	< 4.3 × 10^{-4}	CL=90%
Γ_{17}	$\gamma X \to \gamma + \geq 4$ prongs	[a] < 2.2 × 10^{-4}	CL=95%

[a] 1.5 GeV < m_X < 5.0 GeV

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Citation: C. Amsler *et al.* (Particle Data Group), PL B667, 1 (2008) (URL: http://pdg.lbl.gov)

$\Upsilon(2S)$

$I^G(J^{PC}) = 0^-(1^{--})$

$\Upsilon(2S)$ MASS

VALUE (GeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
10.02326±0.00031 OUR AVERAGE			
10.0235 ±0.0005	[1] ARTAMONOV 00	MD1	$e^+e^- \to$ hadrons
10.0231 ±0.0004	BARBER 84	REDE	$e^+e^- \to$ hadrons
• • • We do not use the following data for averages, fits, limits, etc. • • •			
10.0236 ±0.0005	[2,3] BARU 86B	REDE	$e^+e^- \to$ hadrons

[1] Reanalysis of BARU 86B using new electron mass (COHEN 87).
[2] Reanalysis of ARTAMONOV 84.
[3] Superseded by ARTAMONOV 00.

$\Upsilon(2S)$ WIDTH

VALUE (keV)	*DOCUMENT ID*
31.98±2.63 OUR EVALUATION	See the Note on "Width Determinations of the Υ States"

$\Upsilon(2S)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	$\Upsilon(1S)\pi^+\pi^-$	(18.8 ± 0.6) %	
Γ_2	$\Upsilon(1S)\pi^0\pi^0$	(9.0 ± 0.8) %	
Γ_3	$\tau^+\tau^-$	(2.00± 0.21) %	
Γ_4	$\mu^+\mu^-$	(1.93± 0.17) %	S=2.2
Γ_5	e^+e^-	(1.91± 0.16) %	
Γ_6	$\Upsilon(1S)\pi^0$	< 1.1 × 10^{-3}	CL=90%
Γ_7	$\Upsilon(1S)\eta$	< 2 × 10^{-3}	CL=90%
Γ_8	$J/\psi(1S)$ anything	< 6 × 10^{-3}	CL=90%
Γ_9	$\overline{d}$ anything	(3.4 ± 0.6) × 10^{-5}	
Γ_{10}	hadrons	(94 ±11) %	
	Radiative decays		
Γ_{11}	$\gamma\chi_{b1}(1P)$	(6.9 ± 0.4) %	
Γ_{12}	$\gamma\chi_{b2}(1P)$	(7.15± 0.35) %	
Γ_{13}	$\gamma\chi_{b0}(1P)$	(3.8 ± 0.4) %	
Γ_{14}	$\gamma f_0(1710)$	< 5.9 × 10^{-4}	CL=90%
Γ_{15}	$\gamma f'_2(1525)$	< 5.3 × 10^{-4}	CL=90%
Γ_{16}	$\gamma f_2(1270)$	< 2.41 × 10^{-4}	CL=90%
Γ_{17}	$\gamma f_J(2220)$		
Γ_{18}	$\gamma\eta_b(1S)$	< 5.1 × 10^{-4}	CL=90%
Γ_{19}	$\gamma X \to \gamma + \geq 4$ prongs	[a] < 1.95 × 10^{-4}	CL=95%

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The RPP 2006 summary tables for the Upsilon states below $B\overline{B}$ threshold take up 4 pages – less than 50% of the allowed decays are known

Citation: C. Amsler *et al.* (Particle Data Group), PL B667, 1 (2008) (URL: http://pdg.lbl.gov)

$\Upsilon(1S)$

$I^G(J^{PC}) = 0^-(1^{--})$

$\Upsilon(1S)$ MASS

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
9460.30±0.26 OUR AVERAGE	Error includes scale factor of 3.3.		
9460.51±0.09±0.05	[1] ARTAMONOV 00	MD1	$e^+e^- \to$ hadrons
9459.97±0.11±0.07	MACKAY 84	REDE	$e^+e^- \to$ hadrons
• • • We do not use the following data for averages, fits, limits, etc. • • •			
9460.60±0.09±0.05	[2,3] BARU 92B	REDE	$e^+e^- \to$ hadrons
9460.59±0.12	BARU 86	REDE	$e^+e^- \to$ hadrons
9460.6 ±0.4	[3,4] ARTAMONOV 84	REDE	$e^+e^- \to$ hadrons

[1] Reanalysis of BARU 92B and ARTAMONOV 84 using new electron mass (COHEN 87).
[2] Superseding BARU 86.
[3] Superseded by ARTAMONOV 00.
[4] Value includes data of ARTAMONOV 82.

$\Upsilon(1S)$ WIDTH

VALUE (keV)	*DOCUMENT ID*
54.02±1.25 OUR EVALUATION	See the Note on "Width Determinations of the Υ States"

$\Upsilon(1S)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\tau^+\tau^-$	(2.60±0.10) %	
Γ_2	e^+e^-	(2.38±0.11) %	
Γ_3	$\mu^+\mu^-$	(2.48±0.05) %	
	Hadronic decays		
Γ_4	$\eta'(958)$ anything	(2.94±0.24) %	
Γ_5	$J/\psi(1S)$ anything	(6.5 ±0.7) × 10^{-4}	
Γ_6	χ_{c0} anything	< 5 × 10^{-3}	90%
Γ_7	χ_{c1} anything	(2.3 ±0.7) × 10^{-4}	
Γ_8	χ_{c2} anything	(3.4 ±1.0) × 10^{-4}	
Γ_9	$\psi(2S)$ anything	(2.7 ±0.9) × 10^{-4}	
Γ_{10}	$\rho\pi$	< 2 × 10^{-4}	90%
Γ_{11}	$\pi^+\pi^-$	< 5 × 10^{-4}	90%
Γ_{12}	K^+K^-	< 5 × 10^{-4}	90%
Γ_{13}	$p\overline{p}$	< 5 × 10^{-4}	90%
Γ_{14}	$\pi^0\pi^+\pi^-$	< 1.84 × 10^{-5}	90%
Γ_{15}	$D^*(2010)^{\pm}$ anything		
Γ_{16}	$\overline{d}$ anything	(2.86±0.28) × 10^{-5}	

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Citation: C. Amsler *et al.* (Particle Data Group), PL B667, 1 (2008) (URL: http://pdg.lbl.gov)

	Mode	Fraction (Γ_i/Γ)	Confidence level
	Radiative decays		
Γ_{17}	$\gamma\pi^+\pi^-$	(6.3 ±1.8) × 10^{-5}	
Γ_{18}	$\gamma\pi^0\pi^0$	(1.7 ±0.7) × 10^{-5}	
Γ_{19}	$\gamma\pi^0\eta$	< 2.4 × 10^{-6}	90%
Γ_{20}	K^+K^- with $2 < m_{K^+K^-} < 3$ GeV	(1.14±0.13) × 10^{-5}	
Γ_{21}	$\gamma p\overline{p}$ with $2 < m_{p\overline{p}} < 3$ GeV	< 6 × 10^{-6}	90%
Γ_{22}	$\gamma 2h^+2h^-$	(7.0 ±1.5) × 10^{-4}	
Γ_{23}	$\gamma 3h^+3h^-$	(5.4 ±2.0) × 10^{-4}	
Γ_{24}	$\gamma 4h^+4h^-$	(7.4 ±3.5) × 10^{-4}	
Γ_{25}	$\gamma\pi^+\pi^-K^+K^-$	(2.9 ±0.9) × 10^{-4}	
Γ_{26}	$\gamma 2\pi^+2\pi^-$	(2.5 ±0.9) × 10^{-4}	
Γ_{27}	$\gamma 3\pi^+3\pi^-$	(2.5 ±1.2) × 10^{-4}	
Γ_{28}	$\gamma 2\pi^+2\pi^-K^+K^-$	(2.4 ±1.2) × 10^{-4}	
Γ_{29}	$\gamma\pi^+\pi^-p\overline{p}$	(1.5 ±0.6) × 10^{-4}	
Γ_{30}	$\gamma 2\pi^+2\pi^-p\overline{p}$	(4 ±6) × 10^{-5}	
Γ_{31}	$\gamma 2K^+2K^-$	(2.0 ±2.0) × 10^{-5}	
Γ_{32}	$\gamma\eta'(958)$	< 1.9 × 10^{-6}	90%
Γ_{33}	$\gamma\eta$	< 1.0 × 10^{-6}	90%
Γ_{34}	$\gamma f_0(980)$	< 3 × 10^{-5}	90%
Γ_{35}	$\gamma f'_2(1525)$	$(3.7\ ^{+1.2}_{-1.1})$ × 10^{-5}	
Γ_{36}	$\gamma f_2(1270)$	(1.01±0.09) × 10^{-4}	
Γ_{37}	$\gamma\eta(1405)$	< 8.2 × 10^{-5}	90%
Γ_{38}	$\gamma f_0(1500)$	< 1.5 × 10^{-5}	90%
Γ_{39}	$\gamma f_0(1710)$	< 2.6 × 10^{-4}	90%
Γ_{40}	$\gamma f_0(1710) \to \gamma K^+K^-$	< 7 × 10^{-6}	90%
Γ_{41}	$\gamma f_0(1710) \to \gamma\pi^0\pi^0$	< 1.4 × 10^{-6}	90%
Γ_{42}	$\gamma f_0(1710) \to \gamma\eta\eta$	< 1.8 × 10^{-6}	90%
Γ_{43}	$\gamma f_4(2050)$	< 5.3 × 10^{-5}	90%
Γ_{44}	$\gamma f_0(2200) \to \gamma K^+K^-$	< 2 × 10^{-4}	90%
Γ_{45}	$\gamma f_J(2220) \to \gamma K^+K^-$	< 8 × 10^{-7}	90%
Γ_{46}	$\gamma f_J(2220) \to \gamma\pi^+\pi^-$	< 6 × 10^{-7}	90%
Γ_{47}	$\gamma f_J(2220) \to \gamma p\overline{p}$	< 1.1 × 10^{-6}	90%
Γ_{48}	$\gamma\eta(2225) \to \gamma\phi\phi$	< 3 × 10^{-3}	90%
Γ_{49}	γX	[a] < 3 × 10^{-5}	90%
Γ_{50}	$\gamma X\overline{X}$	[b] < 1 × 10^{-3}	90%
Γ_{51}	$\gamma X \to \gamma + \geq 4$ prongs	[c] < 1.78 × 10^{-4}	95%
	Other decays		
Γ_{52}	invisible	< 2.5 × 10^{-3}	90%

[a] X = pseudoscalar with $m < 7.2$ GeV
[b] $X\overline{X}$ = vectors with $m < 3.1$ GeV

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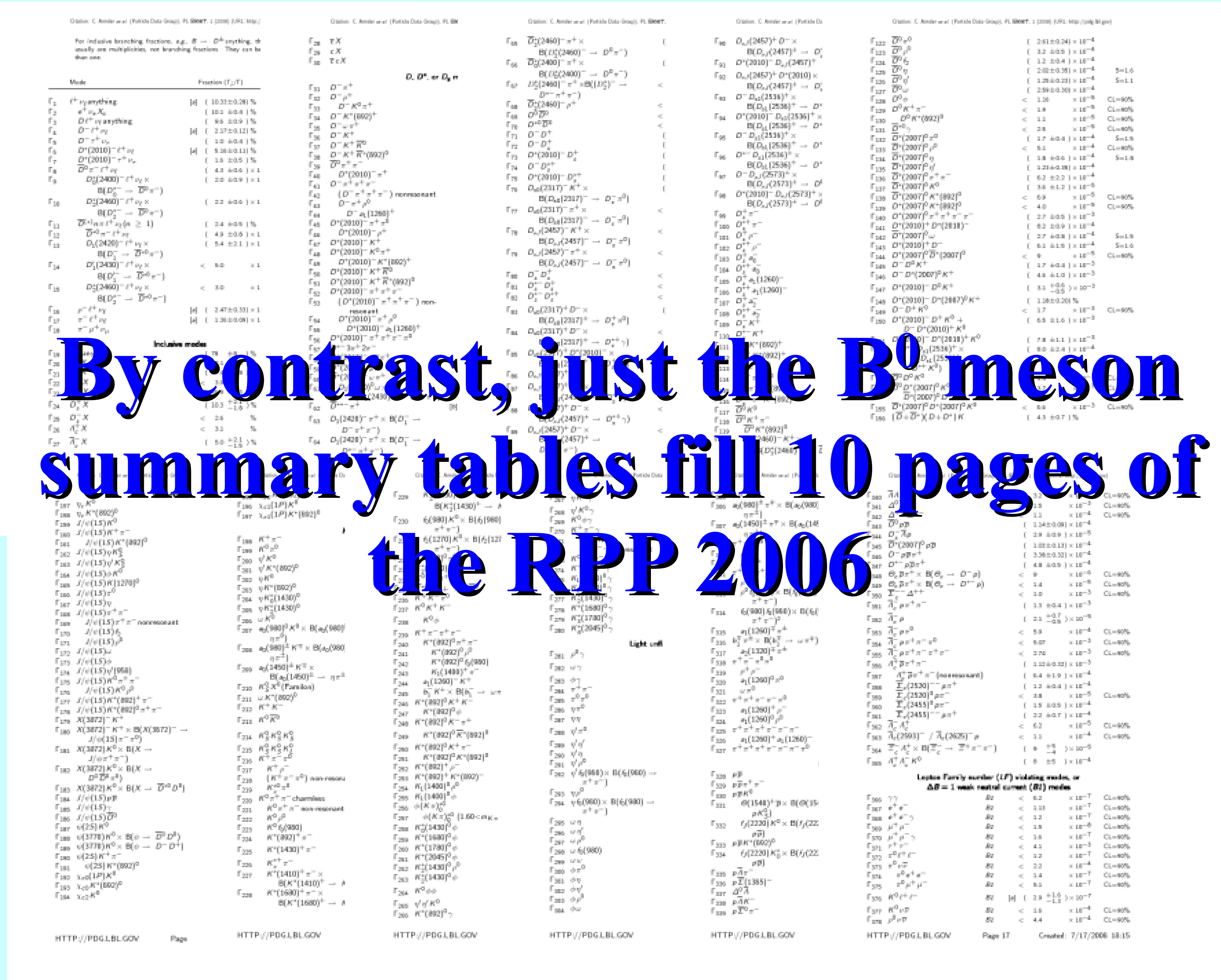


By contrast, just the B^0 meson summary tables fill 10 pages of the RPP 2006

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

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

Babar Home

Higgs Workshop, Monday October 29, 2007

December Collaboration Meeting, 2007

Run Strategy	
17:30-17:40	Upsilon (3S) SM Physics (pdf) (ppt) (video)
17:40-17:50	Upsilon (3S) non-SM Physics (pdf) (ppt) (video)
17:50-18:10	Upsilon (5S) Physics (pdf) (ppt) (video)
18:10-18:25	Off-resonance data (pdf) (ppt) (video)

By mid-December, 2007, there were several competing proposals on the table for taking a few weeks of data, away from the Y(4S), in mid-2008.

After December 17, 2007:

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

Claudia Patrignani, Silvano Tosi

Università di Genova, Dipartimento di Fisica and INFN

Yury G. Kolomensky

Lawrence Berkeley National Laboratory and University of California, Berkeley

Stephen Jacob Sekula

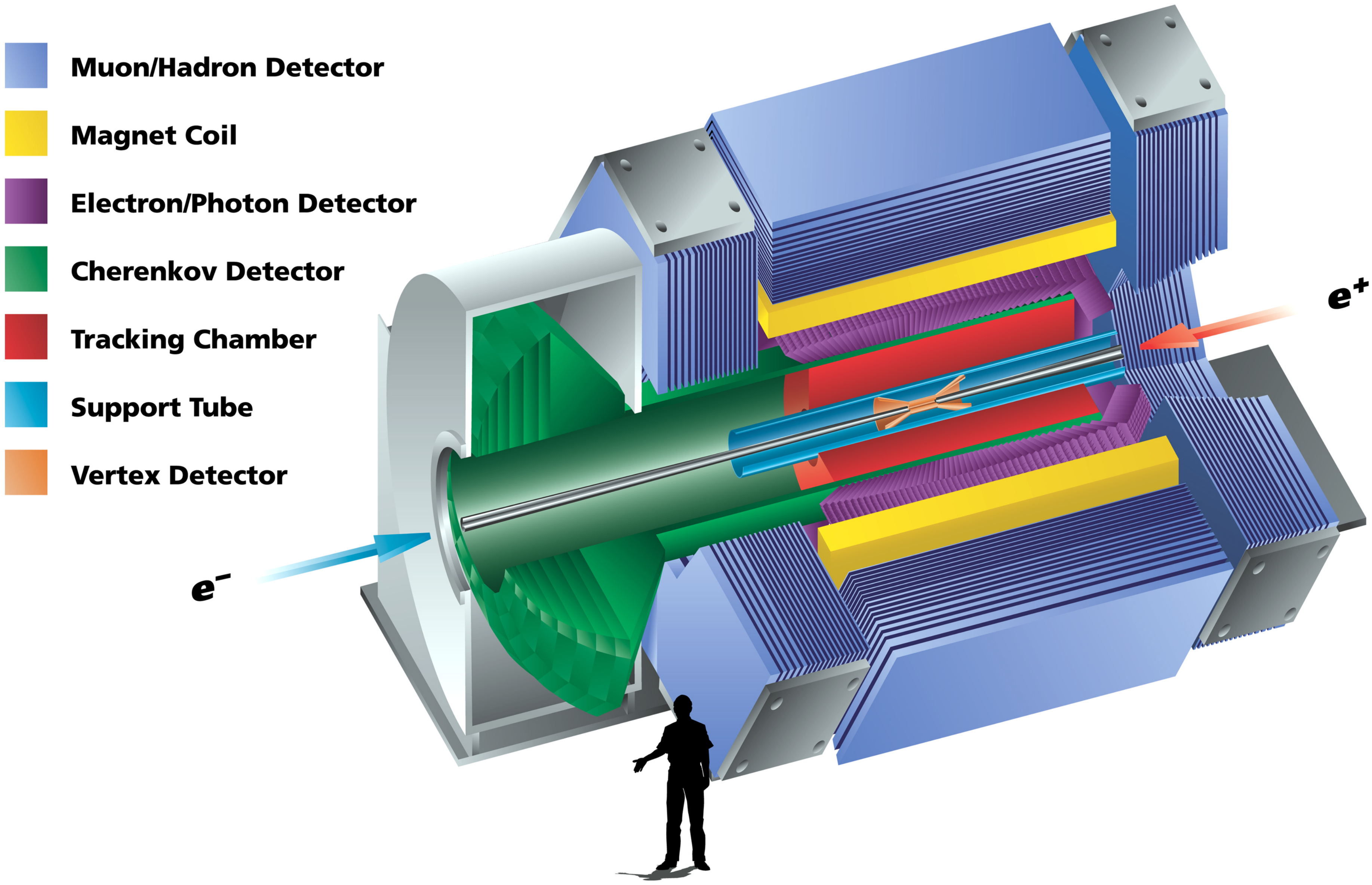
The Ohio State University

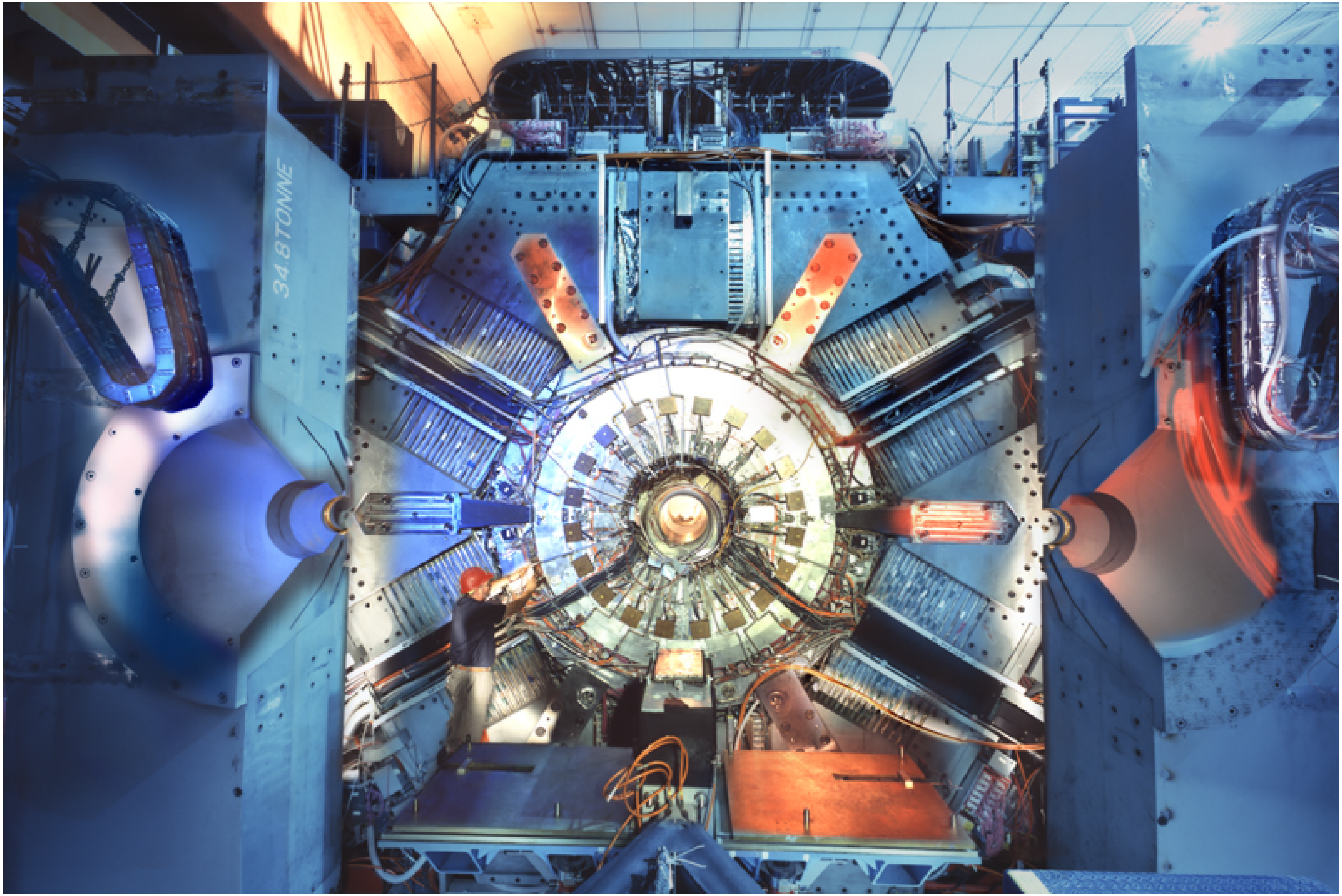
Art Snyder

Stanford Linear Accelerator Center

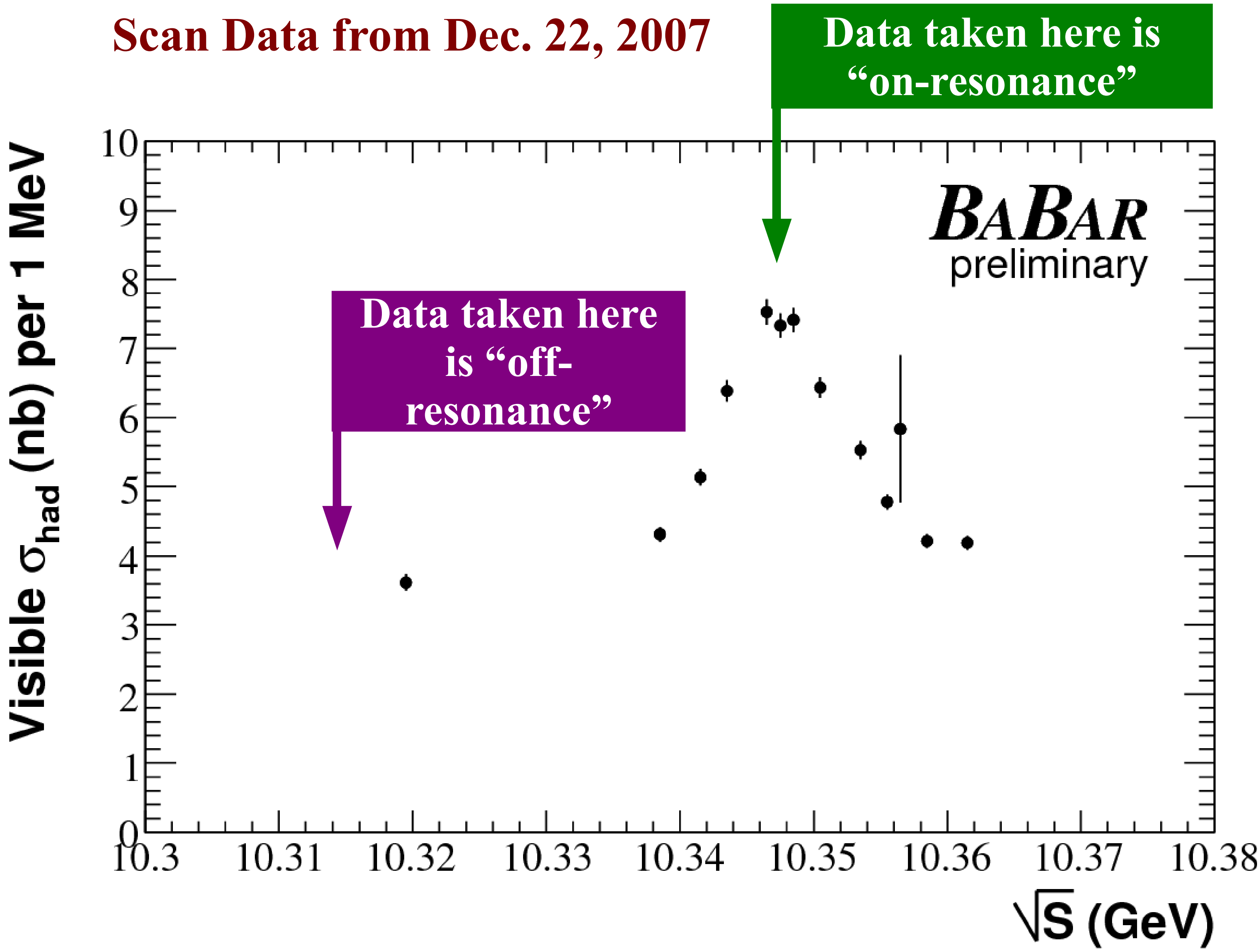
The BaBar/PEP-II b-Factory

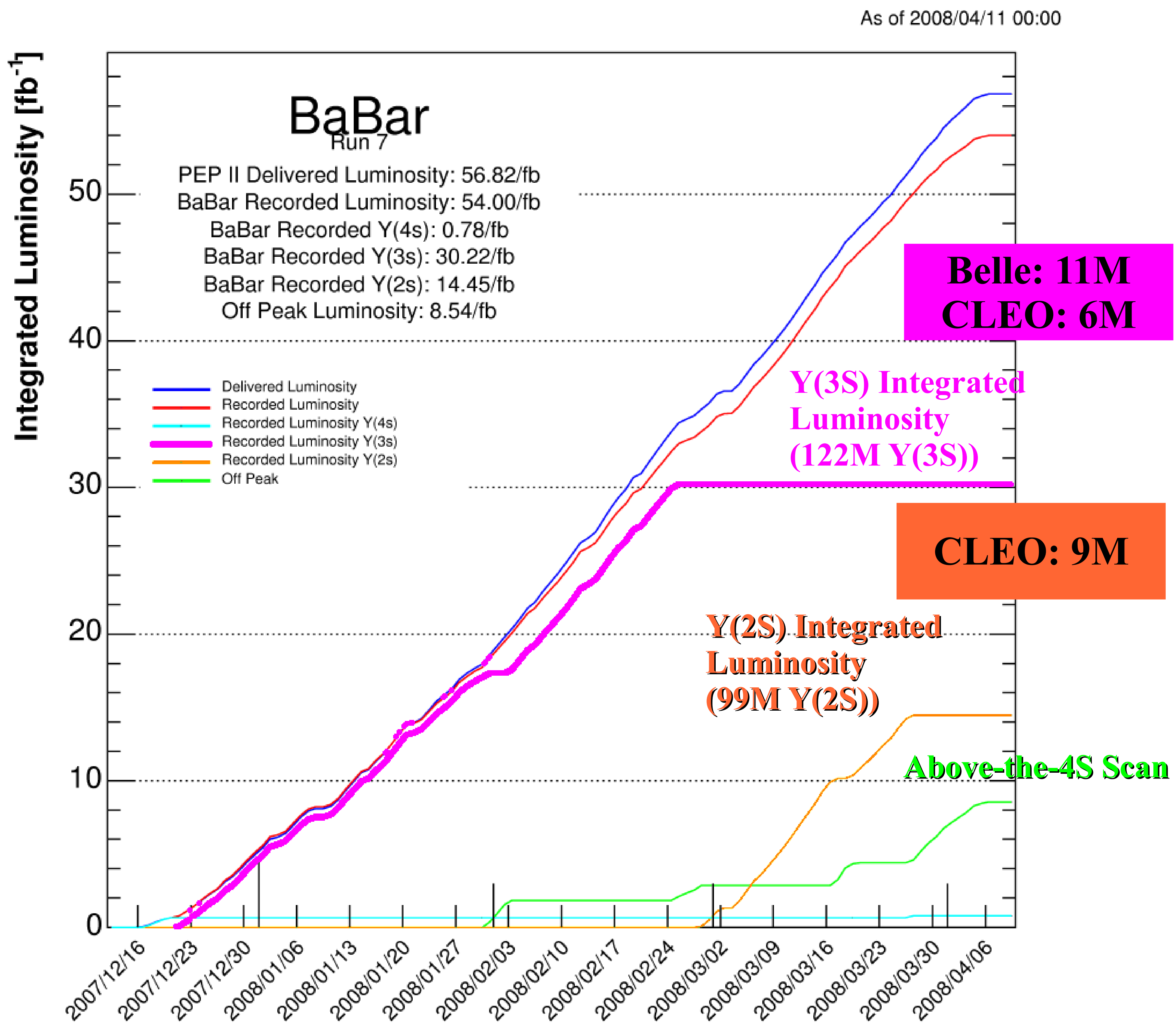
BaBar Detector



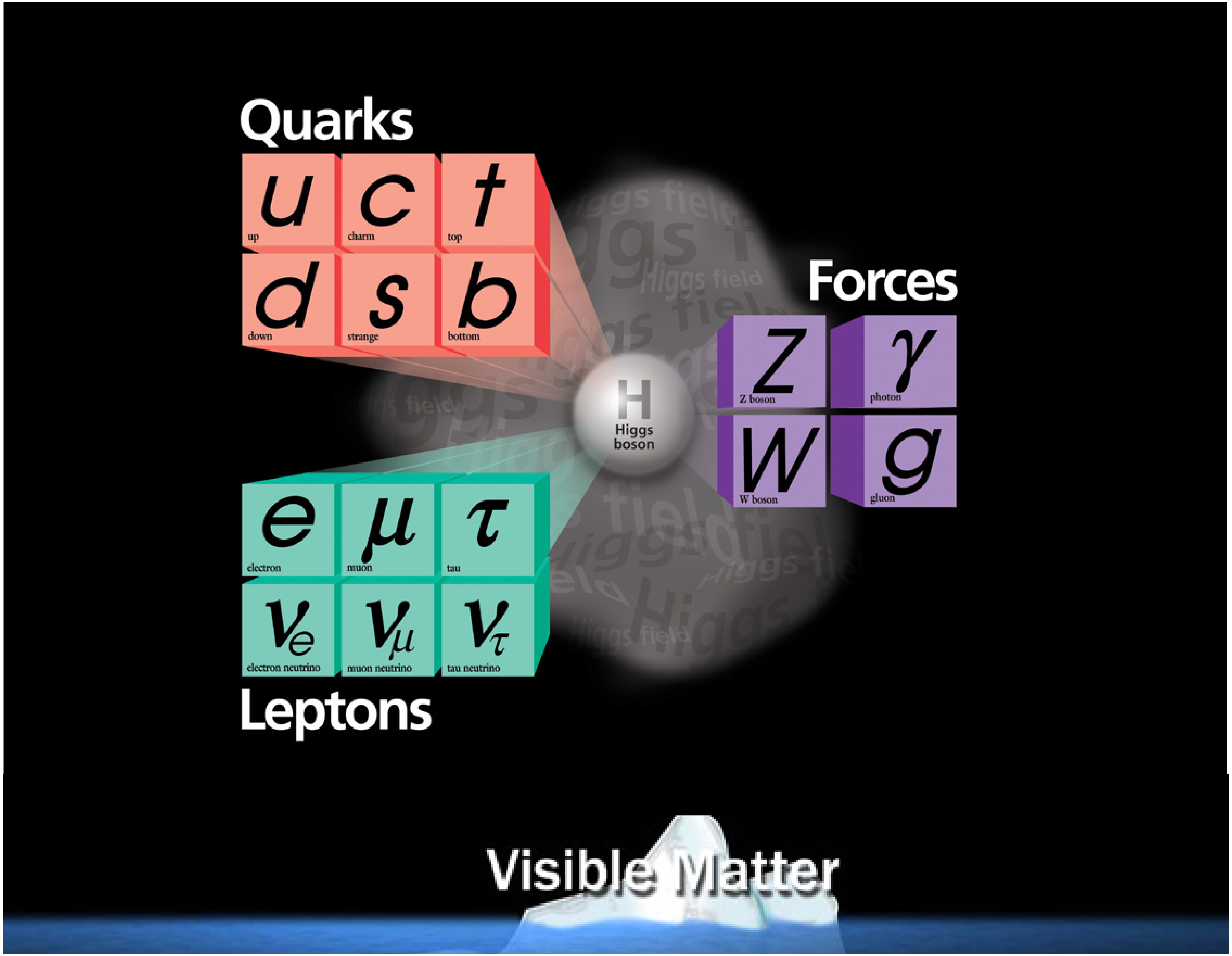

34.8TONNE

Scan Data from Dec. 22, 2007




As of 2008/04/11 00:00
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
Delivered Luminosity
Recorded Luminosity
Recorded Luminosity Y(4s)
Recorded Luminosity Y(3s)
Recorded Luminosity Y(2s)
Off Peak
Integrated Luminosity [fb^-1]
Belle: 11M
CLEO: 6M
Y(3S) Integrated Luminosity (122M Y(3S))
CLEO: 9M
Y(2S) Integrated Luminosity (99M Y(2S))
Above-the-4S Scan
2007/12/16
2007/12/23
2007/12/30
2008/01/06
2008/01/13
2008/01/20
2008/01/27
2008/02/03
2008/02/10
2008/02/17
2008/02/24
2008/03/02
2008/03/09
2008/03/16
2008/03/23
2008/03/30
2008/04/06

A matter of QCD: The search for the η_b

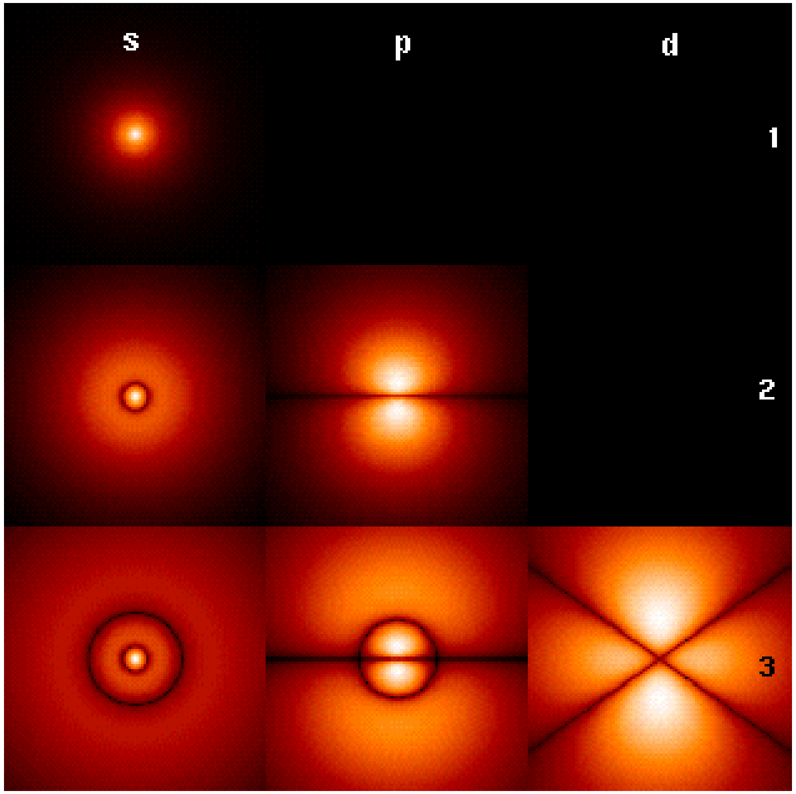

Quarks
u
up
c
charm
t
top
d
down
s
strange
b
bottom
Forces
Z
Z boson
γ
photon
W
W boson
g
gluon
H
Higgs
boson
e
electron
μ
muon
τ
tau
ν_e
electron neutrino
ν_μ
muon neutrino
ν_τ
tau neutrino
Leptons
Visible Matter

Remember your Quantum Mechanics

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

SPIN: ↑↓ , ↓↑ , ↑↑ , ↓↓ → $S_{b\bar{b}} = 0,\ 1$

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



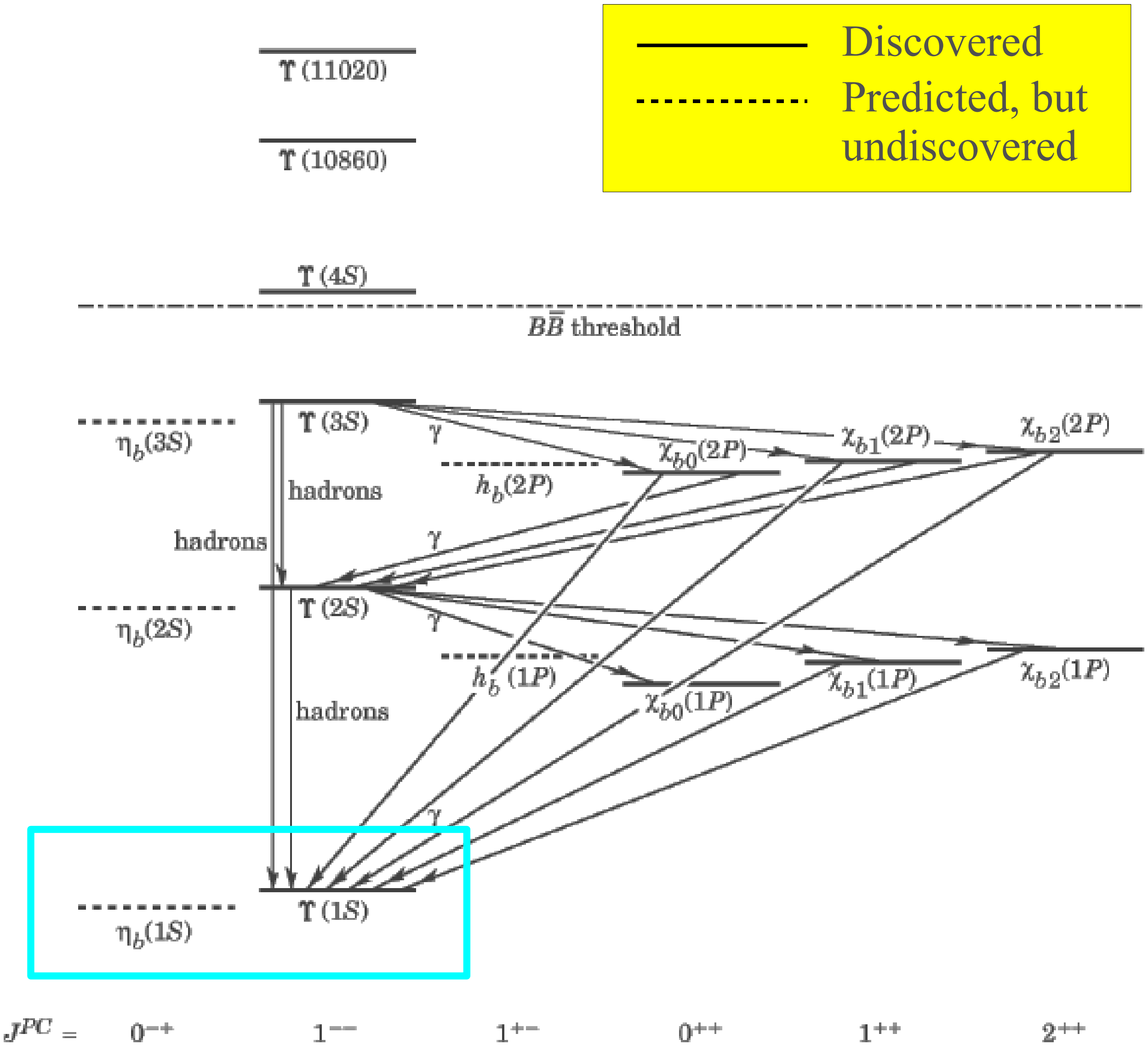
TOTAL ANGULAR MOMENTUM (J):

$$|L-S| < J < L+S$$

THE FIRST FEW STATES:

L	S	J	State
0	0	0	η_b(1S, 2S, ...)
0	1	1	Υ(1S, 2S, ...)
1	0	1	h_b(1P, 2P, ...)
1	1	0,1,2	χ_{bJ}(1P, 2P, ...)

Spectroscopy: Find the bottomonium ground state



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

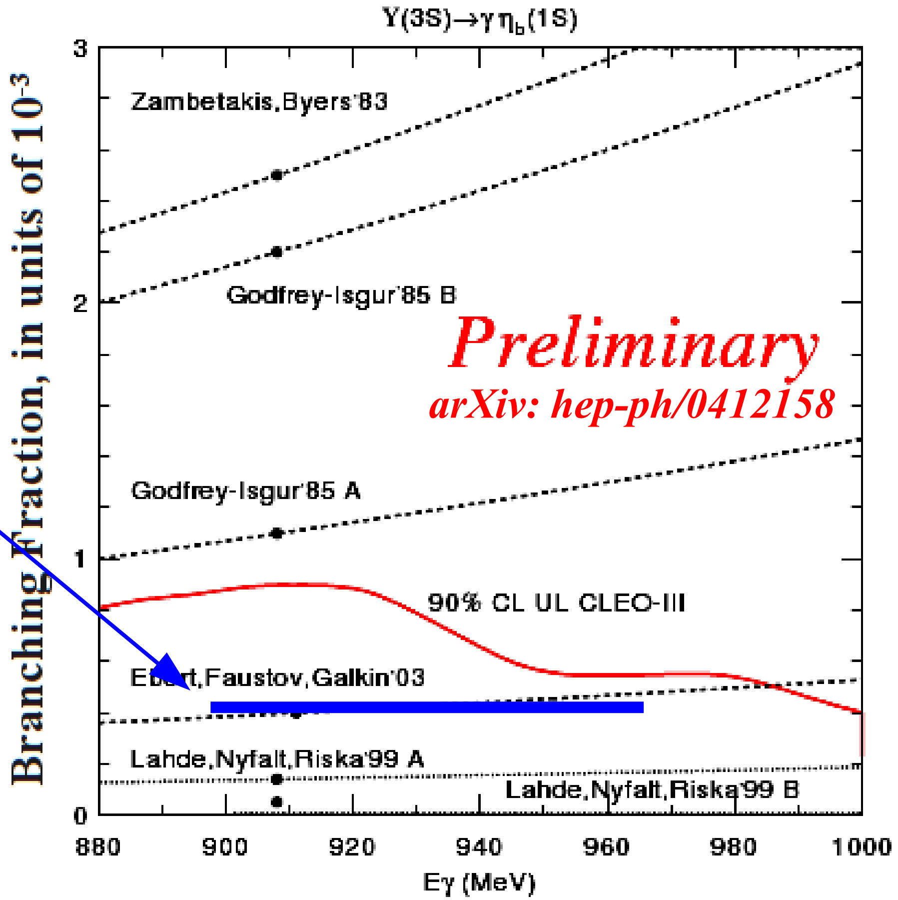
Hyperfine splitting predictions ($1^3S_1 - 1^1S_0$)

- 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?

$$\Upsilon(nS) \to \gamma\,\eta_b$$

Published CLEO limits
PRL 94 032001 (2005)



$$e^+e^- \to e^+e^-\gamma^*\gamma^*(\to \eta_b)$$

Expt	final state	$\Gamma_{\gamma\gamma} \times \mathcal{B}$ (keV)
ALEPH	4 charged	< 0.048
	6 charged	< 0.132
L3	$K^+K^-\pi^0$	< 2.83
	4 charged	< 0.21
	4 charged π^0	< 0.50
	6 charged	< 0.33
	6 charged π^0	< 5.50
	$\pi^+\pi^-\eta'$	< 3.00
DELPHI	4 charged	< 0.093
	6 charged	< 0.270
	8 charged	< 0.780

30 years after the discovery of the Upsilon, the ground state of bottomonium had eluded detection

Analysis Strategy

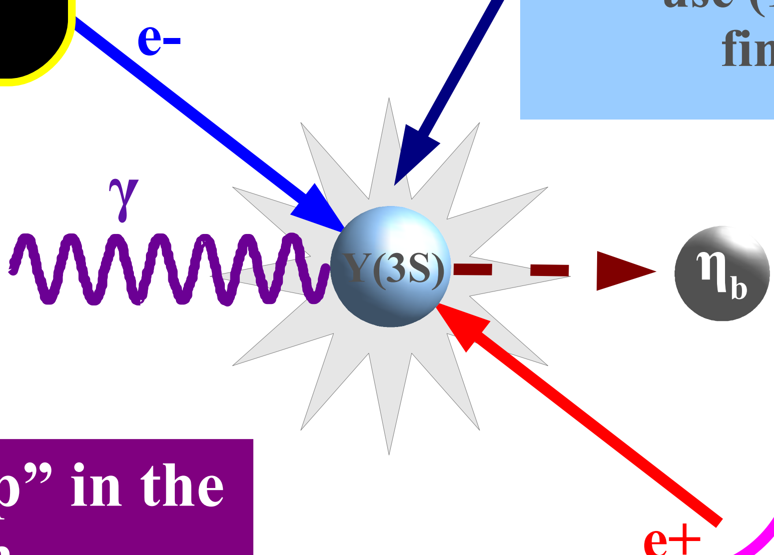
Blind Analysis

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

Full dataset: 122M Υ(3S) mesons

- **use a small sample (9%) for tuning the selection**
- **use $(109 \pm 1)\times 10^6$ Υ(3S) for final result**

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



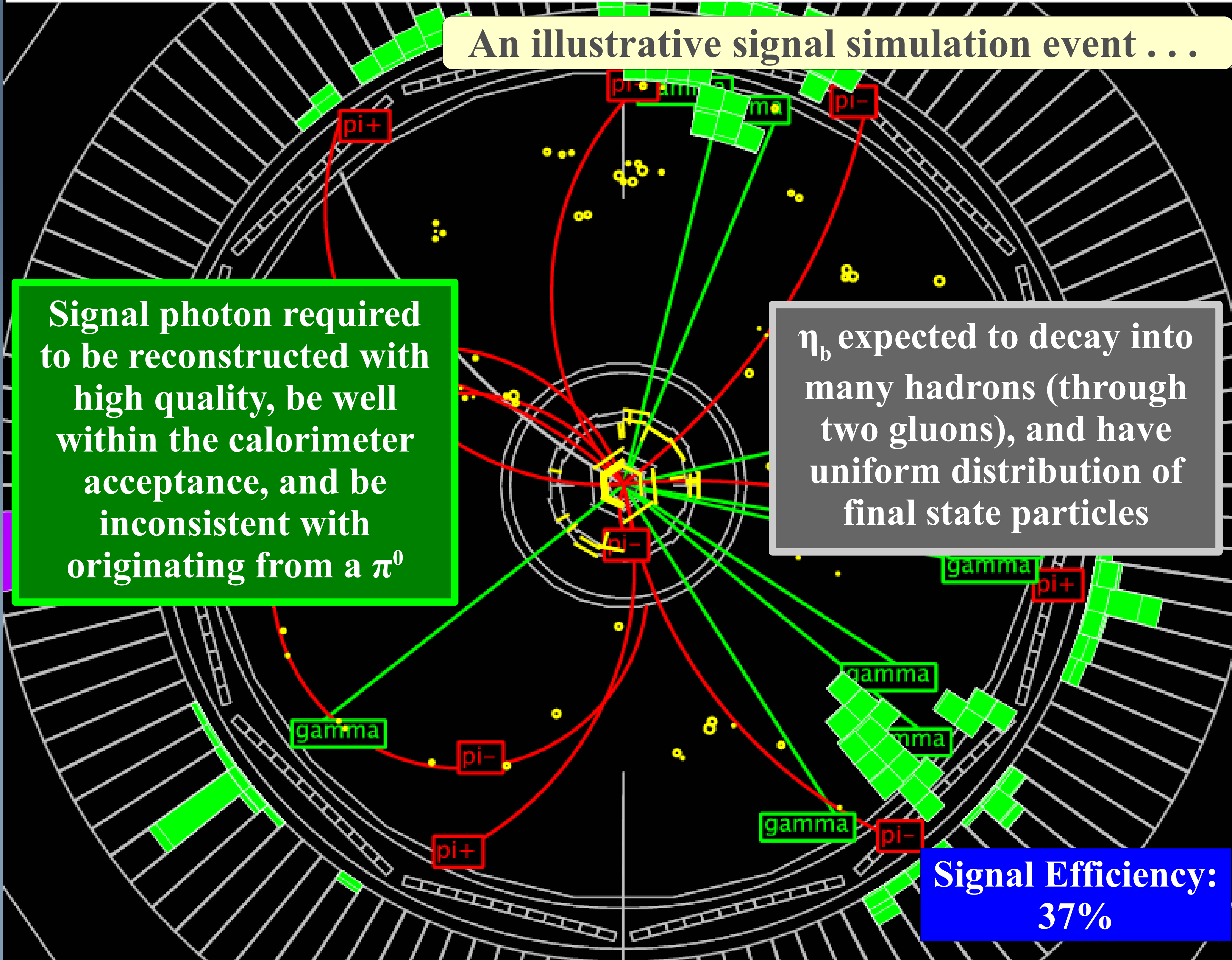
Search for a "bump" in the photon spectrum

- **use maximum likelihood fit, including backgrounds and a possible signal**

Monte Carlo Simulations

- **used for modeling signal and specific backgrounds**
- **tune selection criteria**

An illustrative signal simulation event . . .

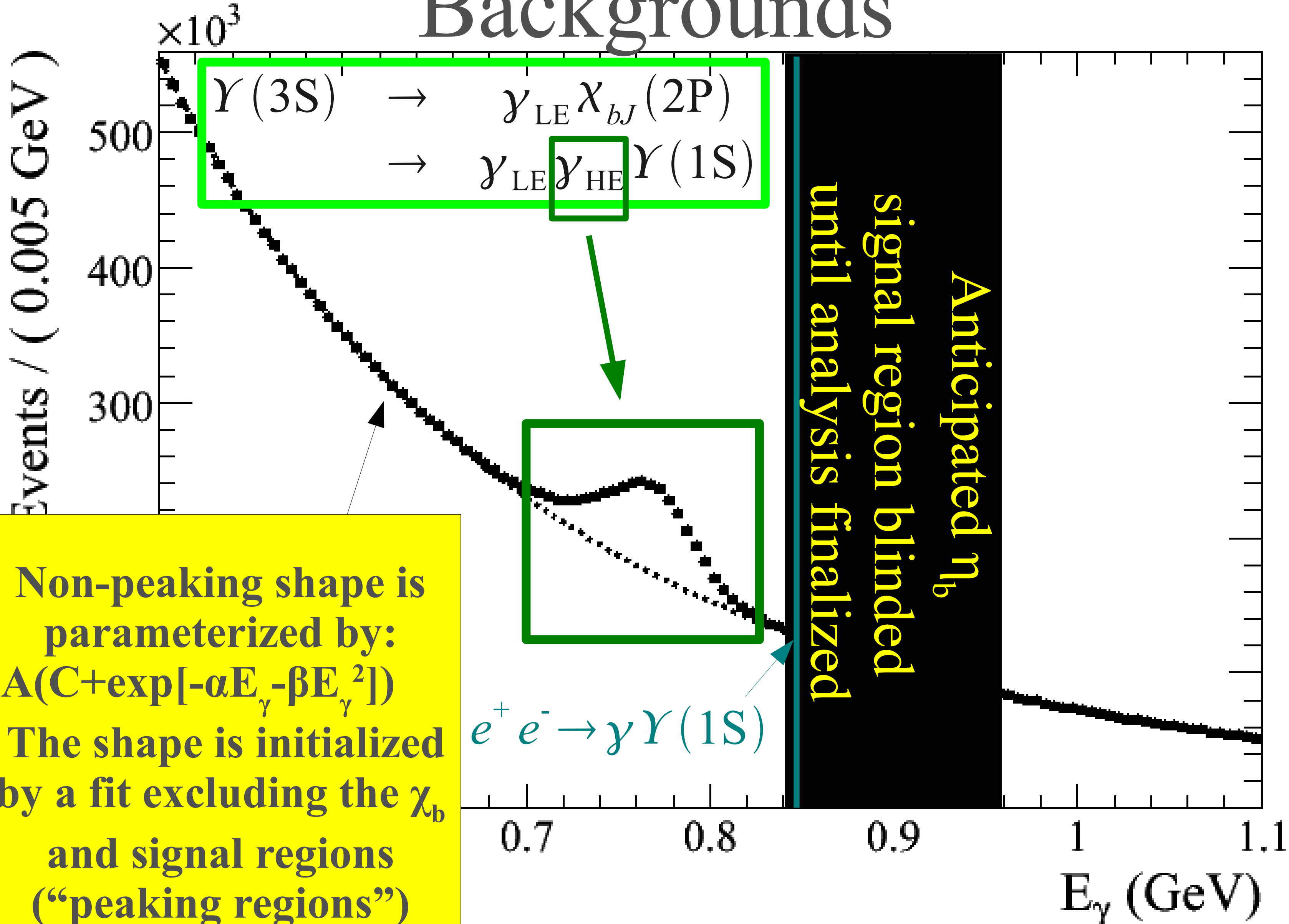


Signal photon required to be reconstructed with high quality, be well within the calorimeter acceptance, and be inconsistent with originating from a π^0

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

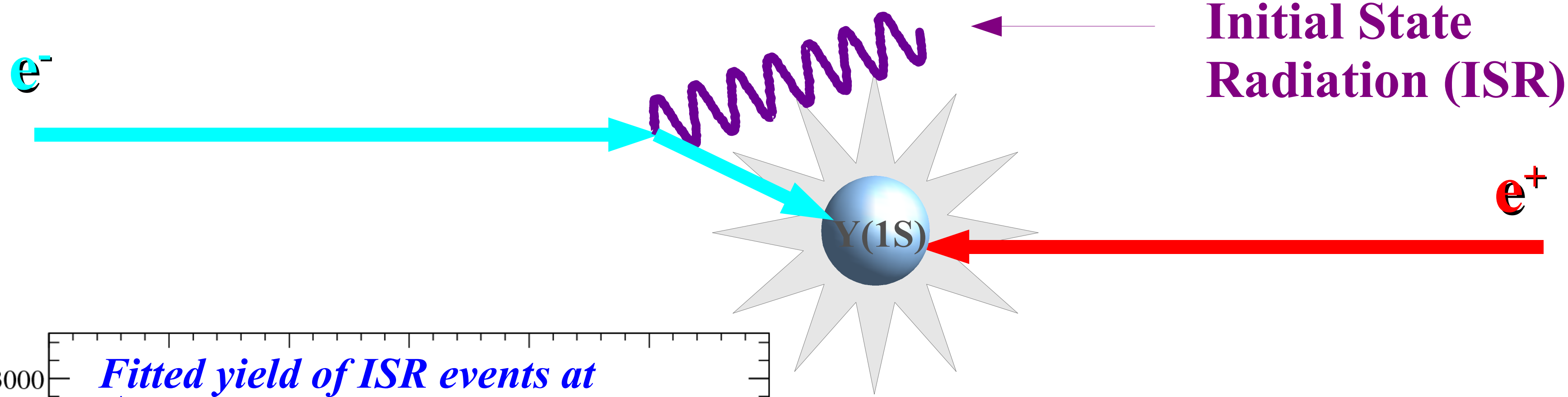
Signal Efficiency: 37%

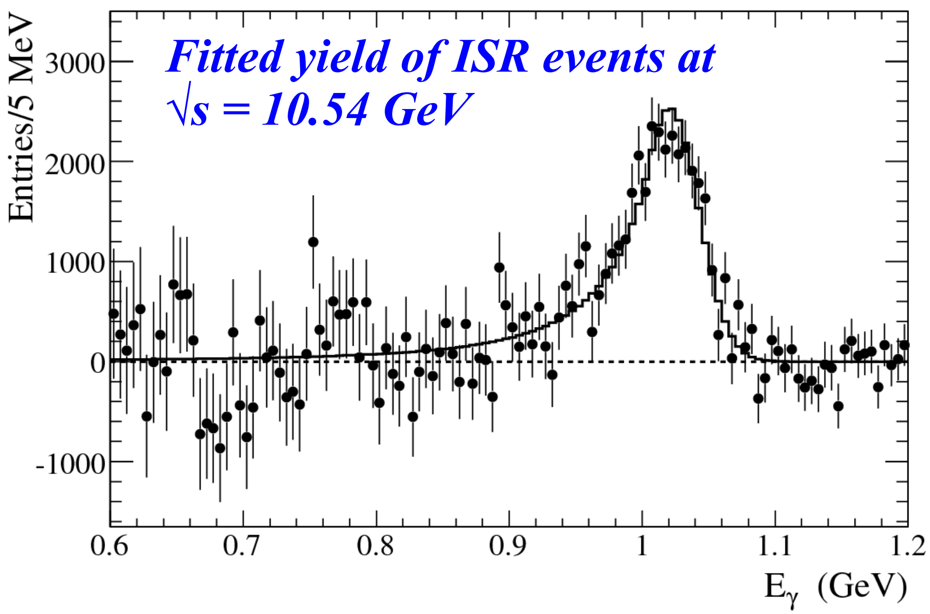
The Single Photon Challenge: Backgrounds



Non-peaking shape is parameterized by:
$A(C+\exp[-\alpha E_\gamma-\beta E_\gamma^2])$
The shape is initialized by a fit excluding the χ_b and signal regions ("peaking regions")

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





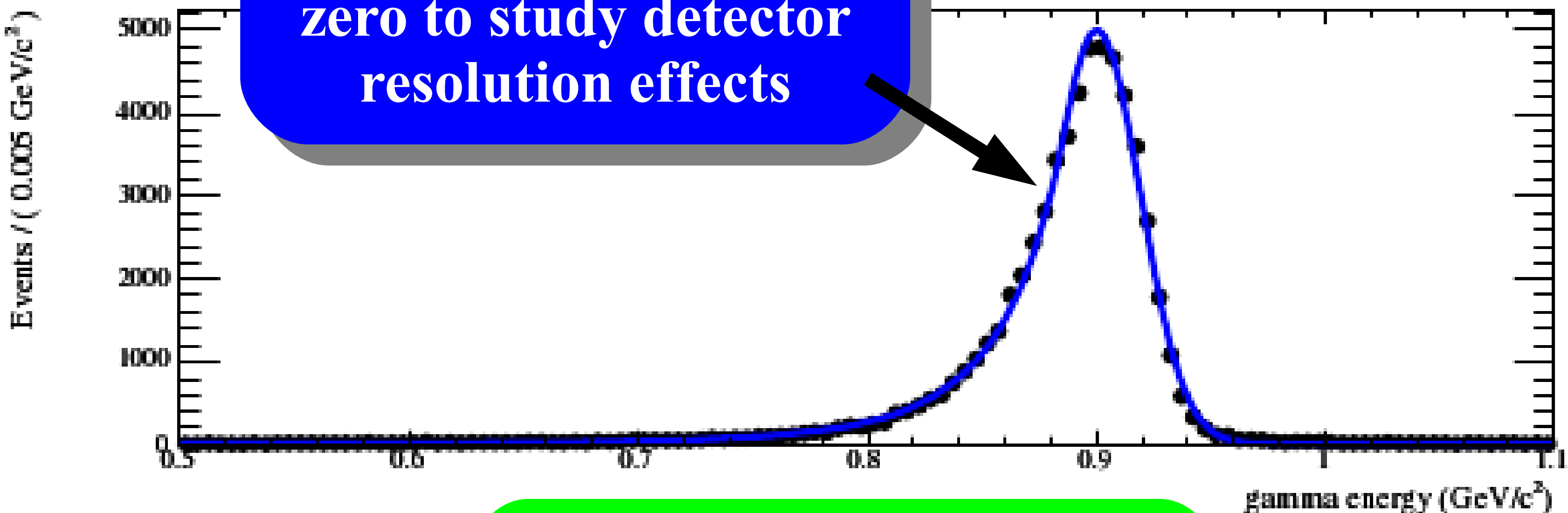
The fitted ISR shape is shifted down to the expected peak position for the Y(3S) CM energy. The yield is scaled using the ratio of cross-sections (computed from theory)

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

$$\sqrt{s} = 10.31\,\text{GeV} \rightarrow \sqrt{s} = 10.3552\,\text{GeV}:\ 29393 \pm 5014$$

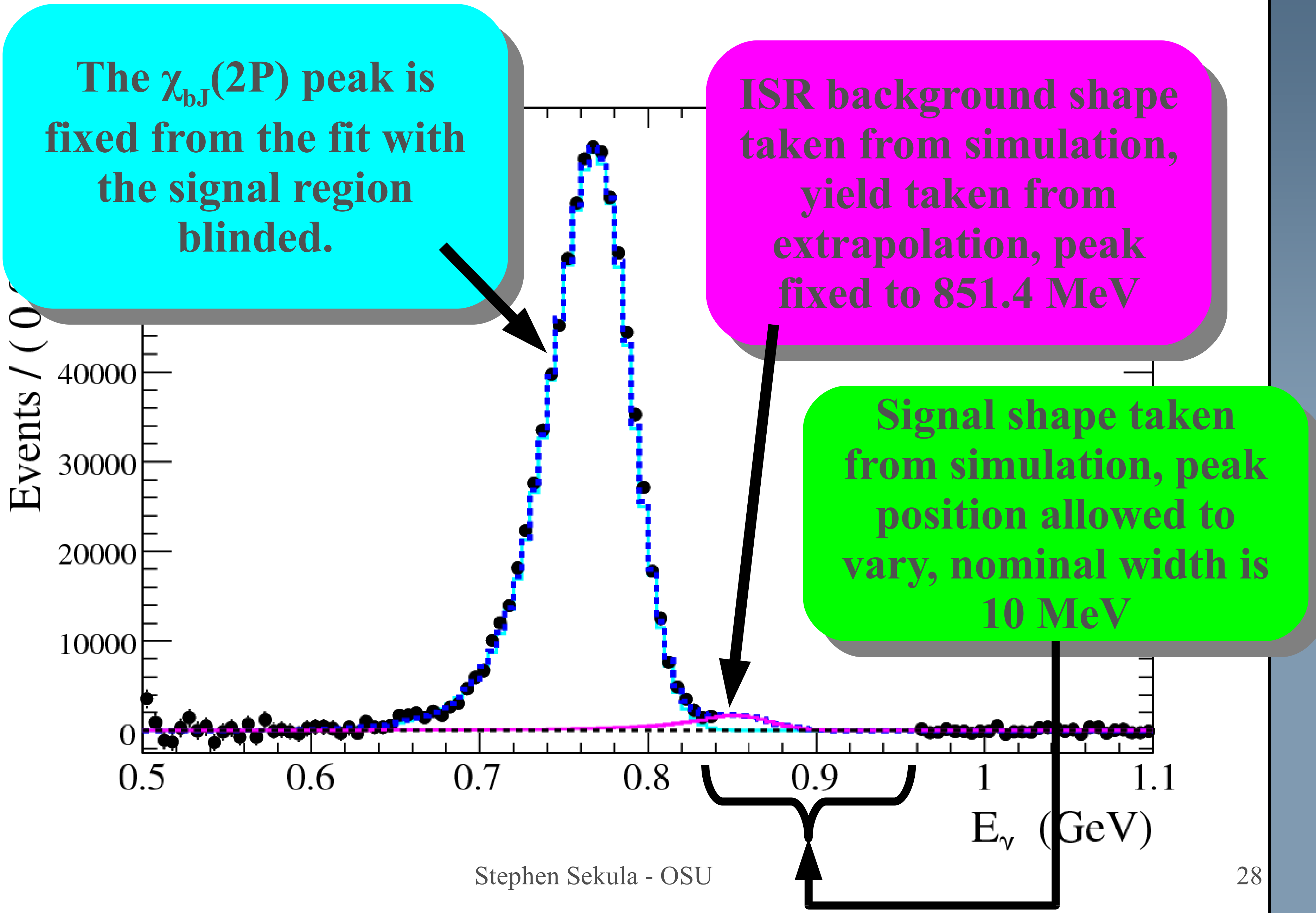
The η_b Signal Model

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

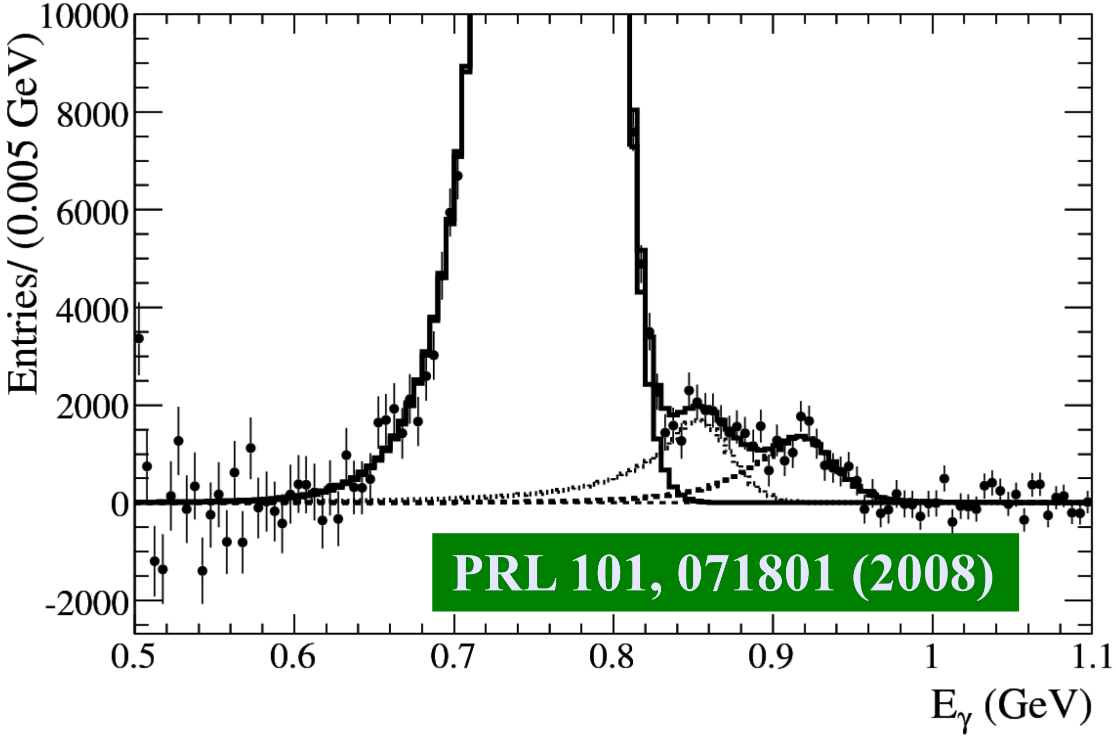


Convolute resolution model with a Breit-Wigner, which represents the resonance

Ingredients in the final fit



Results



Fitted signal yield:

19200 ± 2000 (stat.) ± 2100 (syst.)

Branching Fraction:

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

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

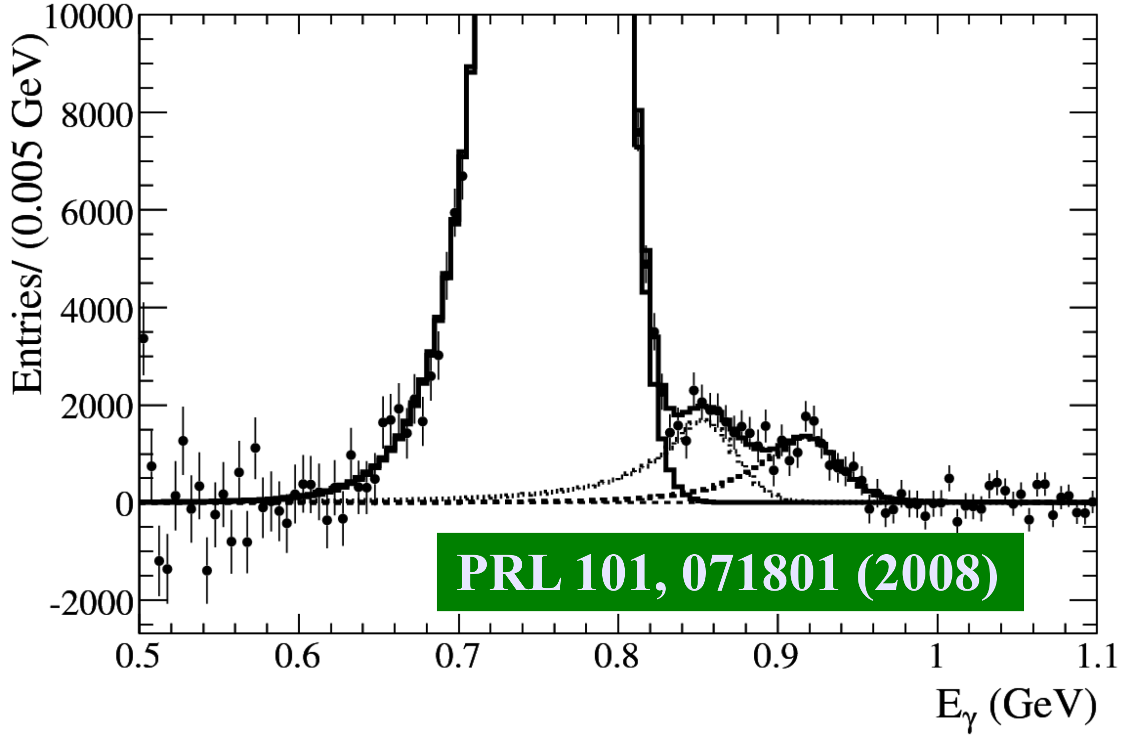
Mass: $9388.9^{+3.1}_{-2.3} \pm 2.7\,\text{MeV}/c^2$

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

Consistent with predictions of the η_b properties

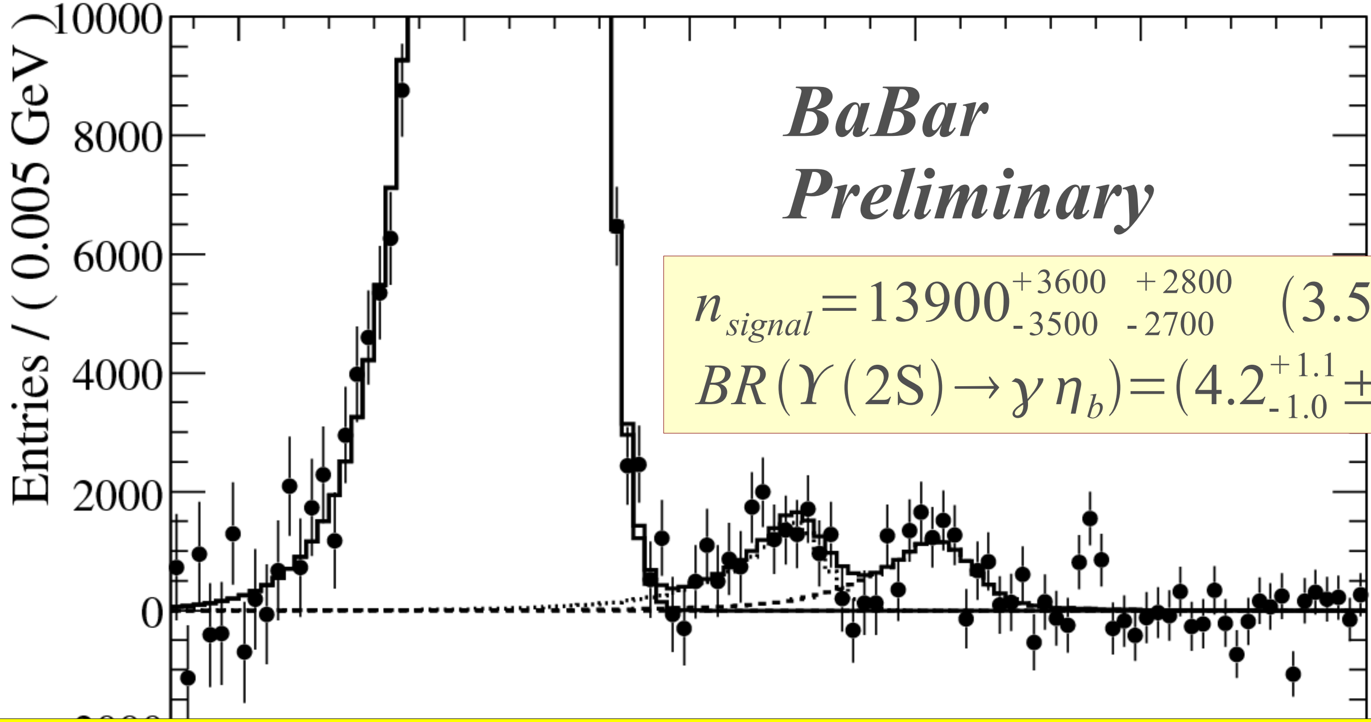
Is this really the ground state?

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



Hot off the Press: Υ(2S) → γ η$_b$

99M Υ(2S) Decays



$$n_{signal} = 13900^{+3600}_{-3500}\ ^{+2800}_{-2700} \quad (3.5\sigma)$$

$$BR(\Upsilon(2S) \to \gamma\,\eta_b) = (4.2^{+1.1}_{-1.0} \pm 0.9) \times 10^{-4}$$

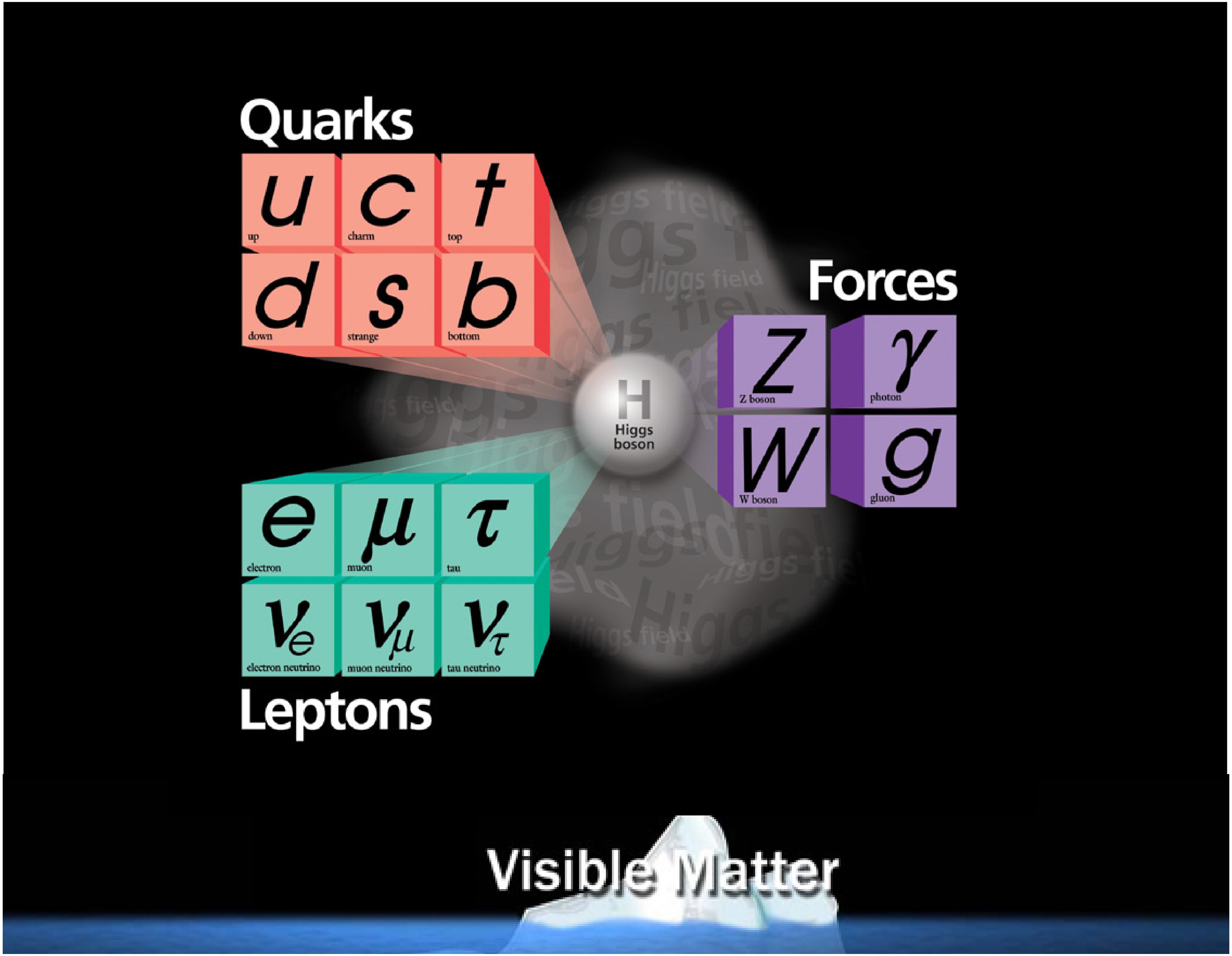
Fitted Mean: $E_\gamma = 610.5^{+4.5}_{-4.3} \pm 1.8\,\mathrm{MeV}$

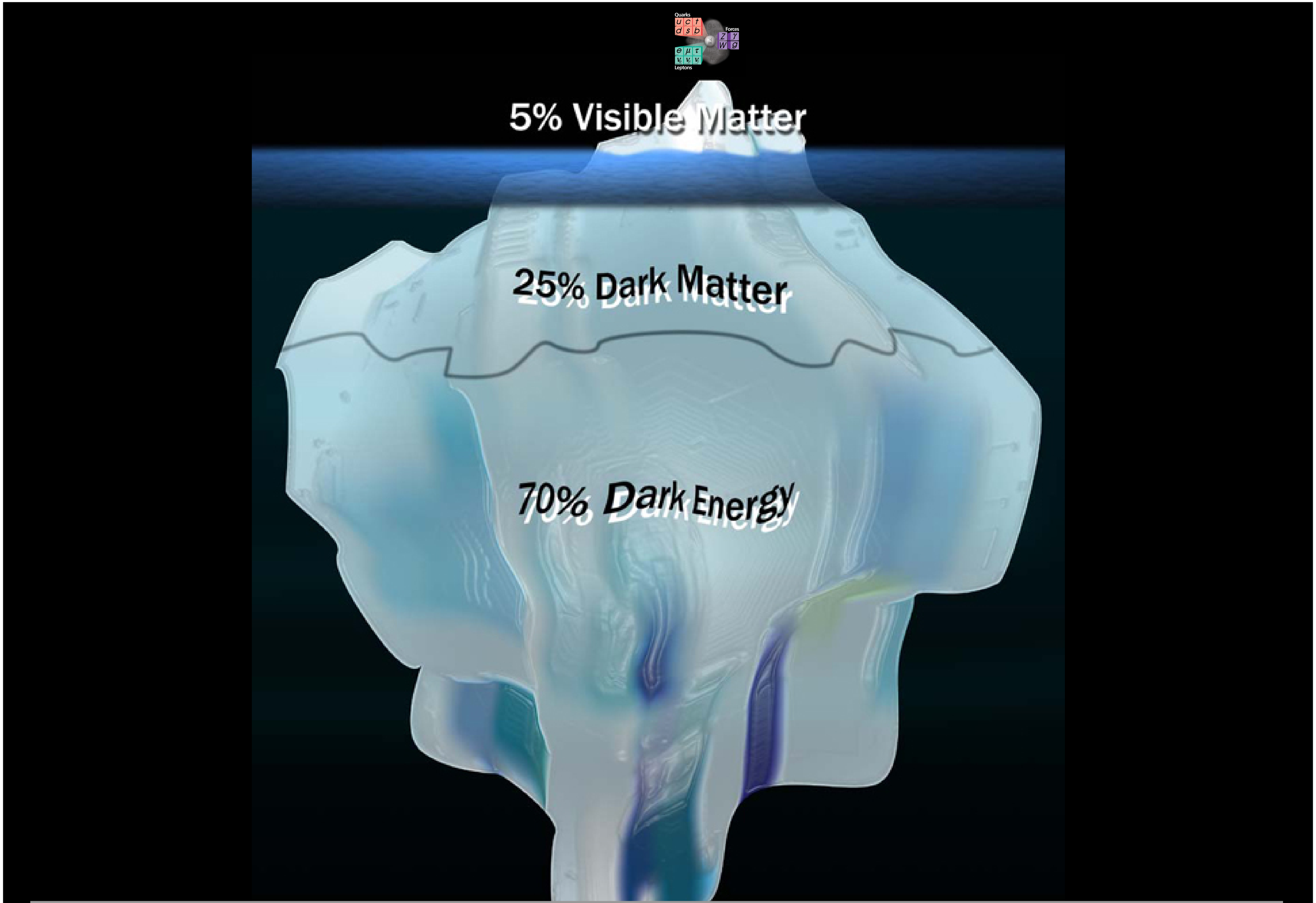
Mass: $9392.9^{+4.6}_{-4.8} \pm 1.8\,\mathrm{MeV}/c^2$

Hyperfine Splitting: $67.4^{+4.8}_{-4.6} \pm 1.9\,\mathrm{MeV}/c^2$

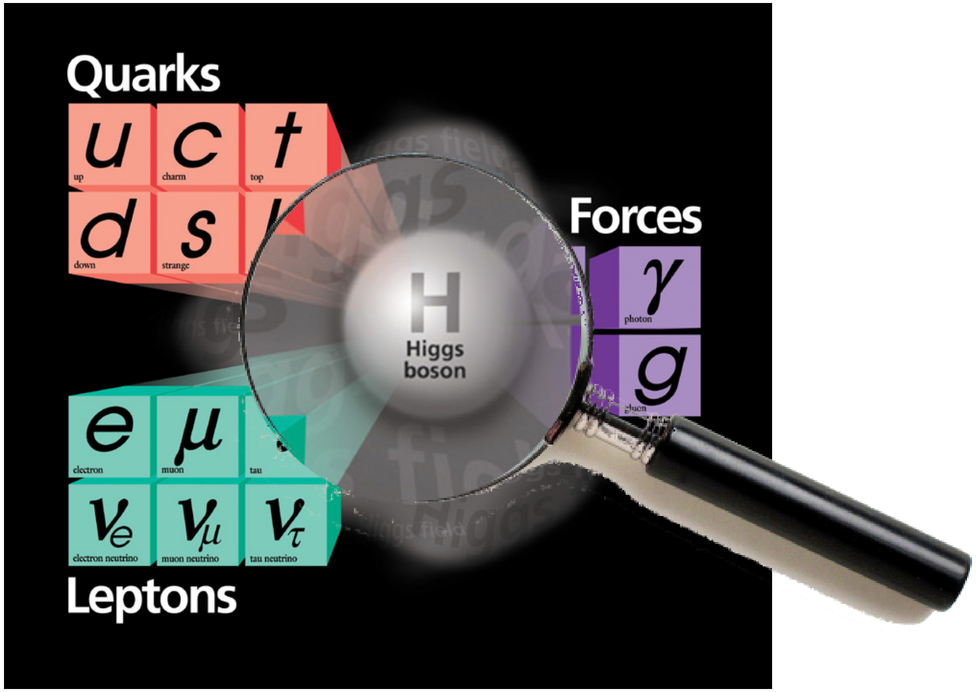
Consistent with the Υ(3S)-based measurement!

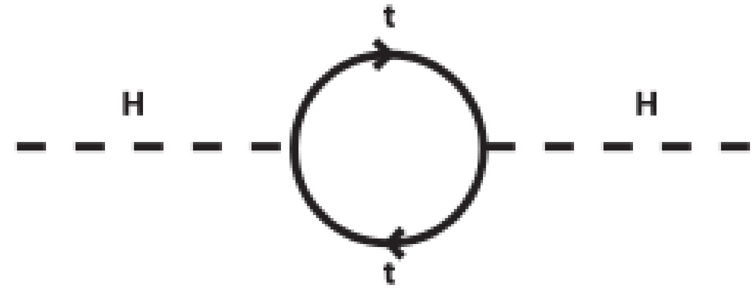
A Matter of New Physics: Search for a Light CP-Odd Higgs


Quarks
u
up
c
charm
t
top
d
down
s
strange
b
bottom
Forces
Z
Z boson
γ
photon
W
W boson
g
gluon
H
Higgs boson
e
electron
μ
muon
τ
tau
ν_e
electron neutrino
ν_μ
muon neutrino
ν_τ
tau neutrino
Leptons
Visible Matter

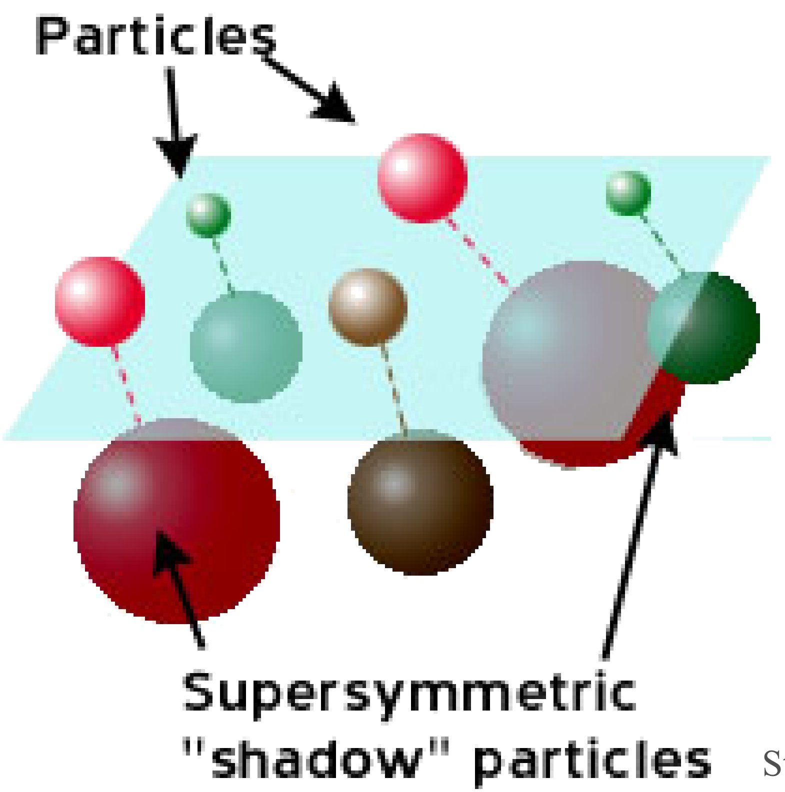


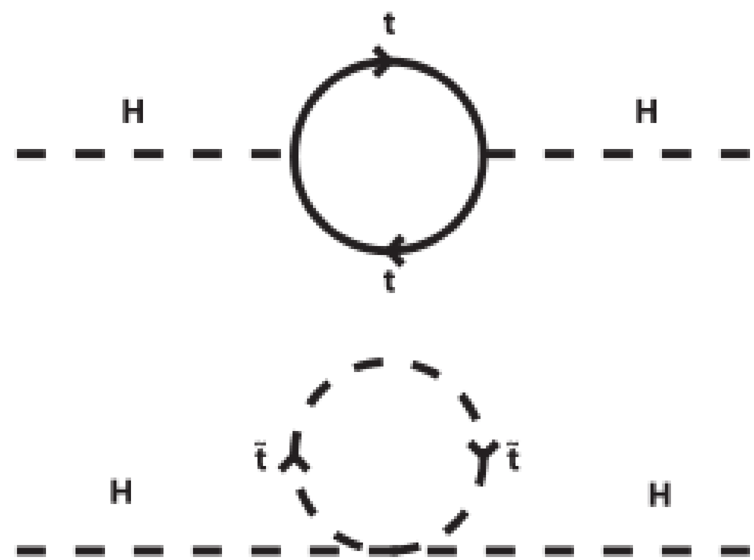
Can we solve the dark matter puzzle and illuminate the Higgs sector at the same time?





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



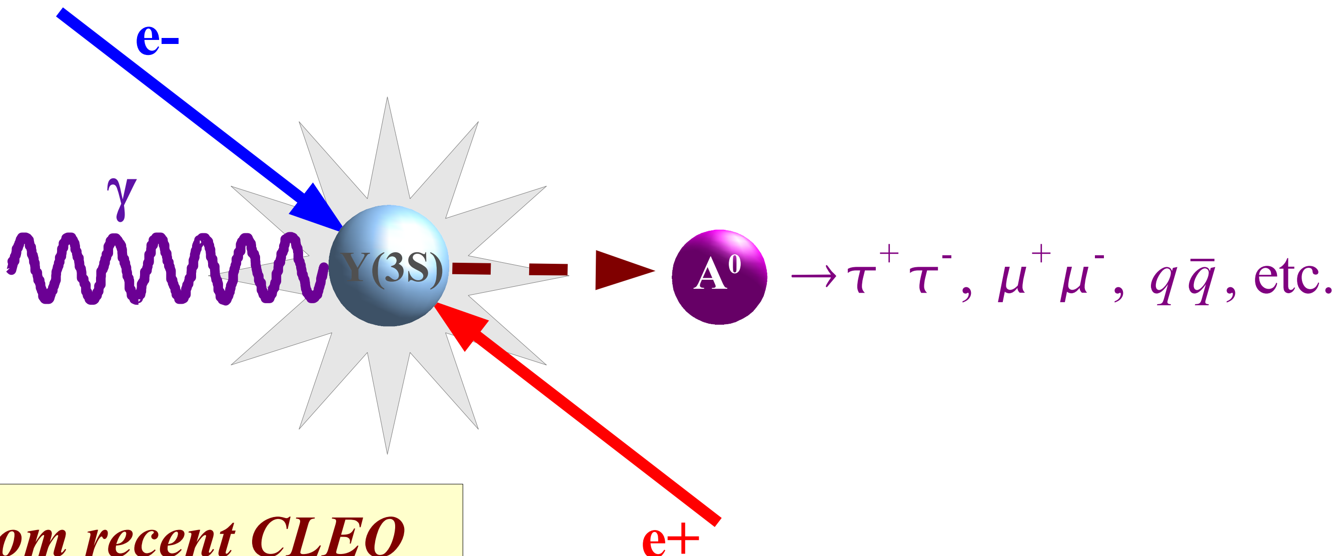


Loops involving superpartners cancel divergences!

New Physics: A Light Higgs Boson

Predicted rate of this process:
~10^{-4} – 10^{-7}

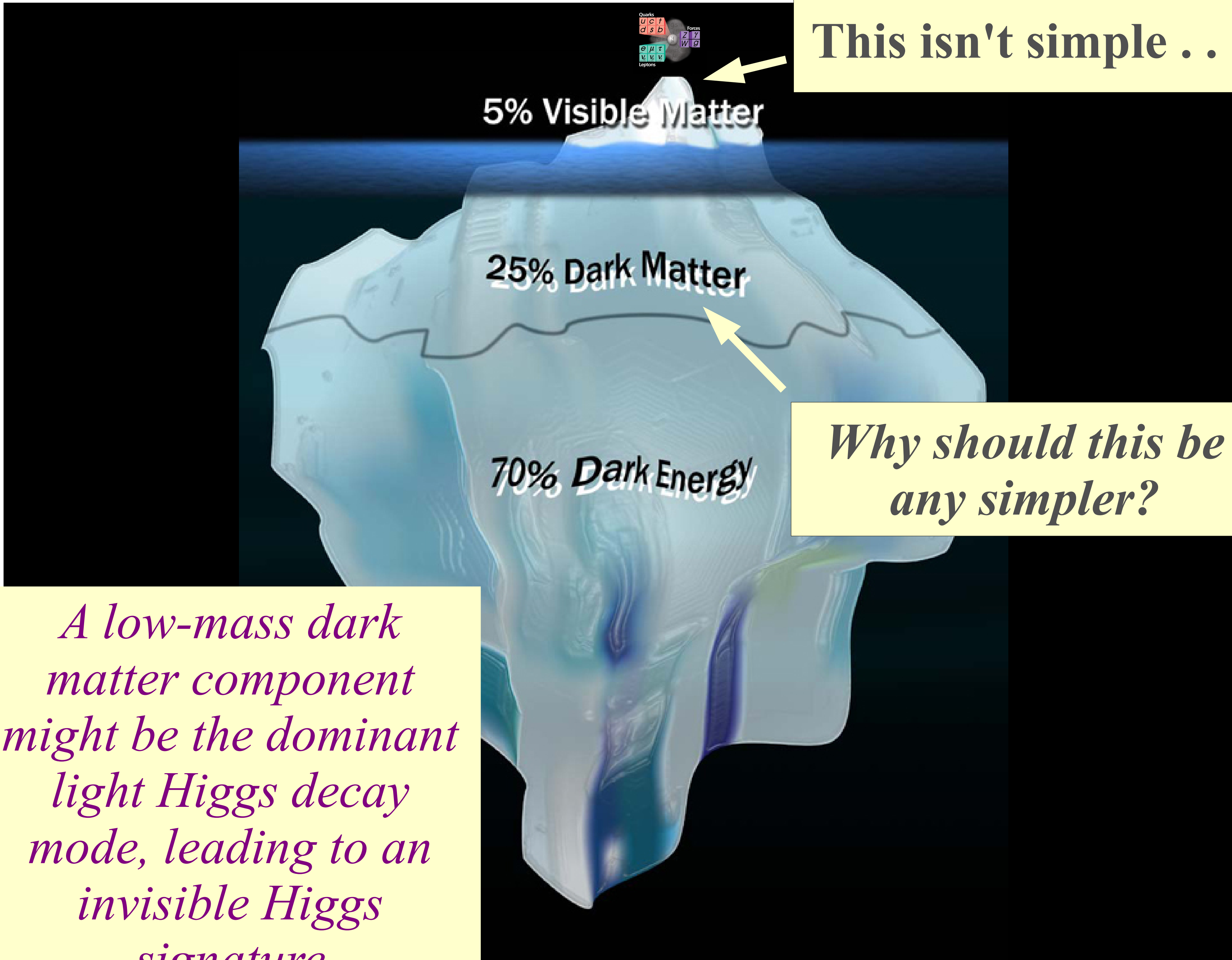
This would mean tens or thousands of events in our data!



Best limits come from recent CLEO search for $A^0 \rightarrow \mu\mu,\ \tau\tau$

hep/ex arXiv:0807.1427

Limits on the rate range from 10^{-4}-10^{-5}



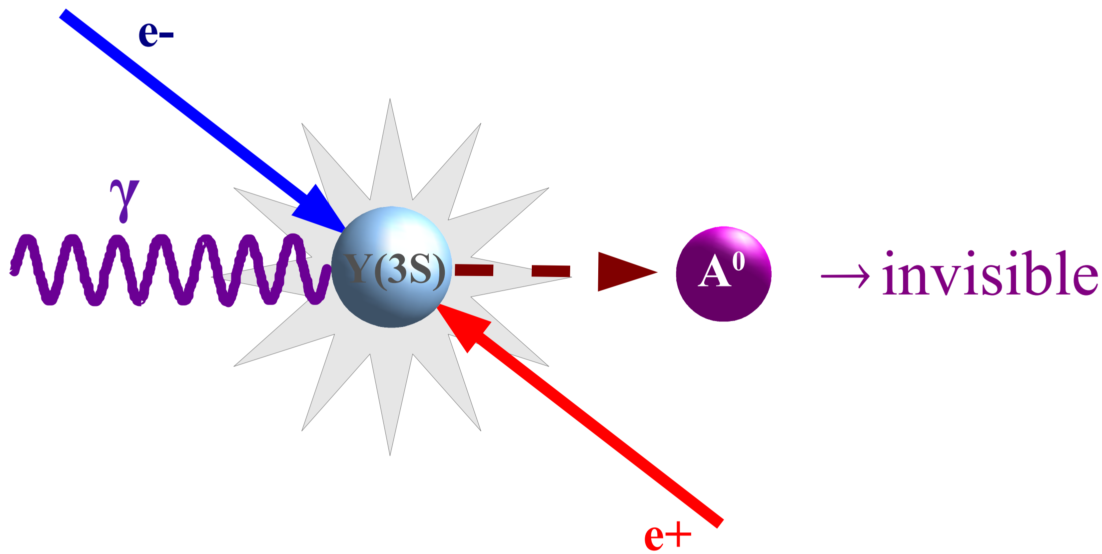
This isn't simple . . .

Why should this be any simpler?

A low-mass dark matter component might be the dominant light Higgs decay mode, leading to an invisible Higgs signature

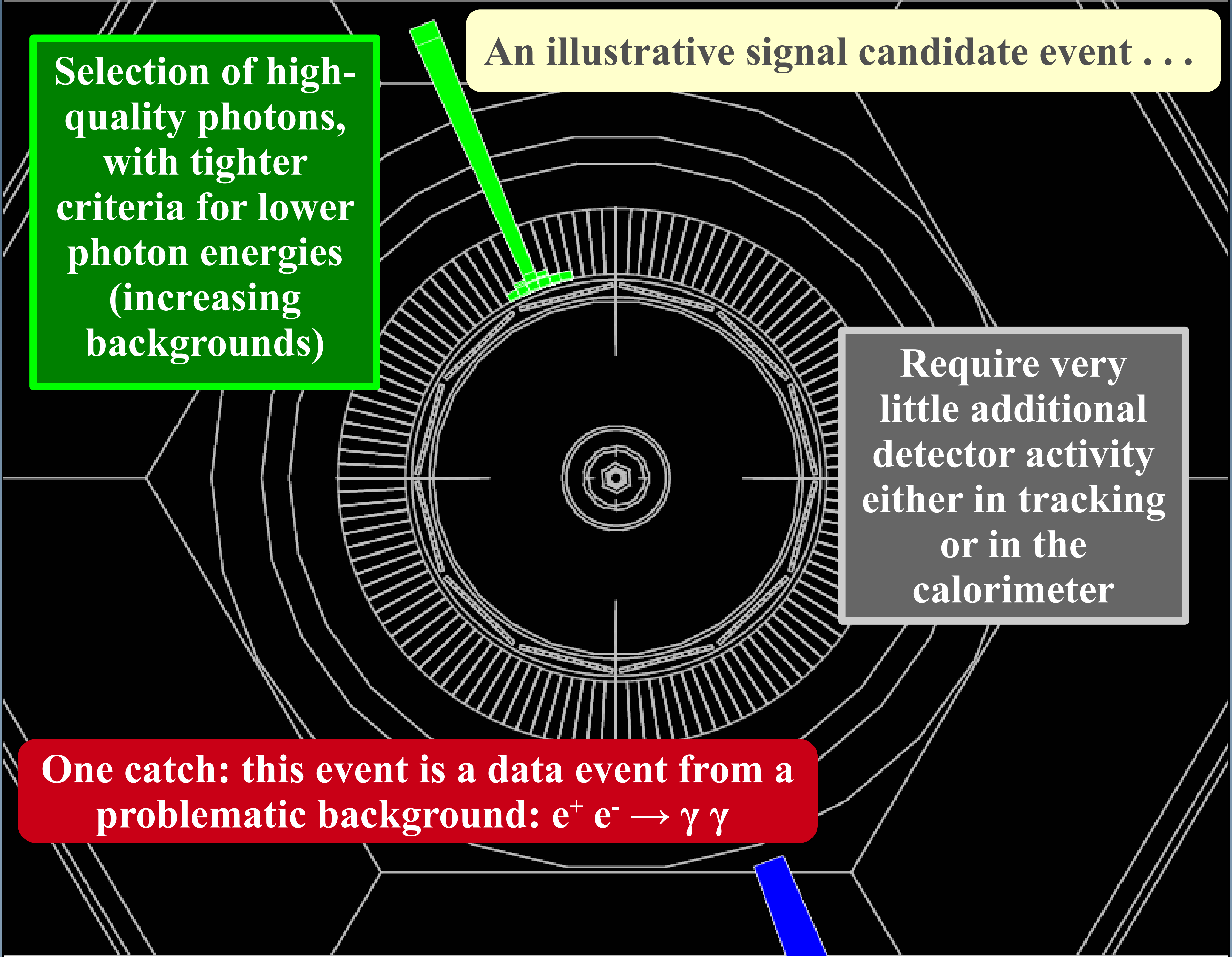
Experimental Signature

$$E^*_\gamma = \frac{m^2_\Upsilon - m^2_{A^0}}{2m_\Upsilon}$$



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

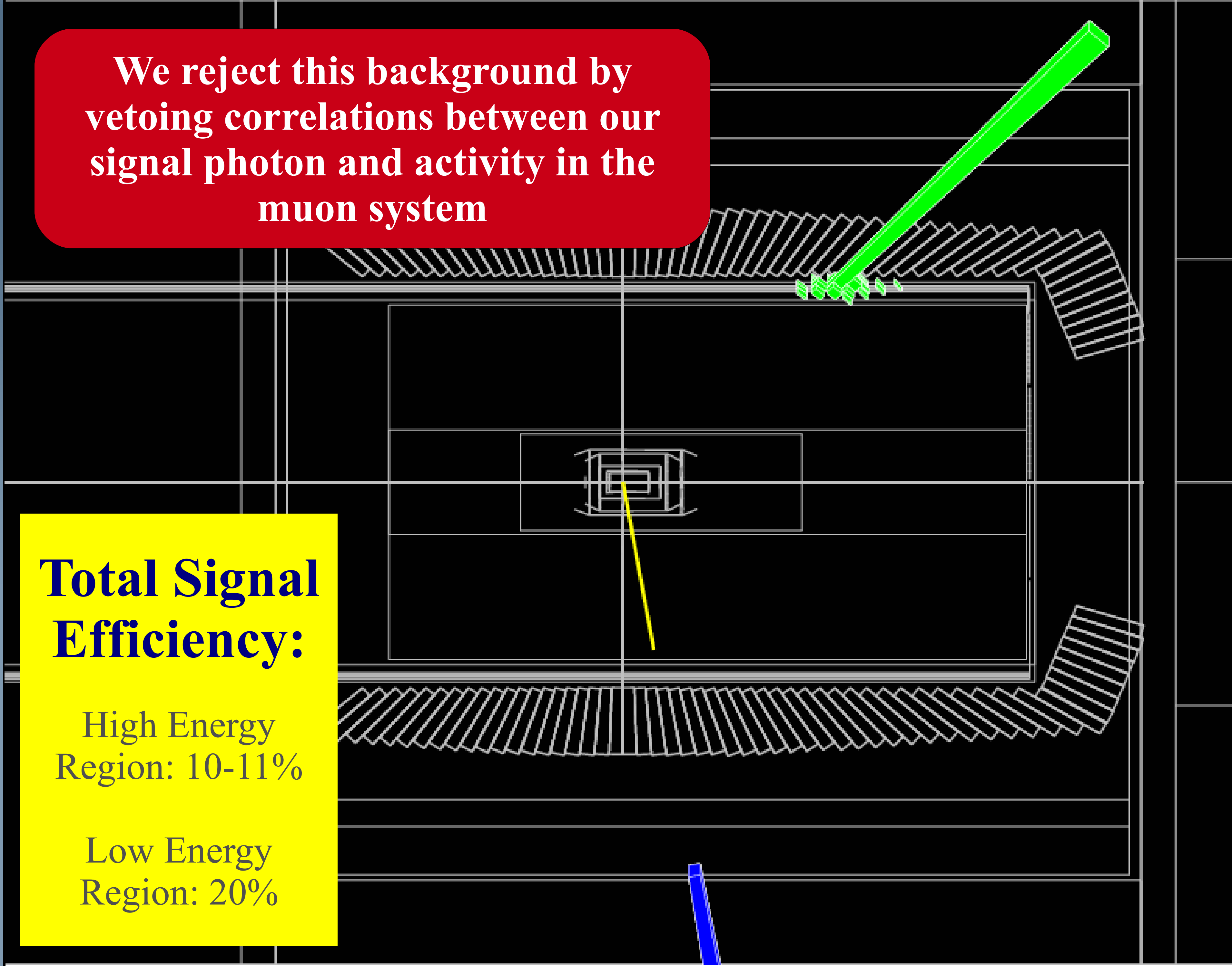
An illustrative signal candidate event . . .



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: $e^+ e^- \to \gamma\gamma$



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

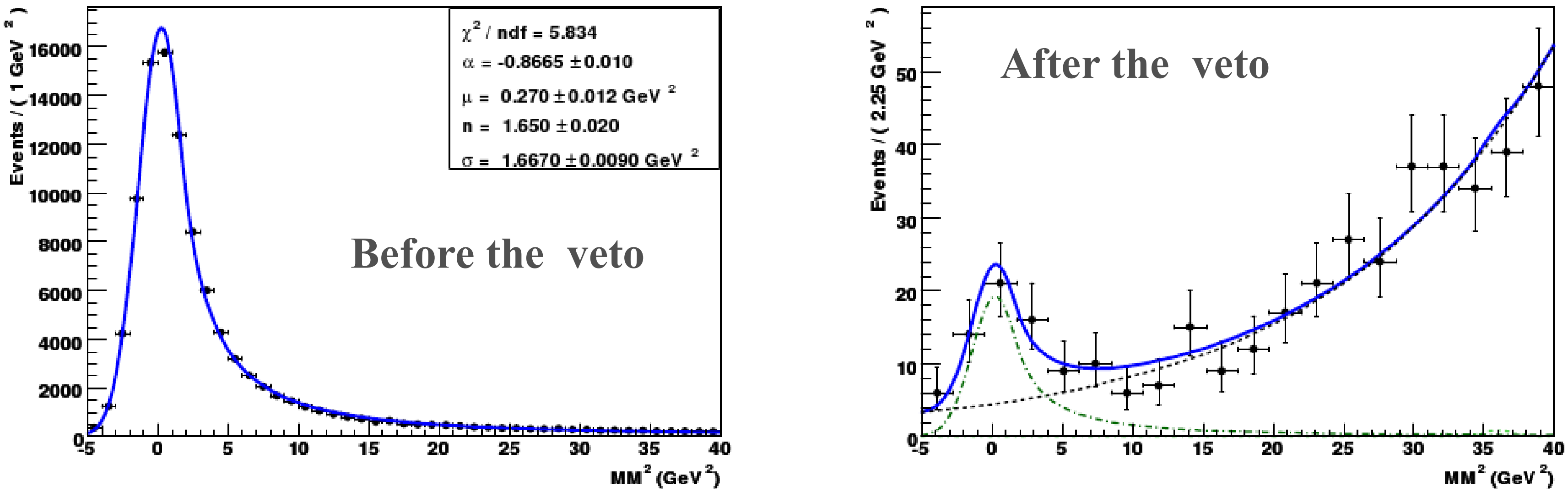
- 1-D fit to the missing mass-squared:

$$m_X^2 = M_{\Upsilon(3S)}^2 - 2E_\gamma^* M_{\Upsilon(3S)}$$

- Signal model
  - parameterized using same detector resolution function as η_b search
  - parameters vary with assumed Higgs mass, due to calorimeter response
- Background models
  - determined from data control samples
  - Major backgrounds: $e^+e^- \rightarrow \gamma\gamma, \gamma\gamma\gamma, e^+e^-\gamma$

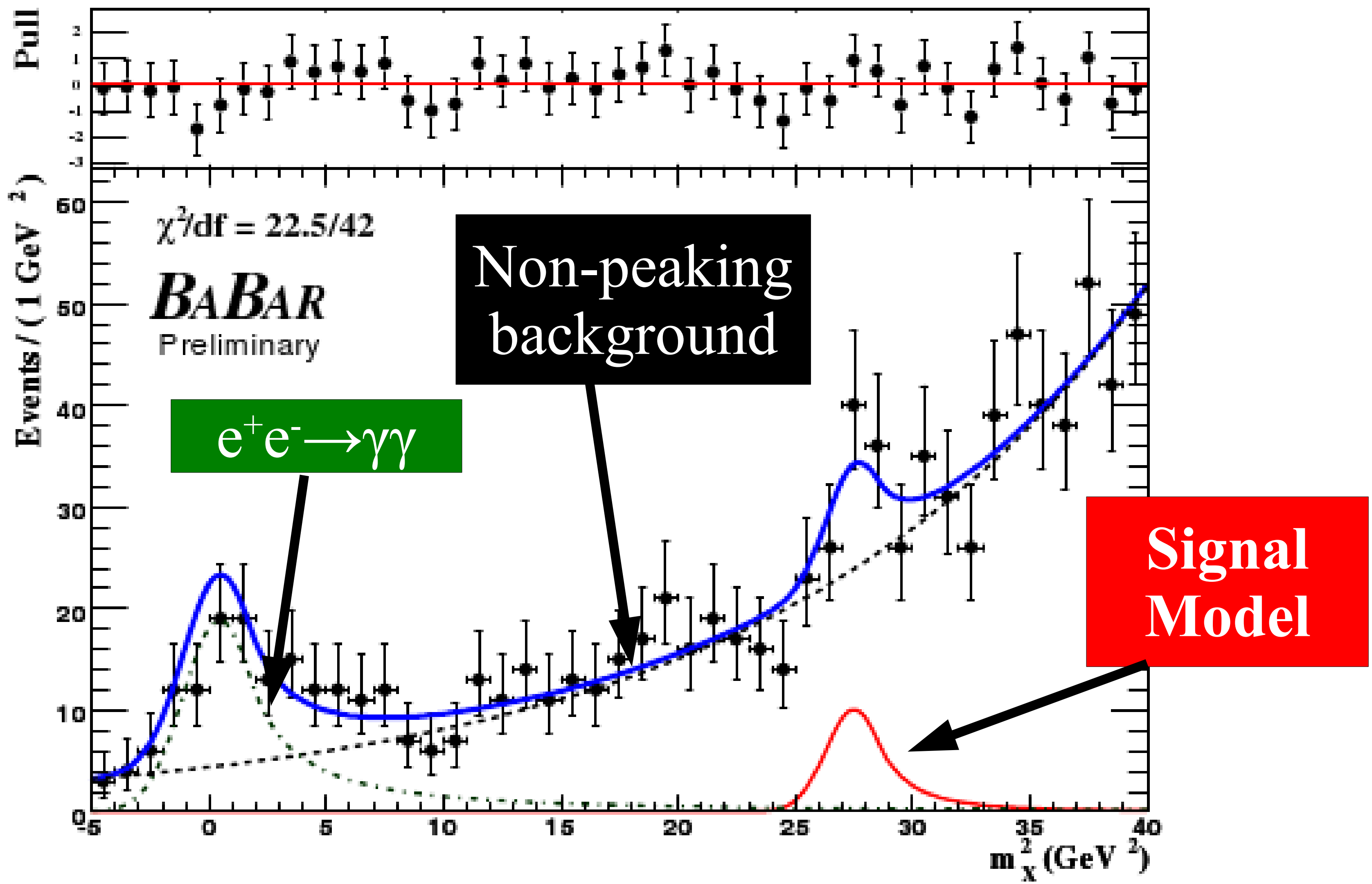
$e^+e^- \rightarrow \gamma\gamma$ background

Data Control Sample (non-Y(3S) events)

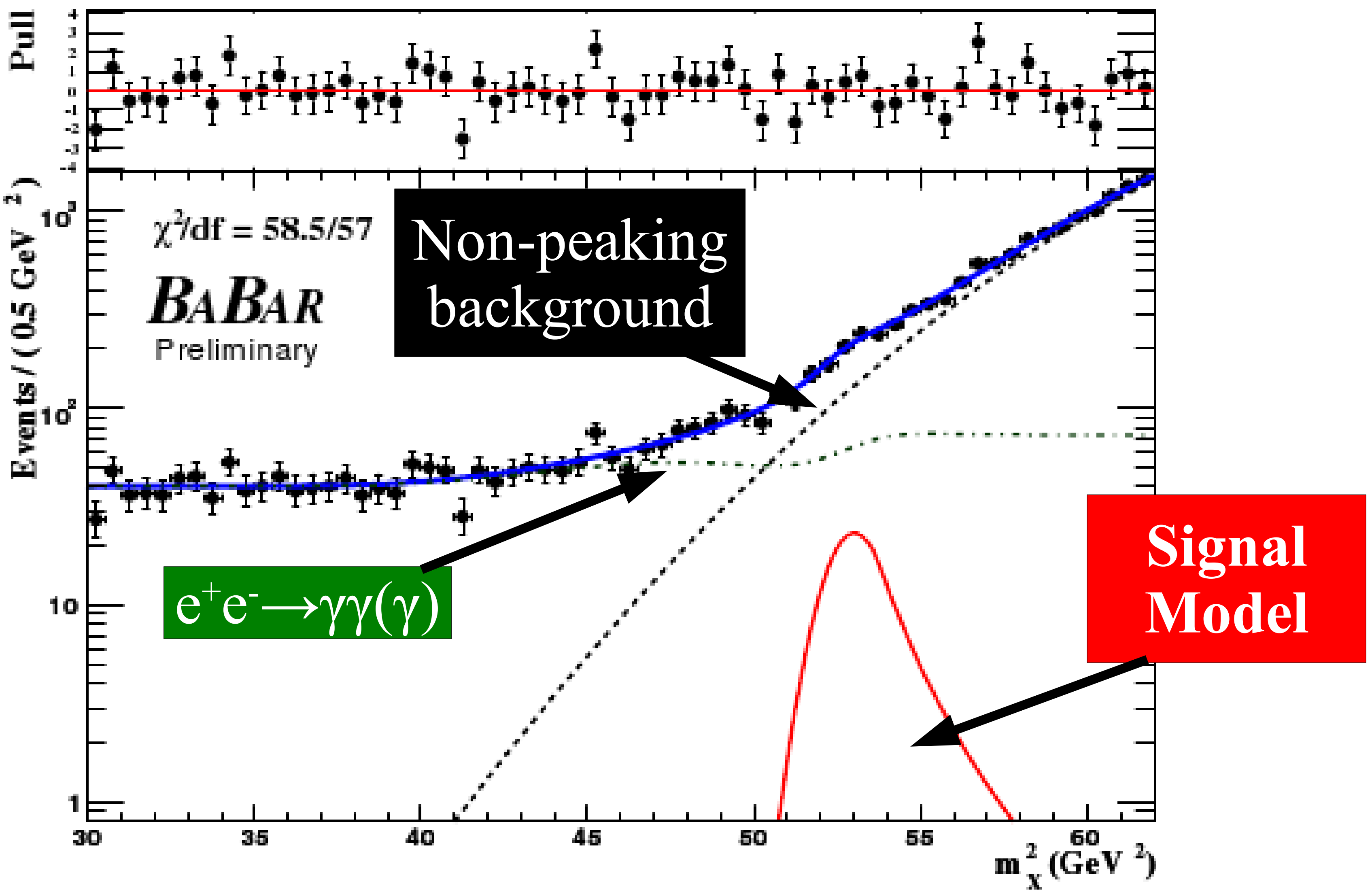


We determine the shape of this background before the veto, and use it to model the background and learn about the signal photons

A Snapshot: Fits to the Spectrum Low-Mass Region



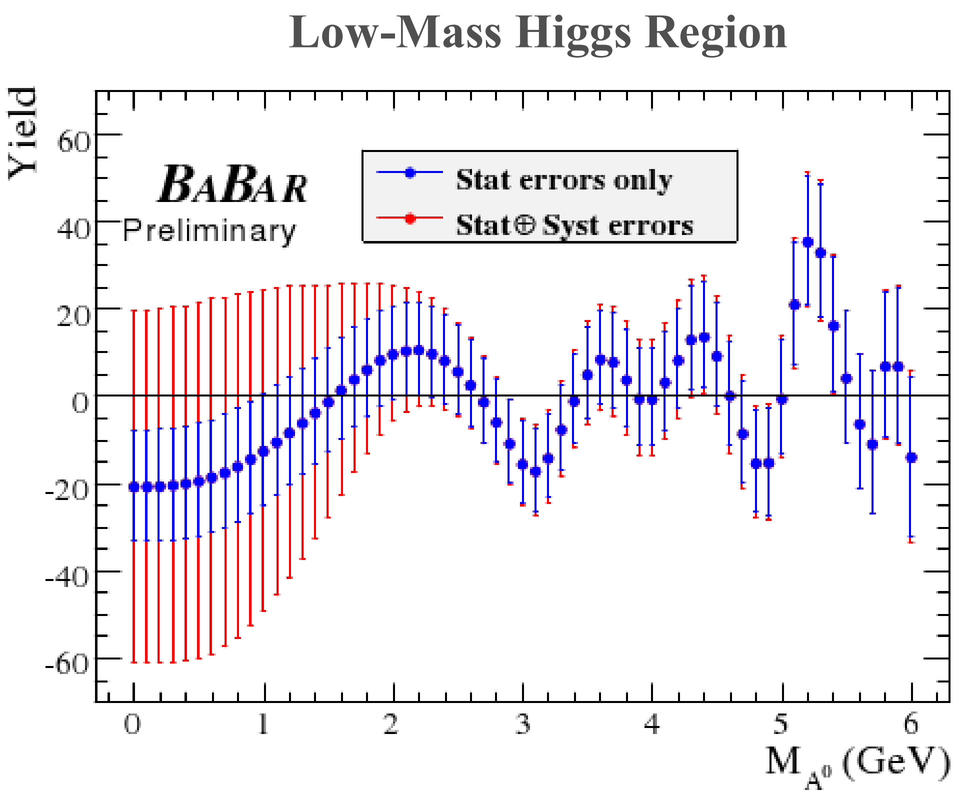
A Snapshot: Fits to the Spectrum High-Mass Region

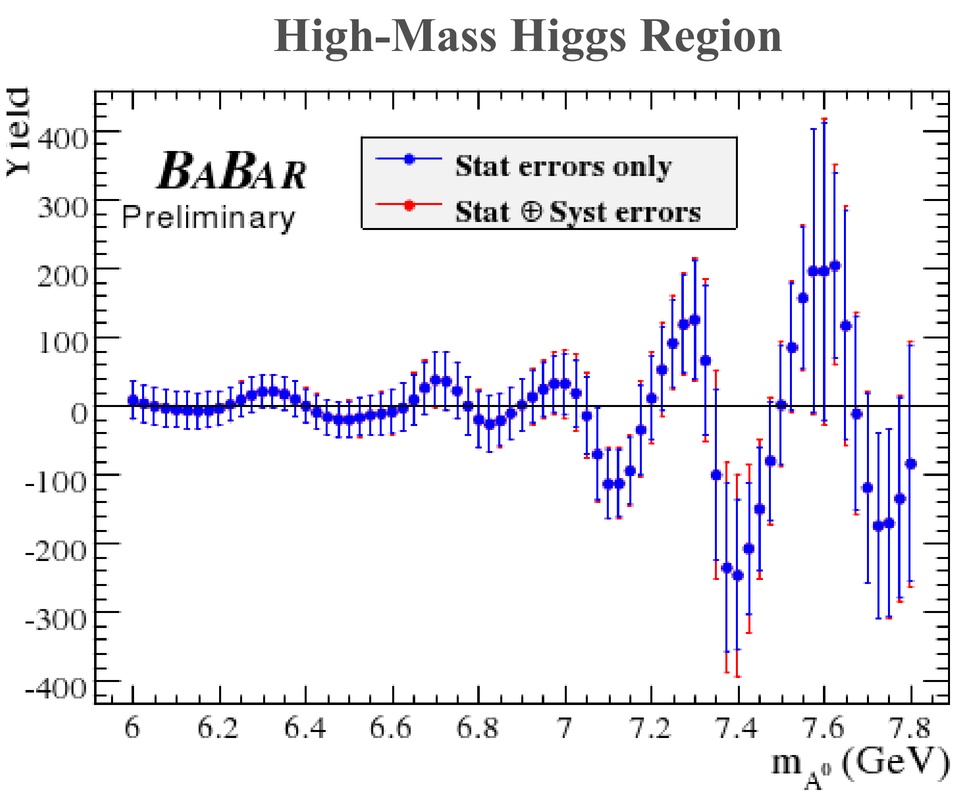


Results

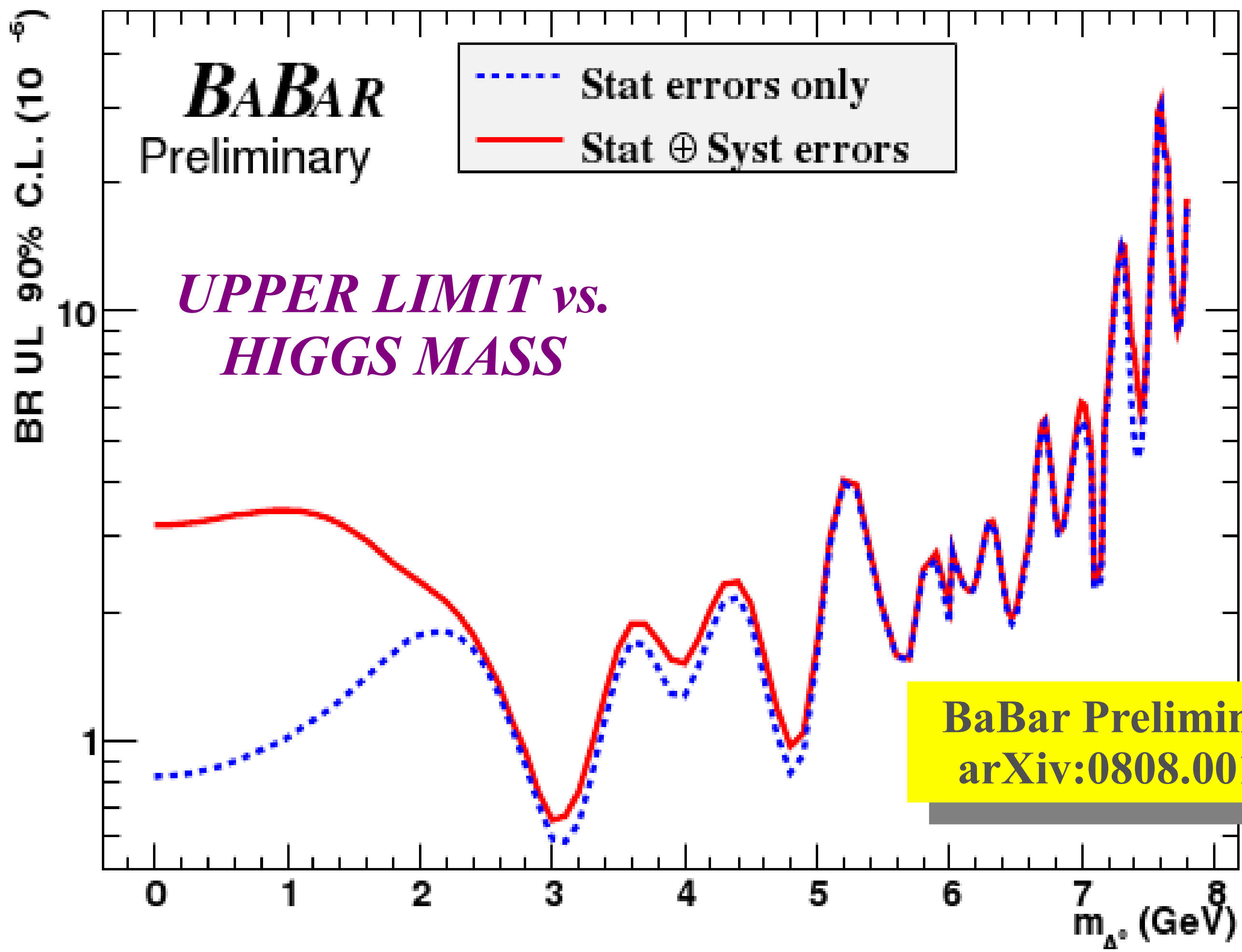
Most significant yields:

- low-mass region: 37 ± 15 (2.6σ, stat. only)
- high-mass region: 119 ± 71 (1.7σ, stat. only)





Results (continued)



BaBar Preliminary Result: arXiv:0808.0017 [hep-ex]

We rule out an invisibly decaying Higgs produced at a rate between ~ 10^{-5} - 10^{-6}.

Concluding Thoughts: Prospects for Further Discovery

First Results from BaBar Upsilon Sample

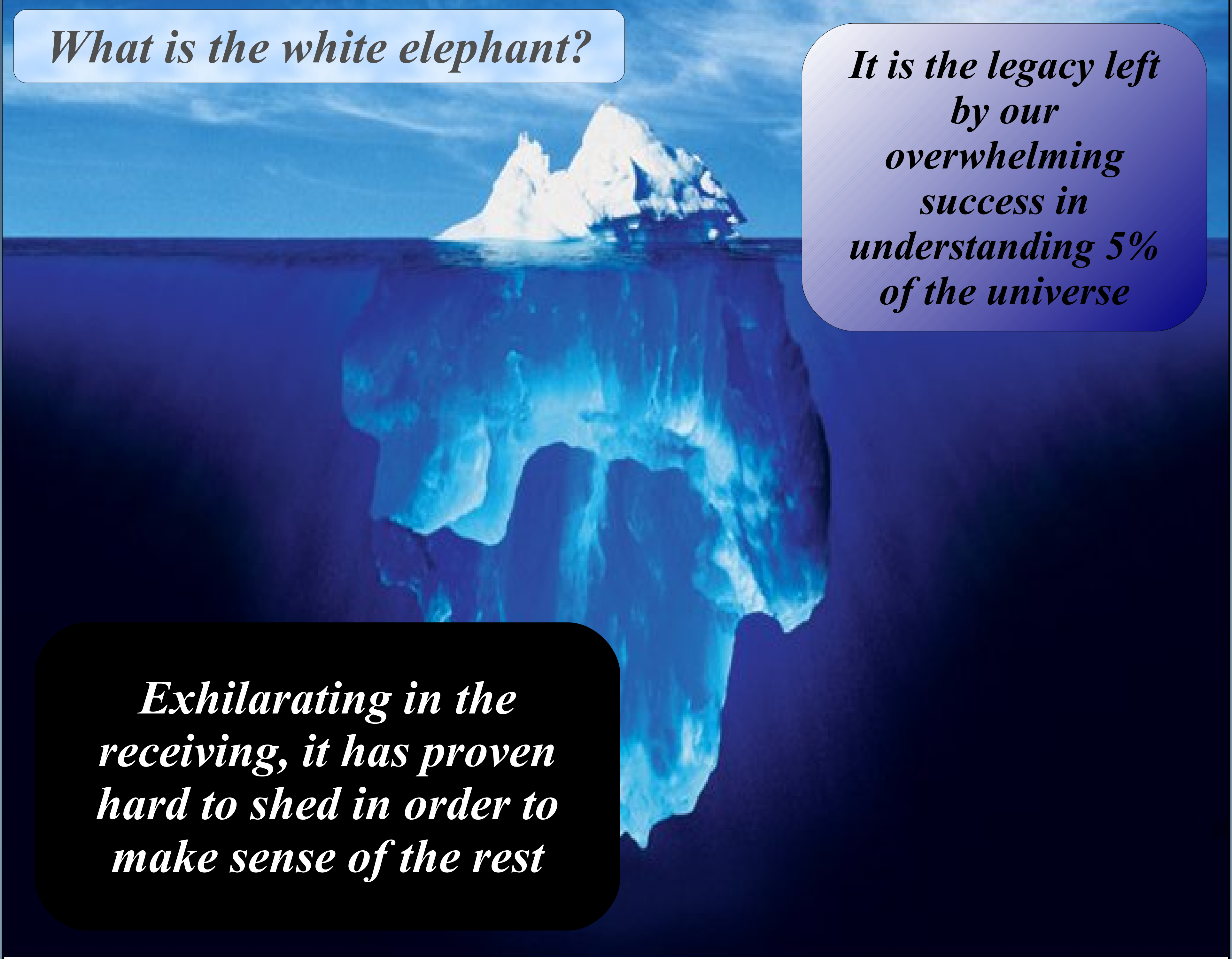
- Unmatched samples of Upsilon mesons below threshold open up new doors of exploration
  - Standard Model – discovery and further study of the η_b

Mass:

$$9388.9^{+3.1}_{-2.3} \pm 2.7\,\mathrm{MeV}/c^2 \; (\Upsilon(3S) \text{ Analysis})$$

$$9392.9^{+4.6}_{-4.8} \pm 1.8\,\mathrm{MeV}/c^2 \; (\Upsilon(2S) \text{ Analysis})$$

  - New Physics – searches for low-mass Higgs and dark matter
    - We exclude an invisibly decaying light Higgs up to 7.8 GeV/c^2 at the 90% CL at the level of $\sim 10^{-5}$ -- 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

References

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]
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Fulcher, PRD 44, 2079 (1991)
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Ebert et al., PRD 67, 014027 (2003) [hep-ph/0210381]
Zeng et al., PRD 52, 5229 (1995) [hep-ph/9412269]

Spectroscopy

N. Brambilla et al., "Heavy Quarkonium Physics," hep-ph/0412158 (December 13, 2004), http://arxiv.org/abs/hep-ph/0412158.

M. Artuso et al., "Photon Transitions in Upsilon(2S) and Upsilon(3S) Decays," Physical Review Letters 94, no. 3 (January 28, 2005): 032001-5

S. W. Herb et al., Physical Review Letters 39, no. 5 (1977)

16 authors

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

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Columbia University, New York, New York 10027

and

J. A. Appel, B. C. Brown, C. N. Brown, W. R. Innes, K. Ueno, and T. Yamanouchi
Fermi National Accelerator Laboratory, Batavia, Illinois 60510

and

A. S. Ito, H. Jöstlein, D. M. Kaplan, and R. D. Kephart
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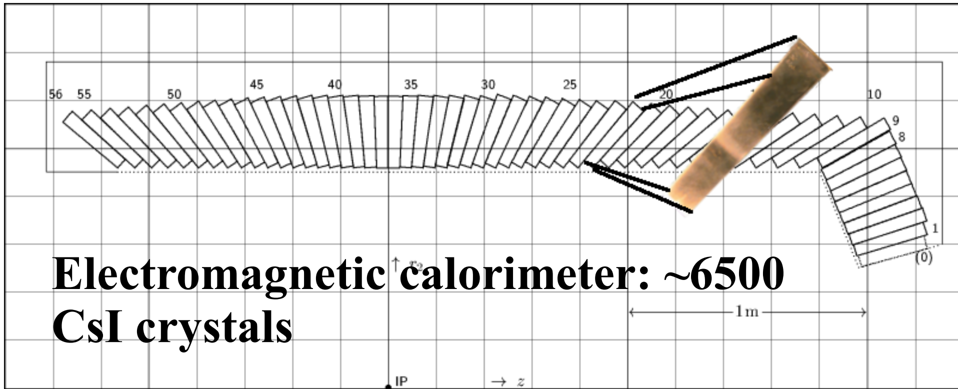
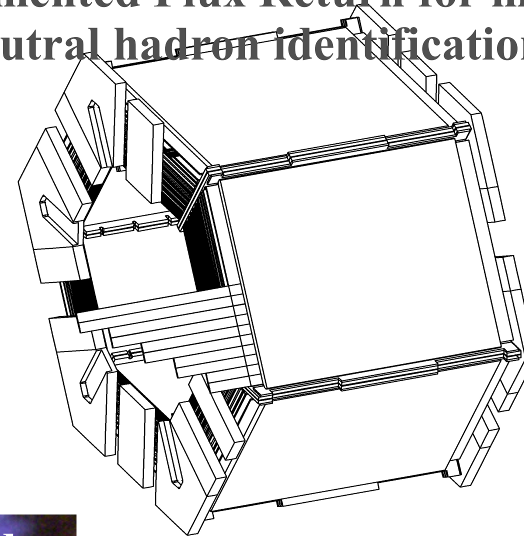
(Received 1 July 1977)

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

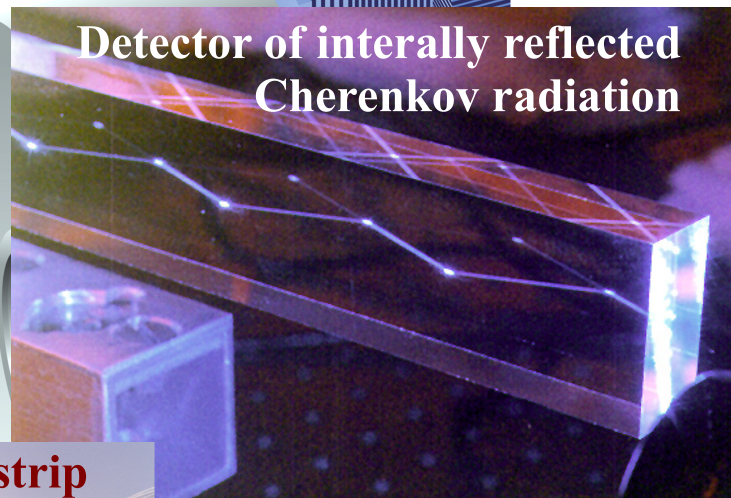
Dimuon production is studied in 400-GeV proton-nucleus collisions. A strong enhancement is observed at 9.5 GeV mass in a sample of 9000 dimuon events with a mass $m_{\mu^+\mu^-} > 5$ GeV.

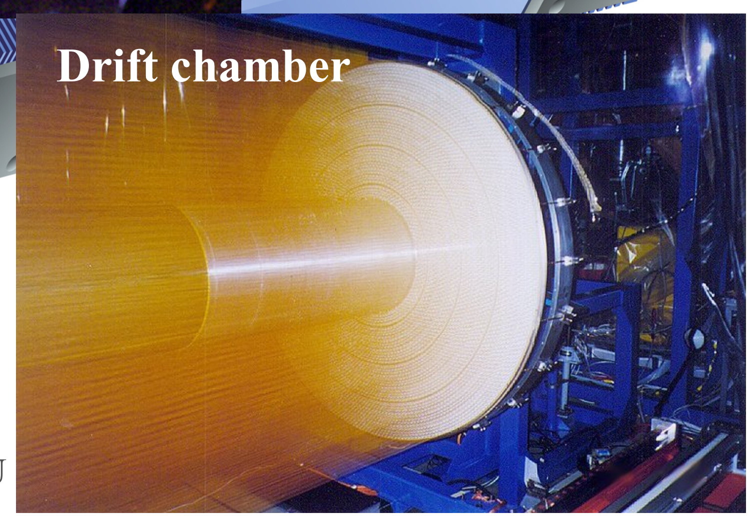


Instrumented Flux Return for muon and neutral hadron identification



- Electron/Photon Detector
- Cherenkov Detector
- Tracking Chamber
- Support Tube
- Vertex Detector





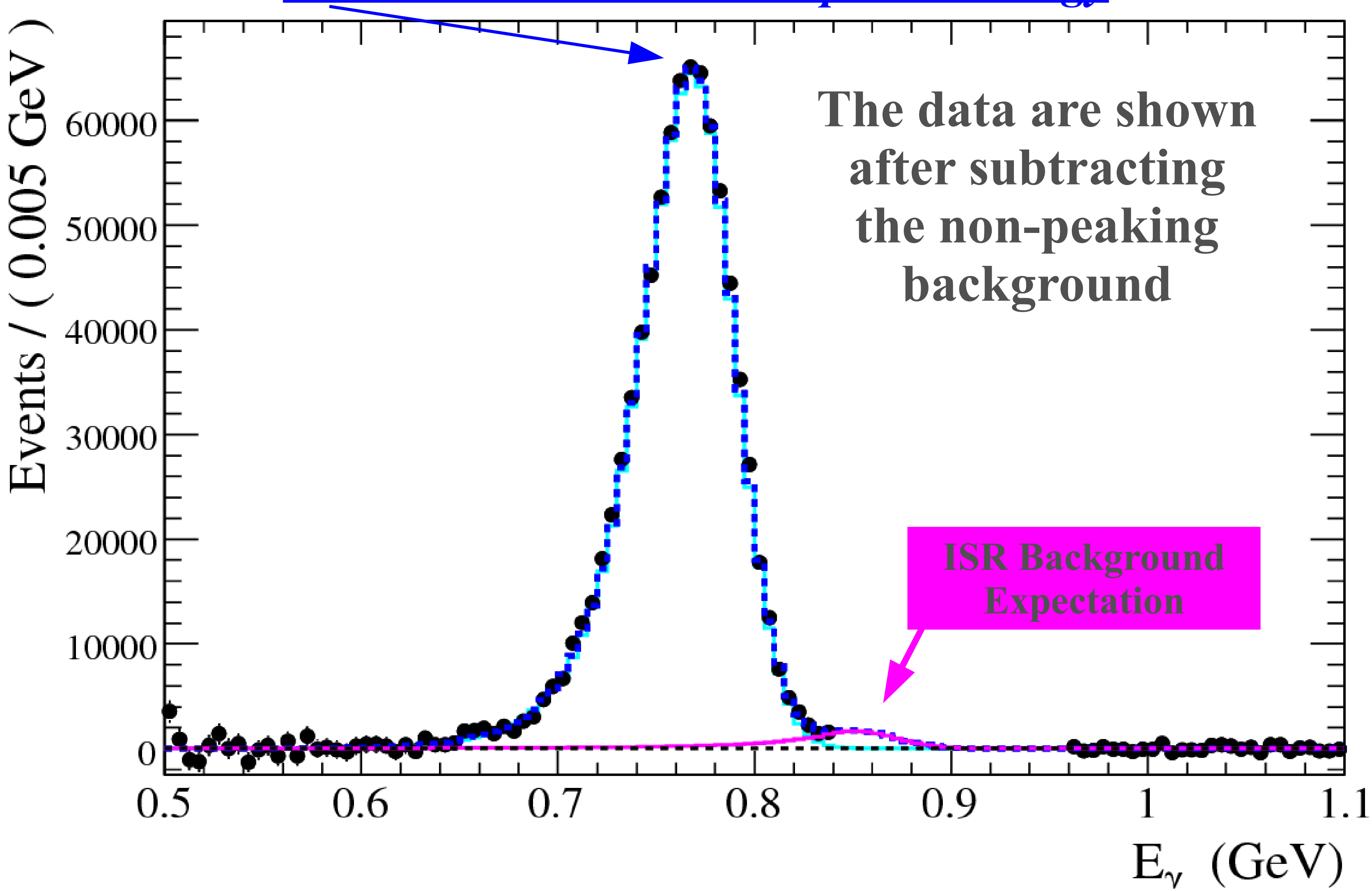
η_b Event Pre-selection

- Selection chosen to have high signal efficiency
  - Dominant η_b decay expected to be $\eta_b \to gg$
    - require >= 4 charged tracks in an event
    - exclude "jetty" events (e.g. $e^+e^- \to qq$) 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 η_b leaves a small correlation between the photon and event thrust axis, in contrast to $e^+e^- \to qq$: $|\cos\theta_T| < 0.7$
    - Veto photons consistent with a π^0 decay

Signal Efficiency: 37%

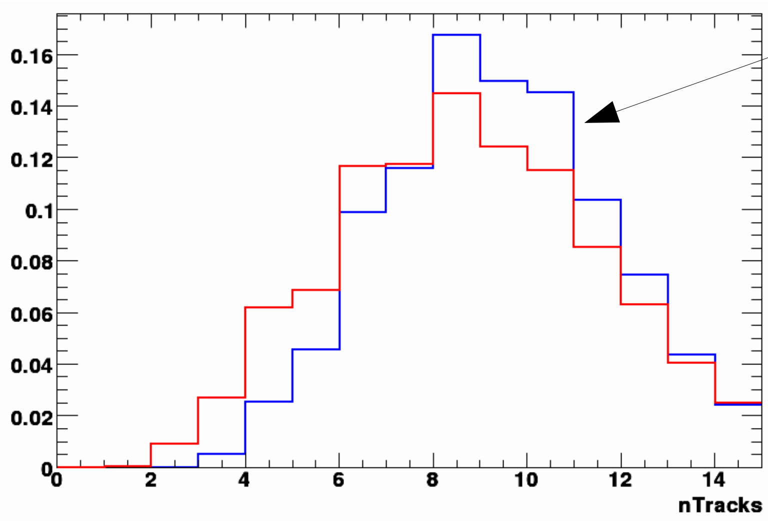
The $\chi_{bJ}(2P)$ – background, calibration

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



η_b – track multiplicity

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



According to MC simulation, the >= 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 $\chi_{bJ}(2P) \rightarrow \gamma\ \Upsilon(1S)$ events (due to $\Upsilon(1S) \rightarrow ggg$), 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

Cut	$S/\sqrt{B}$	Eff. (from χ_b peak)	Eff. (signal MC)
No cut	101.5	-	0.629
BGFMultiHadron	109.8	0.973	0.977
≥ 4 ChargedTracks	107.2	0.903	0.995
LAT<0.55	113.2	0.997	0.991
$-0.762 < \cos(\theta_{\gamma,LAB}) < 0.890$	109.6	0.928	0.901
$\lvert\cos(\theta_T)\rvert < 0.7$	135.2	0.672	0.690
π^0-50 MeV cut	164.7	0.849	0.899

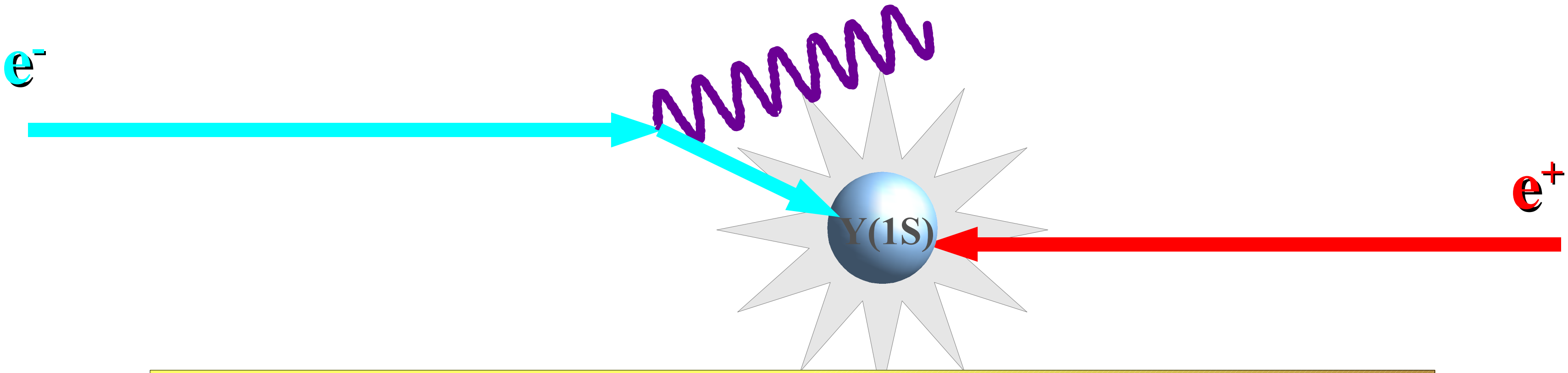
The η_b width

- Predictions of the width:
  - based on the ratio of $\Gamma(\eta_b \to \gamma\gamma)$ and $\Gamma(\eta_b \to gg)$, predictions range from 4-20 MeV/c^2
    - c.f. *W. Kwong et al., Phys. Rev. D 37, 3210 (1988); C. S. Kim, T. Lee, and G. L. Wang, Phys. Lett. B 606, 323 (2005); J. P. Lansberg and T. N. Pham, Phys. Rev. D 75, 017501 (2007).*
- 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 η_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

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



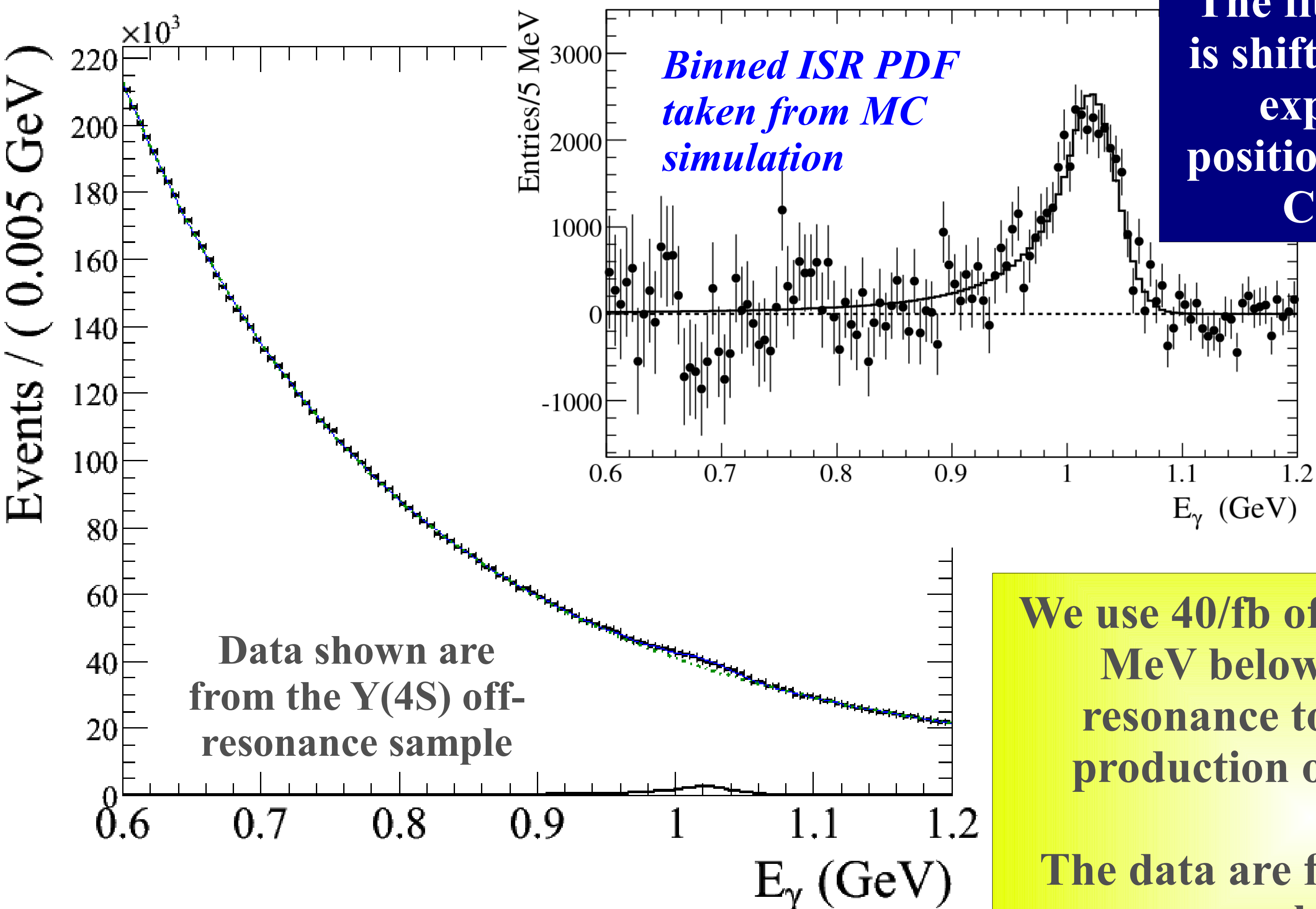
$$\sigma(e^+e^- \to \gamma_{ISR}\Upsilon(1S)) = \frac{12\pi^2 \Gamma_{ee}}{M_{\Upsilon(1S)}\, s} \cdot W(s, 2E_\gamma/\sqrt{s})$$

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

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

Sample	Lumi $[\mathrm{fb}^{-1}]$	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

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



Data shown are from the Υ(4S) off-resonance sample

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

We use 40/fb of data taken 40 MeV below the Υ(4S) resonance to study ISR production of the Υ(1S).

The data are fitted with the same non-peaking model and a Gaussian + Power-Law Tail (ISR peak).

Systematic Uncertainties - η_b

Signal Yield:

ISR Background:

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

ηb 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:

χ_{bJ}(2P) peak shift: (3.8 ± 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%

THE "mu" PROBLEM

$$\mu H_u H_d$$

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)

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

Add an additional Higgs singlet field, 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

Data Samples

- Data with single-photon triggers:
  - 28 fb^{-1} taken at the Υ(3S)
    - signal analysis sample
  - 4.7 fb^{-1} taken at the Υ(4S)
    - used HE trigger, can be used to tune cuts on photons
  - "Off-resonance" data
    - 2.6 fb^{-1} taken 40 MeV below the Υ(3S)
    - 0.97 fb^{-1} taken 30 MeV below the Υ(2S)
    - 4.5 fb^{-1} taken in a scan above the Υ(4S)

Data For Tuning Cuts and Studying Backgrounds

Triggering on Single Photons + $\not{E}$

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

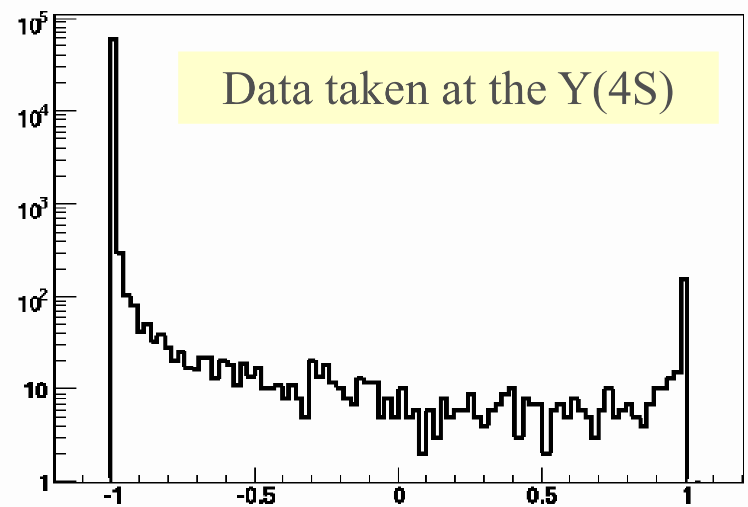
- Dedicated online triggered and filtering were developed
  - Level 1 (hardware trigger): require at least one EMC cluster with energy > 800 MeV (lab frame)
  - Level 3 (software trigger): two lines developed
    - High-energy (HE) line: require isolated EMC cluster with CM-frame energy > 2 GeV
    -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

100 Hz (HE and LE lines)

Event Selection

Variable	$3.2 < E^*_\gamma < 5.5$ GeV	$2.2 < E^*_\gamma < 3.7$ GeV
Number of crystals in EMC cluster	$20 < N_{\mathrm{crys}} < 48$	$12 < N_{\mathrm{crys}} < 36$
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)	$E_{\mathrm{extra}} < 0.1$ GeV	$E_{\mathrm{extra}} < 0.22$ GeV
IFR veto	$\cos(\Delta\phi^*_{\mathrm{NH}}) > -0.9$	$\cos(\Delta\phi^*_{\mathrm{NH}}) > -0.95$
IFR fiducial	$\cos(6\phi^*_\gamma) < 0.96$	...

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



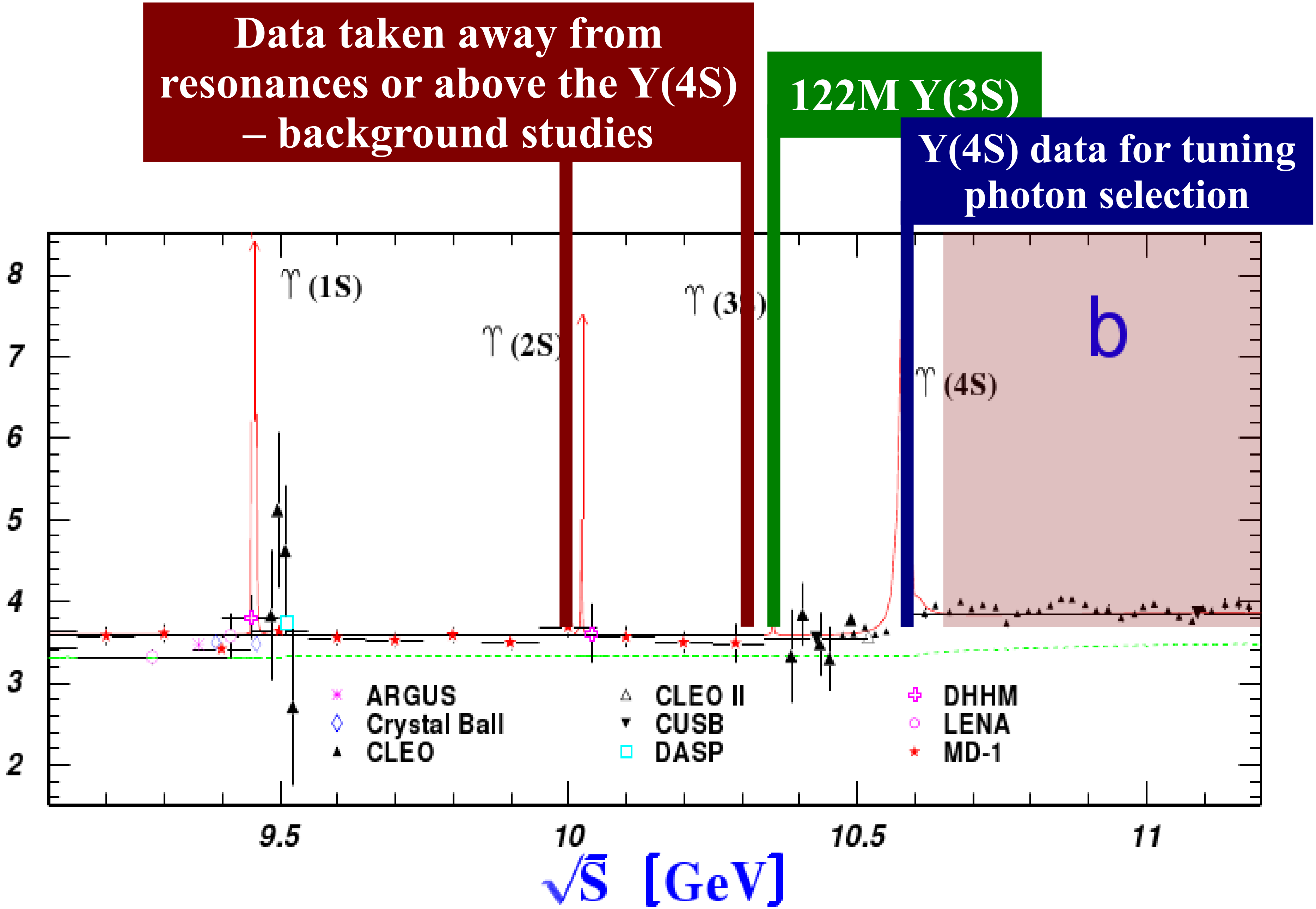
Cosine of the angle of IFR clusters relative to photon

Total Efficiency:

High Energy Region: 10-11%

Low Energy Region: 20%

The plot below is taken from arXiv:hep-ph/0312114v2 and is meant to illustrate the e+e- → hadrons spectrum between 9.1 GeV and 11.2 GeV



Systematic Uncertainties - Higgs

$e^+e^-\to\gamma\gamma$ 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 $e^+e^-\to\gamma\gamma$ 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

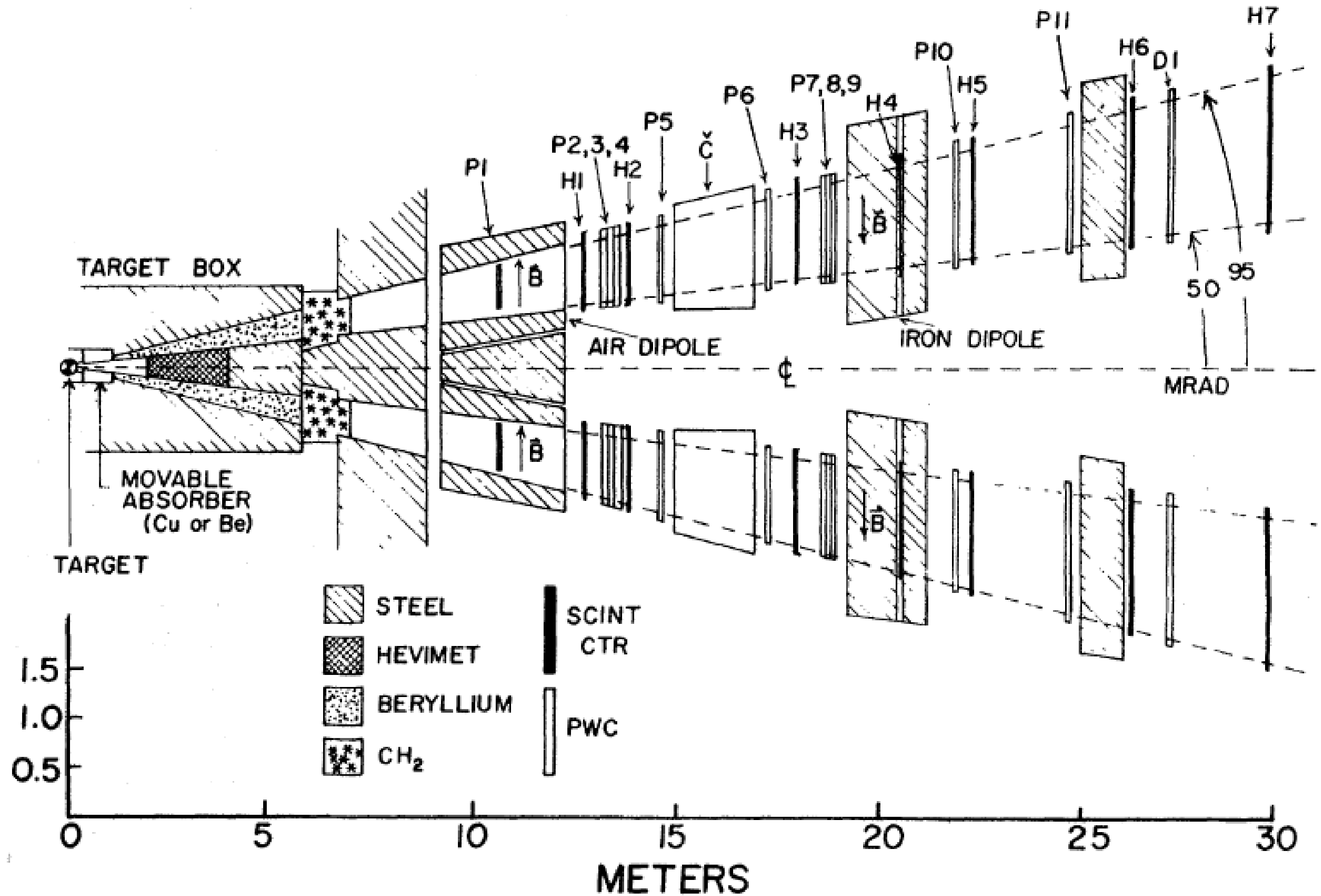
trigger/event filter efficiency checked with $e^+e^-\to\gamma\gamma$ and $e^+e^-\gamma$ (0.4%)

Photon selection checked using $e^+e^-\to\mu\mu\gamma$, $\tau\tau\gamma$, and $\omega\gamma$ (2%)

Neutral reconstruction: 2%

S. W. Herb et al., PRL 39, 252 (1977)

$$p + (\mathrm{Cu}, \mathrm{Pt}) \rightarrow \mu^+ + \mu^- + \text{anything}$$



T. Bohringer et al., PRL 44, 1111 (1980)