The Transition

$\psi(2S) \to \gamma\eta_c(1S)$

at CLEO-c

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QWG 2007

The CLEO-c Experiment

CESR at Cornell University, USA

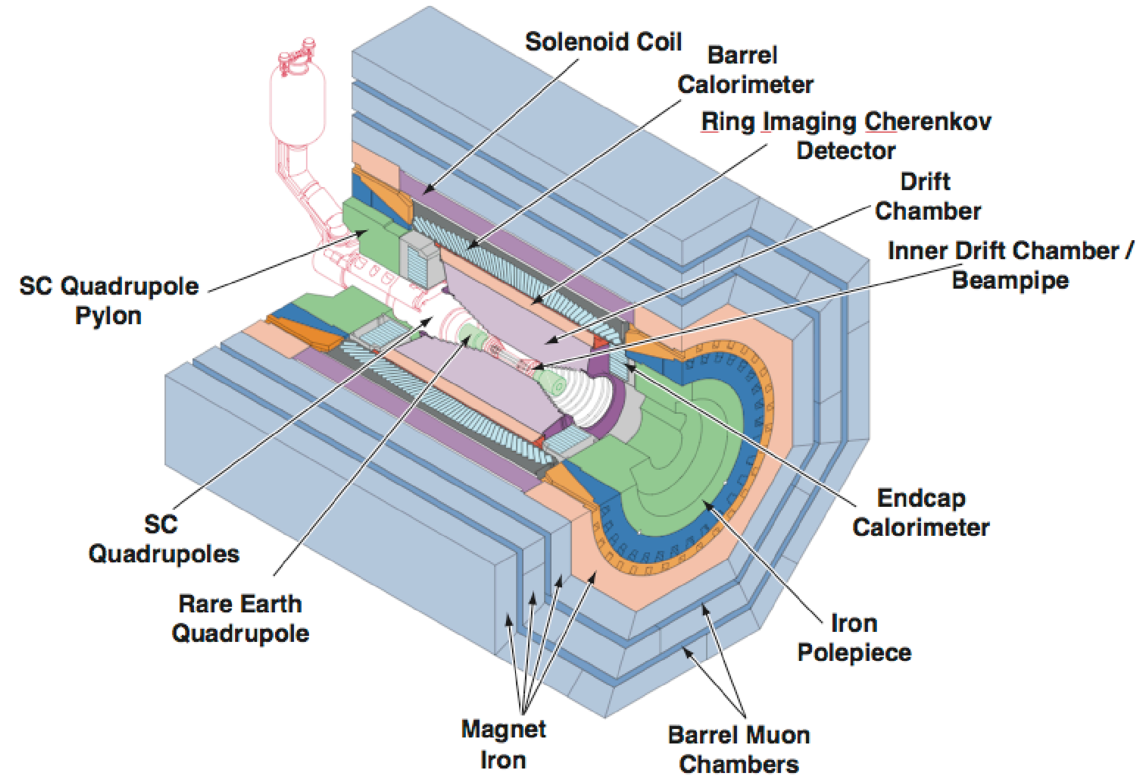
e^+e^- collisions at $\sqrt{s}$ ~ 4 GeV

2003 - present

Data Samples:

3.97 - 4.26 GeV	~ 60 pb^{-1}
4.17 GeV	~ 300 pb^{-1}
ψ(3770)	~ 800 pb^{-1}
ψ(2S)	**~ 3M (1.5M CLEO-III) + ~ 24.5M events**

*Next (**last**) run will be at 4.17 GeV*



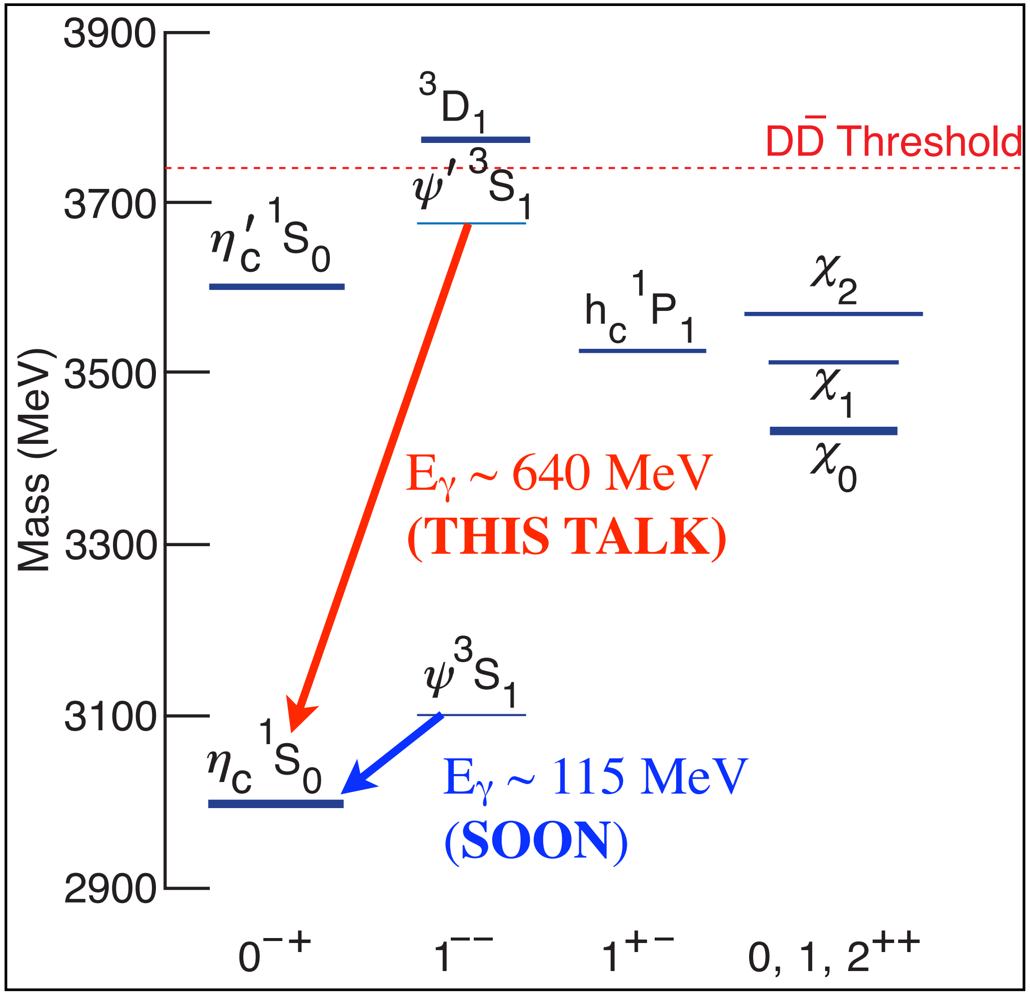
Watch for many new results from the 27M ψ(2S) sample.

The Importance of $\psi(1S,2S)\rightarrow\gamma\eta_c$ (I)

- They serve as a laboratory for the study of relativistic and non-perturbative effects in QCD. *(e.g., why is $B(J/\psi\rightarrow\gamma\eta_c)$ small?)*

- The first Lattice QCD calculations were recently performed at Jefferson Laboratory. **(PRD73, 074507 (2006))**

- There are few previous measurements:
  - Crystal Ball **(PRD34, 711 (1986))**:
    - $B(J/\psi\rightarrow\gamma\eta_c) = 1.3 \pm 0.4$ %
    - $B(\psi(2S)\rightarrow\gamma\eta_c) = (2.8 \pm 0.6) \times 10^{-3}$
  - CLEO **(PRD70, 112002 (2004))**:
    - $B(\psi(2S)\rightarrow\gamma\eta_c) =$
      $(3.3 \pm 0.4 \pm 0.6 \pm 0.2) \times 10^{-3}$



The Importance of $\psi(1S,2S)\rightarrow\gamma\eta_c$ (II)

- ALL η_c branching fractions are currently tied to $\psi(1S,2S)\rightarrow\gamma\eta_c$.

  (example page from PDG 2007)

- These transitions (especially using exclusive η_c decays) are also a source of η_c mass and width measurements.

  (more later)

Citation: W.-M. Yao *et al.* (Particle Data Group), J. Phys. G **33**, 1 (2006) and 2007 partial update for edition 2008 (URL: http://pdg.lbl.gov)

$\Gamma(\rho\rho)/\Gamma_{total}$ — Γ_2/Γ

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
20 ± 7 OUR EVALUATION			(Treating systematicerrors as correlated.)			
18 ± 5 OUR AVERAGE						
12.6± 3.8±5.1		72	[35] ABLIKIM	05L	BES2	$J/\psi\rightarrow\pi^+\pi^-\pi^+\pi^-\gamma$
26.0± 2.4±8.8		113	[35] BISELLO	91	DM2	$J/\psi\rightarrow\gamma\rho^0\rho^0$
23.6±10.6±8.2		32	[35] BISELLO	91	DM2	$J/\psi\rightarrow\gamma\rho^+\rho^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<14	90		[35] BALTRUSAIT...86		MRK3	$J/\psi\rightarrow\eta_c\gamma$

$\Gamma(K^*(892)^0K^-\pi^+ + c.c.)/\Gamma_{total}$ — Γ_3/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.02±0.007	63	[35] BALTRUSAIT...86	MRK3	$J/\psi\rightarrow\eta_c\gamma$

$\Gamma(K^*(892)\overline{K}^*(892))/\Gamma_{total}$ — Γ_4/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
92±34 OUR EVALUATION		(Treating systematicerrors as correlated.)			
91±26 OUR AVERAGE					
108±25±44	60	[35] ABLIKIM	05L	BES2	$J/\psi\rightarrow K^+K^-\pi^+\pi^-\gamma$
82±28±27	14	[35] BISELLO	91	DM2	$e^+e^-\rightarrow\gamma K^+K^-\pi^+\pi^-$
90±50	9	[35] BALTRUSAIT...86		MRK3	$J/\psi\rightarrow\eta_c\gamma$

$\Gamma(K^{*0}\overline{K}^{*0}\pi^+\pi^-)/\Gamma_{total}$ — Γ_5/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
150.±63.±43.	45	[36] ABLIKIM	06A	BES2	$J/\psi\rightarrow K^{*0}\overline{K}^{*0}\pi^+\pi^-\gamma$

$\Gamma(\phi K^+K^-)/\Gamma_{total}$ — Γ_6/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
$\mathbf{2.9^{+0.9}_{-0.8}\pm1.1}$	$14.1^{+4.4}_{-3.7}$	[37] HUANG	03	BELL	$B^+\rightarrow(\phi K^+K^-)K^+$

$\Gamma(\phi\phi)/\Gamma_{total}$ — Γ_7/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
27 ± 9 OUR EVALUATION		(Treating systematic errors as correlated.)			
27 ± 5 OUR AVERAGE					
25.3± 5.1± 9.1	72	[35] ABLIKIM	05L	BES2	$J/\psi\rightarrow K^+K^-K^+K^-\gamma$
26 ± 9	357 ± 64	[35] BAI	04	BES	$J/\psi\rightarrow\gamma K^+K^-K^+K^-$
$18\ ^{+8}_{-6}\ \pm7$	$7.0^{+3.0}_{-2.3}$	[37] HUANG	03	BELL	$B^+\rightarrow(\phi\phi)K^+$
31 ± 7 ±10	19	[35] BISELLO	91	DM2	$J/\psi\rightarrow\gamma K^+K^-K^+K^-$
$30\ ^{+18}_{-12}\ \pm10$	5	[35] BISELLO	91	DM2	$J/\psi\rightarrow\gamma K^+K^-K^0_SK^0_L$
74 ±18 ±24	80	[35] BAI	90B	MRK3	$J/\psi\rightarrow\gamma K^+K^-K^+K^-$
67 ±21 ±24		[35] BAI	90B	MRK3	$J/\psi\rightarrow\gamma K^+K^-K^0_SK^0_L$

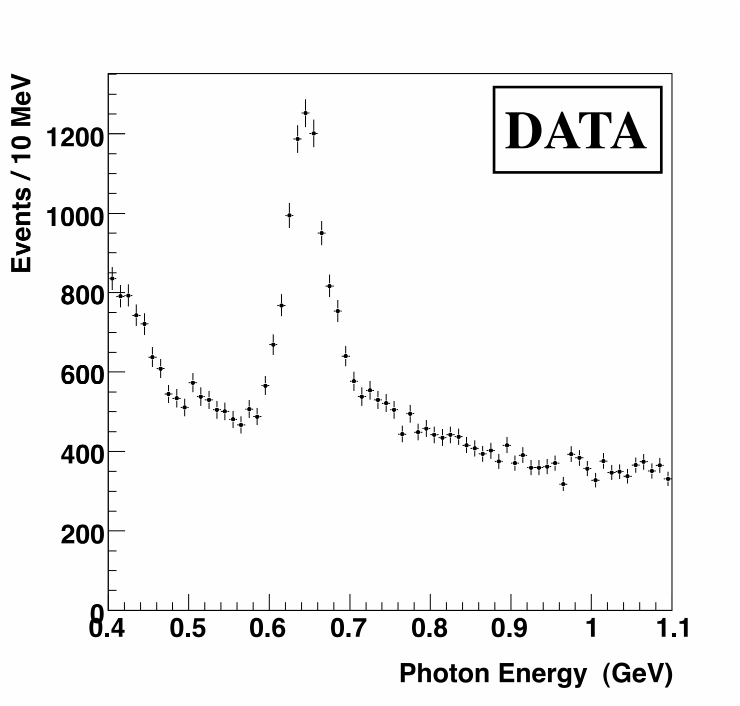
35 The quoted branching ratios use $B(J/\psi(1S)\rightarrow\gamma\eta_c(1S)) = 0.0127\pm0.0036$. Where relevant, the error in this branching ratio is treated as a common systematic in computing averages.

36 ABLIKIM 06A reports $[B(\eta_c(1S)\rightarrow K^{*0}\overline{K}^{*0}\pi^+\pi^-)\times B(J/\psi(1S)\rightarrow\gamma\eta_c(1S))] = (1.91\pm0.64\pm0.48)\times10^{-4}$. We divide by our best value $B(J/\psi(1S)\rightarrow\gamma\eta_c(1S)) = (1.3\pm0.4)\times10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

37 Using $B(B^+\rightarrow\eta_cK^+) = (1.25\pm0.12^{+0.10}_{-0.12})\times10^{-3}$ from FANG 03 and $B(\eta_c\rightarrow K\overline{K}\pi) = (5.5\pm1.7)\times10^{-2}$.

This Talk: $\psi(2S) \to \gamma\eta_c$

1. Measure the line shape (empirically) using **exclusive** decays of the η_c.

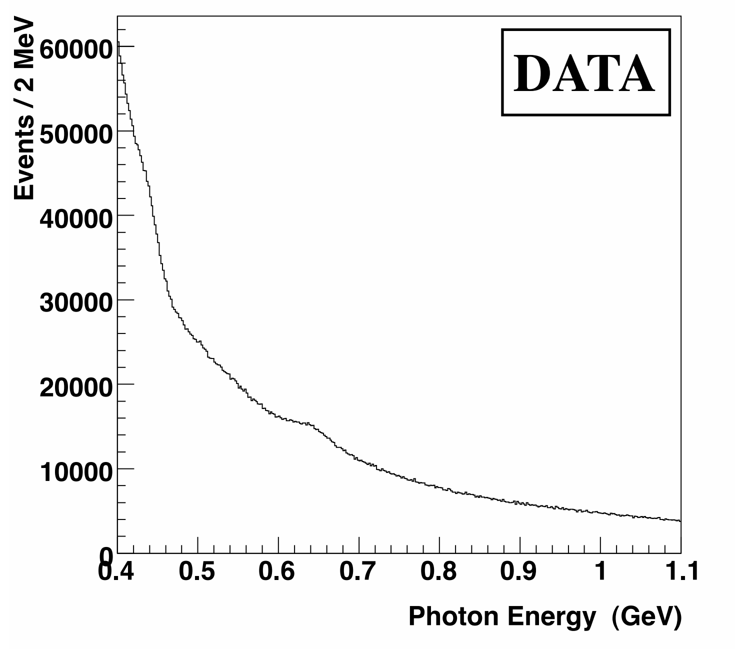


We find a non-trivial and unexpected η_c line-shape.

⇒ Prevents (for now) η_c mass and width extraction.

⇒ Forces us to resort to empirical methods.

2. Use this shape to fit the **inclusive** photon energy spectrum from $\psi(2S)$.



We measure:

$$\mathbf{B(\psi(2S)\to\gamma\eta_c) = (4.02 \pm 0.11 \pm 0.52) \times 10^{-3}}$$

(CLEO preliminary)

I. The η_c Line Shape in

$\psi(2S) \rightarrow \gamma\eta_c$

using Exclusive η_c Decays

Exclusive $\psi(2S) \to \gamma\eta_c$ Reconstruction

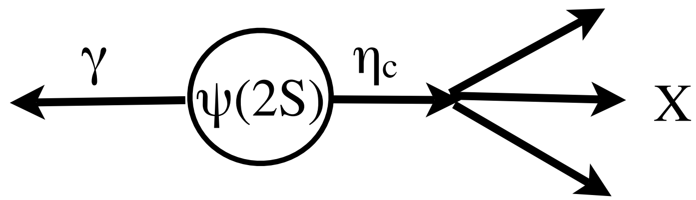
η_c Decay Modes

Decay Mode	Branching Fraction (PDG 2007)	Notes
$\pi^+\pi^-\pi^+\pi^-$	$(1.2 \pm 0.3)\%$	
$\pi^+\pi^-\pi^0\pi^0$	NEW	
$\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$	$(2.0 \pm 0.7)\%$	
$\pi^+\pi^-\pi^+\pi^-\pi^0\pi^0$	NEW	
$K^+K_S\pi^-$ + c.c.	$1/3 \times (7.0 \pm 1.2)\%$	based on $KK\pi$
$K^+K^-\pi^0$	$1/6 \times (7.0 \pm 1.2)\%$	based on $KK\pi$
$K^+K^-\pi^+\pi^-$	$(1.5 \pm 0.6)\%$	
$K^+K_S\pi^+\pi^-\pi^-$ + c.c.	NEW	
$K^+K^-\pi^+\pi^-\pi^0$	NEW	
$K^+K^-\pi^+\pi^-\pi^+\pi^-$	$(1.0 \pm 0.4)\%$	
$K^+K^-K^+K^-$	$(0.15 \pm 0.07)\%$	
$\eta_{\gamma\gamma}\pi^+\pi^-$	$2/3 \times 0.39 \times (4.9 \pm 1.8)\%$	based on $\eta\pi\pi$
$\eta_{+-0}\pi^+\pi^-$	$2/3 \times 0.23 \times (4.9 \pm 1.8)\%$	based on $\eta\pi\pi$
$\eta_{\gamma\gamma}\pi^+\pi^-\pi^+\pi^-$	$2/3 \times 0.39 \times (4.1 \pm 1.7)\%$	based on $\eta'\pi\pi$
$\eta_{+-0}\pi^+\pi^-\pi^+\pi^-$	$2/3 \times 0.23 \times (4.1 \pm 1.7)\%$	based on $\eta'\pi\pi$

- *All modes from the PDG are included (except p^+p^-).*
- *A few new modes were chosen from a comprehensive search.*

Technique:

Perform a kinematic fit of γX to the $\psi(2S)$ 4-momentum. Use χ^2 to select events.



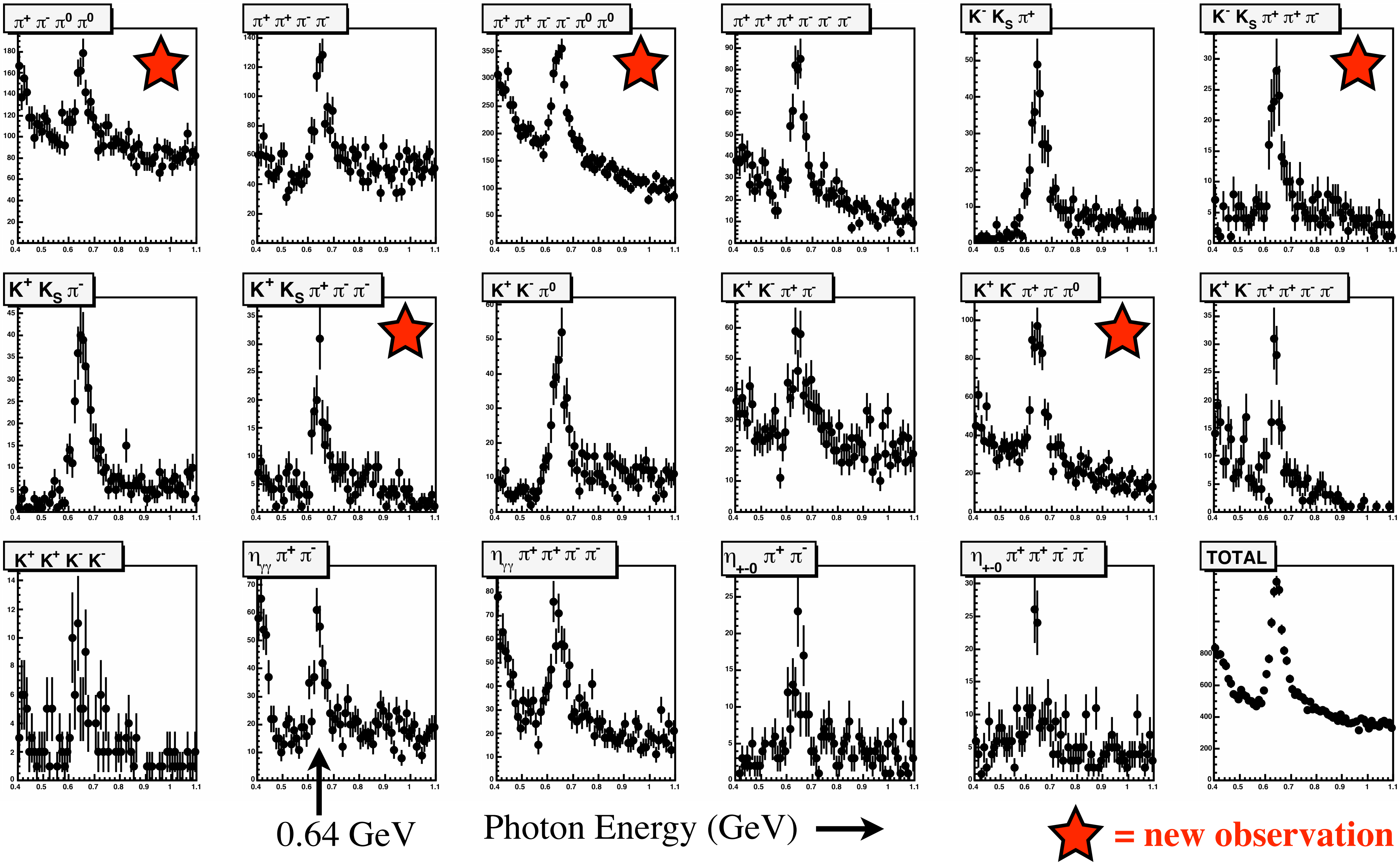
Use the measured photon energy:

→ The resolution (14.6 MeV) is independent of X.

→ Modes can be added.

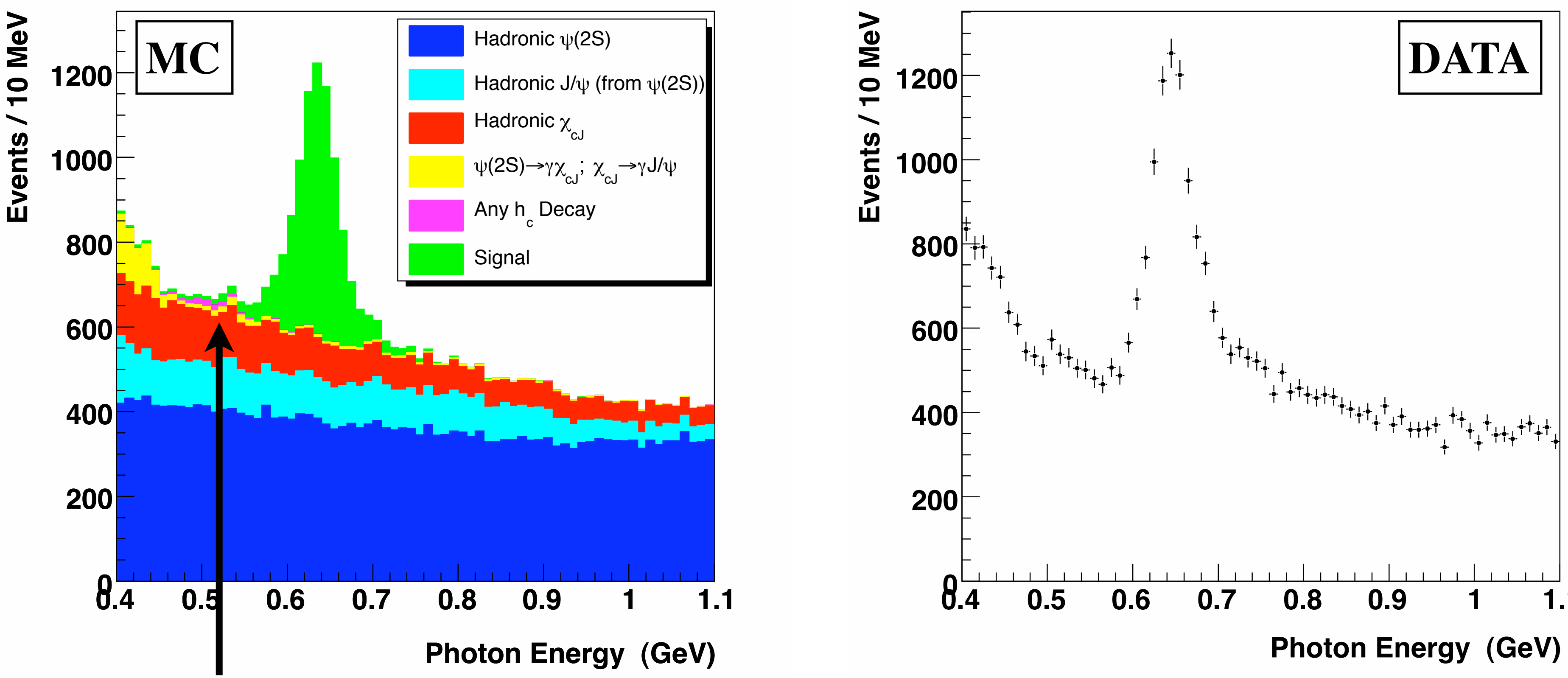
→ Modes can be compared to the inclusive spectrum.

Exclusive $\psi(2S)\rightarrow\gamma\eta_c$ Signals



Sum of Exclusive η_c Modes

Measured Photon Energy



3 peaking backgrounds:

$\psi(2S)\to\gamma\chi_{cJ};\ \chi_{cJ}\to\gamma J/\psi$

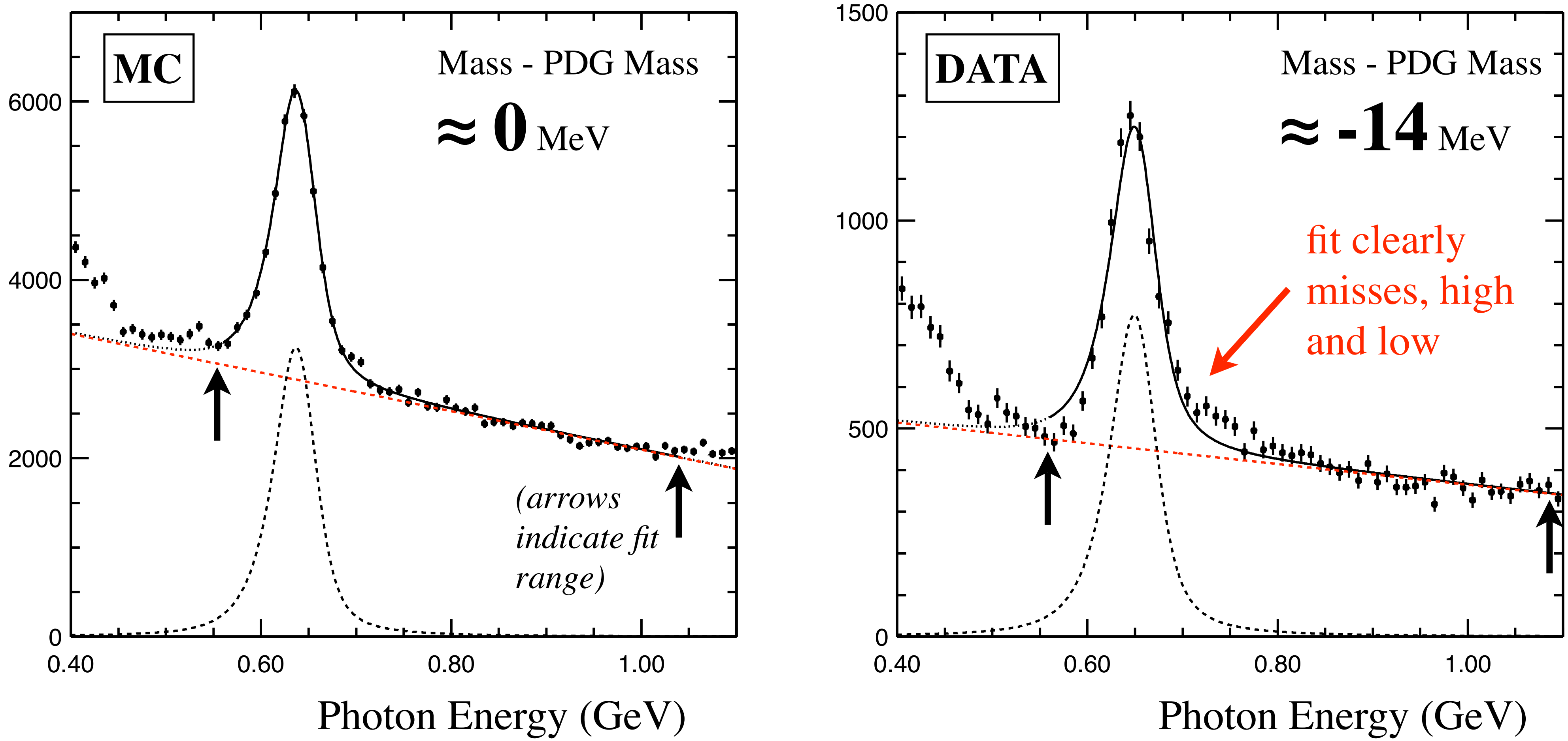
$\psi(2S)\to\pi^0 J/\psi$

$\psi(2S)\to\pi^0 h_c;\ h_c\to\gamma\eta_c$

1. Good, qualitative agreement between data and MC.
2. Smooth backgrounds above 550 MeV.
3. Small peaking backgrounds around 500 MeV.
4. Signal shapes are apparently different...

Fits Using a Non-Relativistic BW

1. Try a non-relativistic Breit-Wigner convoluted with a resolution function (Crystal Ball) with parameters fixed from signal Monte Carlo.



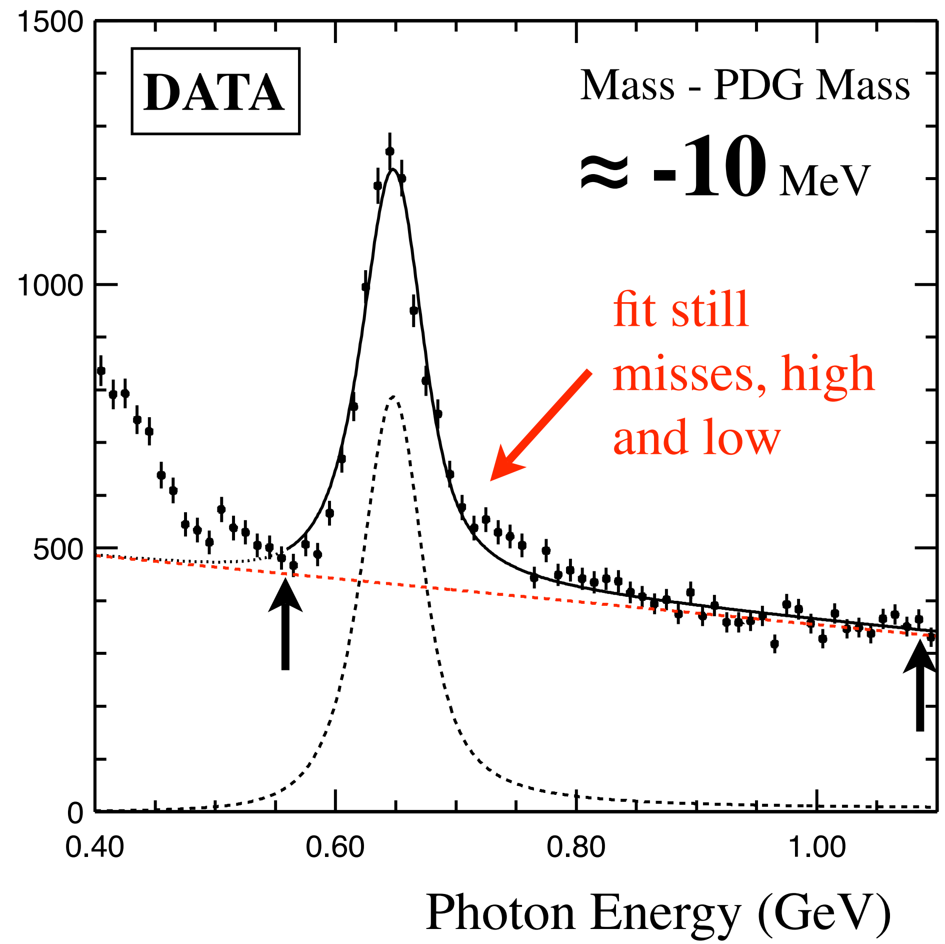
Fit Using a BW × E_γ^3

2. Try a Breit-Wigner with an E_γ^3 term convoluted with a resolution function (Crystal Ball) with parameters fixed from signal Monte Carlo.

A non-relativistic calculation of the partial width has an E_γ^3 dependence...

$$\Gamma_{n^3S_1\to\gamma n'^1S_0} = \frac{4}{3}\alpha e_Q^2 \frac{k_\gamma^3}{m^2}\left|\int_0^\infty dr\, r^2 R_{n'0}(r) R_{n0}(r) j_0\left(\frac{k_\gamma r}{2}\right)\right|^2$$

... assuming no energy dependence in the matrix element.



Fit Using a BW × E_γ^7

3. Try a Breit-Wigner with an E_γ^7 term convoluted with a resolution function (Crystal Ball) with parameters fixed from signal Monte Carlo.

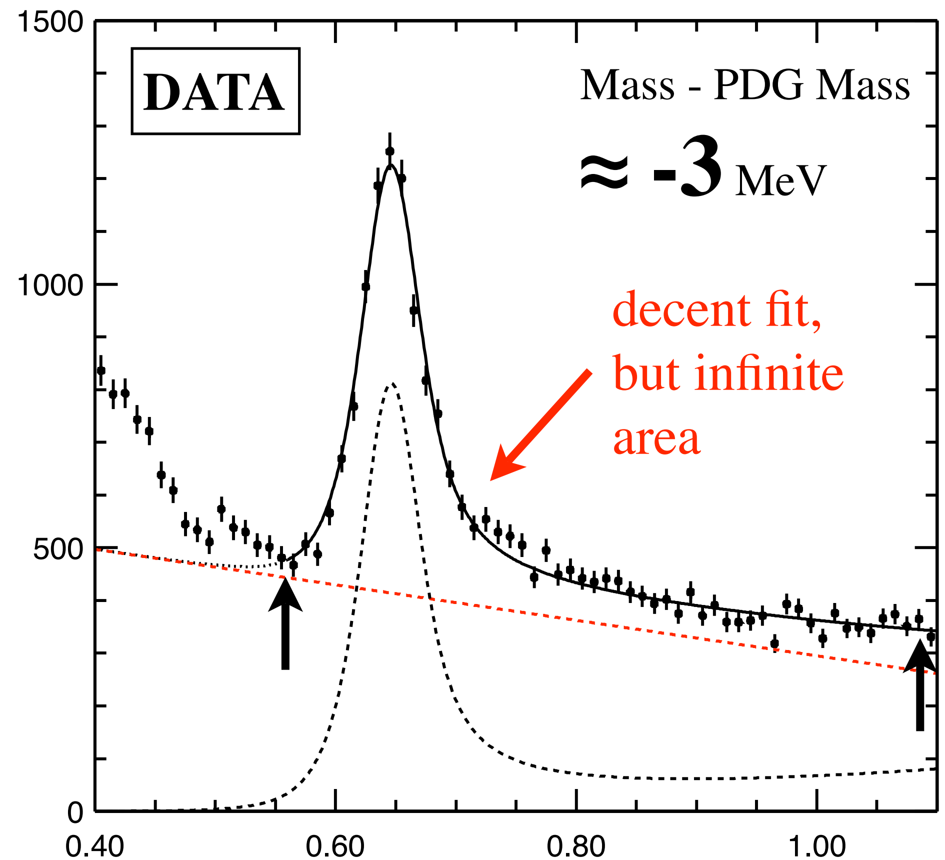
A non-relativistic calculation of the partial width has an E_γ^3 dependence:

$$\Gamma_{n^3S_1\to\gamma n'^1S_0} = \frac{4}{3}\alpha e_Q^2 \frac{k_\gamma^3}{m^2}\left|\int_0^\infty dr\, r^2 R_{n'0}(r) R_{n0}(r) j_0\left(\frac{k_\gamma r}{2}\right)\right|^2$$

Expanding the spherical Bessel function:

$$j_0\left(\frac{k_\gamma r}{2}\right) = 1 - \frac{(k_\gamma r)^2}{24} + \ldots$$

The first order term vanishes when n ≠ n'.
The second term gives another E_γ^4.



⇒ We are yet to find an adequate, physically meaningful description of the line-shape.

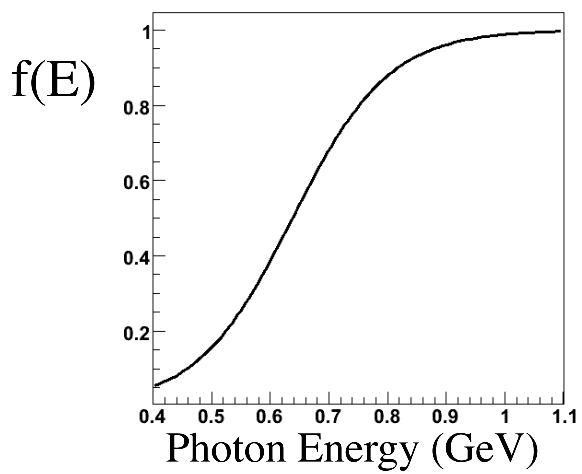
Fit Using a BW × f(E)

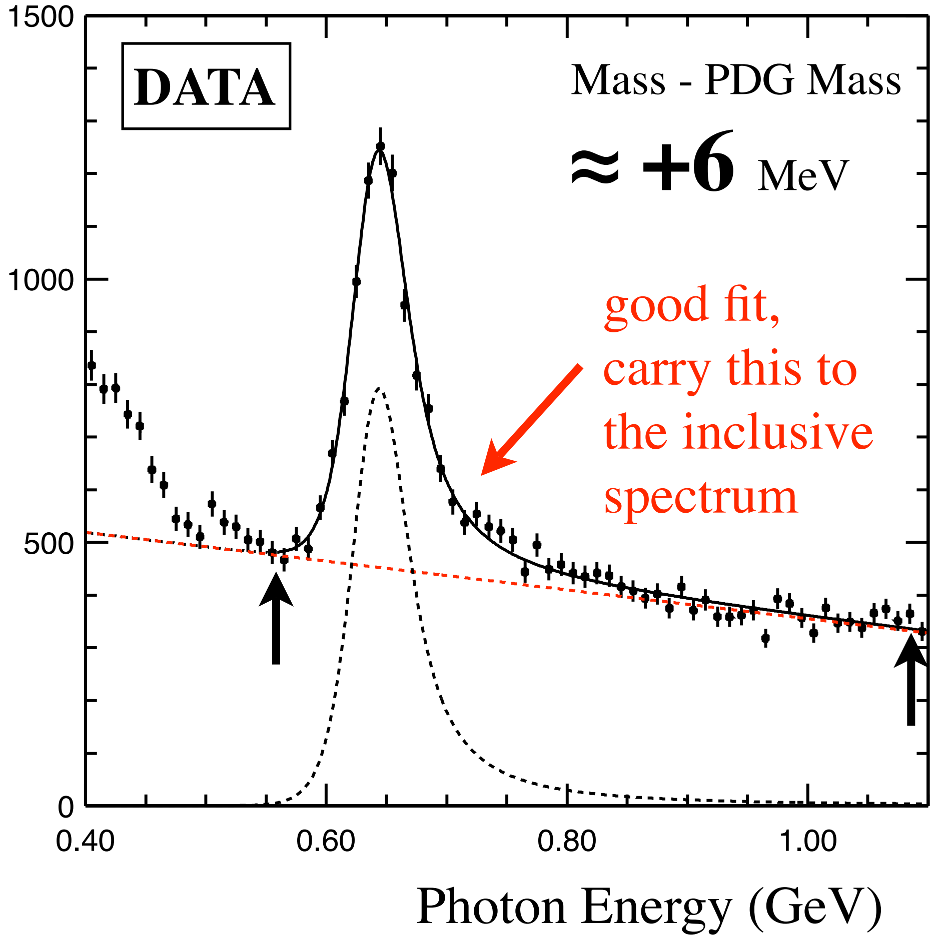
4. Try a Breit-Wigner × f(E), where f(E) is an empirical function, again convoluted with a resolution function from signal Monte Carlo.

f(E) is an empirical function,
i.e., no physics inspiration:

$$f(E) = \frac{1}{1 + e^{\frac{E_0 - E}{2\Gamma}}}$$

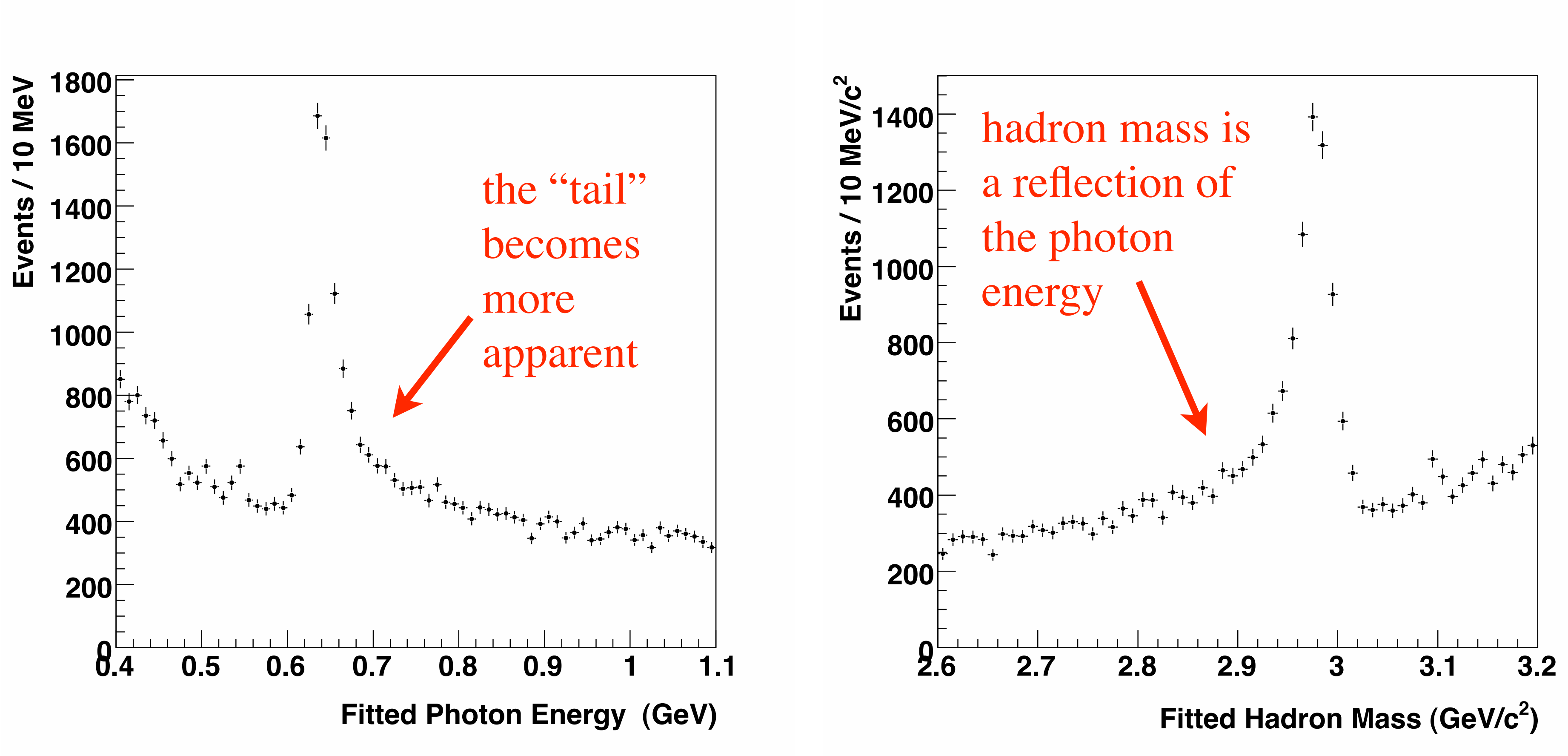
where E_0 and Γ are BW parameters.





Checks (I): Sharpening the Resolution with a Kinematic Fit

Constrain particle 4-momenta in $\psi(2S) \to \gamma X$ to the 4-momentum of the $\psi(2S)$.



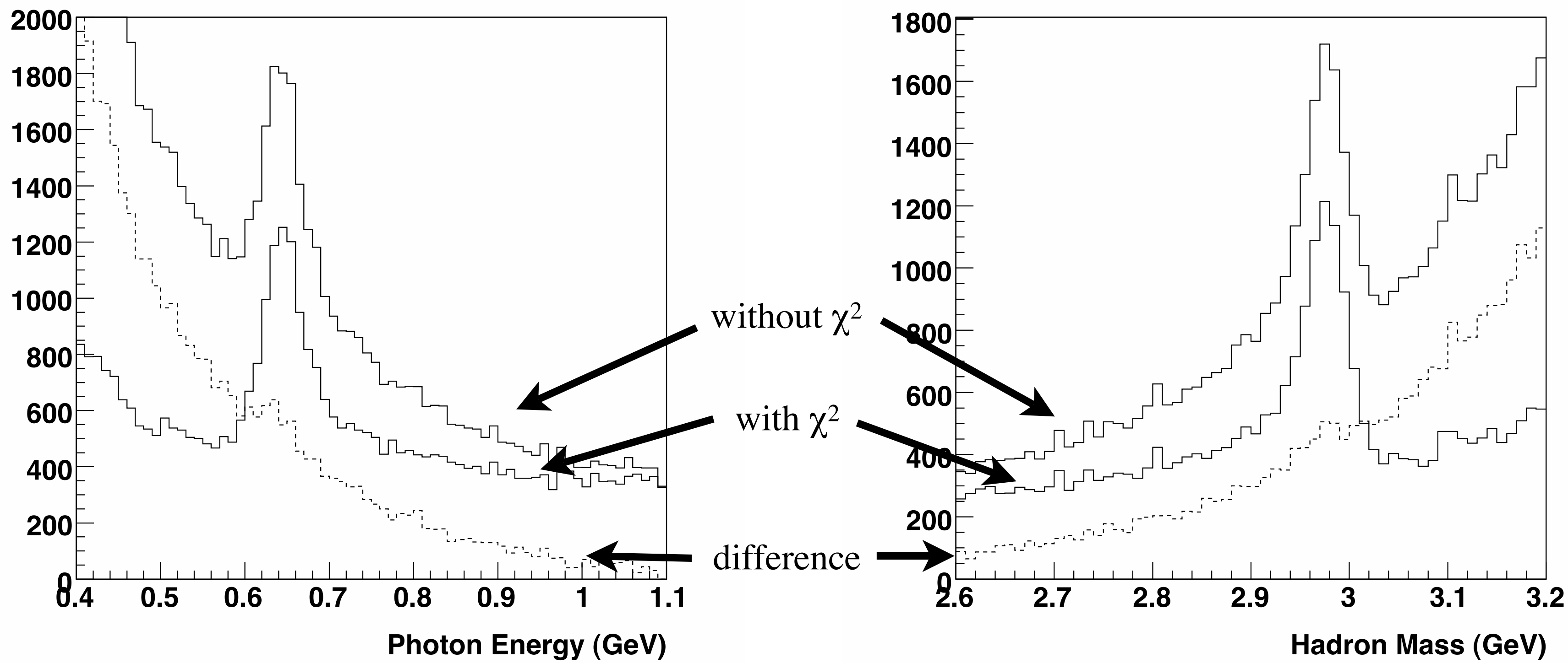
Checks (II): Artifact of Kinematic Fitting?

Replace the χ^2 cut with cuts on total mass and hadronic recoil mass (i.e. photon mass).

Tail appears independently in measured photon energy and measured mass.

→ not an artifact of kinematic fitting
→ not something peculiar to γ measurement
→ not something peculiar to tracking

Measured γ energy with and without χ^2 cut | Measured mass with and without χ^2 cut

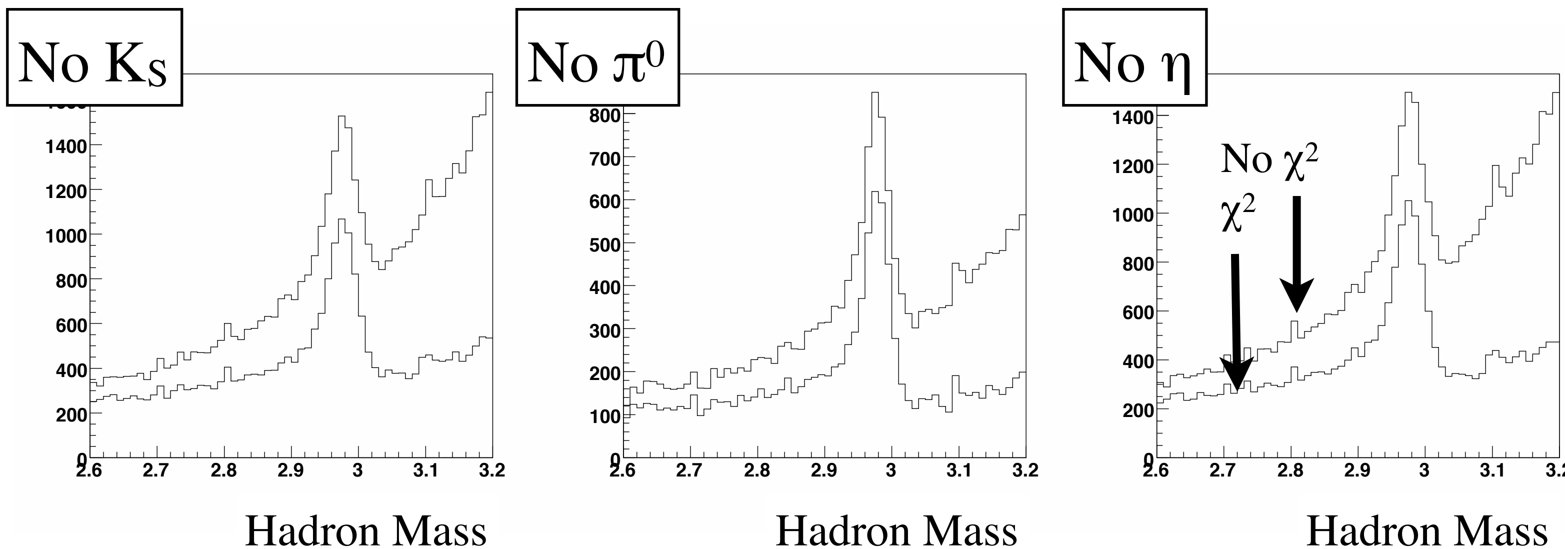


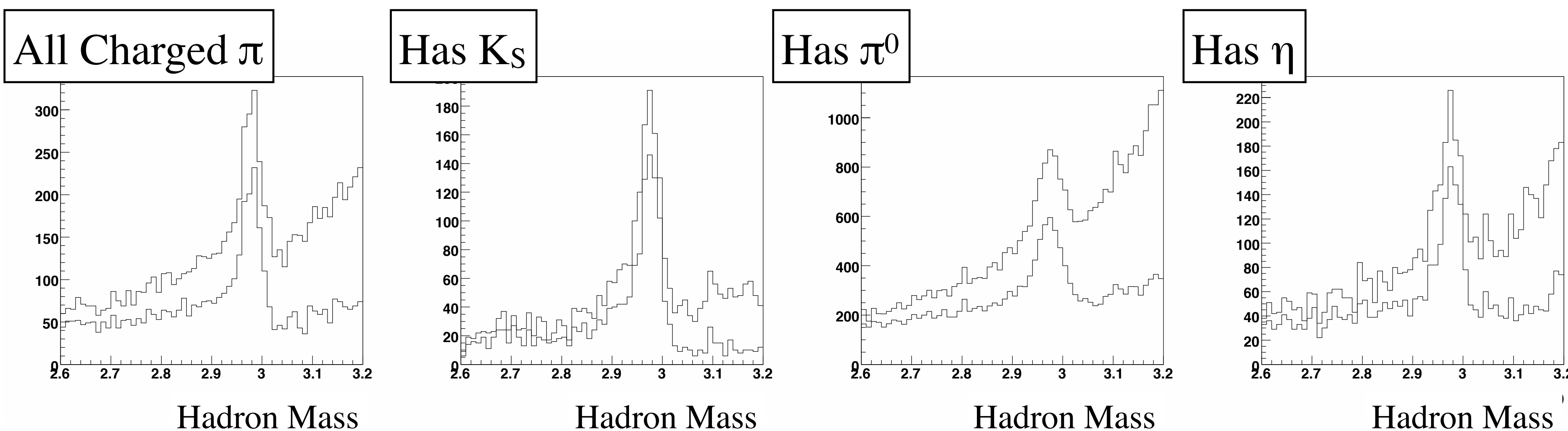
Checks (III): Is it due to π^0, η, K_S.... ?

The tail appears in all combinations of modes, with and without χ^2 cut.

→ e.g. not due to a K_S systematic problem

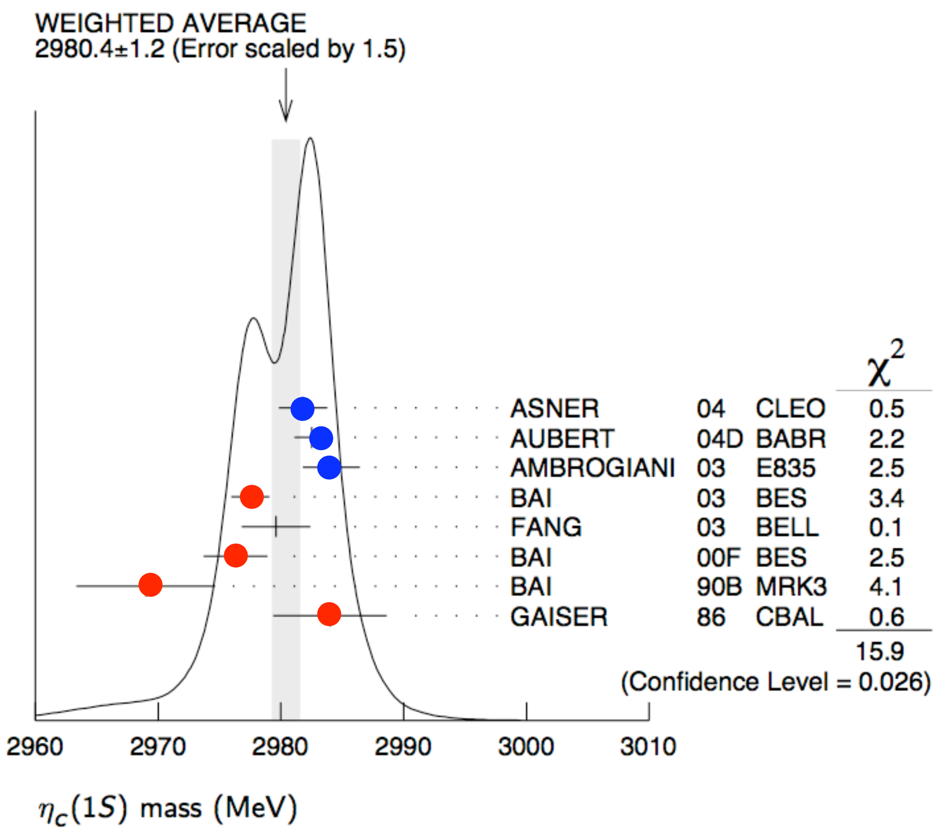
→ physics bg would have to be peculiar



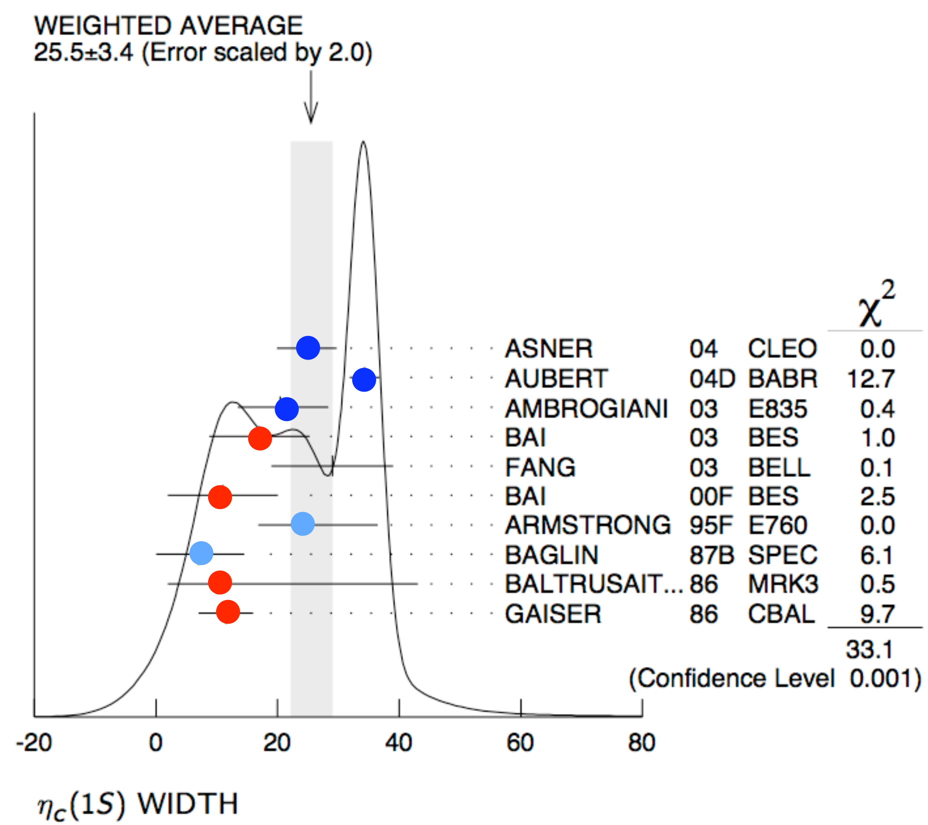


Line Shape Problems in the Past?

PDG 2006 Mass



PDG 2006 Width



- $\gamma\gamma$ or p^+p^-
- $\gamma\gamma$ or p^+p^- (used for width, but not mass)
- $\psi(1S,2S) \to \gamma\eta_c$

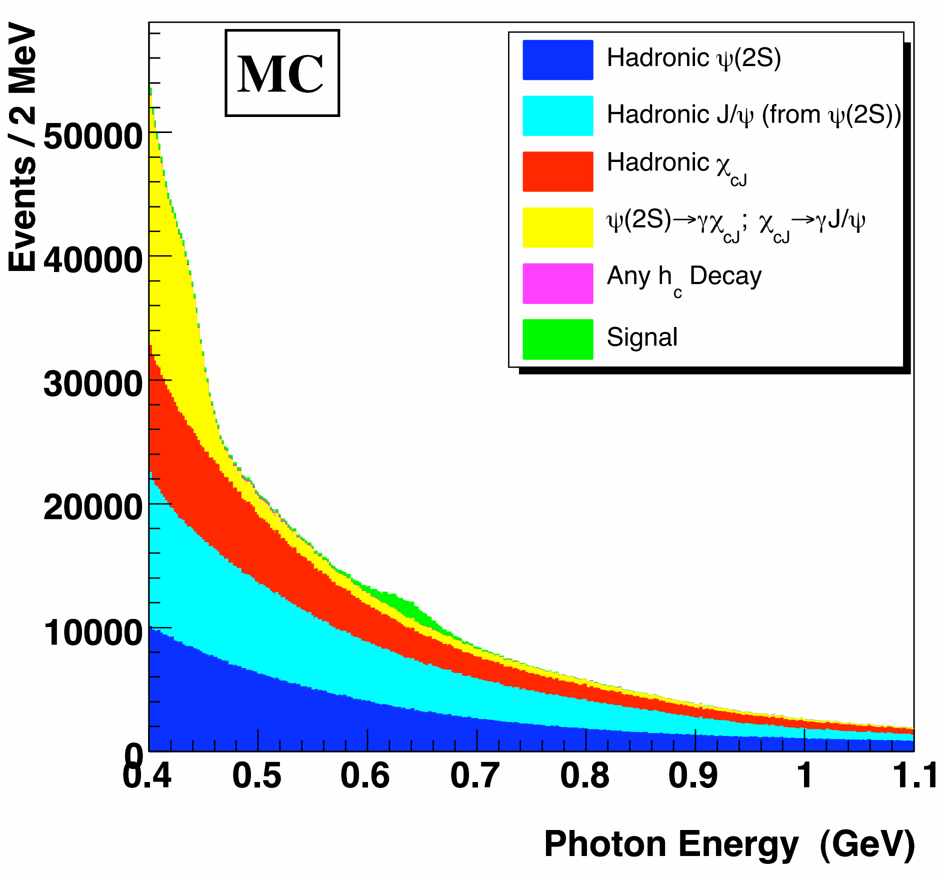
II. Measurement of

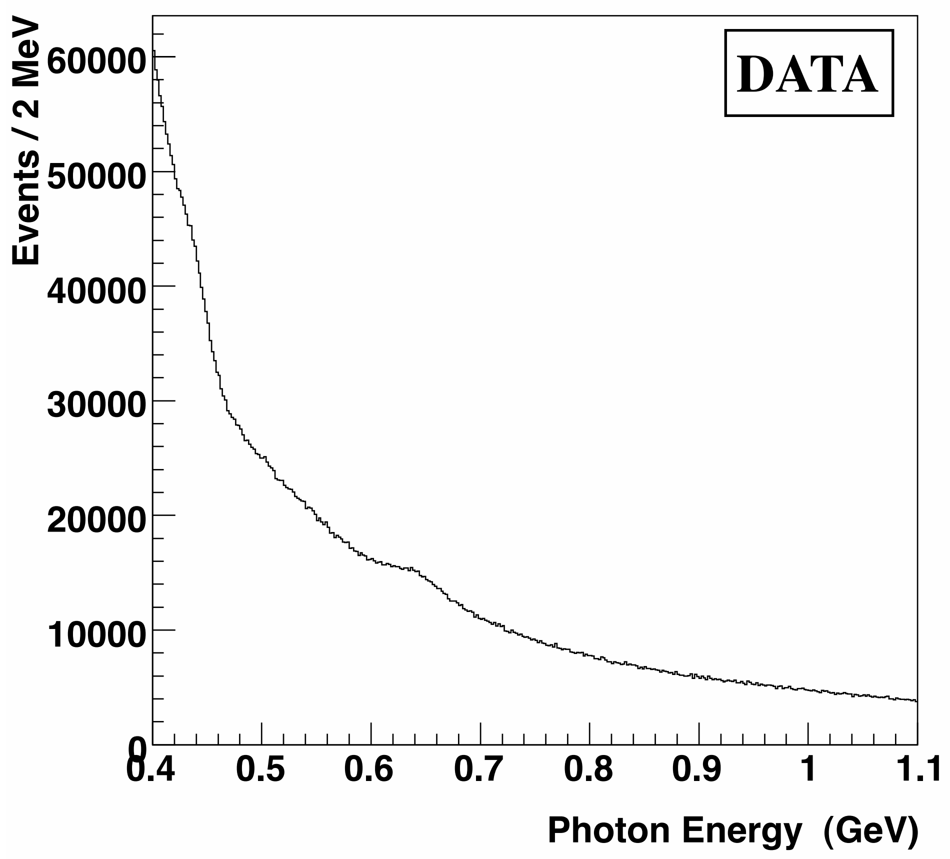
$B(\psi(2S) \rightarrow \gamma\eta_c)$

from the Inclusive Photon Spectrum

Inclusive Photon Energy Spectrum From ψ(2S)

- Use loose criteria to select photons:
  - Reject events from $\psi(2S)\rightarrow\pi^+\pi^-J/\psi$.
  - Reject photons that pair with another photon to create a π^0.
- Smooth backgrounds, plus nice agreement between MC and data.





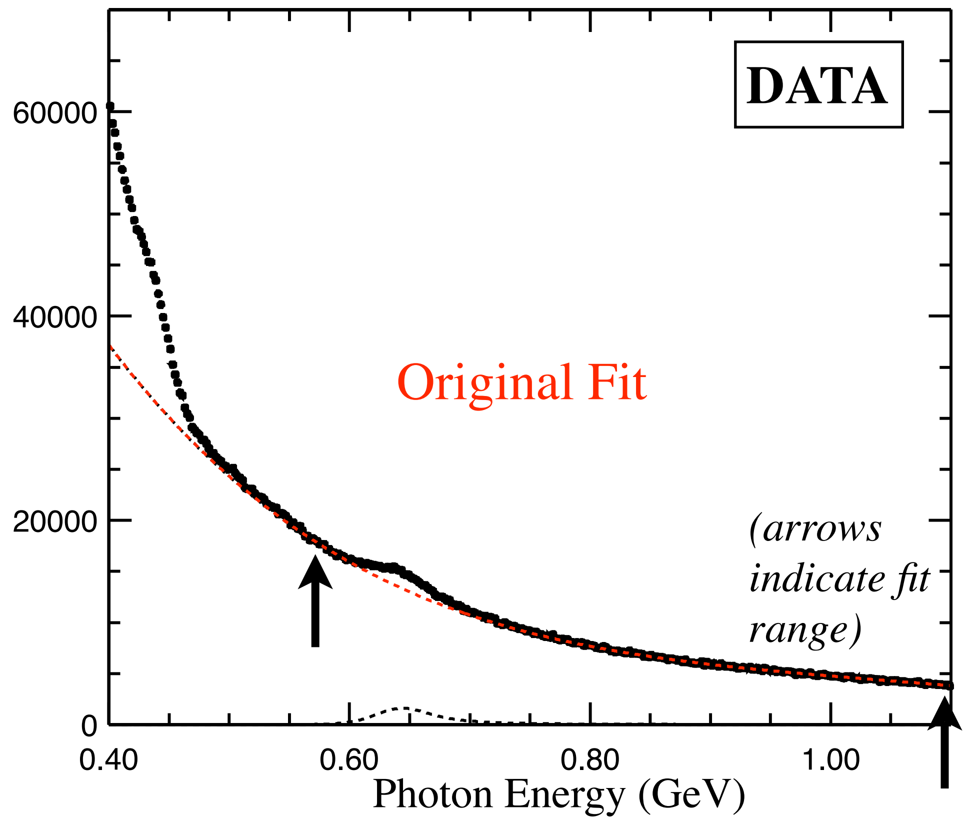
Fit to the Inclusive Spectrum

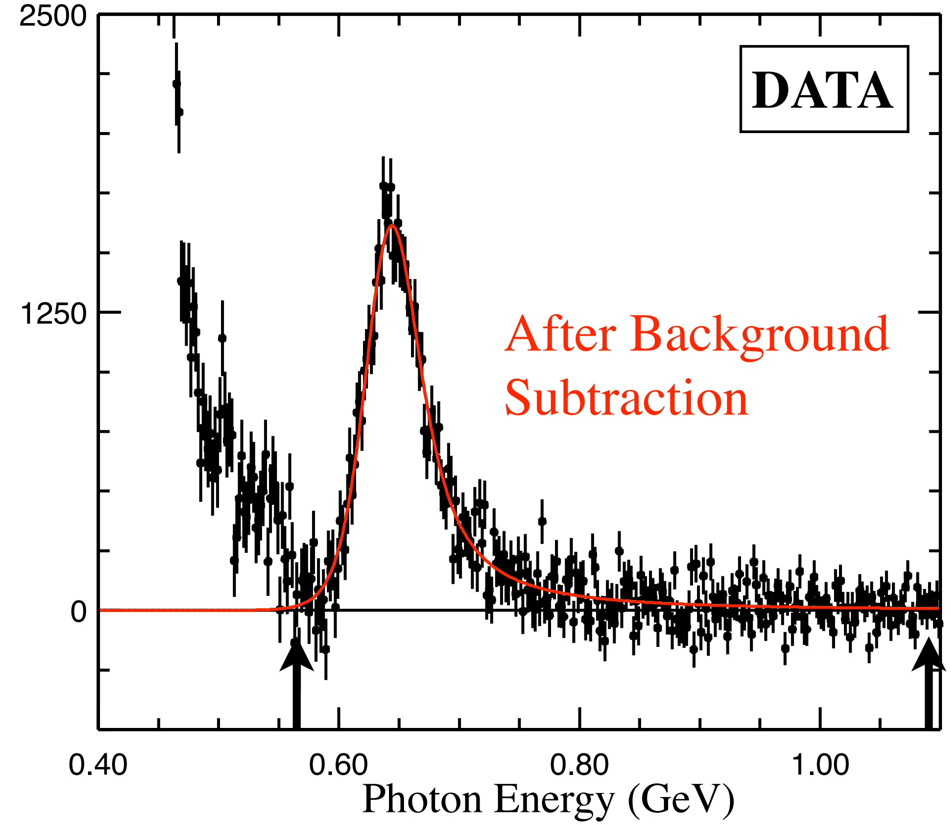
Use a BW × f(E) with all parameters fixed from the exclusive fit.

Measured Events = 60500 ± 1700
Efficiency = 61.7%
Number $\psi(2S)$ = 24.45 million

$B(\psi(2S)\rightarrow\gamma\eta_c) = (4.02 \pm 0.11) \times 10^{-3}$

(CLEO Preliminary, statistical only)

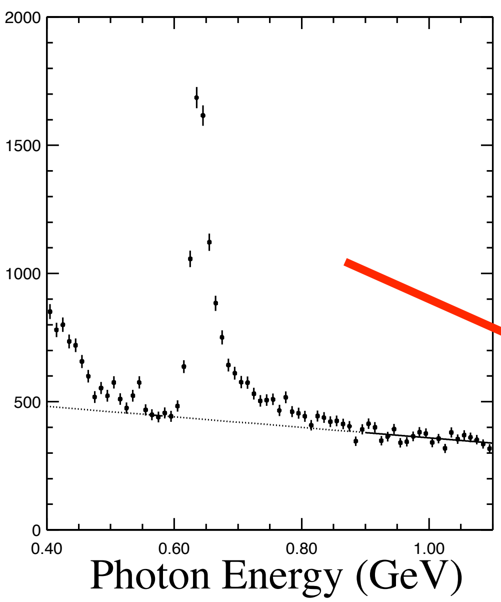




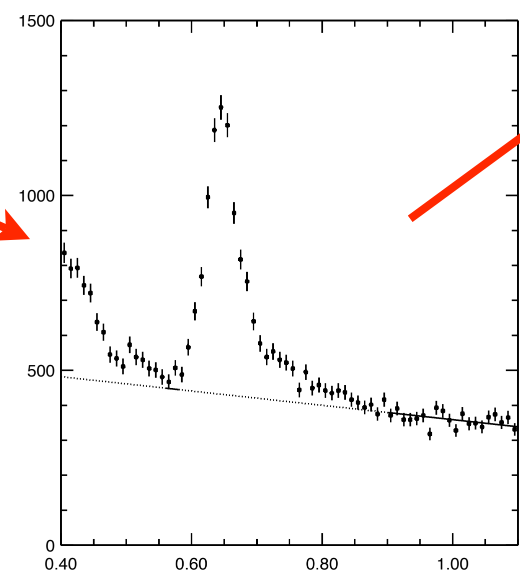
Evaluating a Fitting Systematic

Use the exclusive histogram to parameterize the line shape.

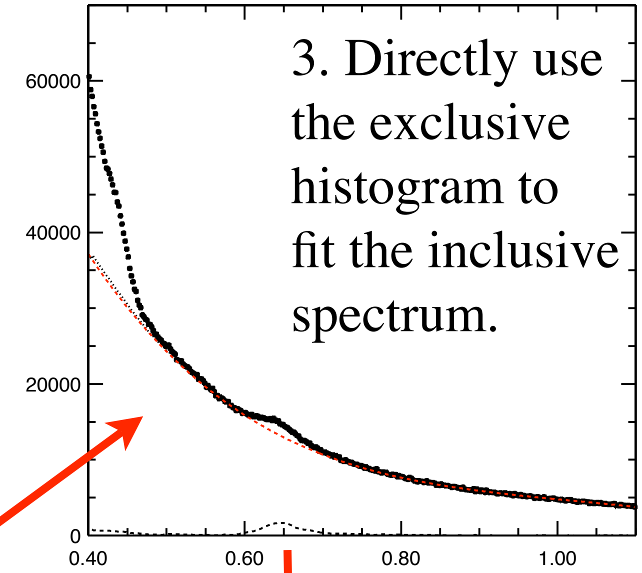
1. Fit the background shape from the fitted photon energy spectrum from exclusive modes.



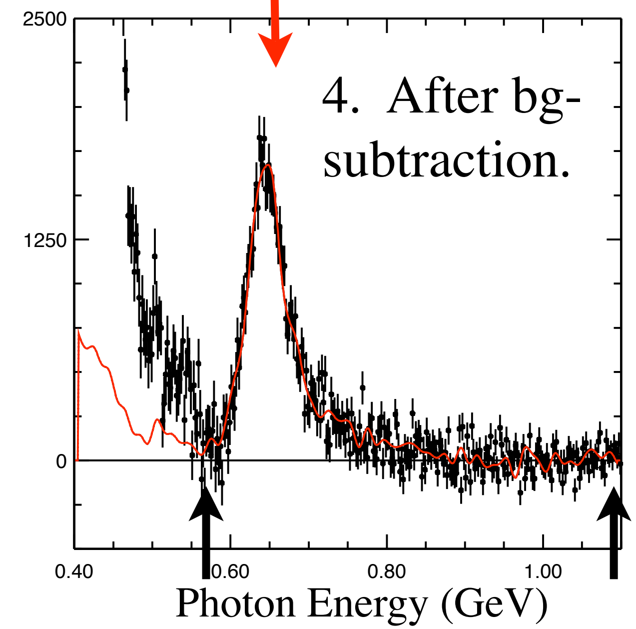
2. Carry this shape to the measured spectrum and subtract to get a signal shape.



3. Directly use the exclusive histogram to fit the inclusive spectrum.



4. After bg-subtraction.



⇒ Vary background shapes and ranges.

⇒ Assign a 10% systematic error.

Other Systematic Errors

Systematic	Value
Line Shape and Fitting	10%
MC Modeling	8%
Photon Efficiency	2%
Number of $\psi(2S)$	2%
Total	13%

→ *i.e., modeling unknown decays of the η_c.*

CLEO Preliminary:

$$B(\psi(2S)\to\gamma\eta_c) = (4.02 \pm 0.11 \pm 0.52) \times 10^{-3}$$

Summary

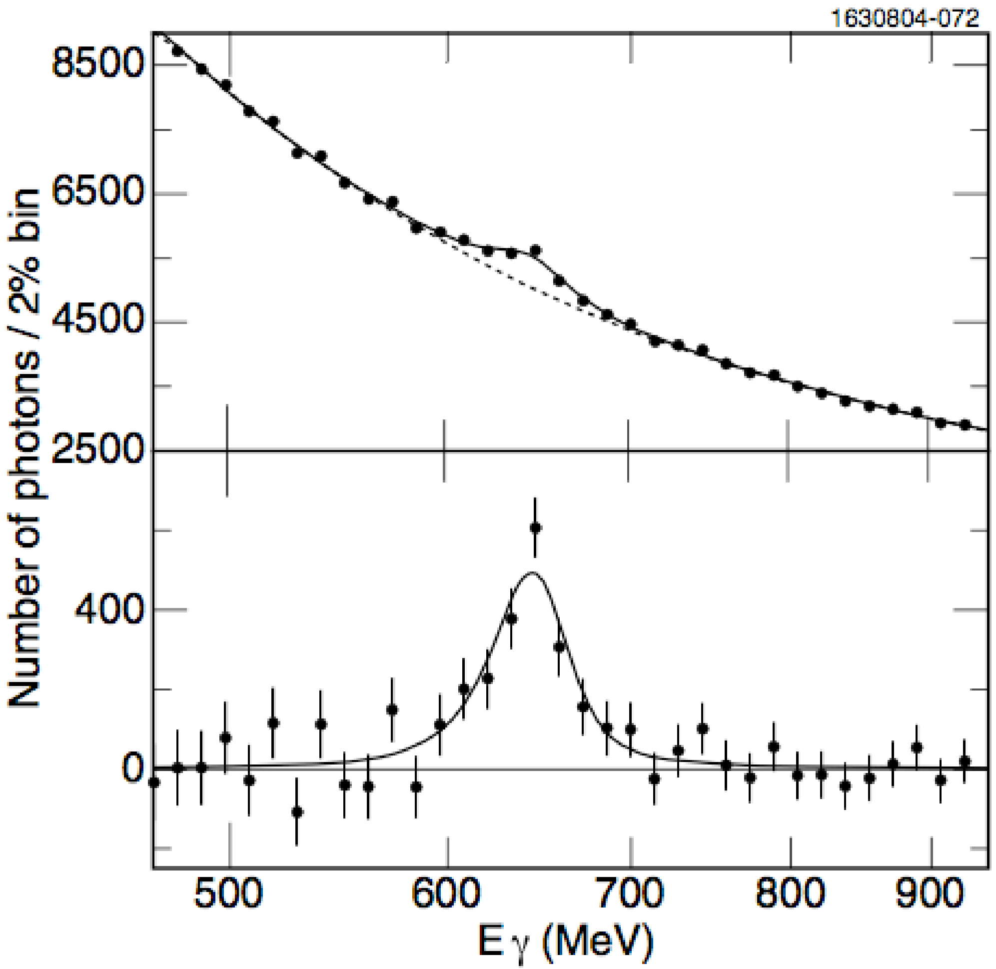
- The η_c line shape in $\psi(2S)\to\gamma\eta_c$ is non-trivial.
  - Extracting the mass and width of the η_c from this process requires theoretical help.
  - Perhaps this is one factor causing the wide variation in measurements of the η_c mass and width.
  - We resorted to empirical methods to count events.
- We measure (CLEO preliminary):
  - **$B(\psi(2S)\to\gamma\eta_c) = (4.02 \pm 0.11 \pm 0.52) \times 10^{-3}$**
  - Compared to (2004) CLEO's $(3.3 \pm 0.4 \pm 0.6 \pm 0.2) \times 10^{-3}$ using 1.5 million $\psi(2S)$ and assuming the PDG η_c width.
  - Compared to (1986) Crystal Ball's $(2.8 \pm 0.6) \times 10^{-3}$.
- These techniques will carry over into our measurement of $B(J/\psi\to\gamma\eta_c)$.

Backup Slides

B(ψ(2S)→γη$_c$) from CLEO (2004)

PHYSICAL REVIEW D **70,** 112002 (2004)

Photon transitions in $\psi(2S)$ decays to $\chi_{cJ}(1P)$ and $\eta_c(1S)$



$$\mathcal{B} = \left(0.324 + 0.028\,\frac{\Gamma_{\eta_c(1S)} - 24.8\text{ MeV}}{4.9\text{ MeV}}\right)\%$$

and the errors are

$$(\pm 0.039 \pm 0.055)\frac{\mathcal{B}}{0.324\%} \quad \pm\left(0.028\,\frac{\Delta\Gamma_{\eta_c(1S)}}{4.9\text{ MeV}}\right)\%.$$