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

flickr.com/photos/shoshannabauer/2215305114/

Stephen Sekula

The Ohio State University

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

BABAR

THE OHIO STATE UNIVERSITY

Programme

- **The bottomonium system: prospects for discovery**
- **The BaBar/PEP-II ~~B~~b-factory**

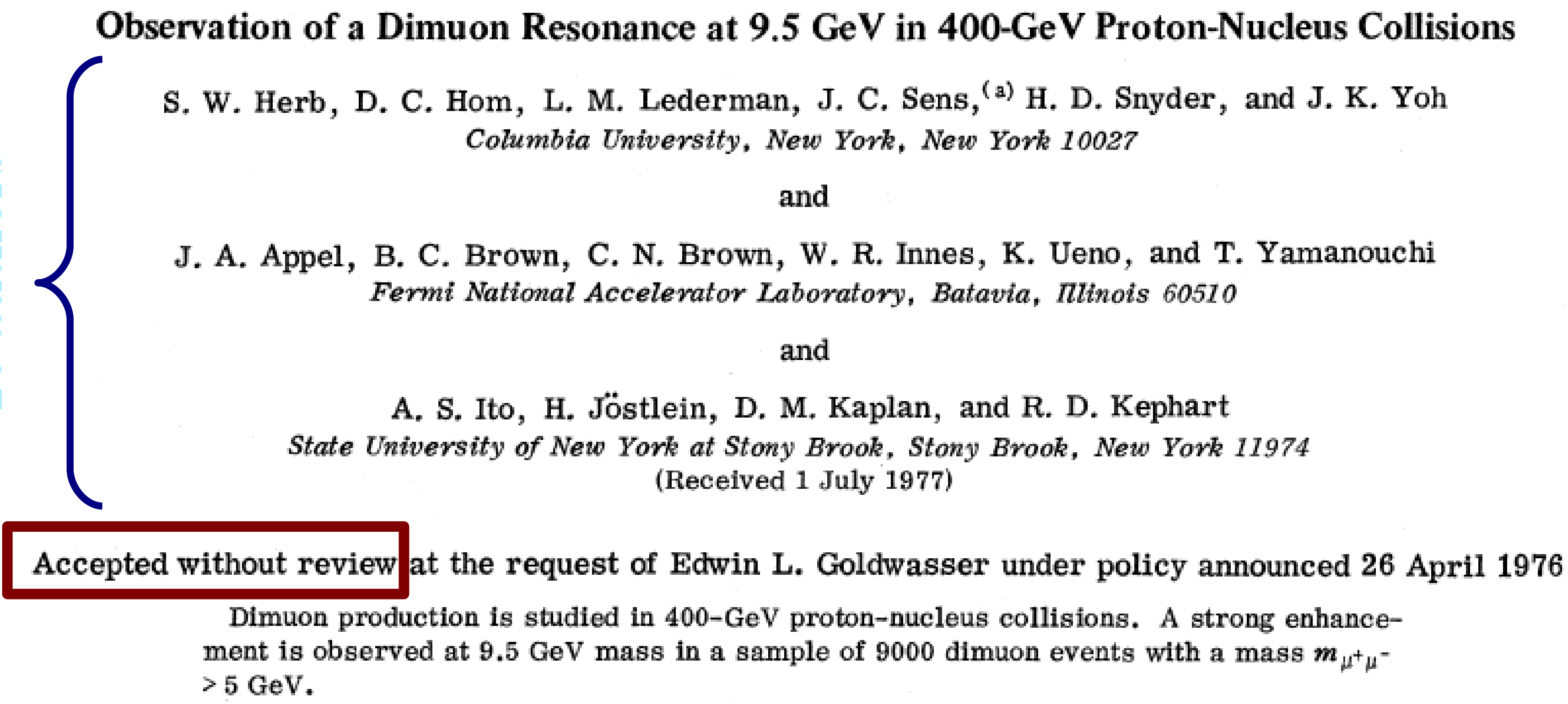
$$B^0 = (\bar{b}\, d) \qquad \Upsilon = (\bar{b}\, b)$$
$$B^+ = (\bar{b}\, u)$$

- **A matter of QCD – the η_b**
- **A matter of new physics – the light Higgs**
- **Prospects for further discovery**

The Bottomonium System: Prospects for Discovery

1977

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

S. W. Herb, D. C. Hom, L. M. Lederman, J. C. Sens,(a) H. D. Snyder, and J. K. Yoh
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

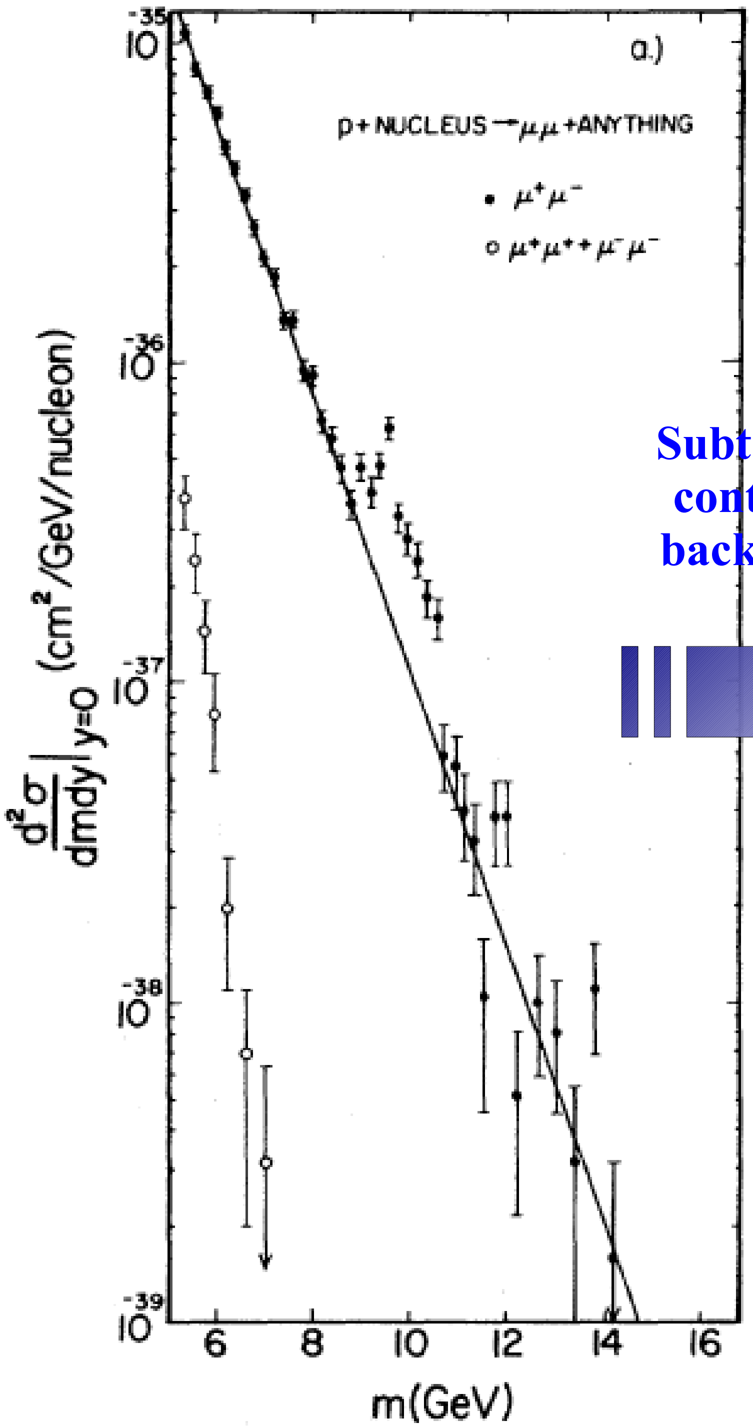
and

A. S. Ito, H. Jöstlein, D. M. Kaplan, and R. D. Kephart
State University of New York at Stony Brook, Stony Brook, New York 11974

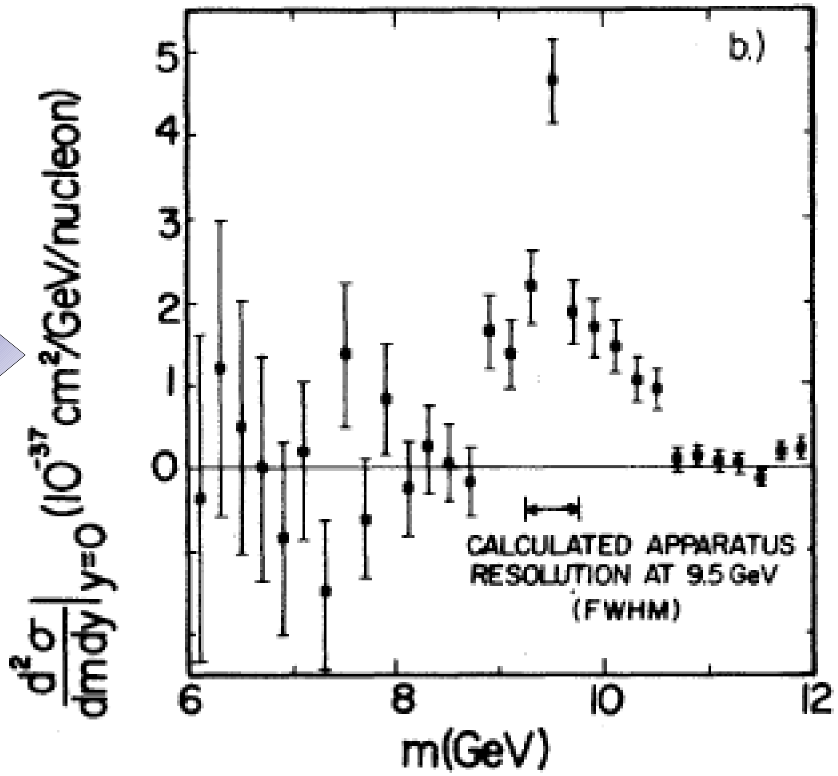
(Received 1 July 1977)

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

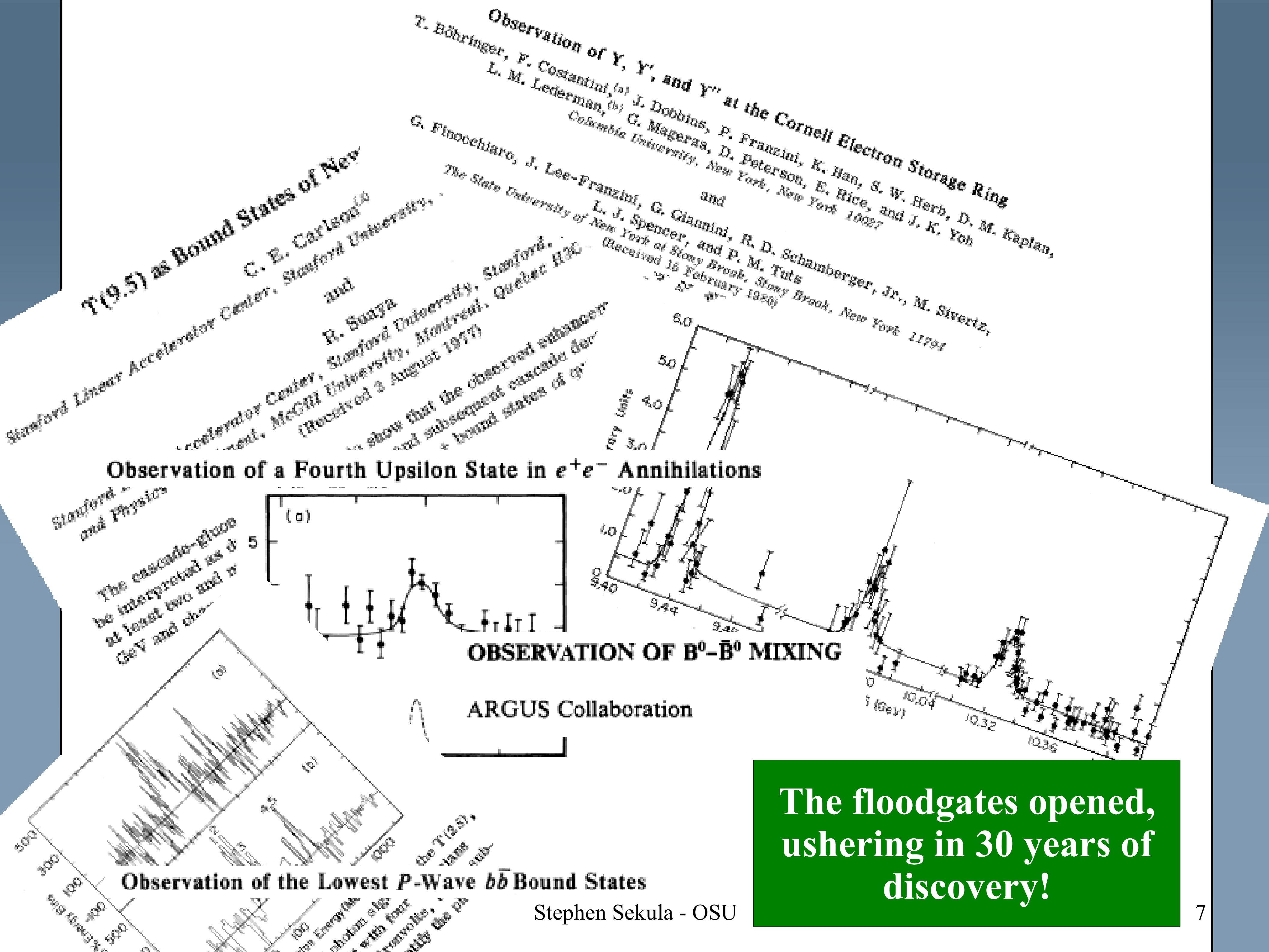
Dimuon production is studied in 400-GeV proton-nucleus collisions. A strong enhancement is observed at 9.5 GeV mass in a sample of 9000 dimuon events with a mass $m_{\mu^+\mu^-} > 5$ GeV.



Subtract the continuum background



The Upsilon is discovered, and identified as the first resonance of a new quark – the bottom quark



Observation of Υ, Υ′, and Υ″ at the Cornell Electron Storage Ring

T. Böhringer, F. Costantini,[a] J. Dobbins, P. Franzini, K. Han, S. W. Herb, D. M. Kaplan,
L. M. Lederman,[b] G. Mageras, D. Peterson, E. Rice, and J. K. Yoh
Columbia University, New York, New York 10027
and
G. Finocchiaro, J. Lee-Franzini, G. Giannini, R. D. Schamberger, Jr., M. Sivertz,
L. J. Spencer, and P. M. Tuts
The State University of New York at Stony Brook, Stony Brook, New York 11794
(Received 18 February 1980)

Υ(9.5) as Bound States of New

C. E. Carlson
Stanford Linear Accelerator Center, Stanford University,
and
R. Suaya
Accelerator Center, Stanford University, Stanford,
ment, McGill University, Montreal, Quebec H3C
(Received 3 August 1977)

show that the observed enhancem
and subsequent cascade dec
bound states of qu

The cascade-gluon
be interpreted as d
at least two and w
GeV and cha

Observation of a Fourth Upsilon State in e^+e^- Annihilations

OBSERVATION OF B⁰–B̄⁰ MIXING

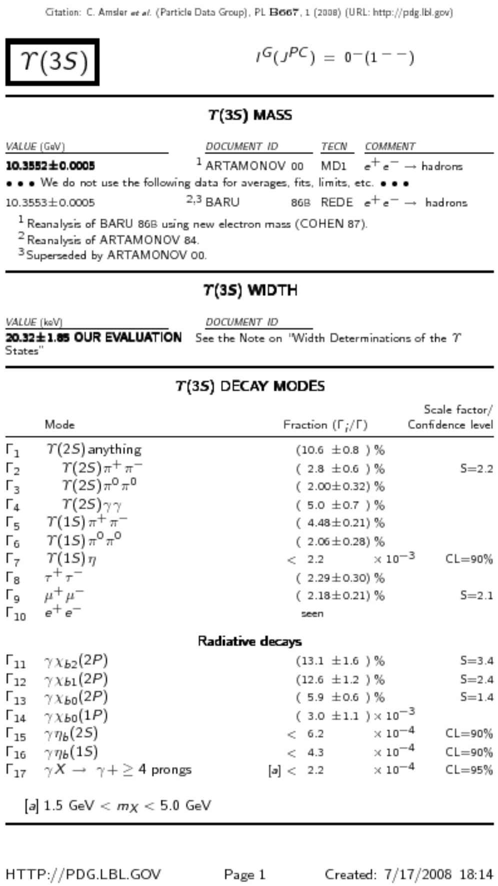
ARGUS Collaboration

Observation of the Lowest *P*-Wave $b\bar{b}$ Bound States

the Υ(2.S),
with four

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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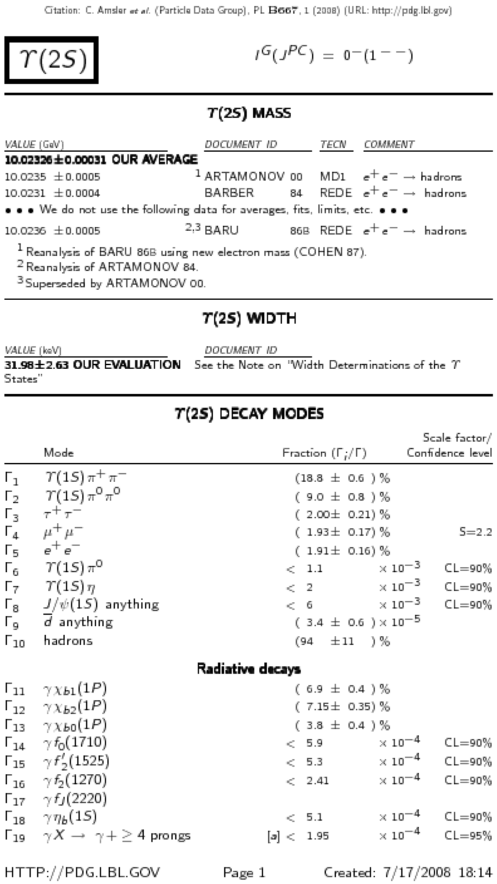

Citation: C. Amsler *et al.* (Particle Data Group), PL B667, 1 (2008) (URL: http://pdg.lbl.gov)

$\Upsilon(2S)$ $I^G(J^{PC}) = 0^-(1^{--})$

$\Upsilon(2S)$ 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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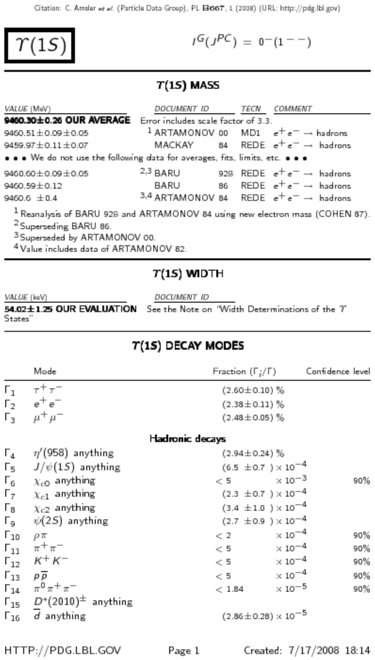

Citation: C. Amsler *et al.* (Particle Data Group), PL B667, 1 (2008) (URL: http://pdg.lbl.gov)

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

$\Upsilon(1S)$ 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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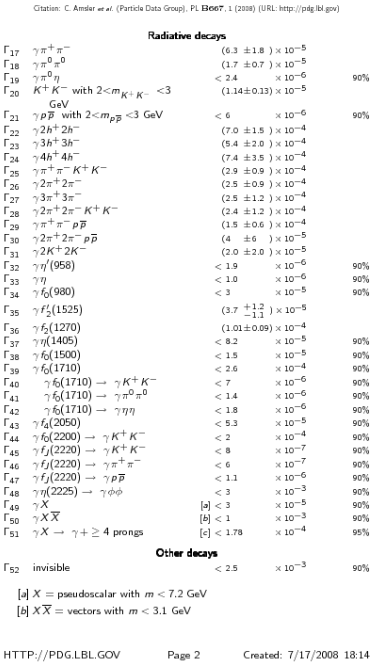

Citation: C. Amsler *et al.* (Particle Data Group), PL B667, 1 (2008) (URL: http://pdg.lbl.gov)

	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}	$\gamma f'_2(1525)$	$(3.7 {}^{+1.2}_{-1.1}) \times 10^{-5}$	
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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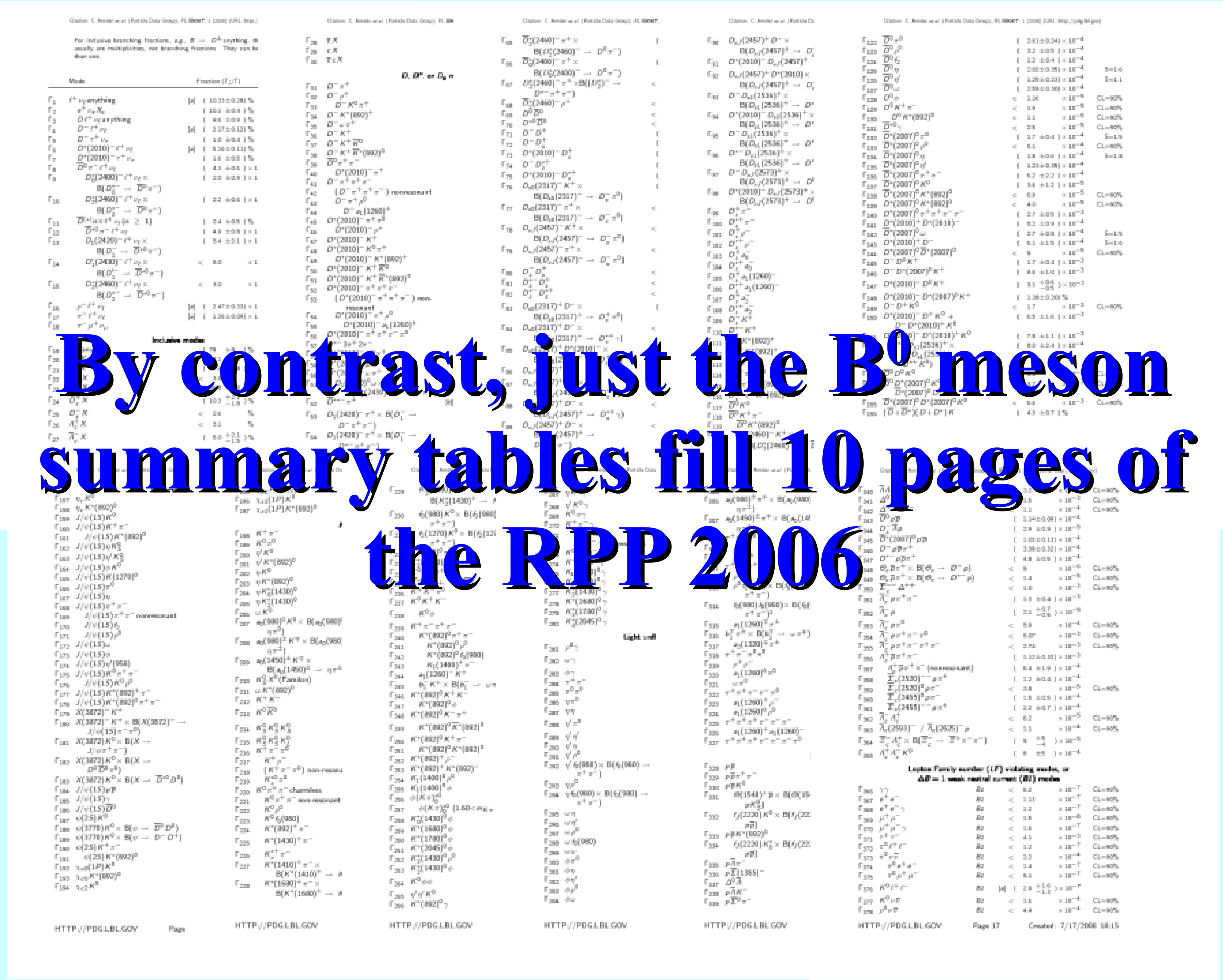
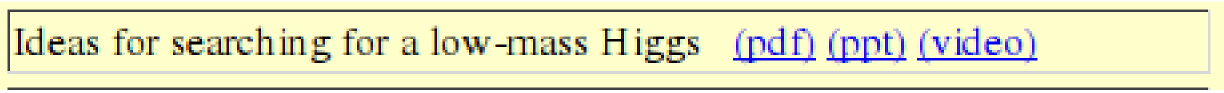
The RPP 2006 summary tables for the Upsilon states below $B\overline{B}$ threshold take up 4 pages – less than 50% of the allowed decays are known



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

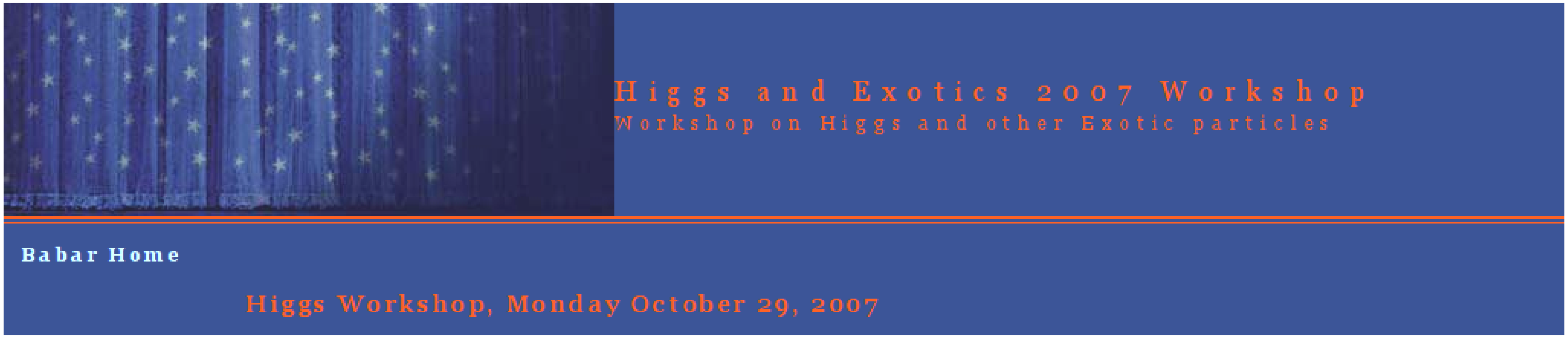
The case for BaBar taking data at one of the narrow Upsilon resonances built over time, and involved the whole collaboration. Here are just a few snapshots . . .

June Collaboration Meeting, 2007



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

October, 2007



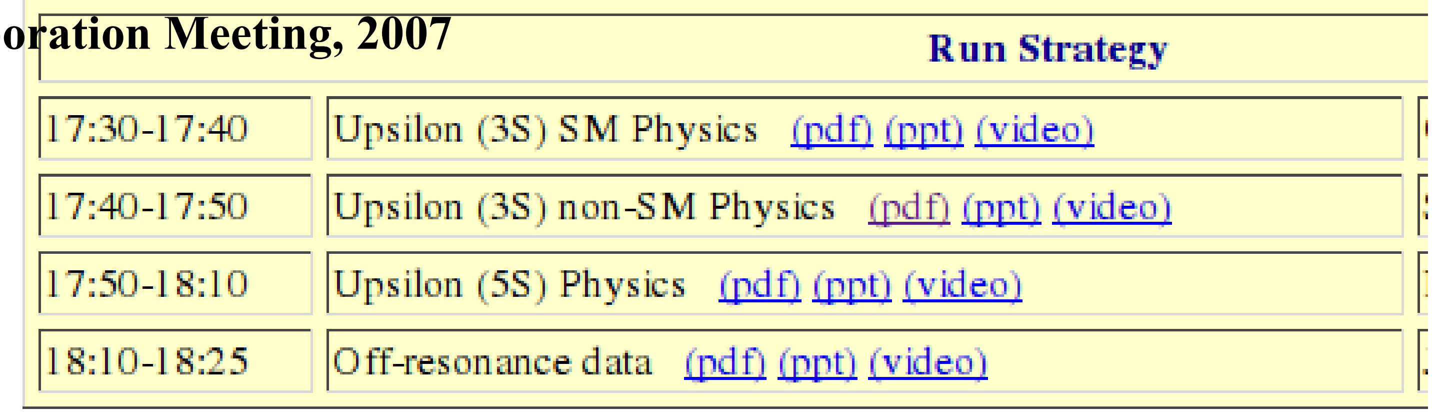
Higgs and Exotics 2007 Workshop

Workshop on Higgs and other Exotic particles

Babar Home

Higgs Workshop, Monday October 29, 2007

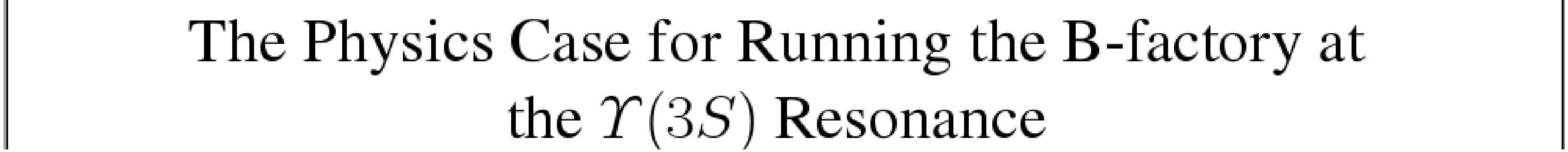
December Collaboration Meeting, 2007



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)

After December 17, 2007:

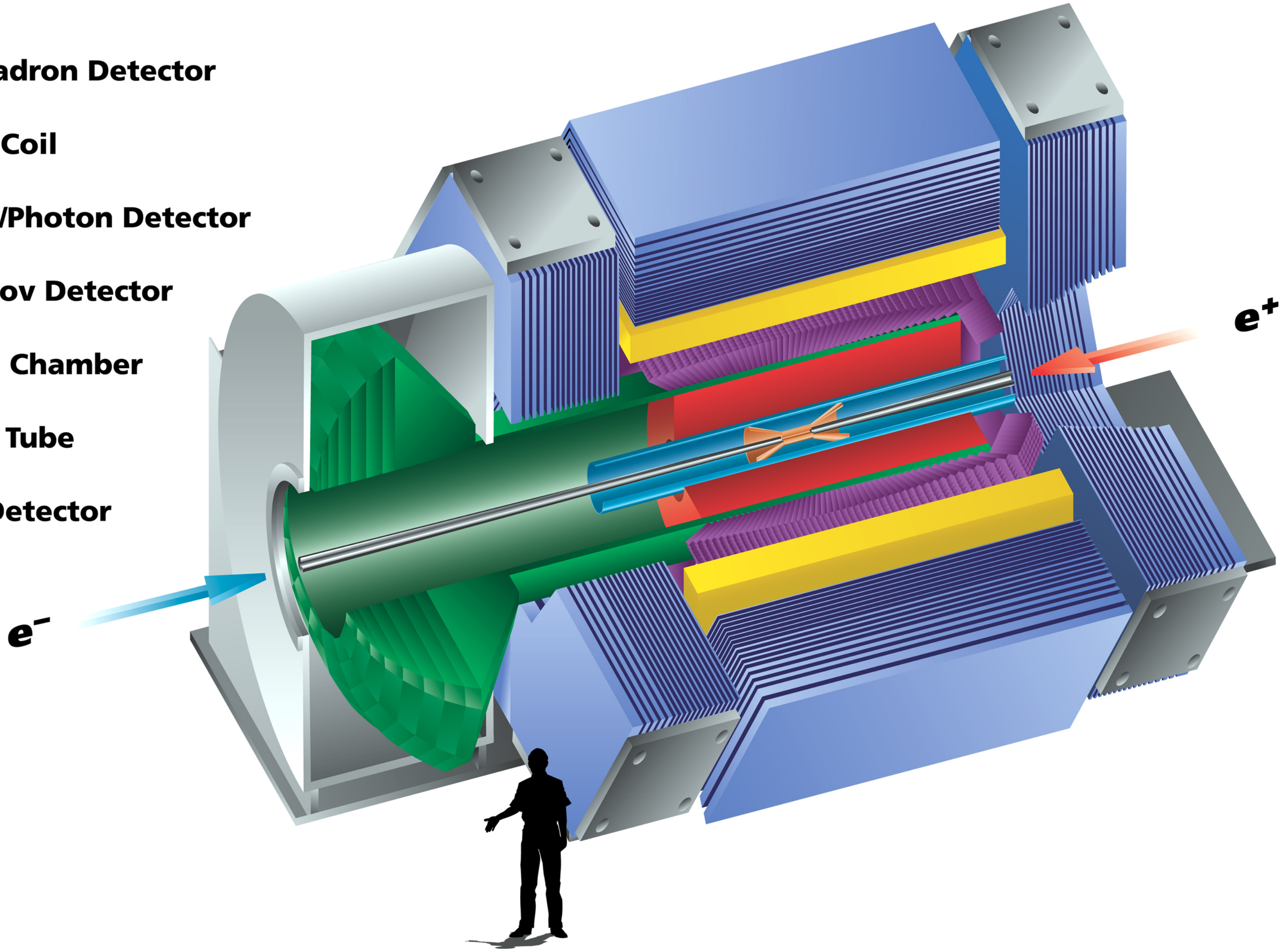


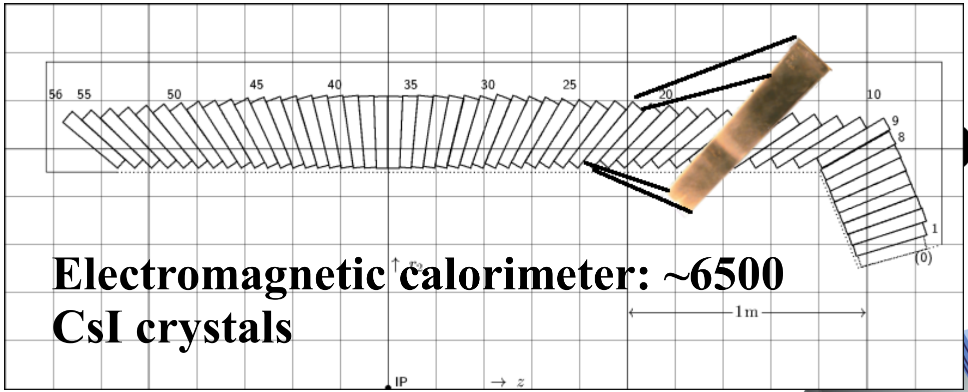
The Physics Case for Running the B-factory at the $\Upsilon(3S)$ Resonance

The BaBar/PEP-II b-Factory

BaBar Detector

- 🟦 **Muon/Hadron Detector**
- 🟨 **Magnet Coil**
- 🟪 **Electron/Photon Detector**
- 🟩 **Cherenkov Detector**
- 🟥 **Tracking Chamber**
- 🟦 **Support Tube**
- 🟧 **Vertex Detector**

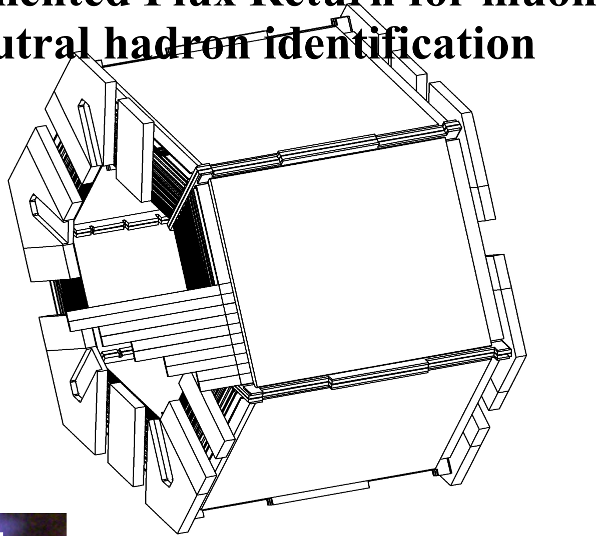


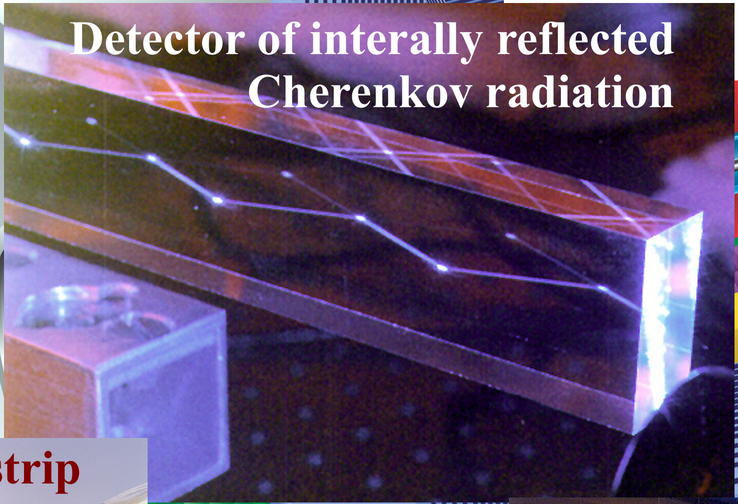


Electromagnetic calorimeter: ~6500 CsI crystals

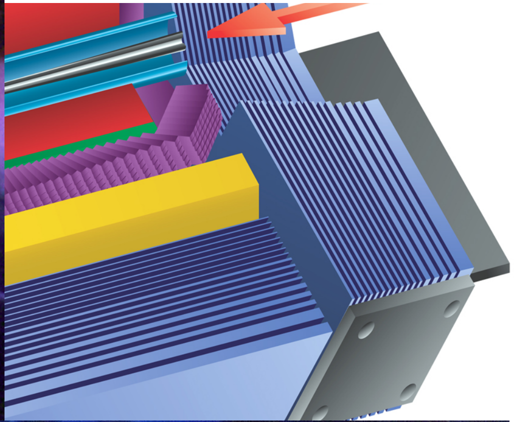
- 🟪 **Electron/Photon Detector**
- 🟩 **Cherenkov Detector**
- 🟥 **Tracking Chamber**
- 🟦 **Support Tube**
- 🟧 **Vertex Detector**

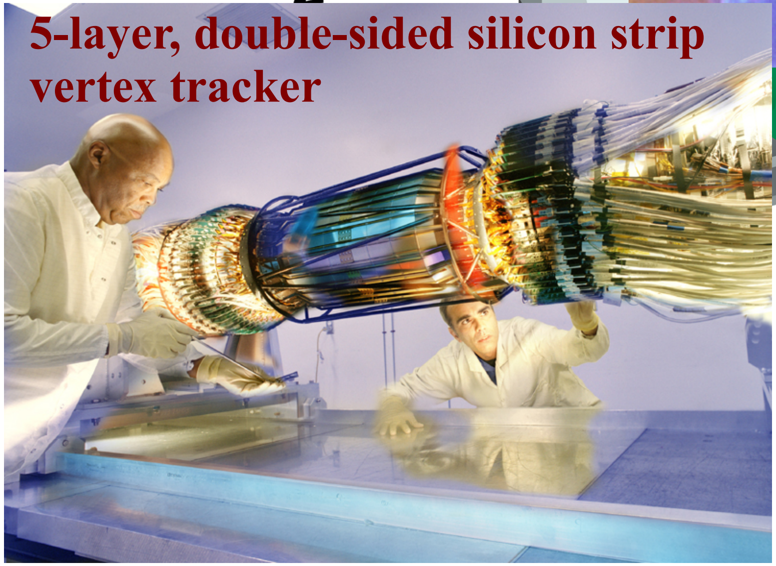
Instrumented Flux Return for muon and neutral hadron identification



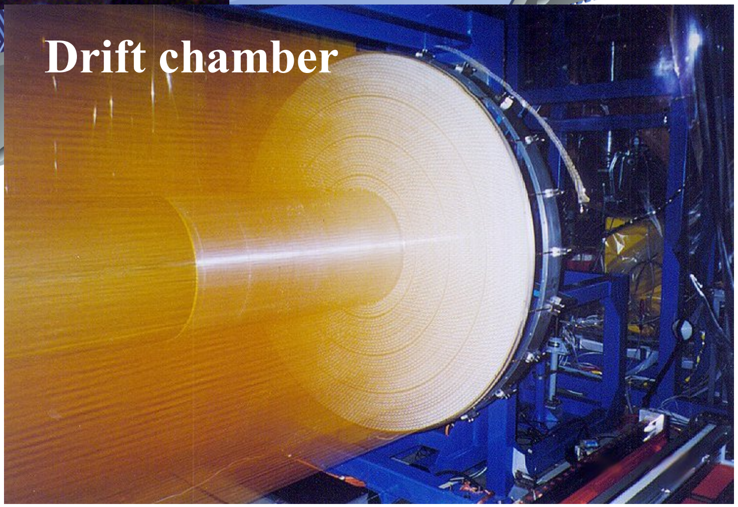


Detector of interally reflected Cherenkov radiation

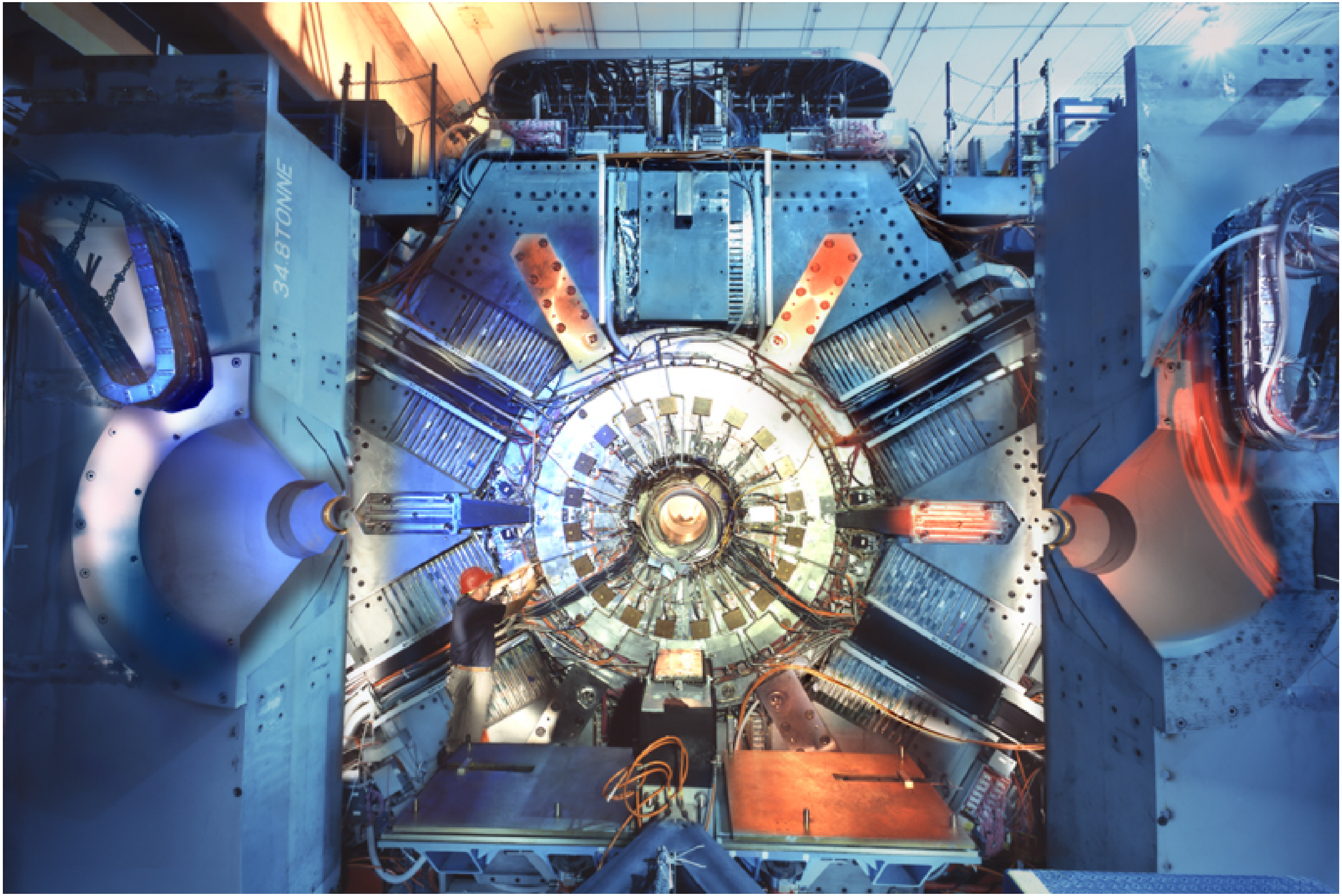




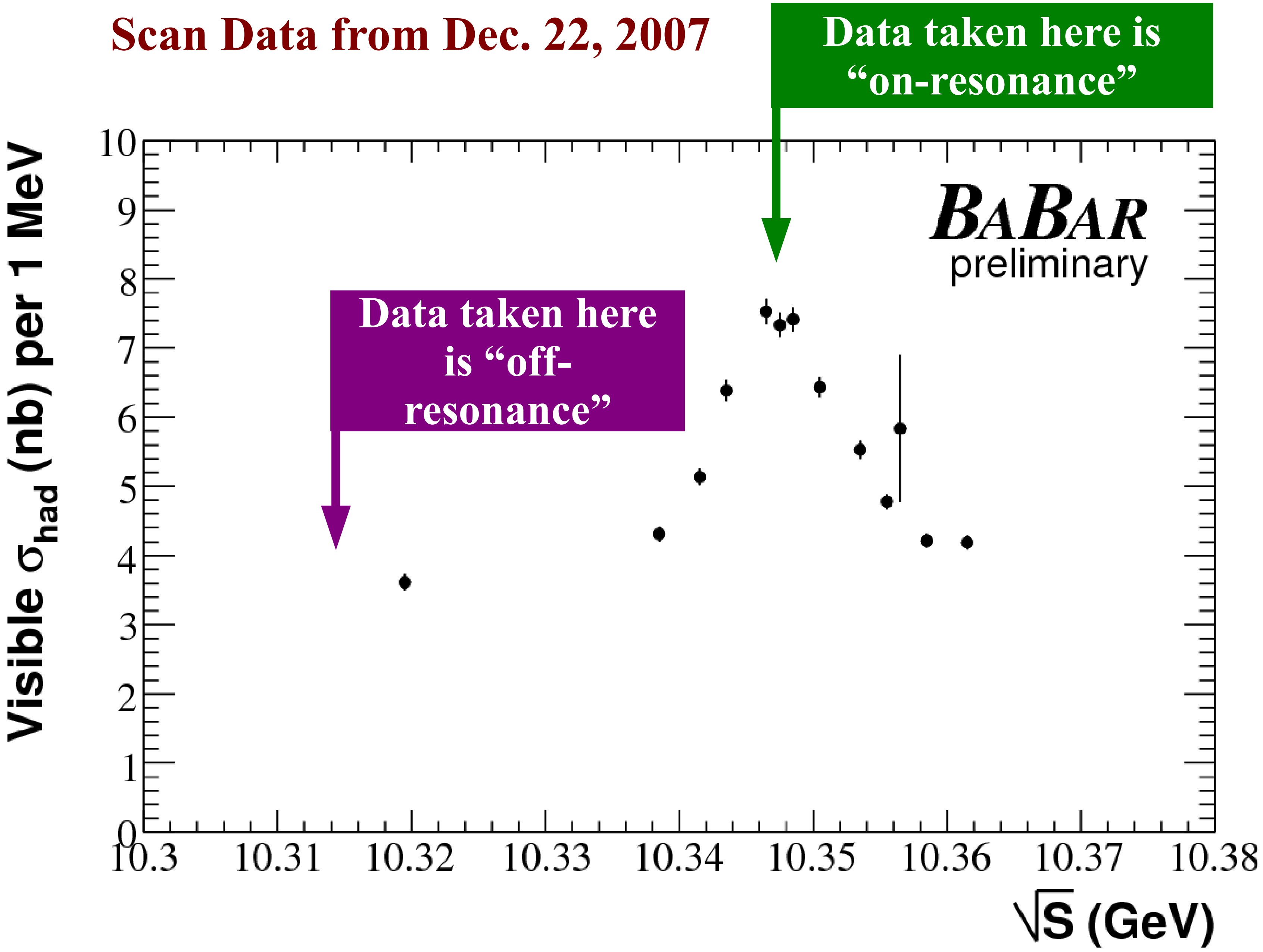
5-layer, double-sided silicon strip vertex tracker



Drift chamber

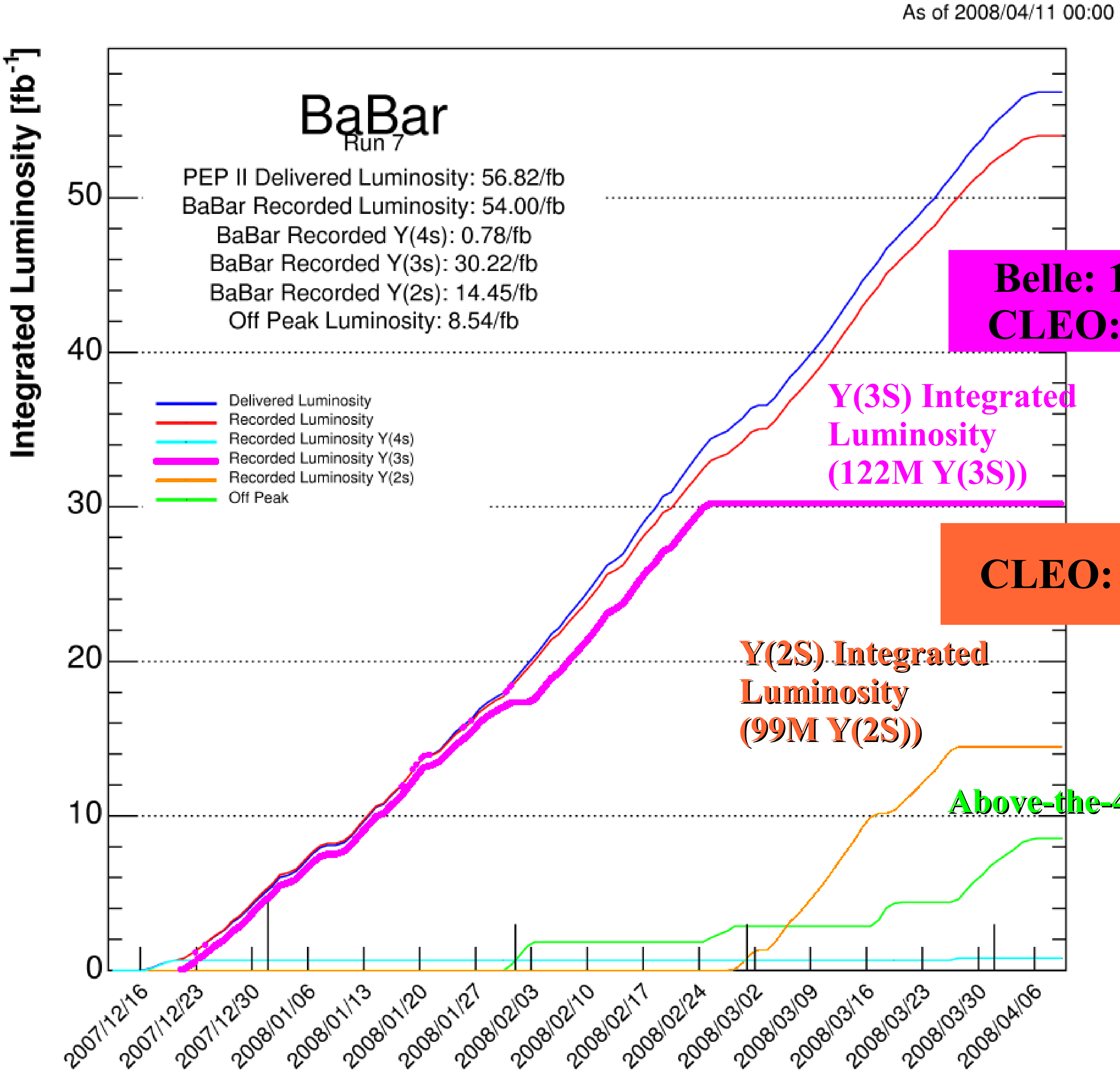

34.8TONNE

Scan Data from Dec. 22, 2007



Data taken here is “on-resonance”

Data taken here is “off-resonance”



Belle: 11M
CLEO: 6M

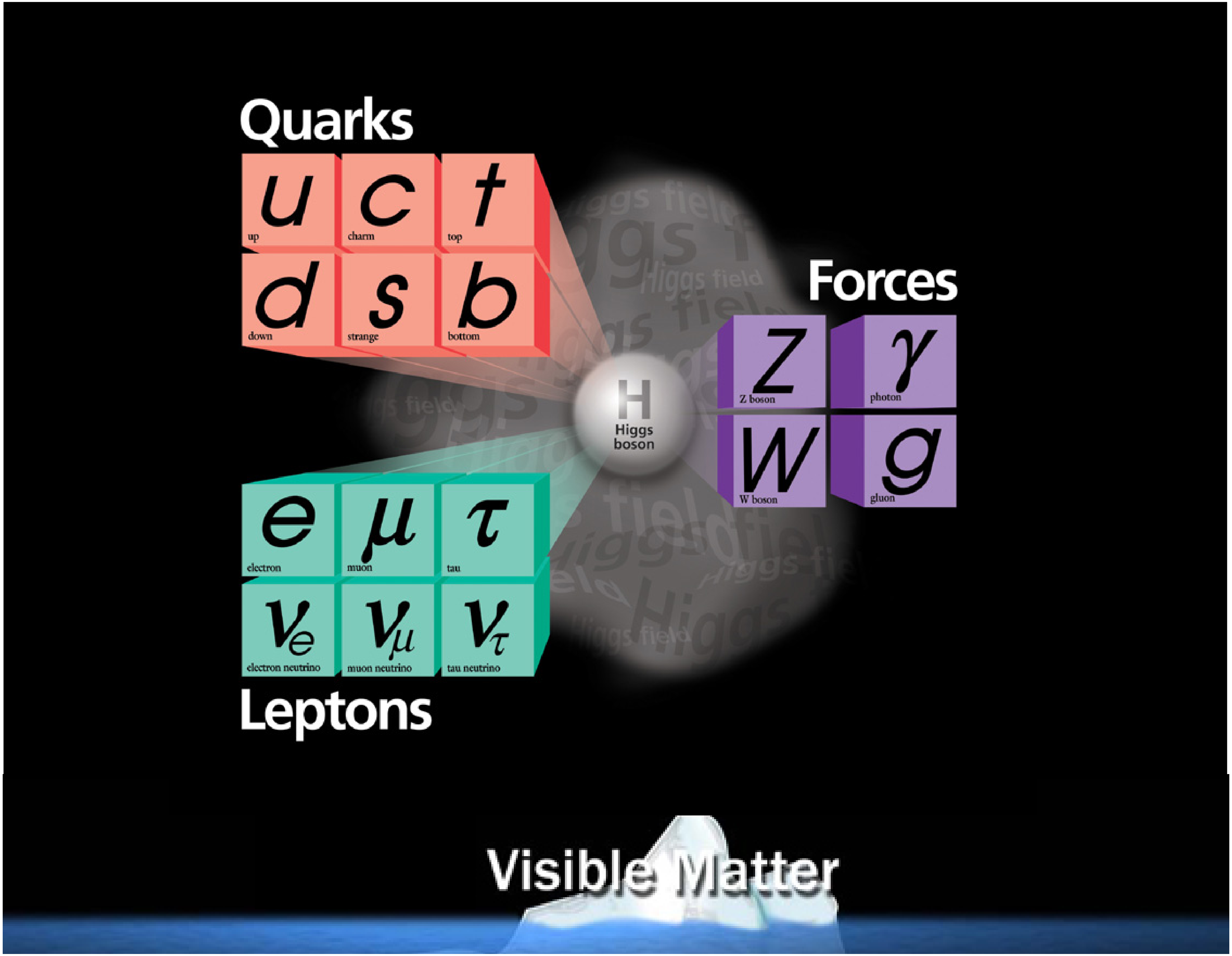
Y(3S) Integrated Luminosity (122M Y(3S))

CLEO: 9M

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

Above-the-4S Scan

A matter of QCD:
The search for the η_b


Quarks
u
up
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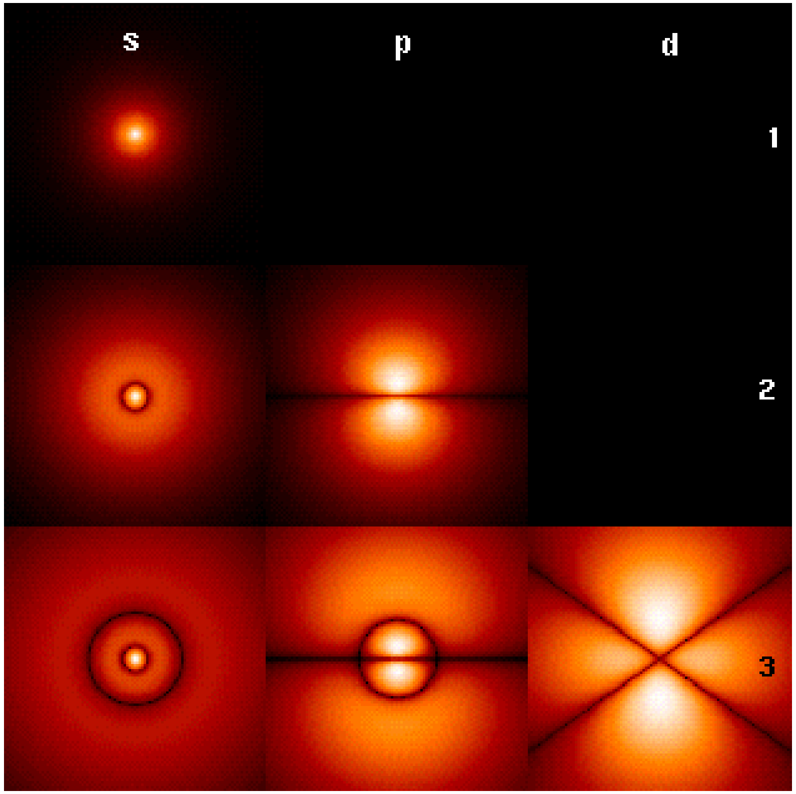
Forces
Z
Z boson
γ
photon
W
W boson
g
gluon
H
Higgs boson
Higgs field
e
electron
μ
muon
τ
tau
ν_e
electron neutrino
ν_μ
muon neutrino
ν_τ
tau neutrino
Leptons
Visible Matter

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, . . .)**



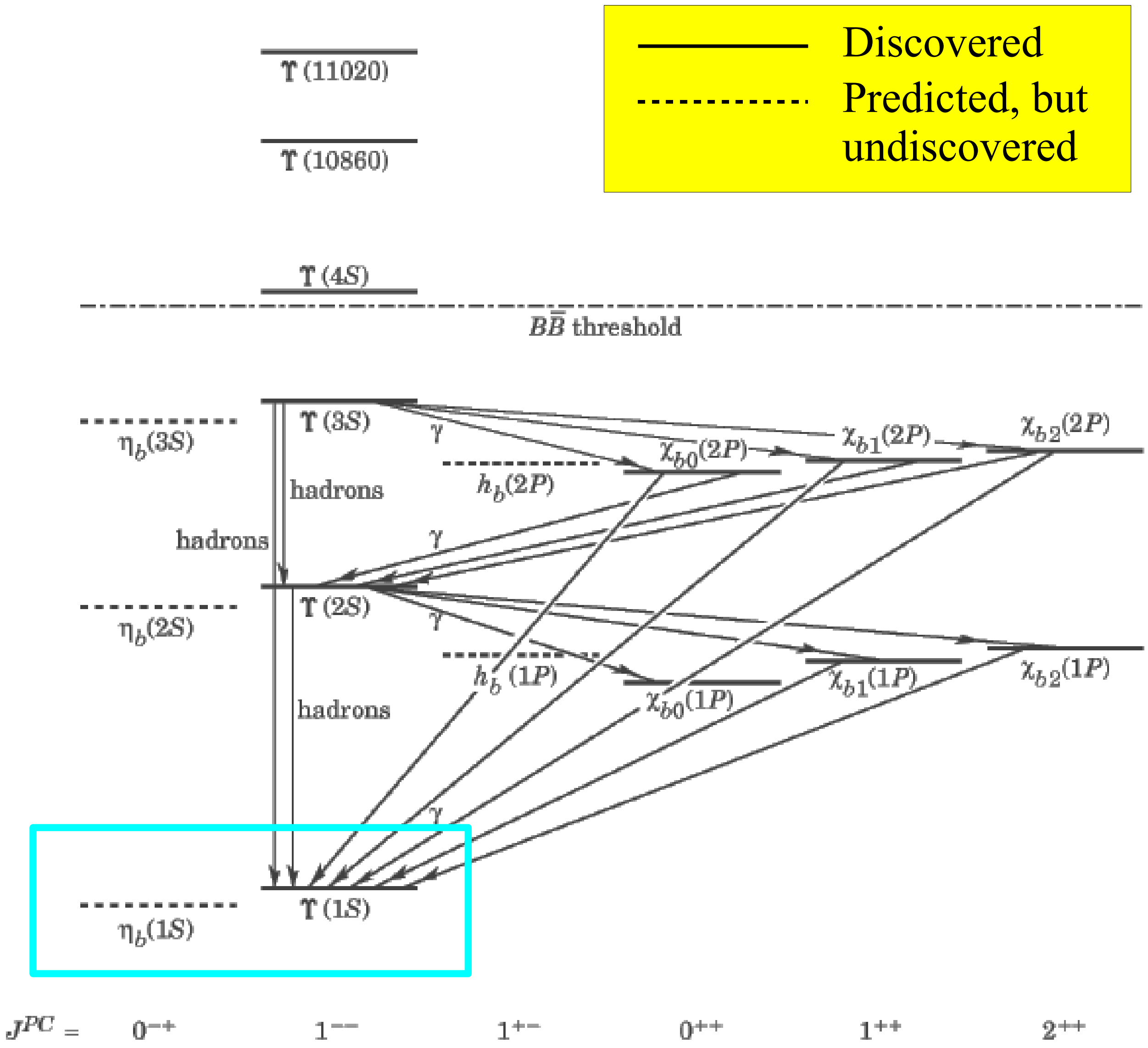
TOTAL ANGULAR MOMENTUM (J):

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

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 . . .

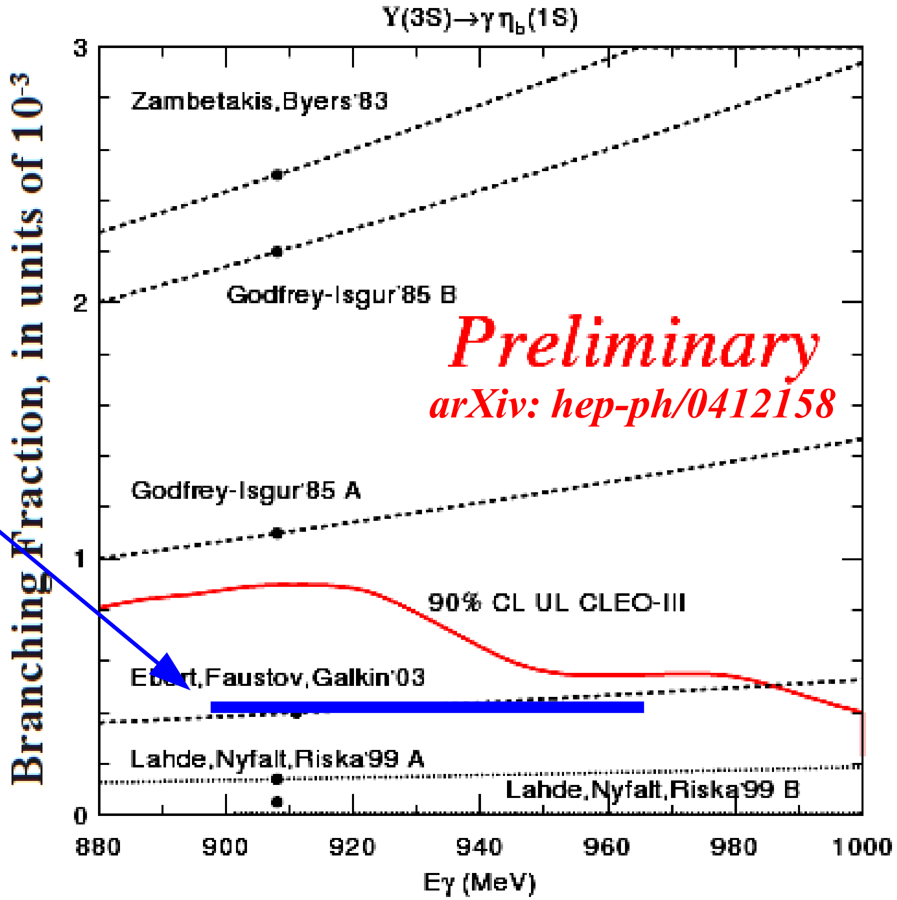
Hyperfine splitting predictions ($1^3S_1 - 1^1S_0$)

- 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)



Preliminary

arXiv: hep-ph/0412158

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

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

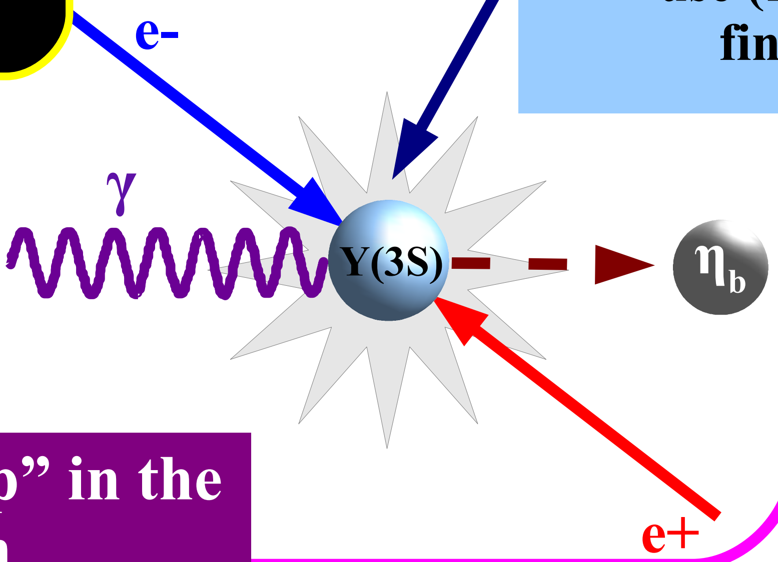
Blind Analysis

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 ± 1)×10^6 Υ(3S) for final result

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



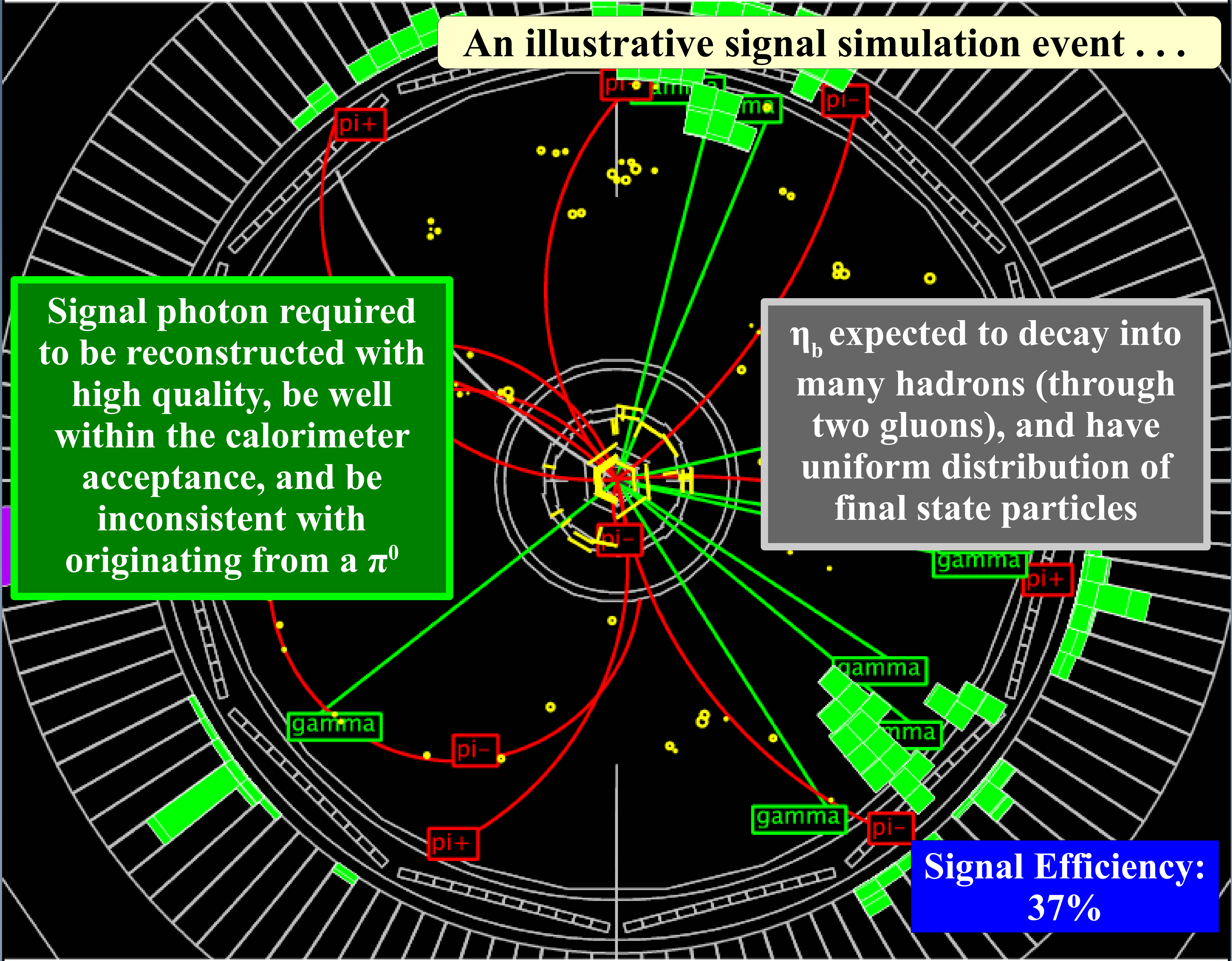
Search for a "bump" in the photon spectrum

- 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 . . .

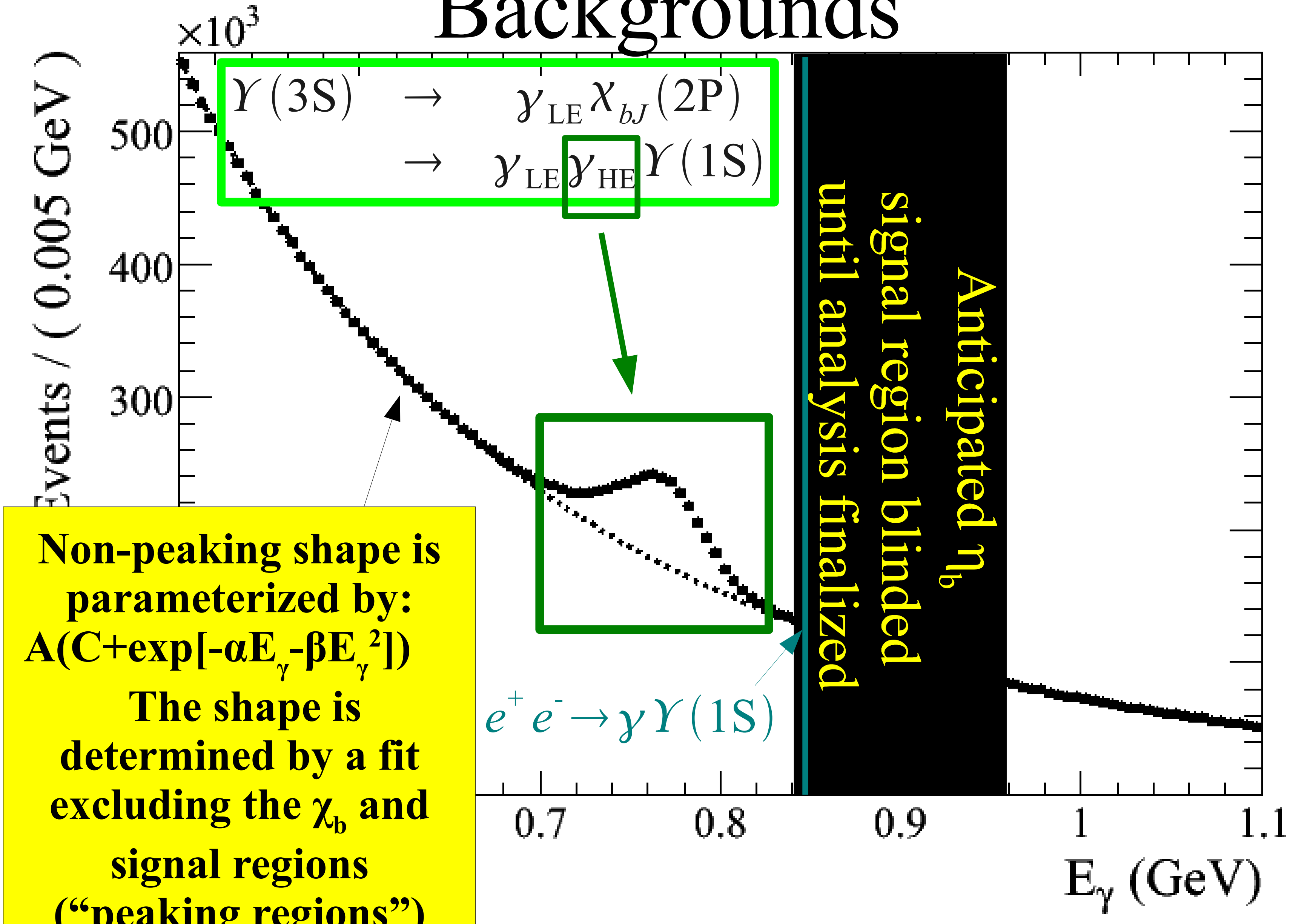


Signal photon required to be reconstructed with high quality, be well within the calorimeter acceptance, and be inconsistent with originating from a π^0

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



$$\Upsilon(3S) \rightarrow \gamma_{LE}\chi_{bJ}(2P)$$
$$\rightarrow \gamma_{LE}\boxed{\gamma_{HE}}\Upsilon(1S)$$

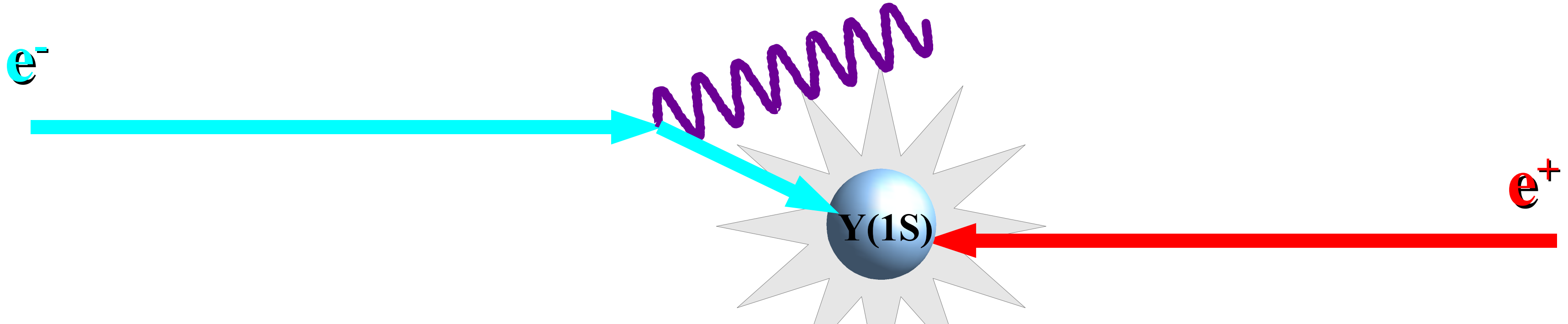
$e^+e^- \rightarrow \gamma\Upsilon(1S)$

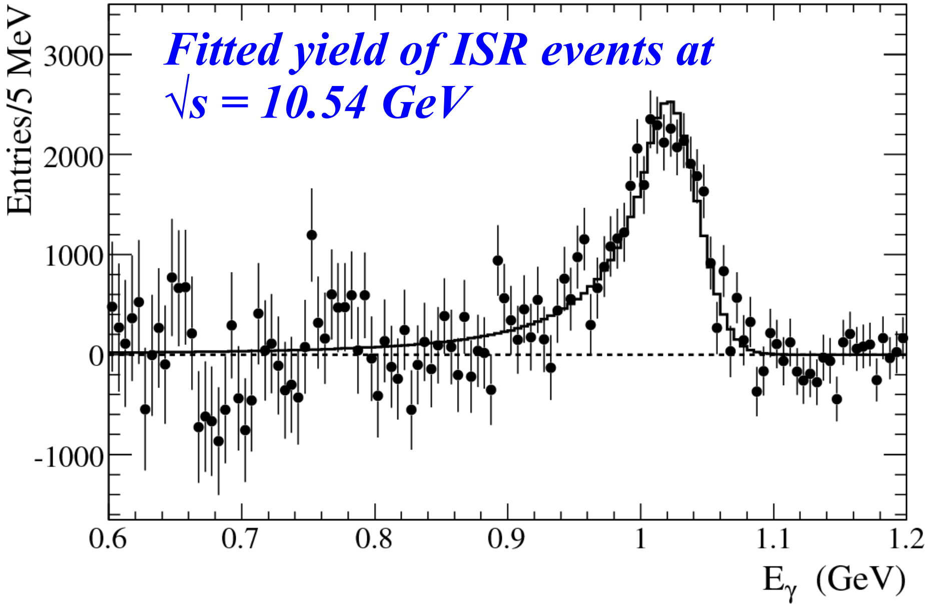
Anticipated η_b signal region blinded until analysis finalized

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 χ_b and signal regions ("peaking regions")

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





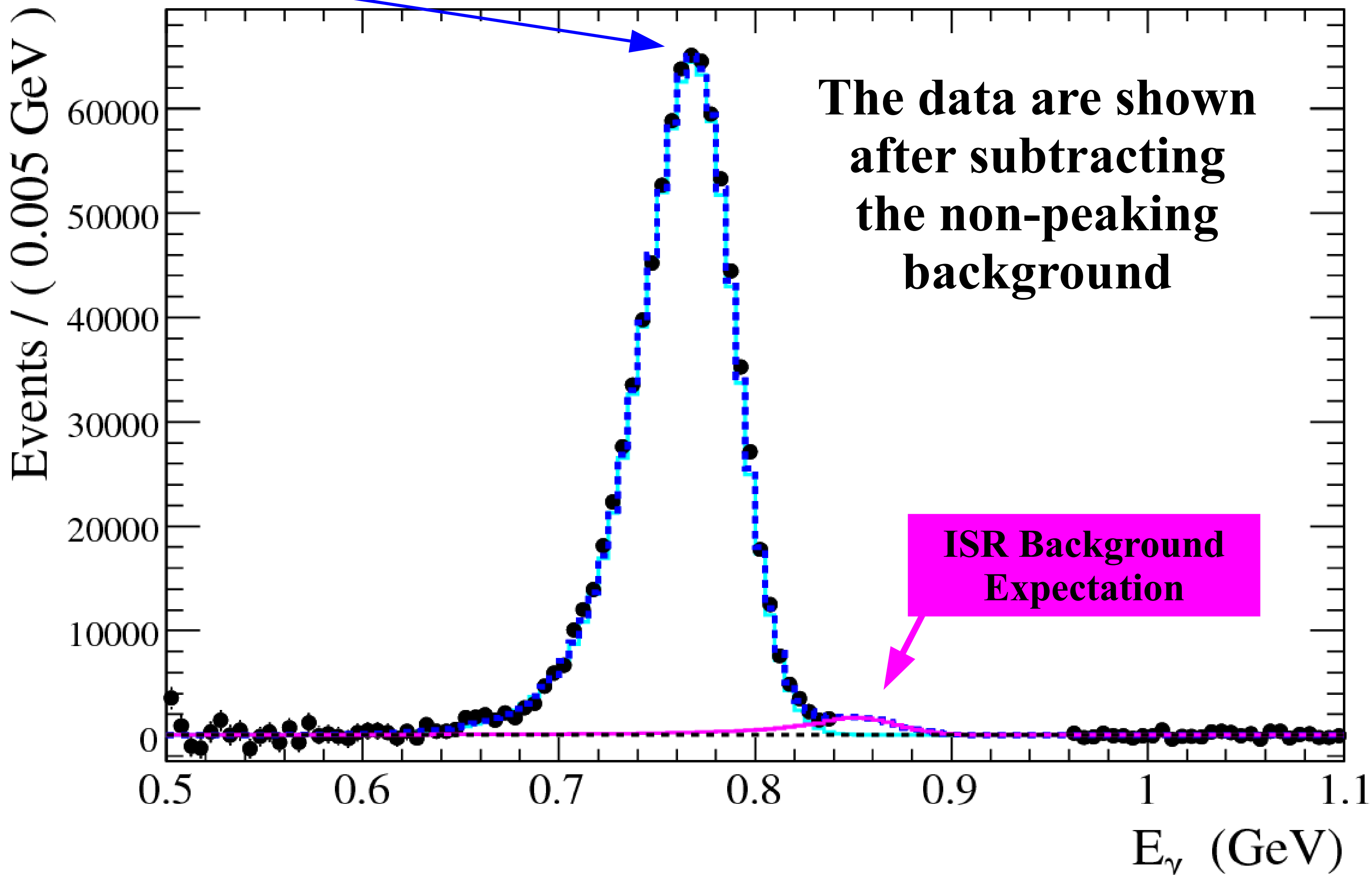
The fitted ISR shape is shifted down to the expected peak position for the Y(3S) CM energy. The yield is scaled using the ratio of cross-sections (computed from theory)

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

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

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

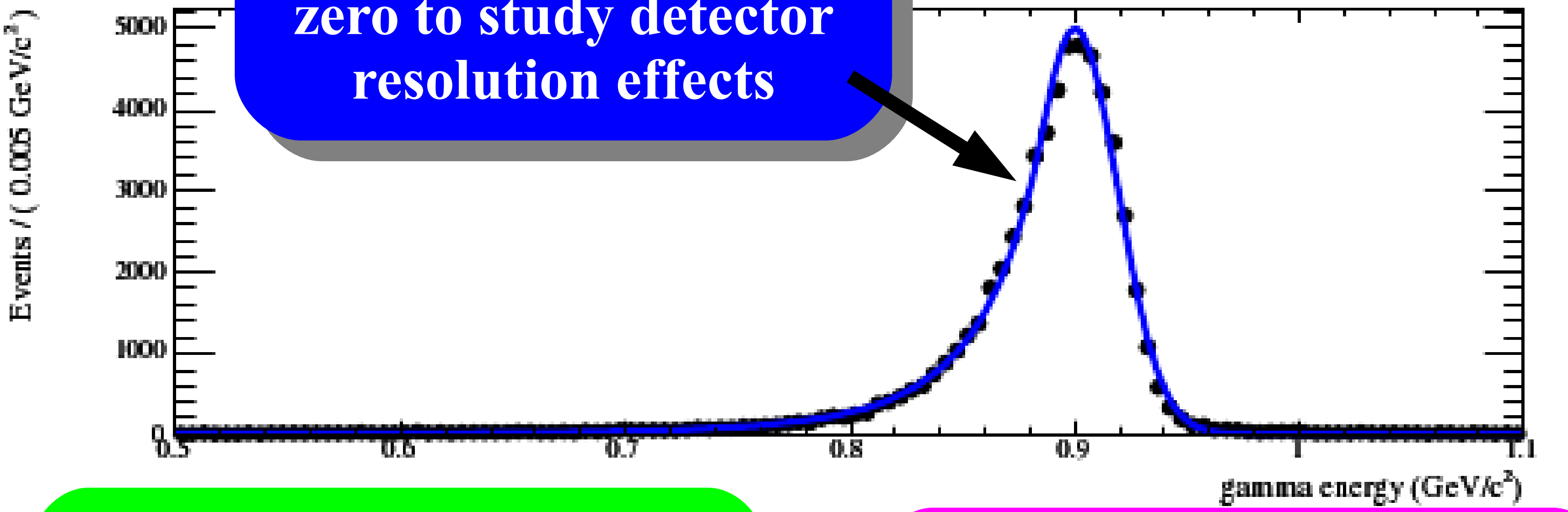


The data are shown after subtracting the non-peaking background

ISR Background Expectation

The η_b Signal Model

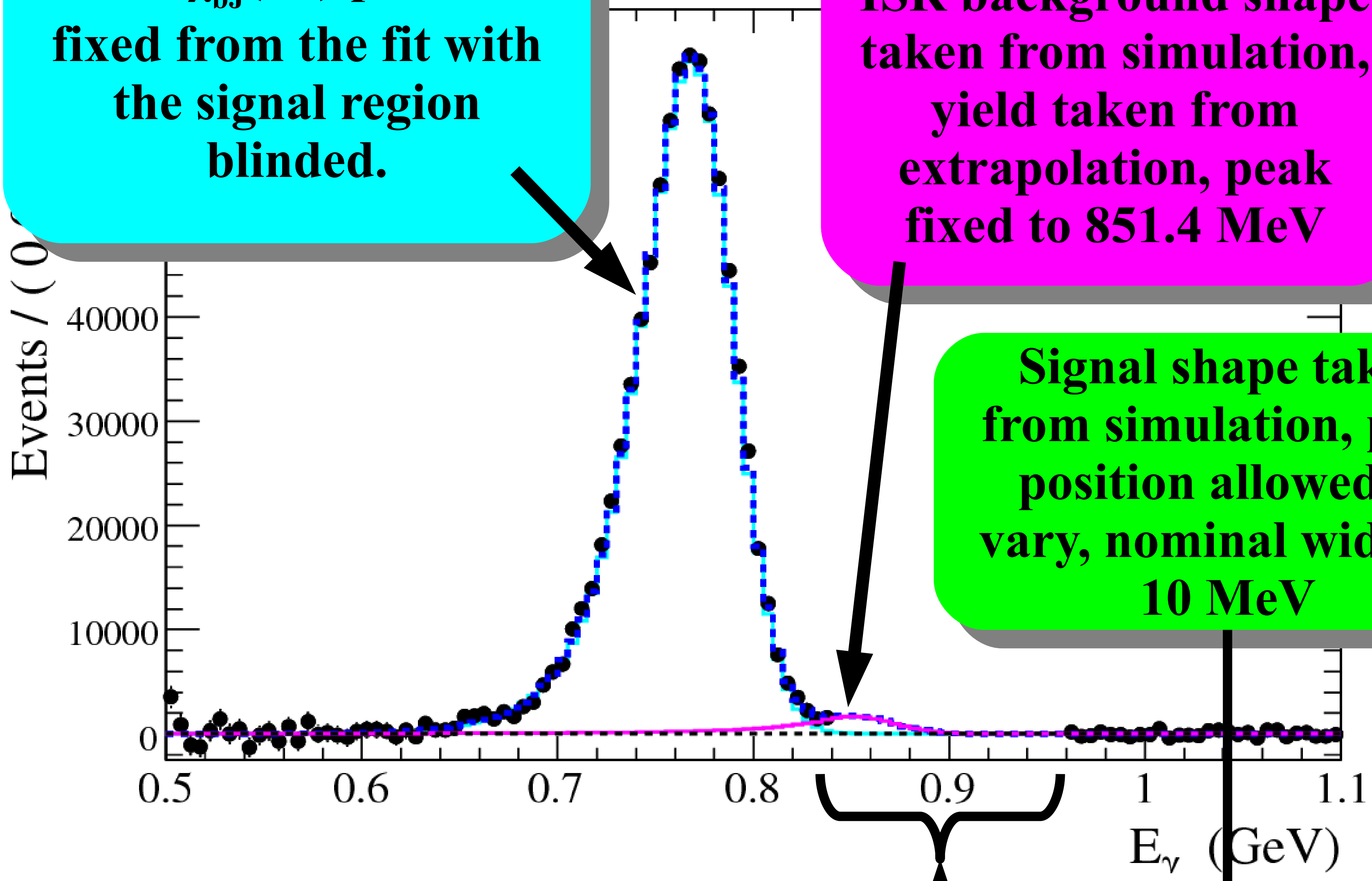
Use a Monte Carlo simulation of signal events. Set η_b width to zero to study detector resolution effects



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

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”

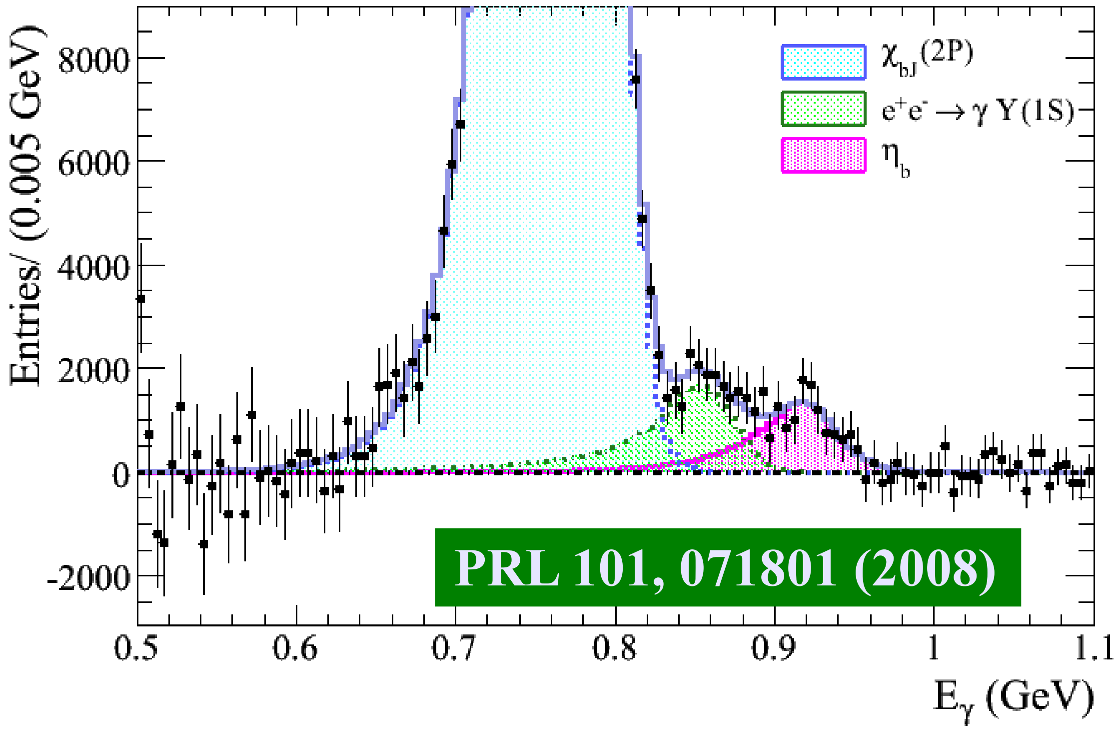


The $\chi_{bJ}(2P)$ peak is fixed from the fit with the signal region blinded.

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

Results



PRL 101, 071801 (2008)

Fitted signal yield:

19200 ± 2000 (stat.)
± 2100 (syst.)

Branching Fraction:

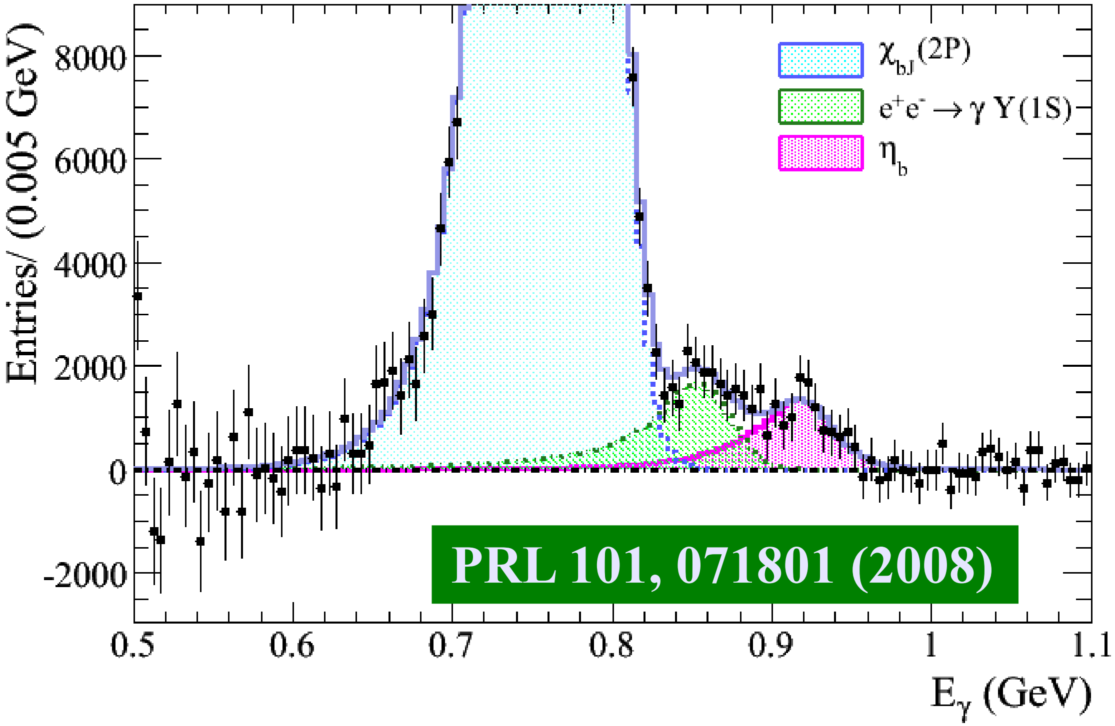
$(٤.٨ \pm ٠.٥ \pm ١.٢) \times ١٠^{-٤}$

Fitted Mean:	$E_\gamma = 921.2^{+2.1}_{-2.8} \pm 2.4\,\mathrm{MeV}$
Mass:	$9388.9^{+3.1}_{-2.3} \pm 2.7\,\mathrm{MeV}/c^2$
Hyperfine Splitting:	$71.4^{+2.3}_{-3.1} \pm 2.7\,\mathrm{MeV}/c^2$

Consistent with predictions of the η_b properties

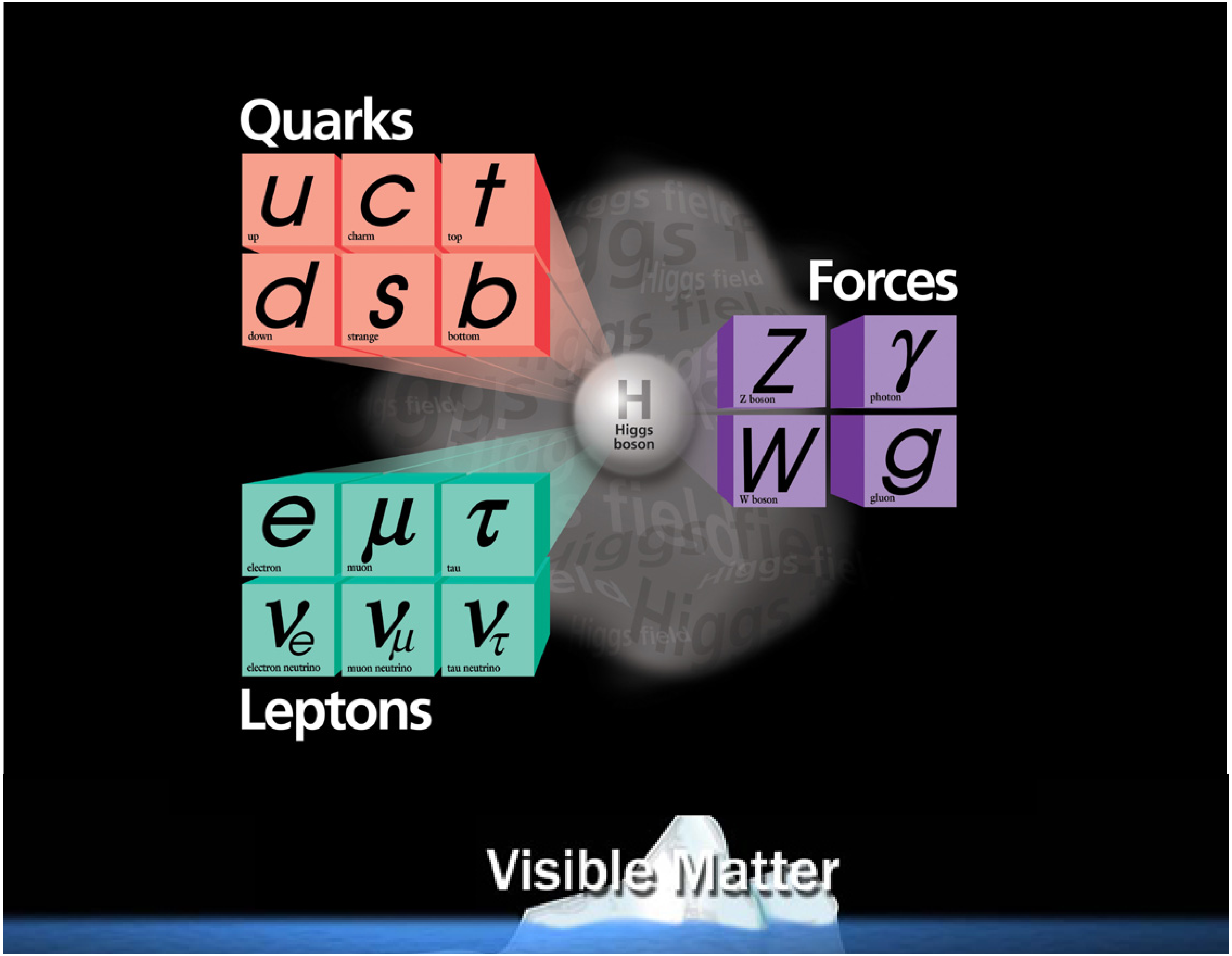
Is this really the ground state?

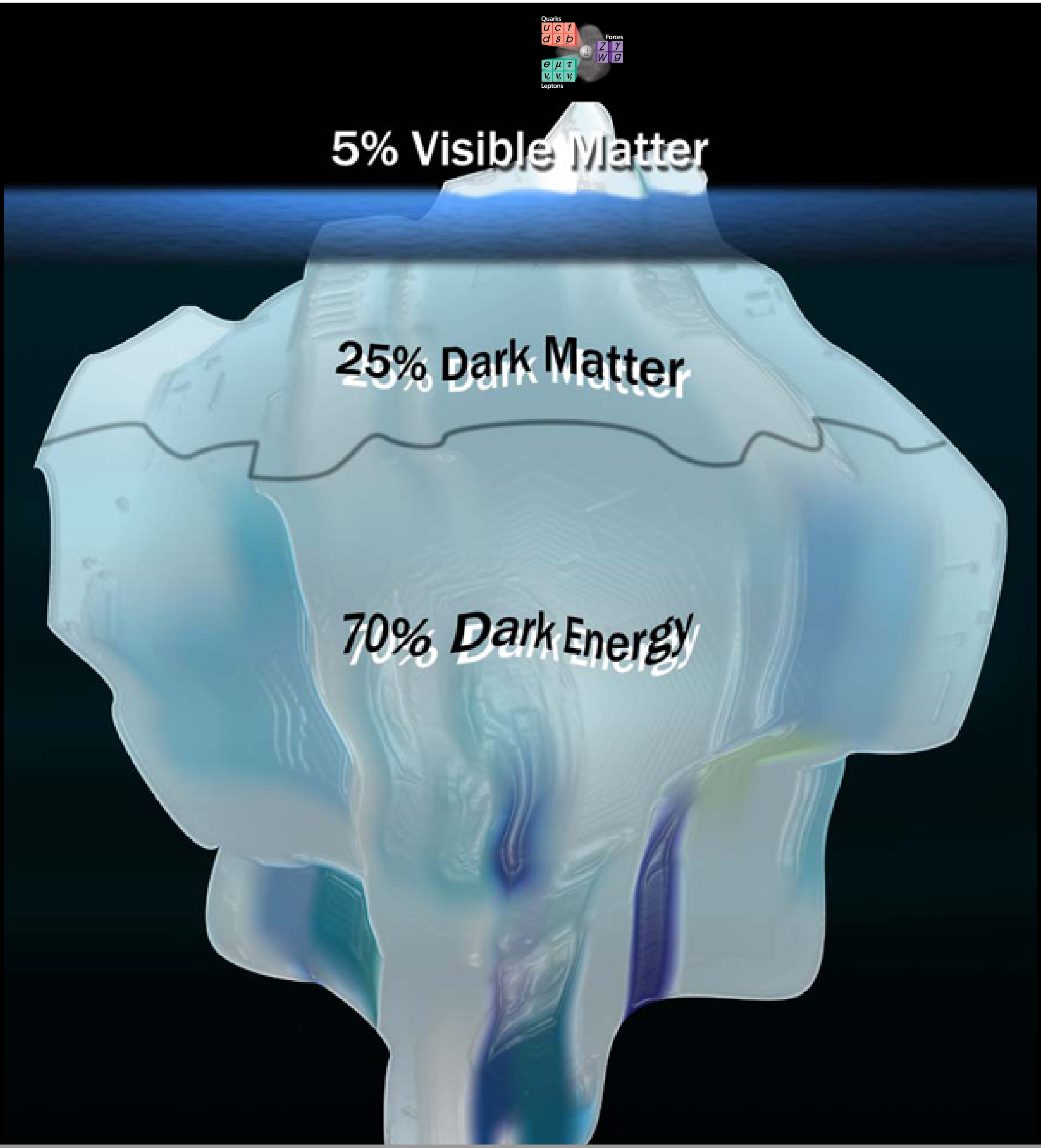
- photon angular distribution can tell us the spin
- are the dominant decay modes to hadrons?
- do we see the "same" state in Υ(2S) → $\gamma\ \eta_b$?



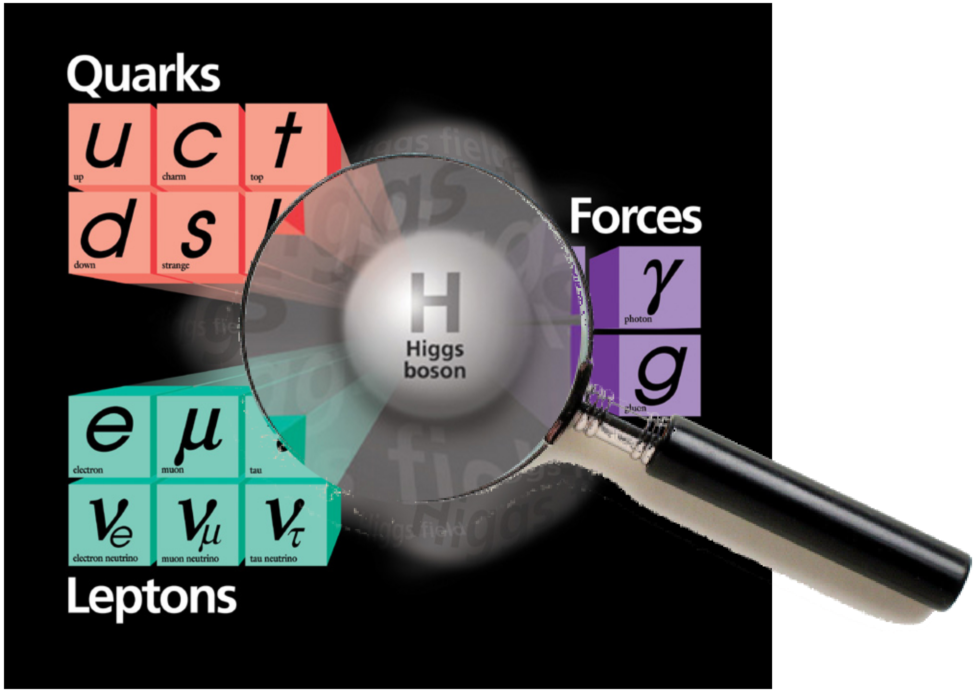
PRL 101, 071801 (2008)

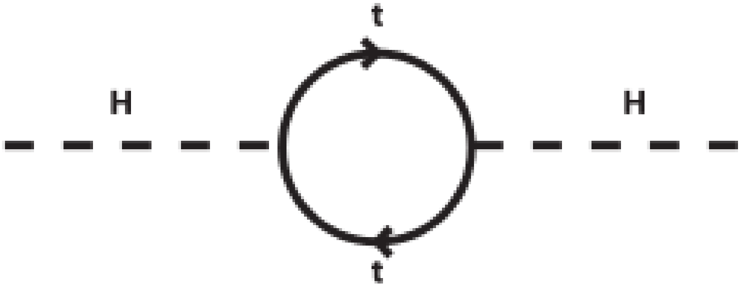
A Matter of New Physics: Search for a Light CP-Odd Higgs


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
Higgs field
e electron
μ muon
τ tau
νe electron neutrino
νμ muon neutrino
ντ tau neutrino
Leptons
Visible Matter

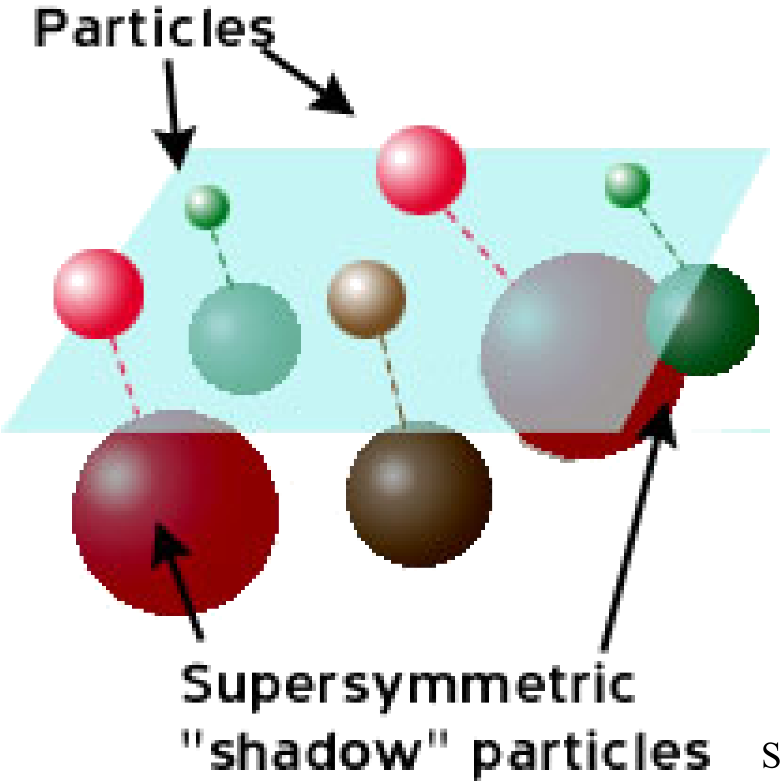


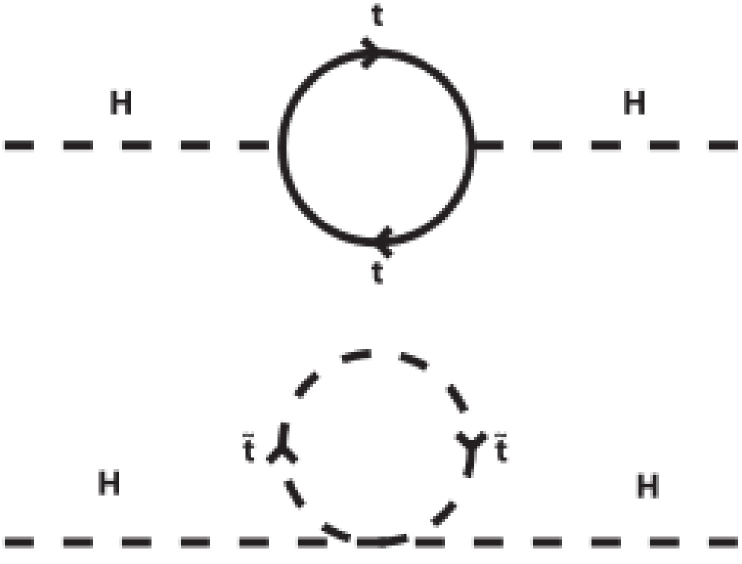
Can we solve the dark matter puzzle and illuminate the Higgs sector at the same time?





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





Loops involving superpartners cancel divergences!

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)

$$\mu H_u H_d \longrightarrow \lambda N H_u H_d$$

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

Parameter Scan

blue points: $m_{A0} < 2m_\tau$

red points: $2m_\tau < m_{A0} < 7.5$ GeV

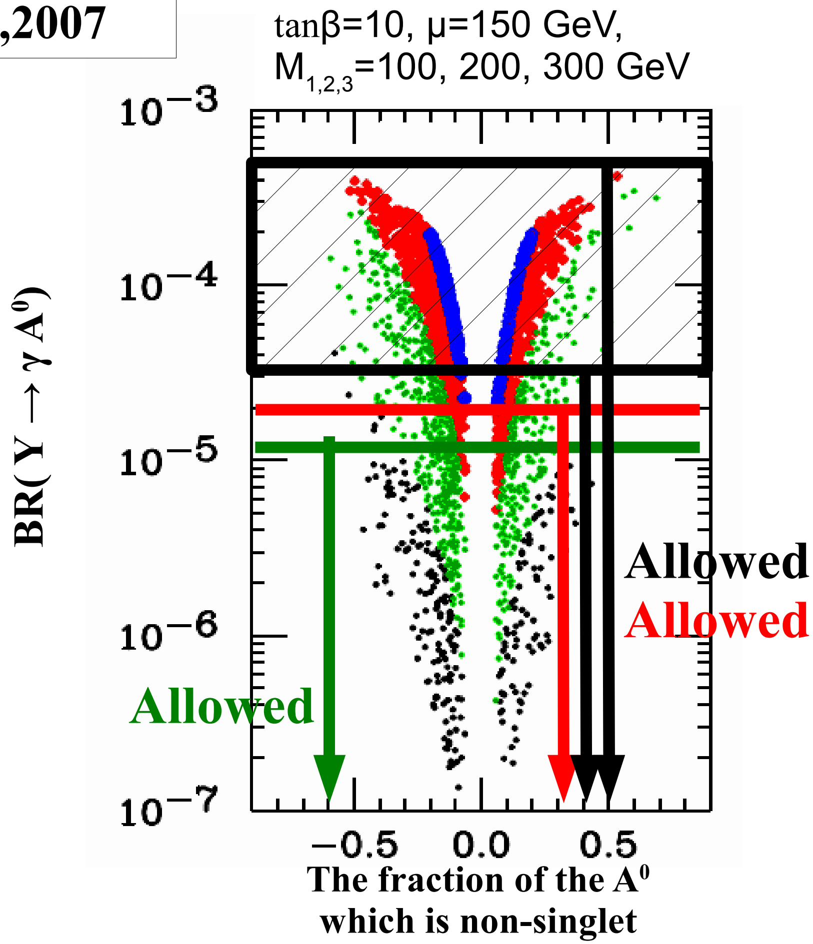
green points: 7.5 GeV $< m_{A0} <$ 8.8 GeV

black points: 8.8 GeV $< m_{A0} <$ 9.2 GeV

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

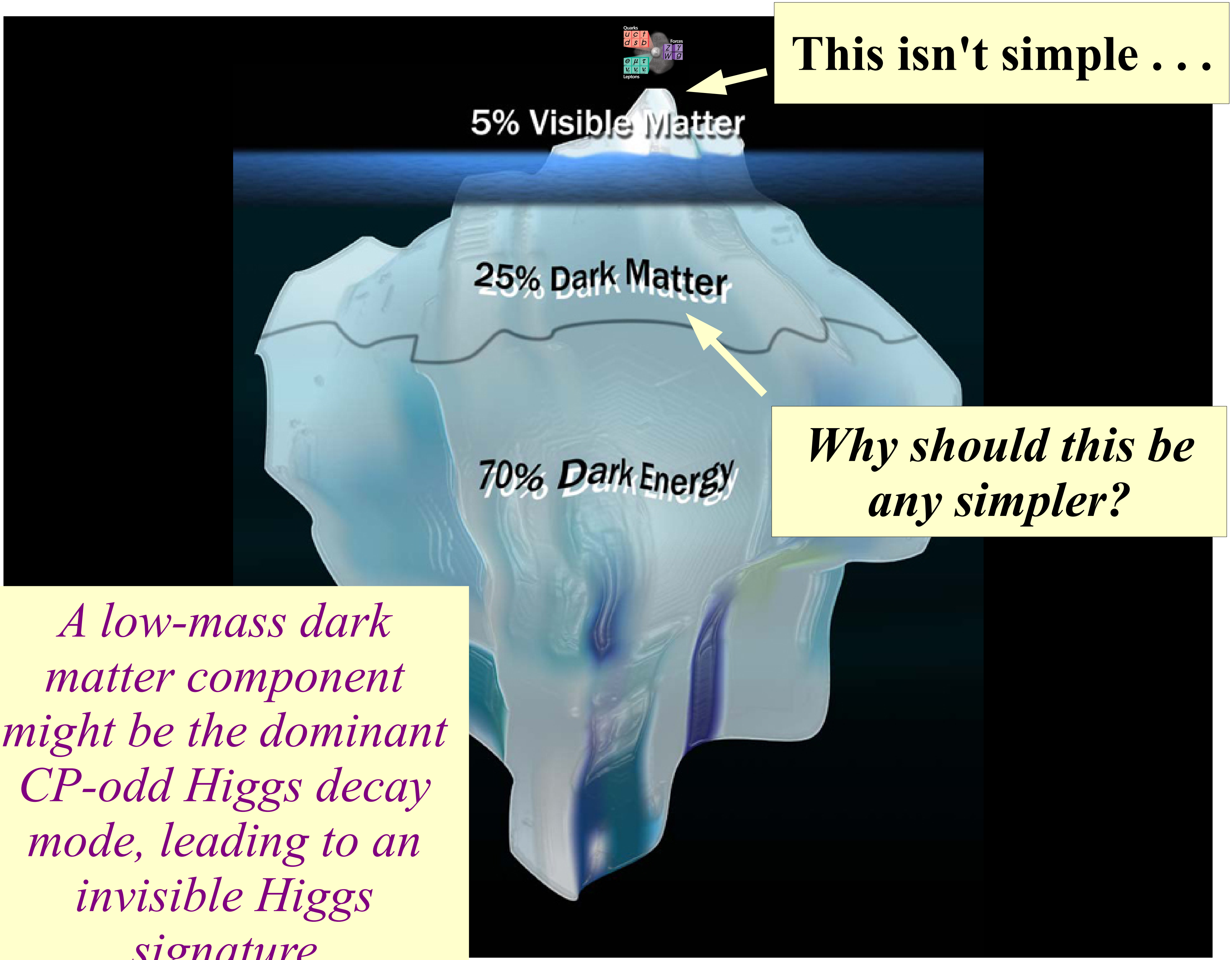
For a light A^0, the dominant SM Higgs decay will be $h \to A^0 A^0$

Depending on the A^0 mass, the dominant decay could be:
$A^0 \to \tau^+ \tau^-$
Leading to 4-τ final states at LEP, which were never explored.



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

hep/ex arXiv:0807.1427

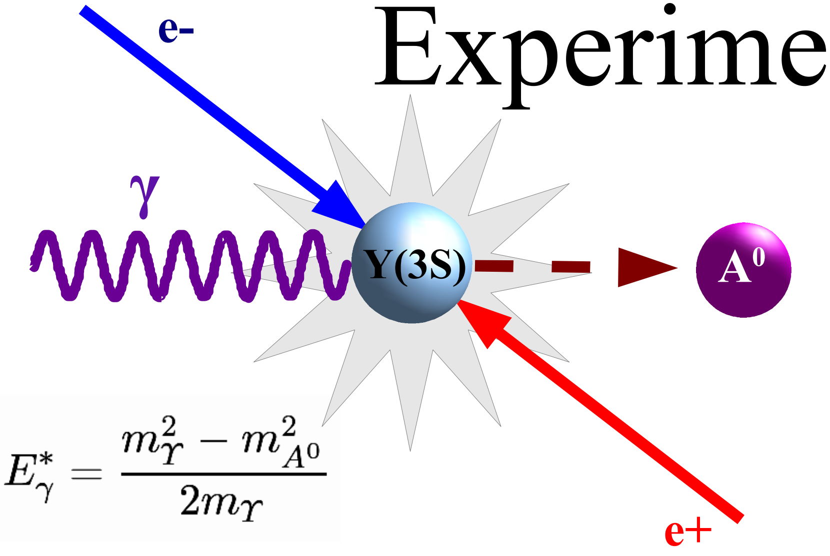


This isn't simple . . .

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

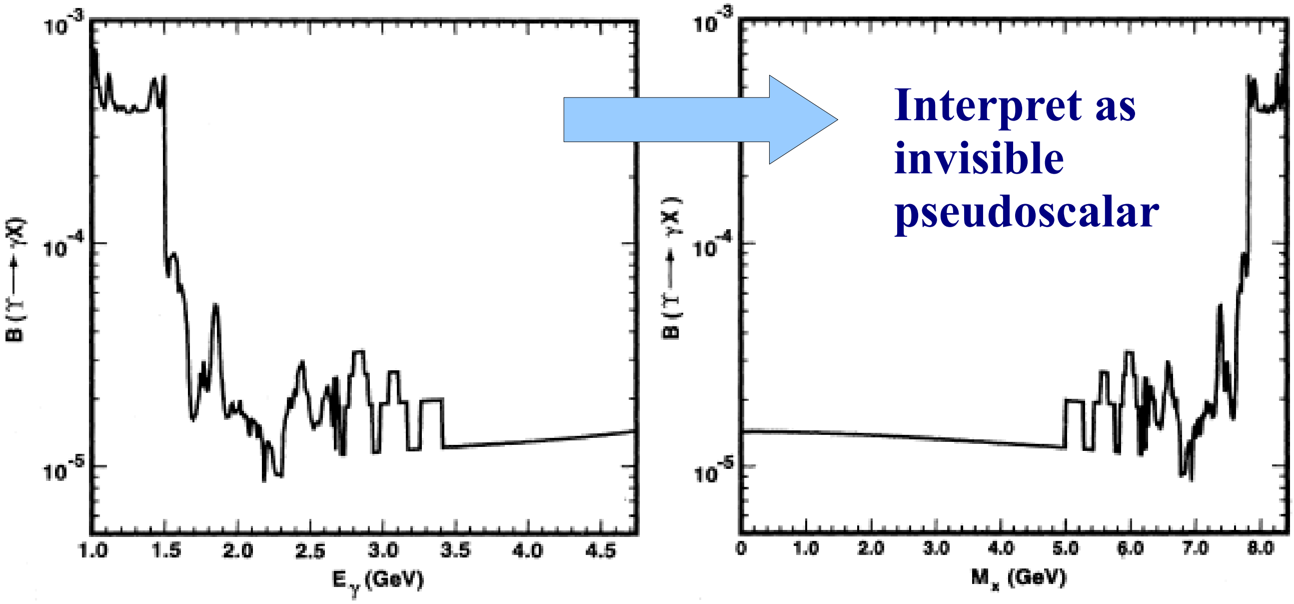


$$E^*_\gamma = \frac{m^2_\Upsilon - m^2_{A^0}}{2m_\Upsilon}$$

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

---

$\Upsilon(1S) \rightarrow \gamma + \text{noninteracting particles}$ (best existing limits from CLEO), for $1.0<E_\gamma<4.7$ GeV, range between about 10^{-5} and 6×10^{-4}, and were obtained while running at the Y(1S).

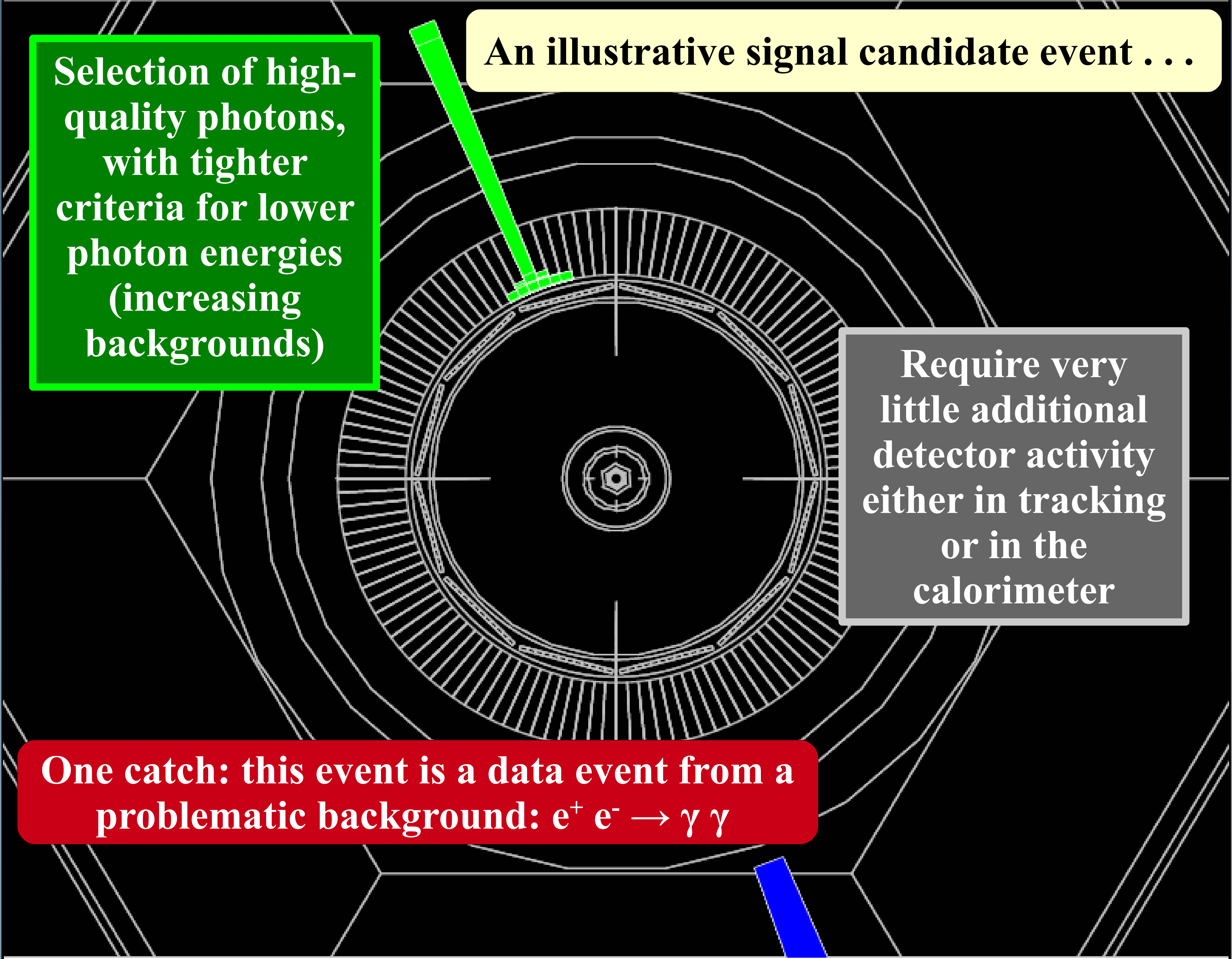


Interpret as invisible pseudoscalar

PRD 51, no. 5 2053 (1995)

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

An illustrative signal candidate event . . .

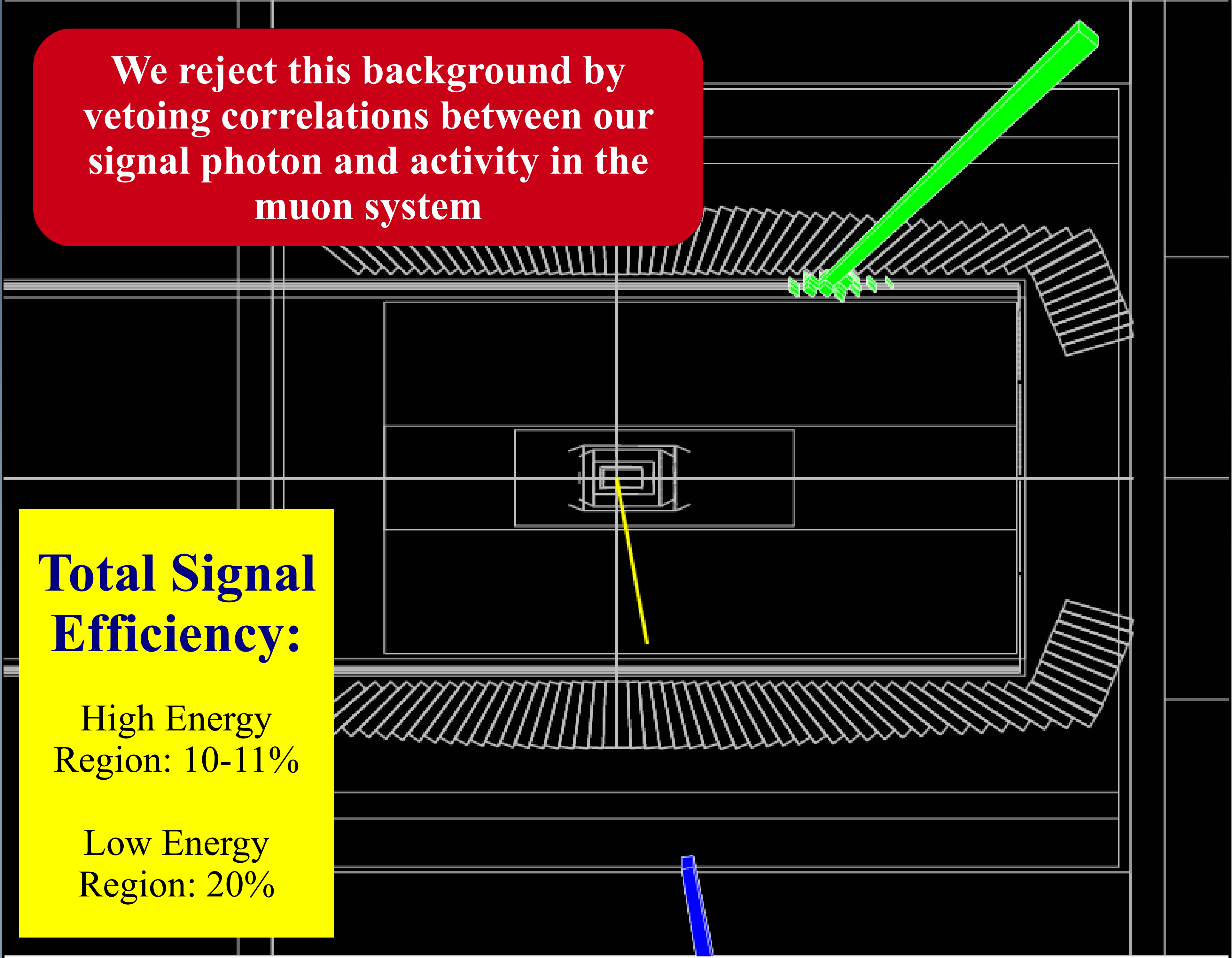


Selection of high-quality photons, with tighter criteria for lower photon energies (increasing backgrounds)

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

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

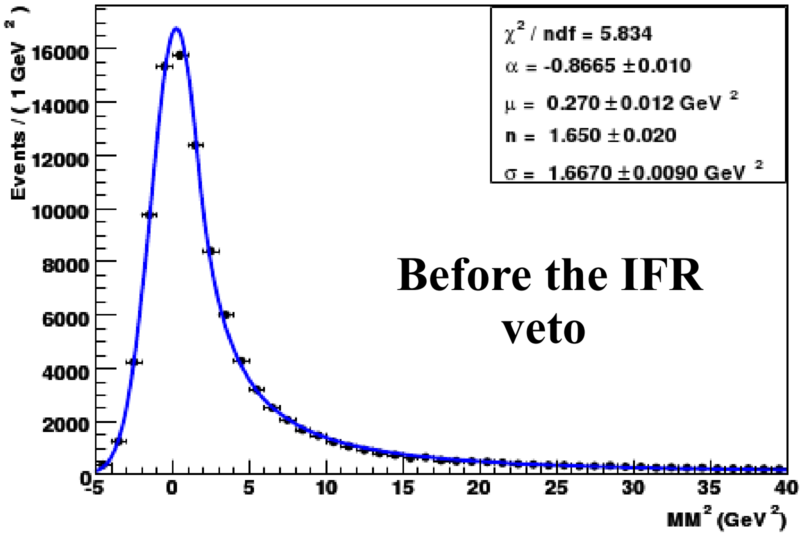
- 1-D fit to the missing mass-squared:

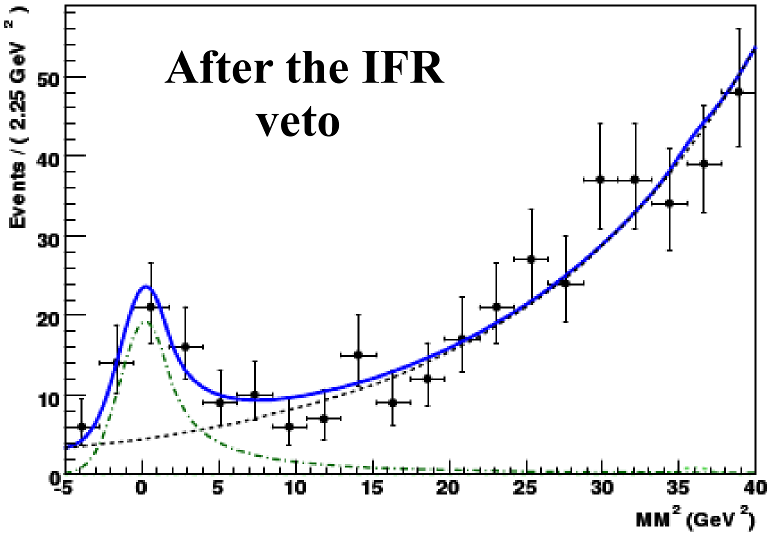
$$m_X^2 = M_{\Upsilon(3S)}^2 - 2E_\gamma^* M_{\Upsilon(3S)}$$

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

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

Off-Resonance Υ(3S) Data



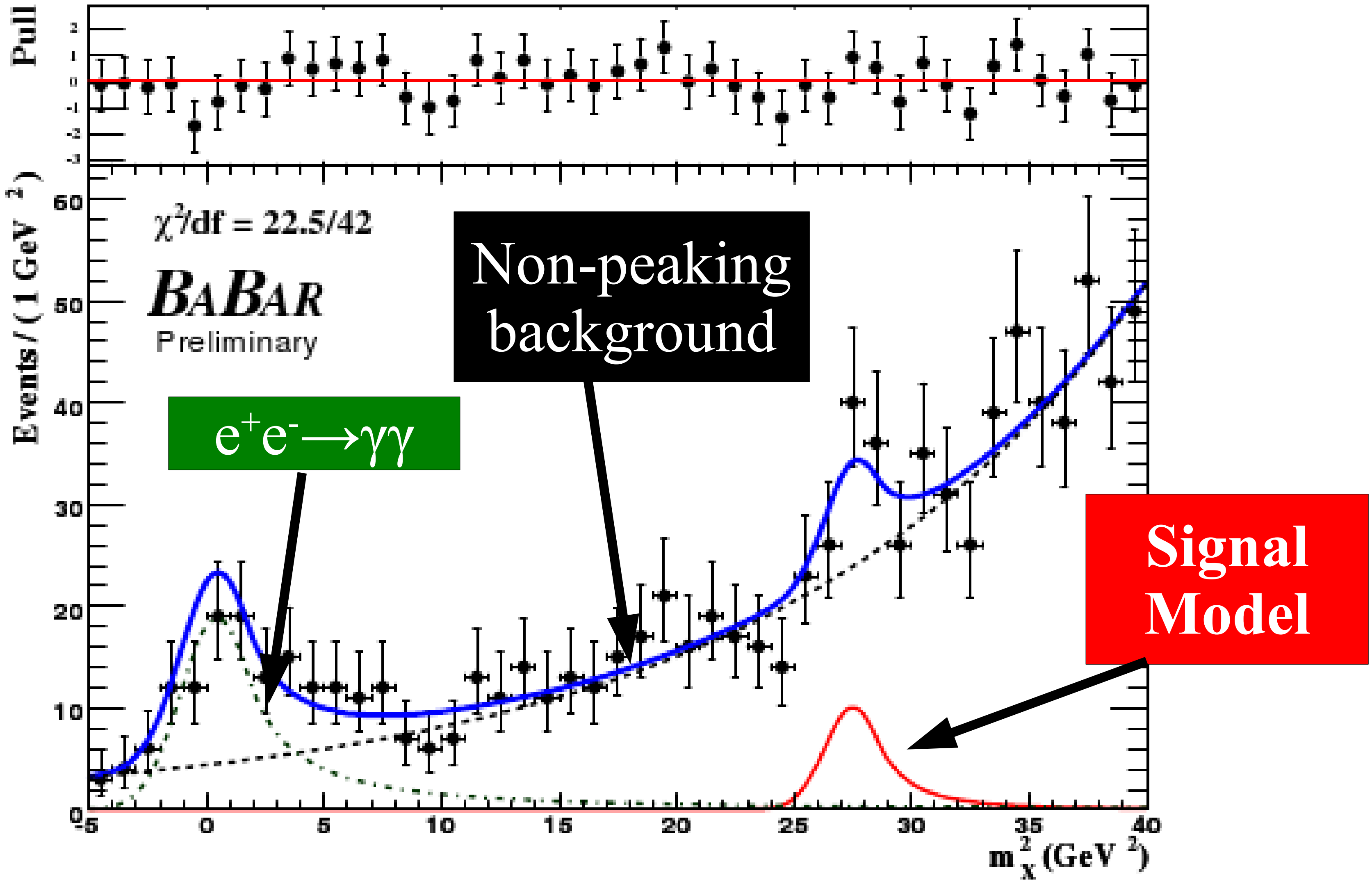


The γγ background model is taken from data before the IFR veto.

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

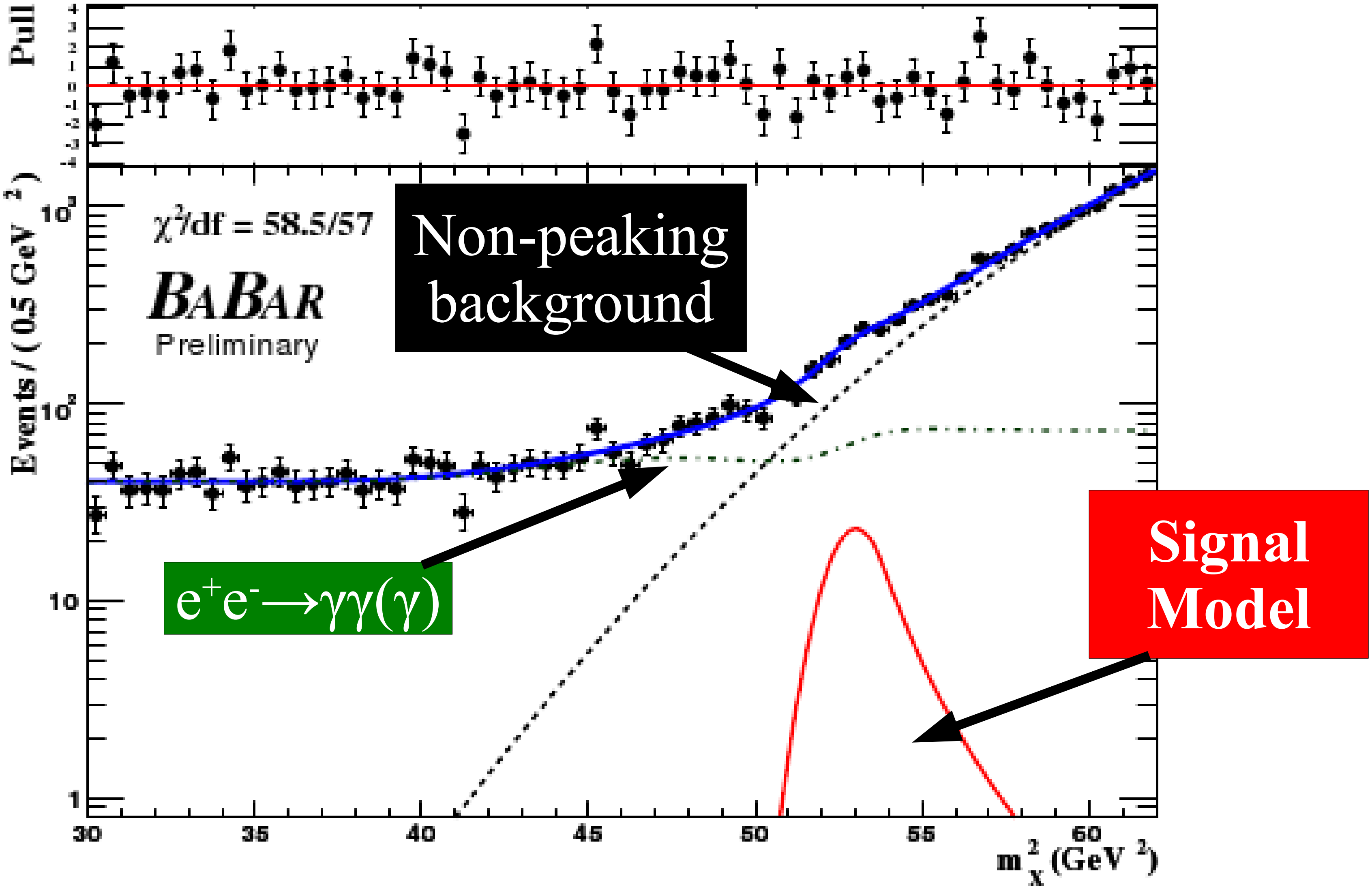


Non-peaking background

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

Signal Model

A Snapshot: Fits to the Spectrum High-Mass Region



Non-peaking background

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

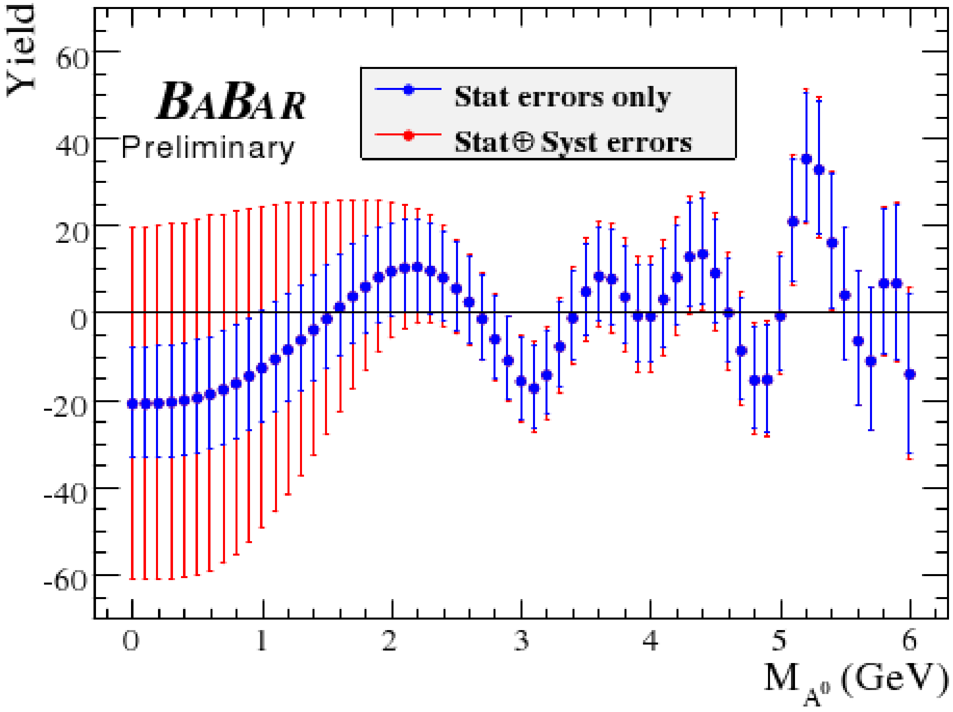
Signal Model

Results

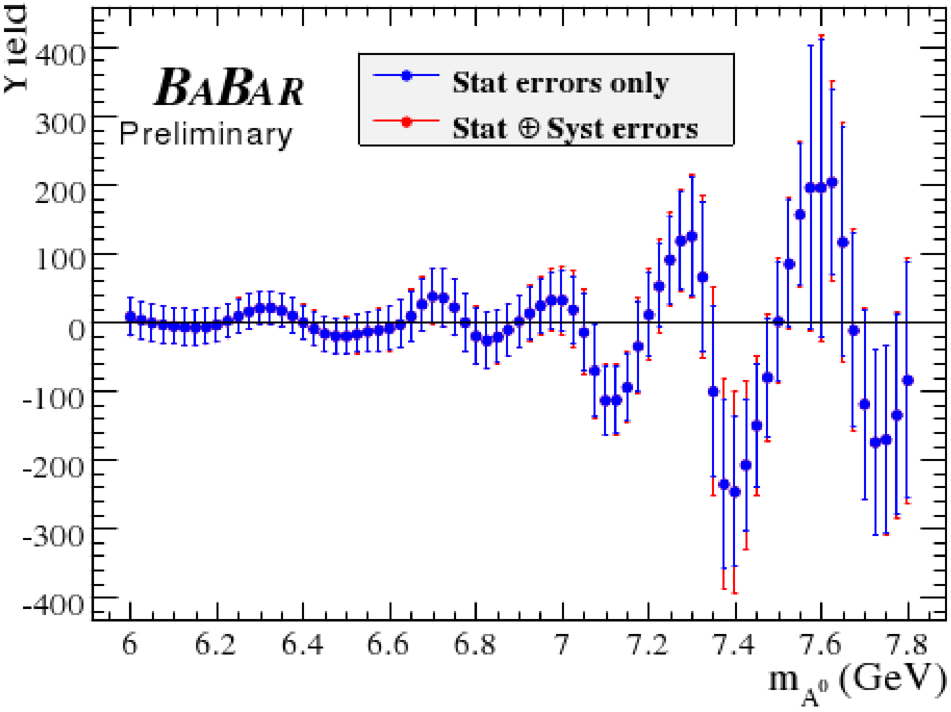
Most significant yields:

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

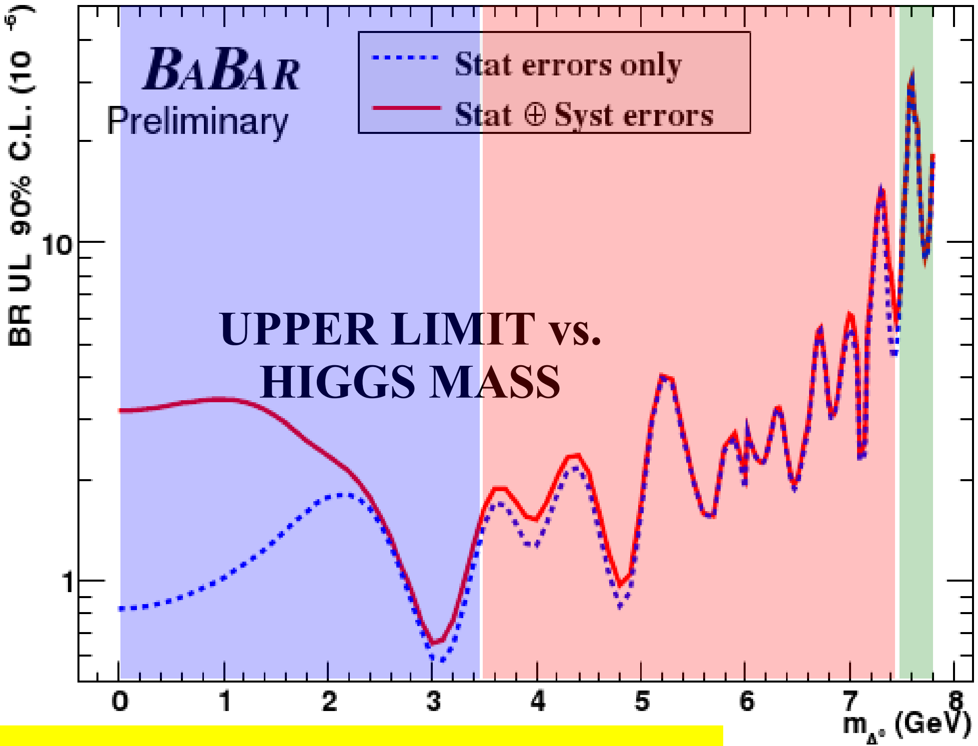
HE-PHOTON REGION



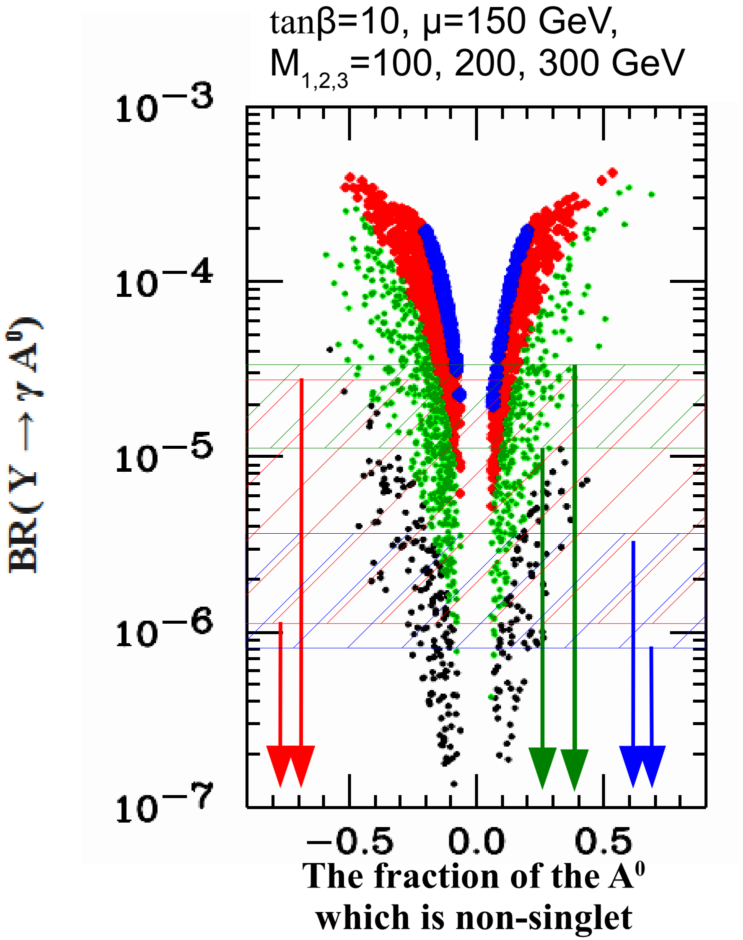
LE-PHOTON REGION



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 η_b

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

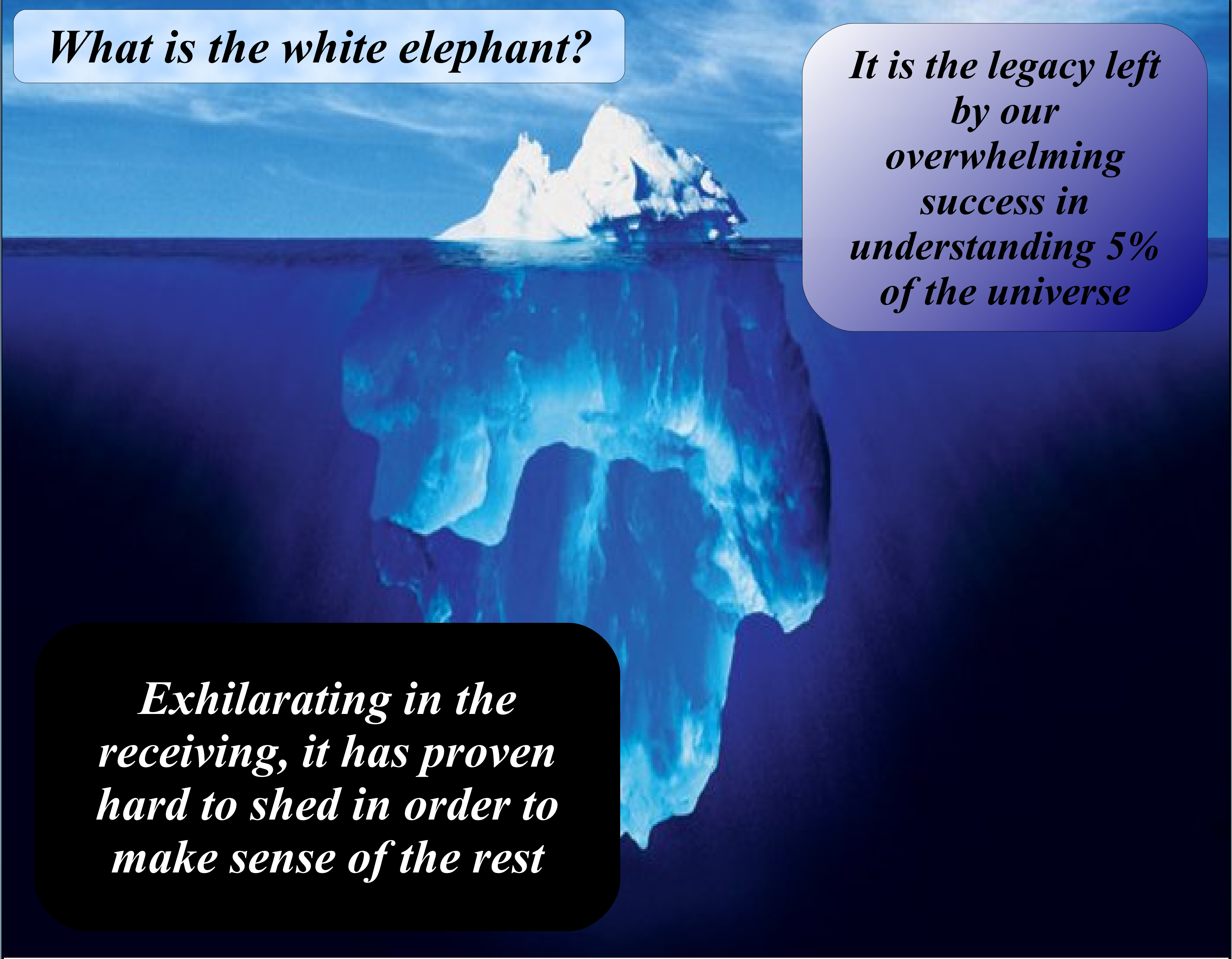
Hyperfine Splitting: $71.4^{+2.3}_{-3.1} \pm 2.7\,\mathrm{MeV}/c^2$

Branching Fraction:

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

  - 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

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]
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]

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

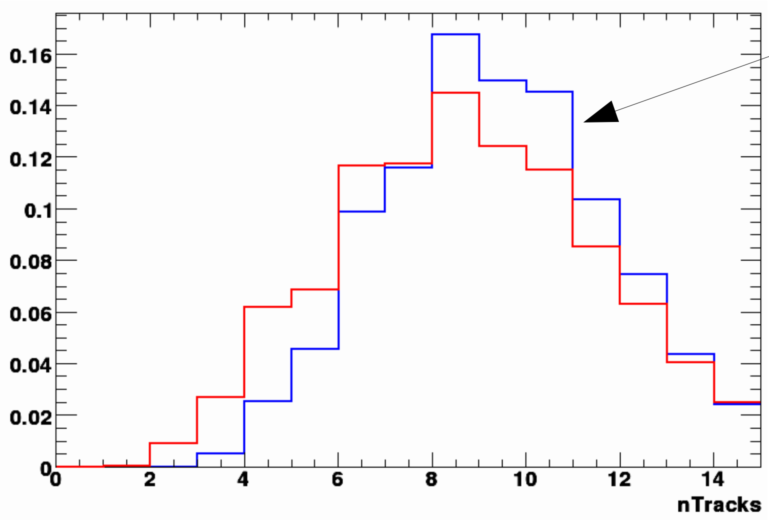
η_b Event Pre-selection

- Selection chosen to have high signal efficiency
  - Dominant η_b decay expected to be $\eta_b \rightarrow gg$
    - require >= 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 η_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 π^0 decay

Signal Efficiency: 37%

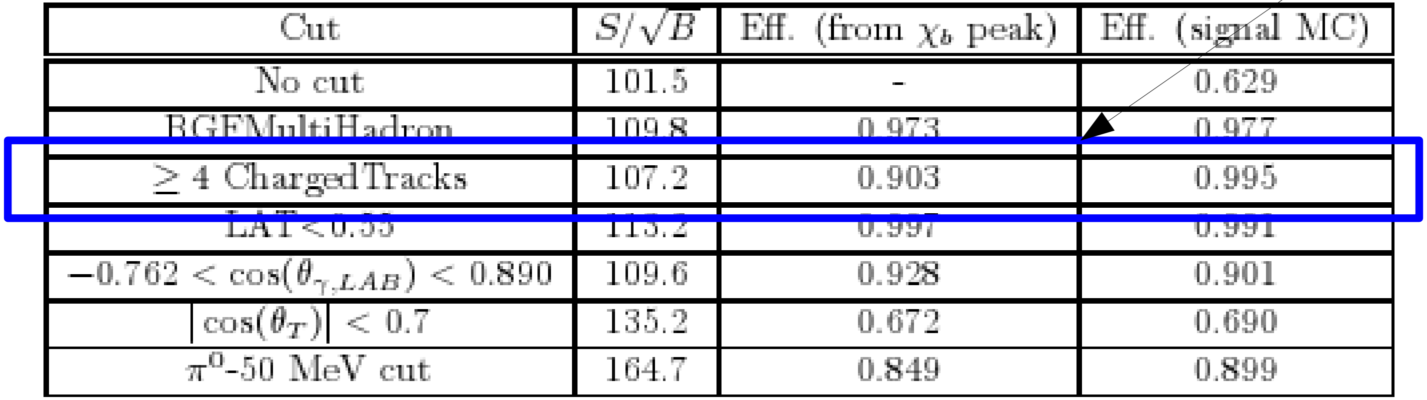
η_b – track multiplicity

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 χ_{bJ}(2P) data!

Despite the expected higher multiplicity of the χ_{bJ}(2P) → γ Y(1S) events (due to Y(1S) → 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
$\geq$ 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
$\|\cos(\theta_T)\| < 0.7$	135.2	0.672	0.690
π^0-50 MeV cut	164.7	0.849	0.899

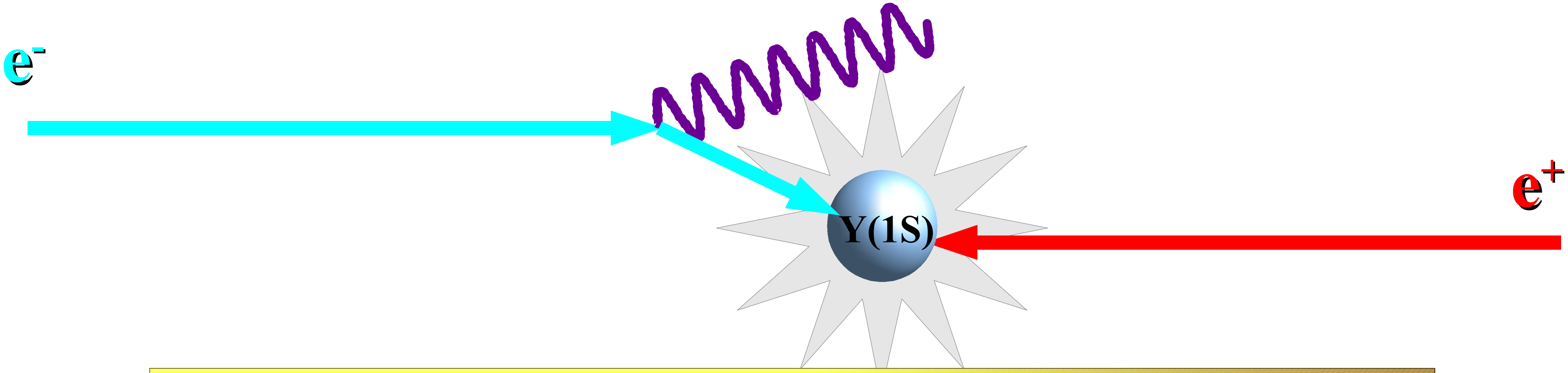
The η_b width

- Predictions of the width:
  - based on the ratio of $\Gamma(\eta_b \rightarrow \gamma\gamma)$ and $\Gamma(\eta_b \rightarrow gg)$, 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

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



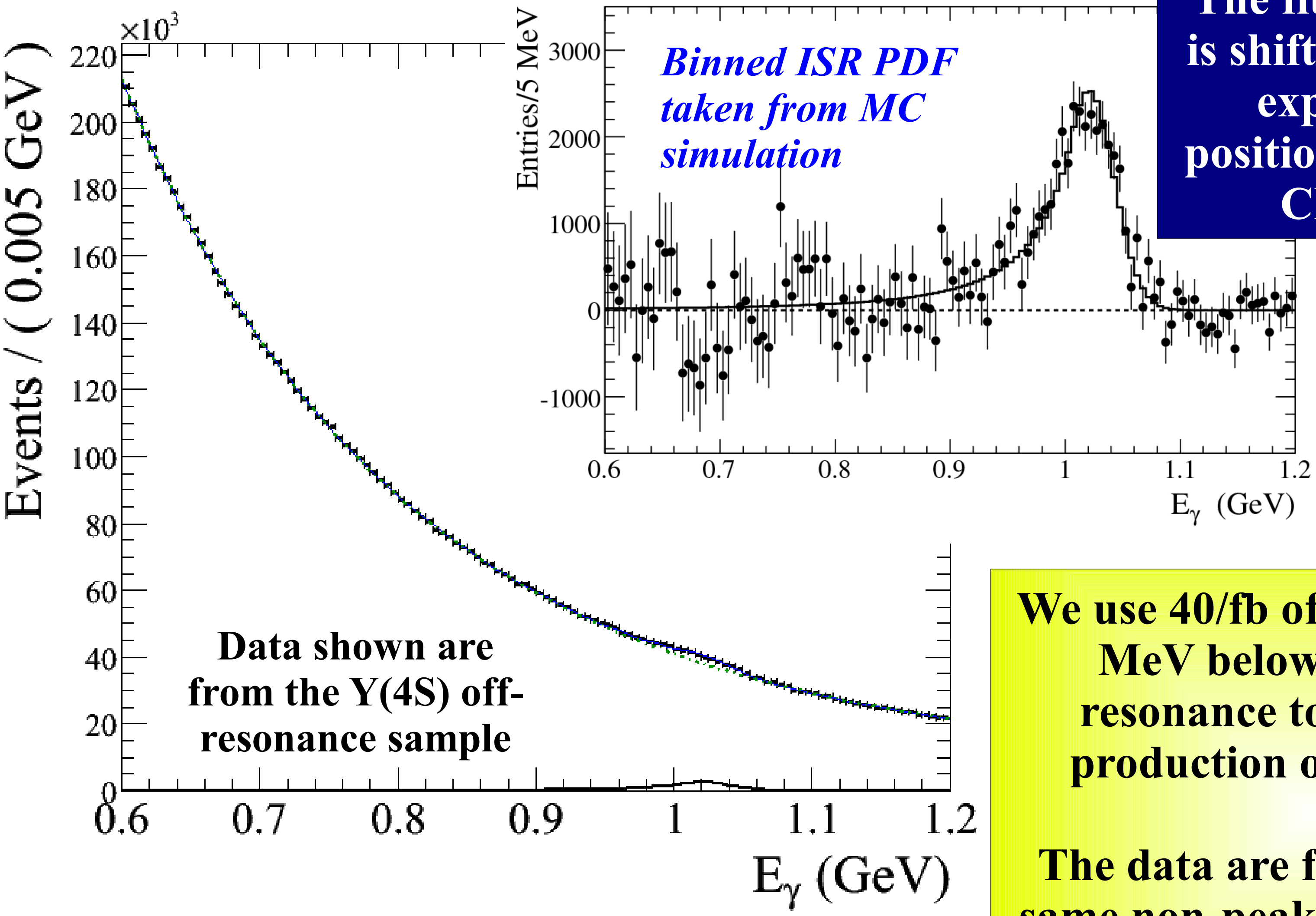
$$\sigma(e^+e^- \to \gamma_{ISR}\Upsilon(\text{١}\mathrm{S})) = \frac{\text{١٢}\pi^{\text{٢}}\Gamma_{ee}}{M_{\Upsilon(1\mathrm{S})}s} \cdot W(s, 2E_\gamma/\sqrt{s})$$

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

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

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



Binned ISR PDF taken from MC simulation

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 ±1σ 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 ±1σ

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

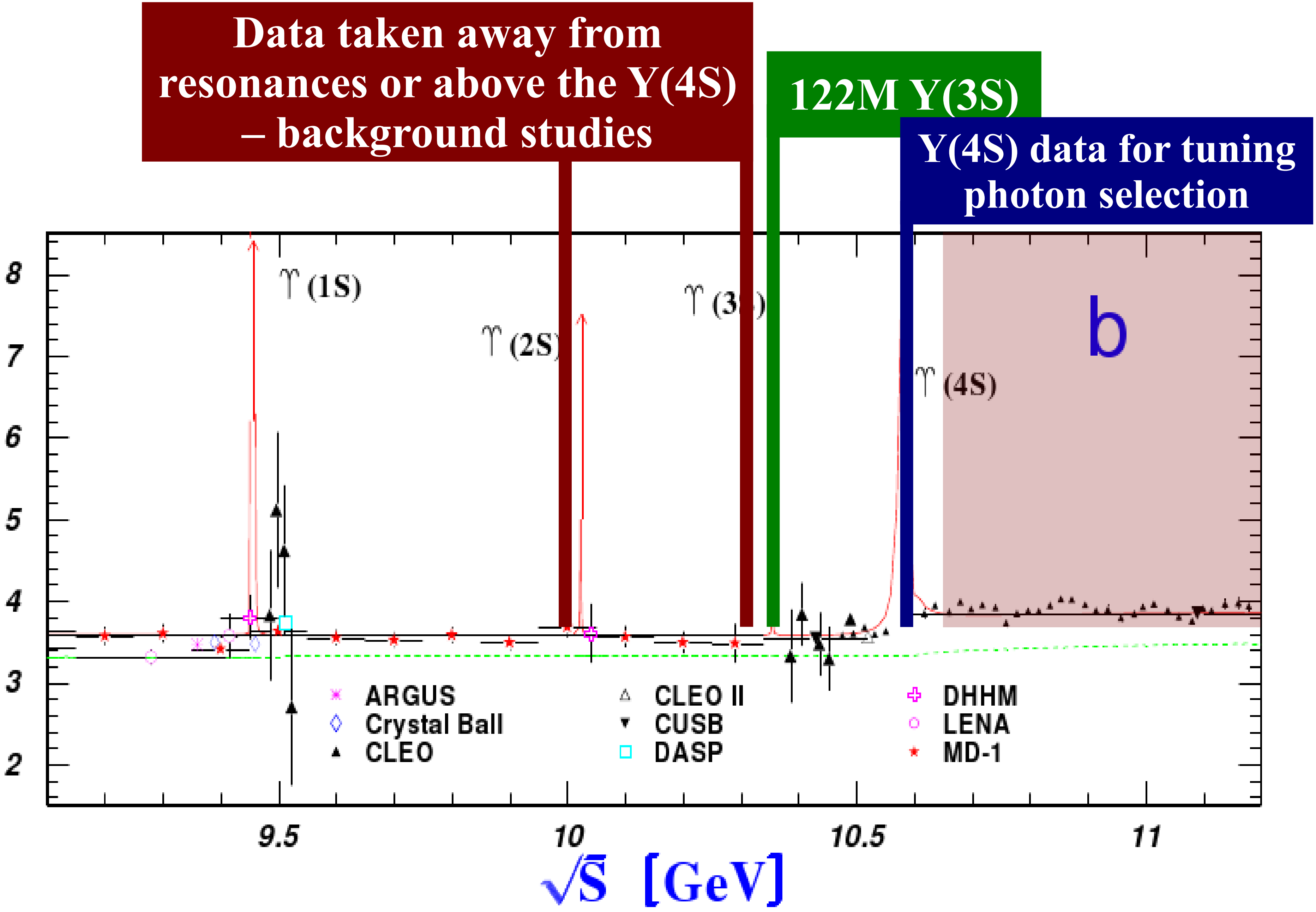
TOTAL UNCERTAINTY: 25%

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)

Data For Tuning Cuts and Studying Backgrounds

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



Data taken away from resonances or above the Y(4S) – background studies

122M Y(3S)

Y(4S) data for tuning photon selection

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

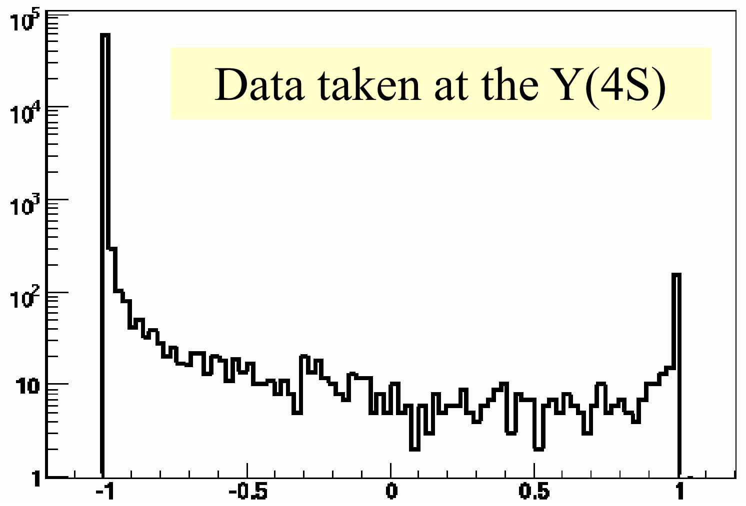
- Dedicated online triggered and filtering were developed
  - Level 1 (hardware trigger): require at least one EMC cluster with energy > 800 MeV (lab frame)
  - Level 3 (software trigger): two lines developed
    - High-energy (HE) line: require isolated EMC cluster with CM-frame energy > 2 GeV
    - 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

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%

Systematic Uncertainties - Higgs

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

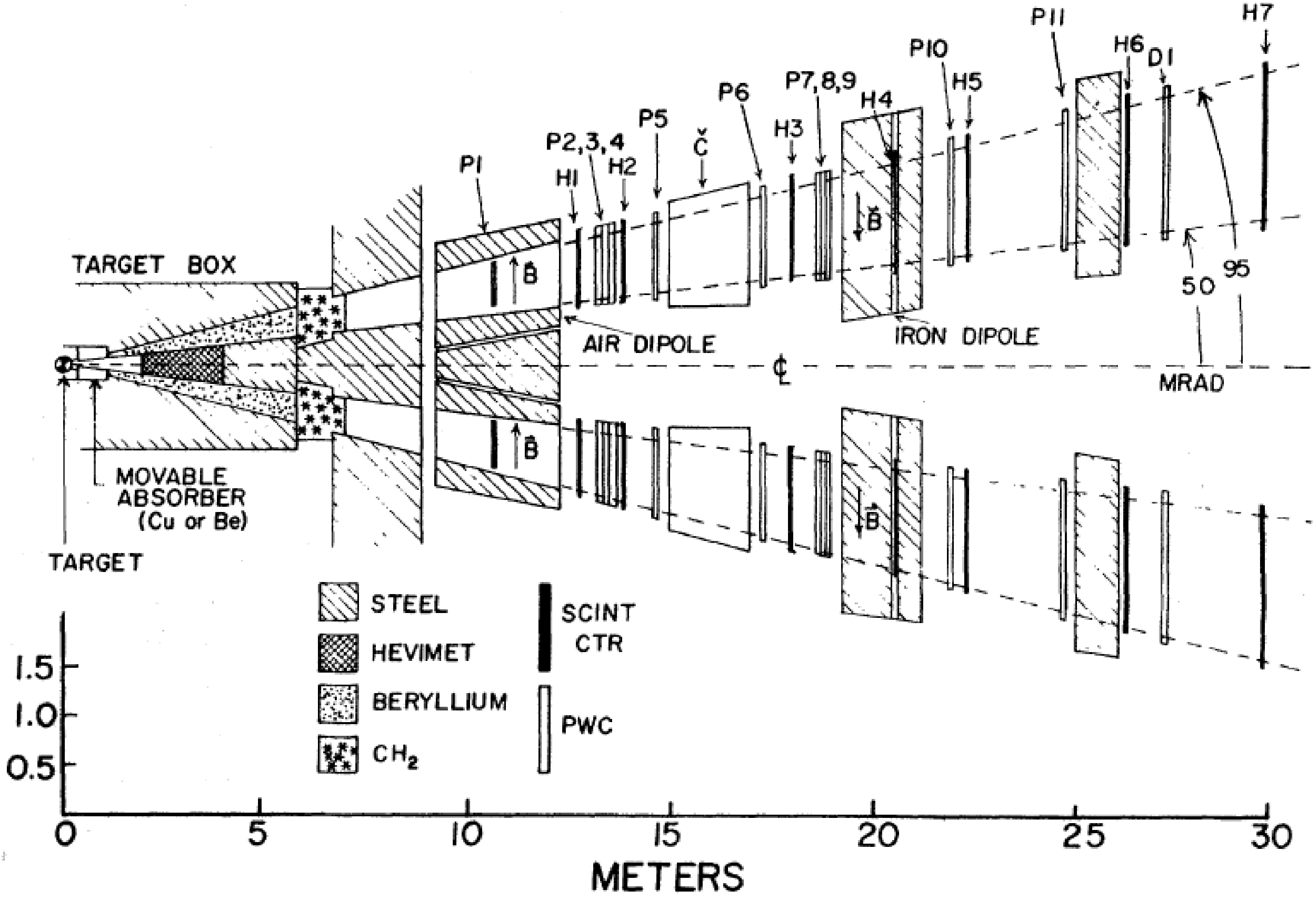
trigger/event filter efficiency checked with $e^+e^- \rightarrow \gamma\gamma$ and $e^+e^- \gamma$ (0.4%)

Photon selection checked using $e^+e^- \rightarrow \mu\mu\gamma$, $\tau\tau\gamma$, 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)