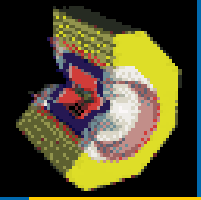

New CLEO Results on Charmonium Decays

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on behalf of the CLEO Collaboration

6th International Workshop on Heavy Quarkonia

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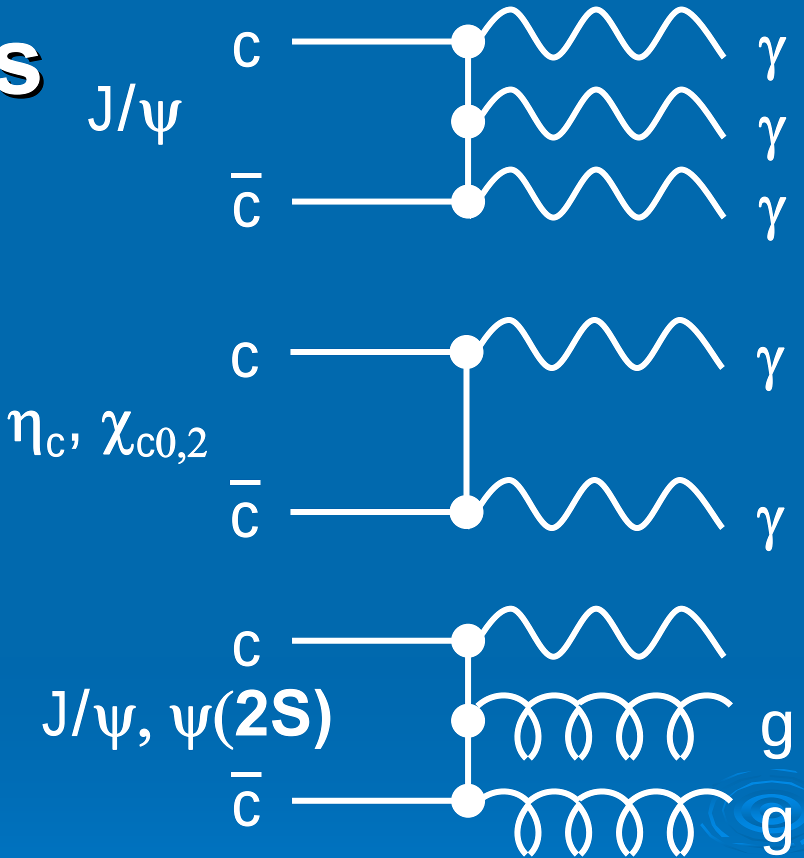
Radiative Charmonia Decays

- **Simplest onia decays**
  - $J/\psi \rightarrow \gamma\,\gamma\,\gamma$
  - $\eta_c \rightarrow \gamma\,\gamma$
  - $\chi_{cJ} \rightarrow \gamma\,\gamma$
- **Next simplest**
  - $J/\psi \rightarrow \gamma$ **gg**
  - ψ**(2S)** $\rightarrow \gamma$ **gg**

New for QWG!



- $\chi_{cJ} \rightarrow \gamma\,(\rho^0, \omega, \varphi)$
- **η' Properties from $J/\psi \rightarrow \gamma\,\eta'$**

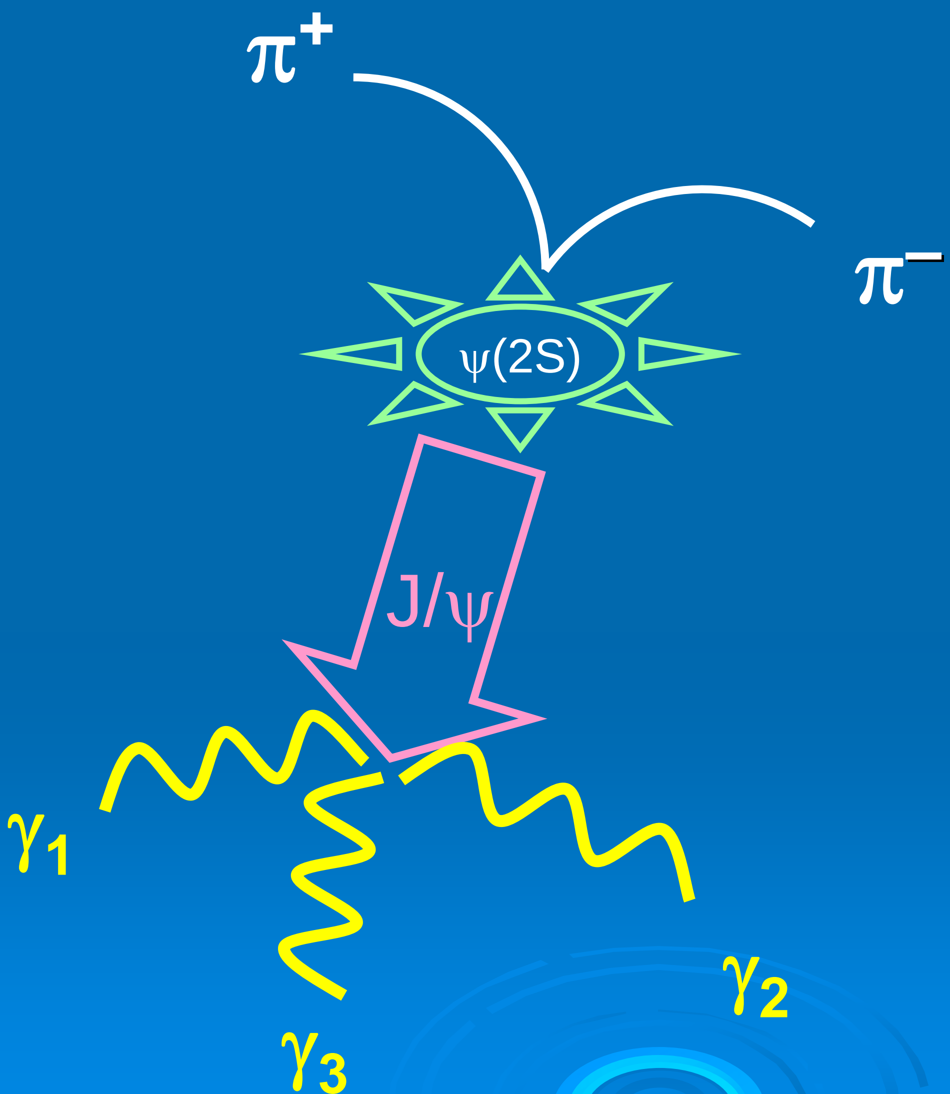
$J/\psi \to 3\gamma$ & $\eta_c \to \gamma\gamma$

- Measure or limit the decay $J/\psi \to 3\gamma$
- Expect $B(J/\psi \to 3\gamma) \sim 10^{-6} - 10^{-5}$
  - $B < 5.5 \times 10^{-5}$ Crystal Ball (1980)
  - No 'particle' ever observed in a 3γ decay!
    - $B(\omega \to 3\gamma) < 1.9 \times 10^{-4}$
    - $B(Z \to 3\gamma) < 1 \times 10^{-5}$
    - However, ortho-positronium (o-Ps), the $^3S_1$ e^+e^- atom, decays nearly 100% to 3γ. Also, $B(\text{o-Ps} \to 5\gamma) \approx 2 \times 10^{-6}$
- Seek $\eta_c \to \gamma\gamma$ in radiative J/ψ decays & measure $B(J/\psi \to \gamma\eta_c) \times B(\eta_c \to \gamma\gamma)$
  - E760 & E835 have observed $\eta_c \to \gamma\gamma$ in $p\bar{p} \to \gamma\gamma$
  - Belle: 4.1σ evidence in $B^\pm \to K^\pm \gamma\gamma$

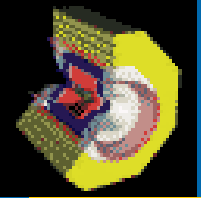
$$B(\eta_c \to \gamma\gamma) = (2.4\,^{+0.9}_{-0.8}\,^{+0.7}_{-0.4}) \times 10^{-4}$$

[PLB 662 (2008) 323]

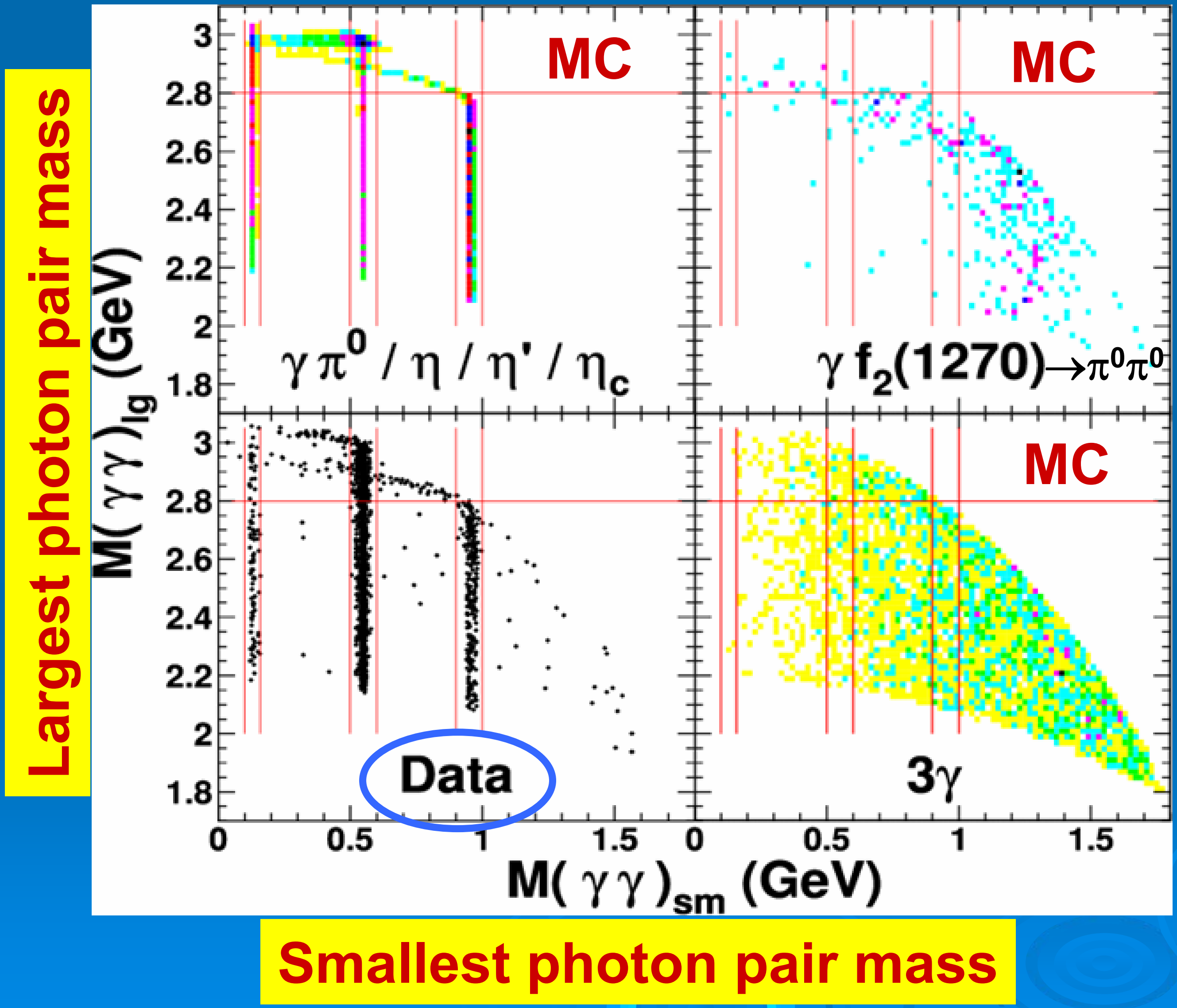
$J/\psi \rightarrow 3\gamma$



- **Unique topology:**
  - **2 tracks provide a tag of the J/ψ**
  - **3 showers with no resonant substructure**
- **Impose 4-momentum conservation**
- **χ^2 of kinematic fit a key variable**
  - **Suppress feed-down from other decays**
- **Also seek $J/\psi \rightarrow \gamma\, \eta_c\, ,\ \eta_c \rightarrow \gamma\, \gamma$**



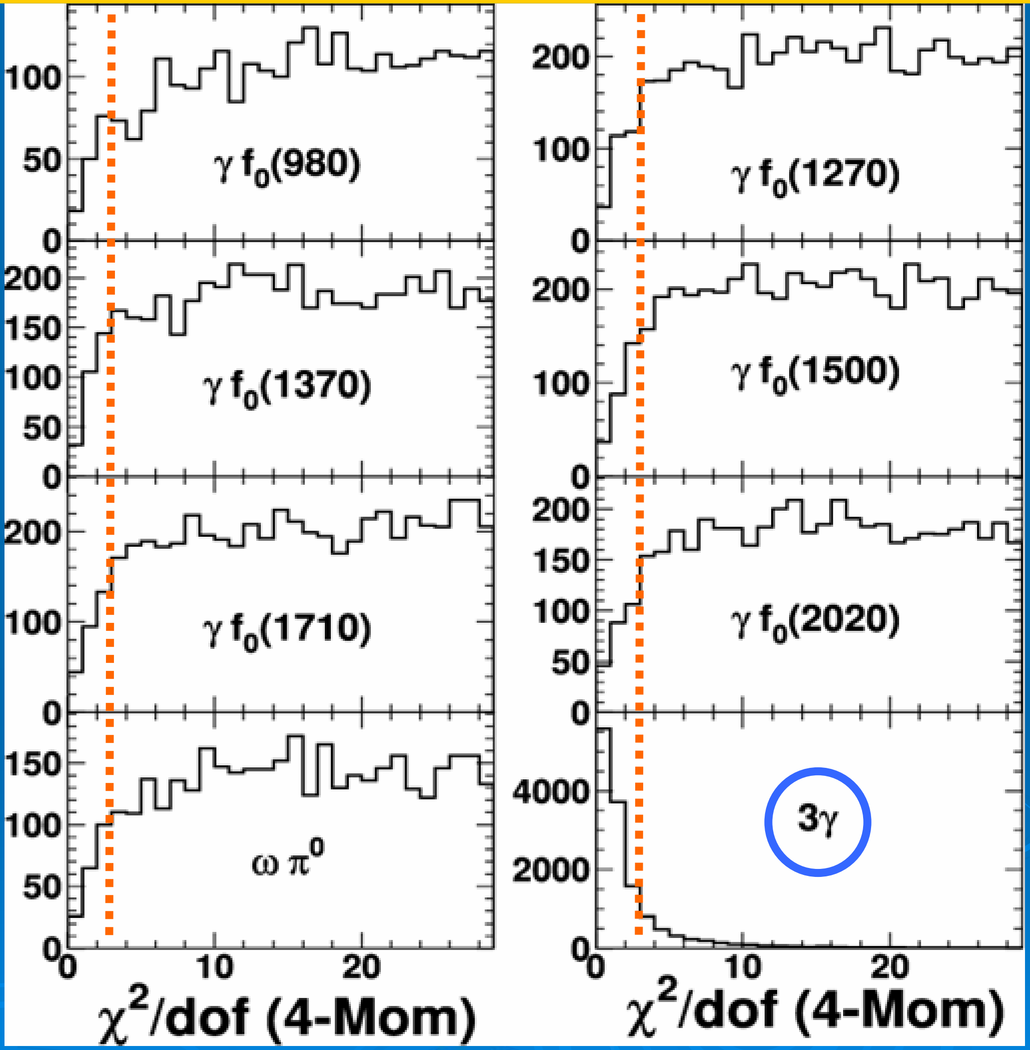
$J/\psi \to 3\gamma$



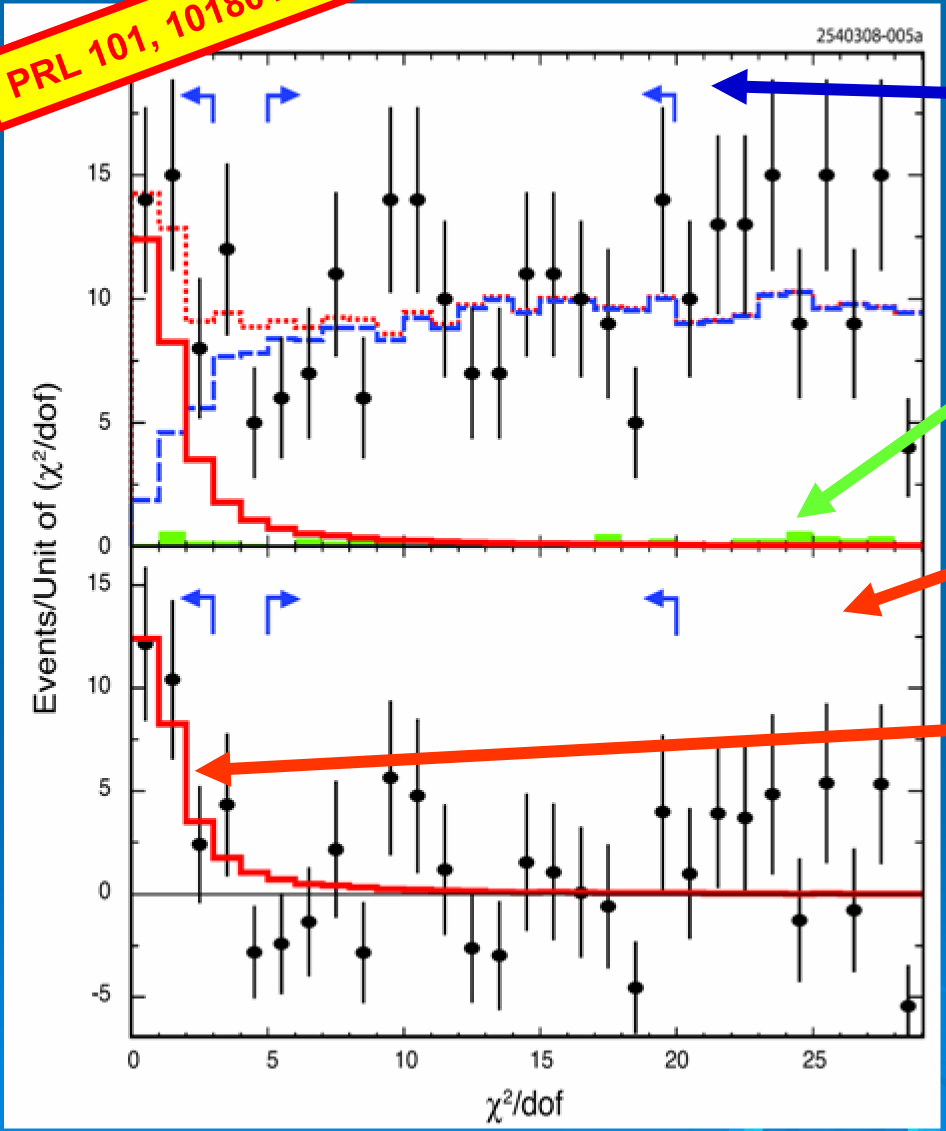
- Plot has $\chi^2<3$ cut in place
- **Veto** on masses inside 0.10-0.16, 0.50-0.60, 0.90-1.00, & >2.8 GeV
- 37 events remain in the data outside these regions

$J/\psi \to \gamma\, \pi^0\pi^0$ feed-down

- Only happens if BOTH π^0's decay asymmetrically
- Demand 4-momentum conservation to suppress: $\chi^2/dof < 3$ for signal
- BRs for various $J/\psi \to \gamma\, f_J$ not well known
- Notice that SHAPES of all 5γ χ^2 distribution are similar
- The data can be used at large χ^2/dof (5-20) for bgd normalization
- Mix of bgd sources does not to matter much for leakage into $\chi^2<3$



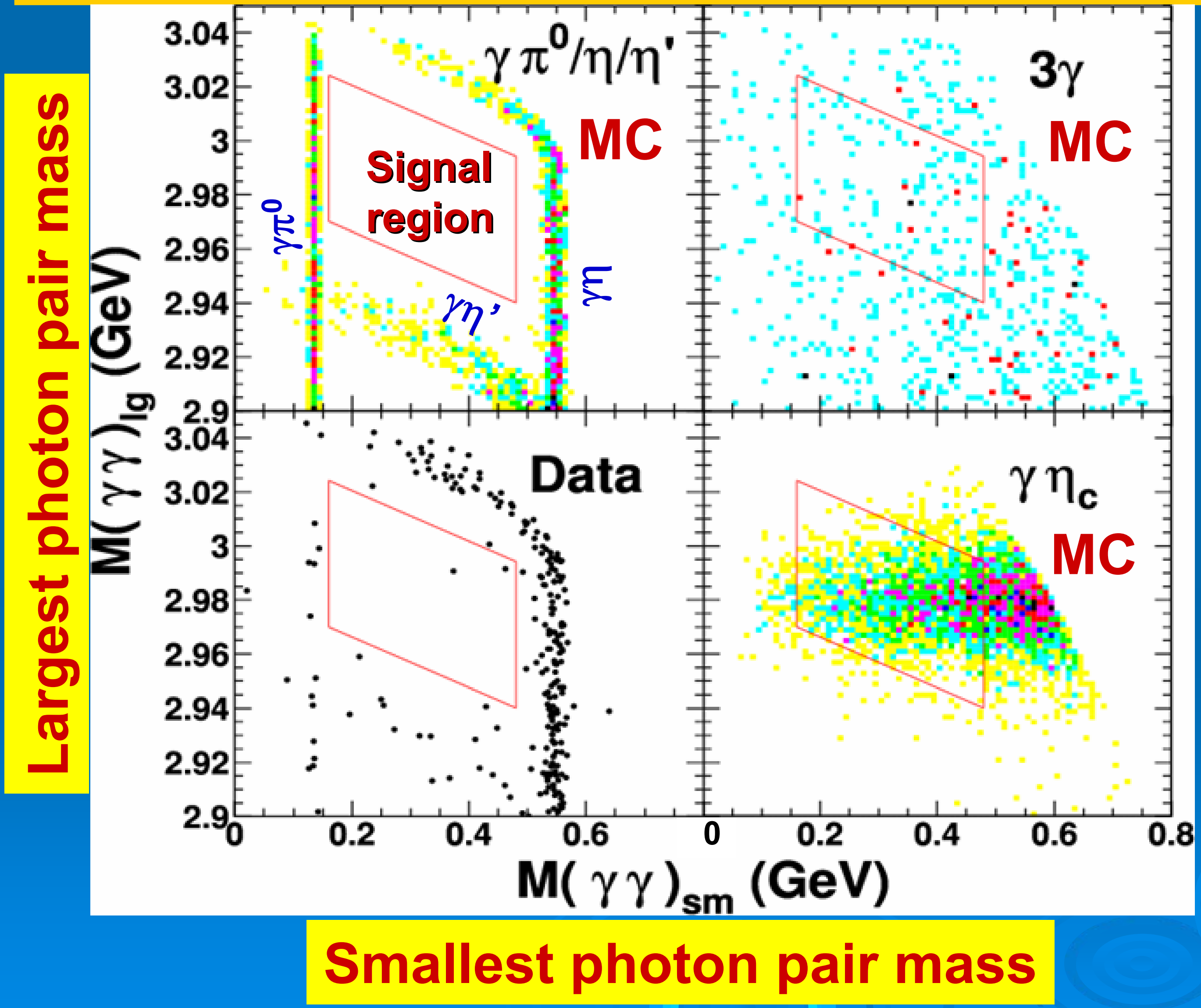
Result for J/ψ → 3γ



- Normalize γ f_J background in χ^2=5-20 region
- Small non-J/ψ bgd from $\pi^+\pi^-$ recoil sidebands
- After normalized bgd subtraction
- Signal shape required to describe data at small χ^2
- Net yield $24.2^{+7.2}_{-6.0}$ evts
- $B = (12 \pm 3 \pm 2) \times 10^{-6}$
- 6σ significance

$\eta_c \to \gamma\,\gamma$

$\eta_c \to \gamma\gamma$ Selection



- 2 signal events
- 0.8 events bgd total
- Eff=10.9%

Source	# bgd
$\gamma\eta$	0.3
$\gamma\eta'$	0.2
3γ	0.3
Total	**0.8**

$\eta_c \to \gamma\gamma$ Result

PRL 101, 101801 (2008)

- $B(J/\psi \to \gamma\eta_c) \times B(\eta_c \to \gamma\gamma)$

  $= (1.2\,^{+2.7}_{-1.1} \pm 0.3) \times 10^{-6}$

  or $< 5.3 \times 10^{-6}$ @90%CL

- Using CLEO's $B(J/\psi \to \gamma\eta_c) = (1.98 \pm 0.09 \pm 0.30)\%$,

  $B(\eta_c \to \gamma\gamma) = (0.6\,^{+1.3}_{-0.5} \pm 0.1) \times 10^{-4}$

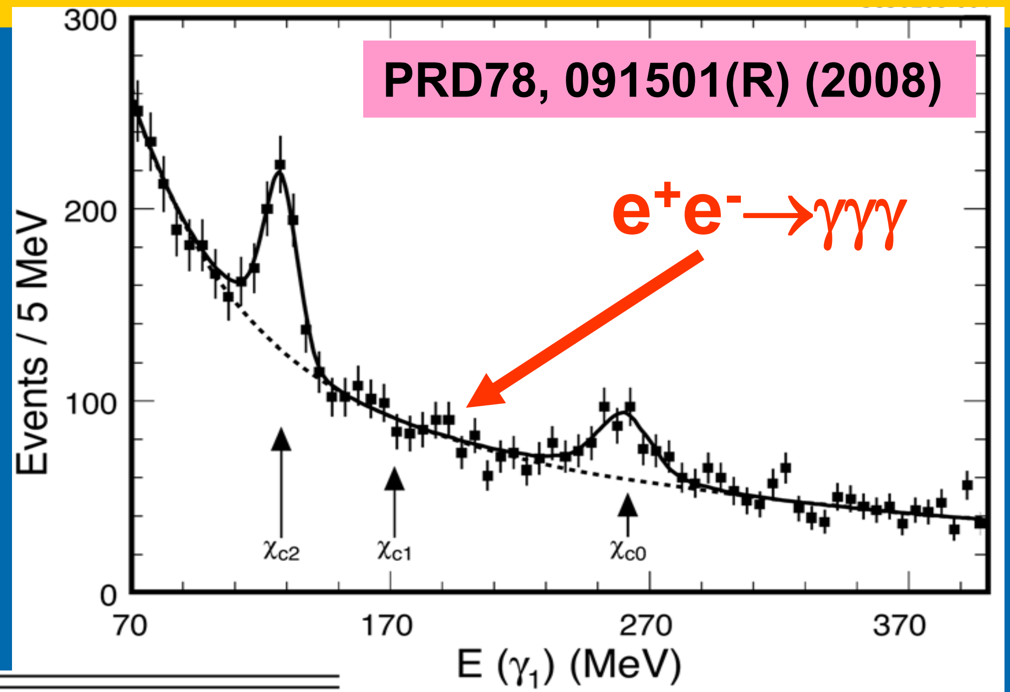
  $< 2.6 \times 10^{-4}$ @90%CL

  - PDG08 value $= (2.4\,^{+1.1}_{-0.9}) \times 10^{-4}$
    - Consistent within 1.1σ

$$\psi(2S) \rightarrow \gamma_1\ \chi_{cJ}\ ,\ \chi_{cJ} \rightarrow \gamma\ \gamma$$

$\psi(2S) \to \gamma_1 \chi_{cJ}$, $\chi_{cJ} \to \gamma\gamma$

- **Shown@QWG5: H. Mahlke**
- **Striking experimental signature: only 3γ !**
- **In $R \equiv \Gamma_2(\gamma\gamma) / \Gamma_0(\gamma\gamma)$ many theo. & exp. uncertainties will cancel**
  - **1st decay-based msmt**
  - **Lowest order: R=0.27**
  - **1st order α_S: R=0.12**



Quantity	χ_{c0}	χ_{c2}
$\mathcal{B}_1 \times \mathcal{B}_2 \times 10^5$	2.17±0.32±0.10	2.68±0.28±0.15
$\mathcal{B}_2 \times 10^4$	2.31±0.34±0.10±0.10	3.23±0.34±0.18±0.16
$\Gamma_{\gamma\gamma}$ (keV)	2.36±0.35±0.11±0.19	0.66±0.07±0.04±0.05
$\mathcal{R}$	0.278±0.050±0.018±0.031	

CLEO

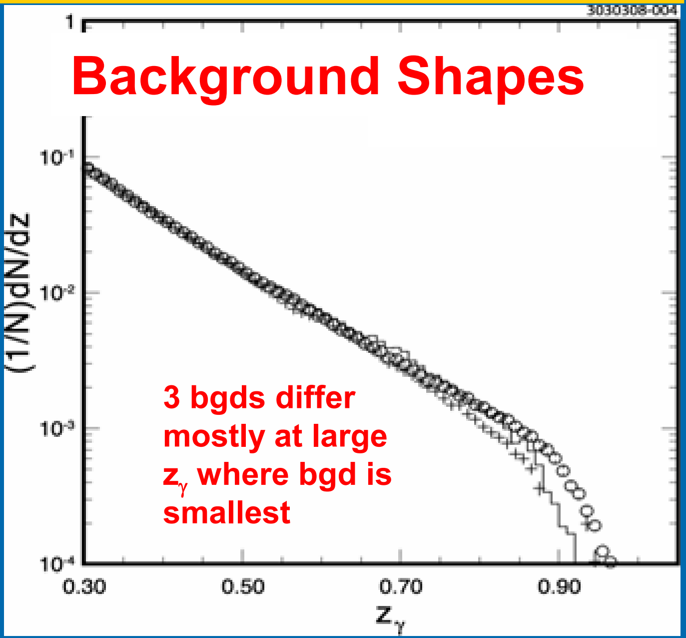
$\mathcal{R}_{\text{PDG}}=0.21\pm0.03$

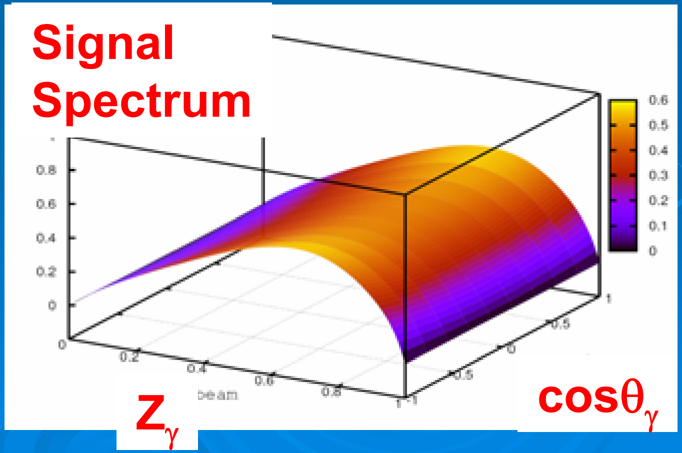
Reference	$\Gamma_{\gamma\gamma}(\chi_{c2})$ (eV)	$\Gamma_{\gamma\gamma}(\chi_{c0})$ (eV)	$\mathcal{R}$
Barbieri [3]	930	3500	0.27
Godfrey [4]	459	1290	0.36
Barnes [5]	560	1560	0.36
Bodwin [6]	820±230	6700±2800	$0.12^{+0.15}_{-0.06}$
Gupta [7]	570	6380	0.09
Münz [8]	440±140	1390±160	$0.32^{+0.16}_{-0.12}$
Huang [9]	490±150	3720±1100	$0.13^{+0.11}_{-0.06}$
Ebert [10]	500	2900	0.17
Schuler [11]	280	2500	0.11

$J/\psi \to \gamma\, gg$

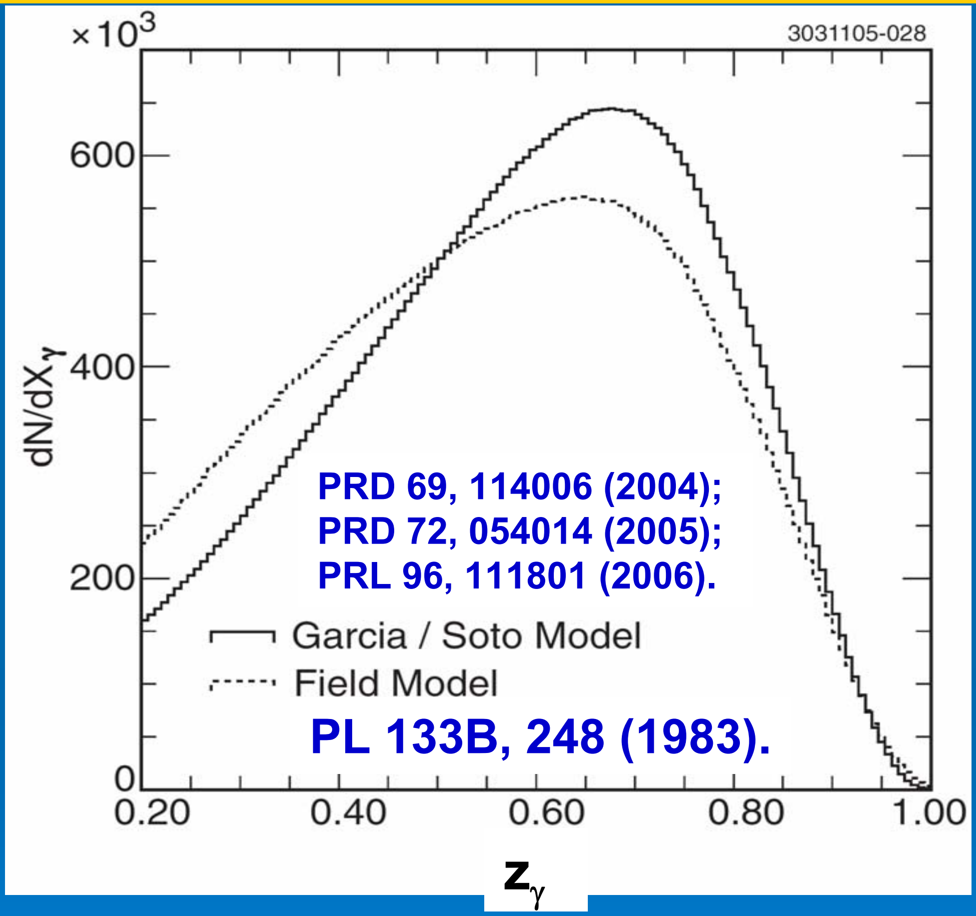
$J/\psi \to \gamma\, gg$

- Select clean primary γ's
  - $z_\gamma \equiv E_\gamma / E_{beam}$: $z_\gamma > 0.3$
  - veto γ's that pair with another to form π^0
  - do not veto $\eta \to \gamma\gamma$ (too much signal killed)
- Eliminate e^+e^- "continuum" bgd, partly ISR, by using $\psi(2S) \to \pi^+\pi^- J/\psi$
  - Makes analysis much simpler than $\Upsilon \to \gamma\, gg$ [PRD74, 012003 (2006)]
  - Small non-J/ψ bgd directly subtracted with $\pi^+\pi^-$ recoil mass sidebands
- Model remaining bgd in 3 systematically complementary ways
  - Two are data-driven, one MC-only
    - See paper for details
  - Spread among them indicative of syst. error
- Model signal as
  - Three 2-body processes: $\gamma\eta$, $\gamma\eta'$, $\gamma\eta(1440)$
  - Theoretical shape validated with CLEO $\Upsilon \to \gamma\, gg$ measurements
    - NEW: also include z_γ-$\cos\theta_\gamma$ correlation & shape a la Koller-Walsh [NP B140, 449 (1978)].



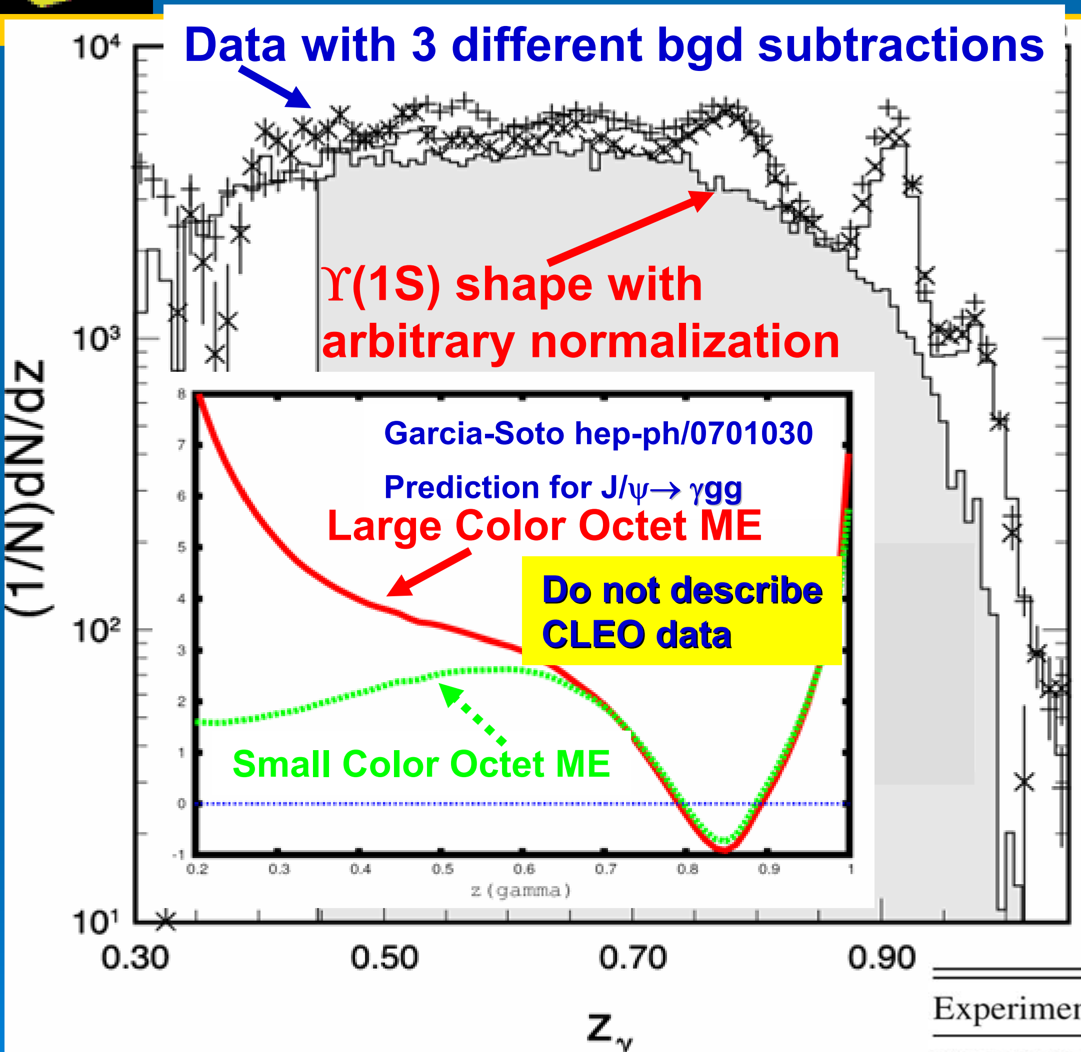


Signal Shape



- These are spectra developed for $\Upsilon \to \gamma gg$
- Found to work adequately for $J/\psi \to \gamma gg$

J/ψ Direct Photon Spectrum



- After correcting for angular acceptance & efficiency, this spectrum gives # $J/\psi \to \gamma gg$ events
- # $J/\psi \to ggg$ from
  - # $\pi^+\pi^-$ J/ψ
  - # $J/\psi \to \gamma gg$
  - $J/\psi \to e^+e^-, \mu^+\mu^-$ (PDG)
  - $J/\psi \to \gamma^* \to q\bar{q}$ (PDG)
- $$R_\gamma \equiv \frac{B_{gg\gamma}}{B_{ggg}} = \frac{N_{gg\gamma}}{N_{ggg}}$$

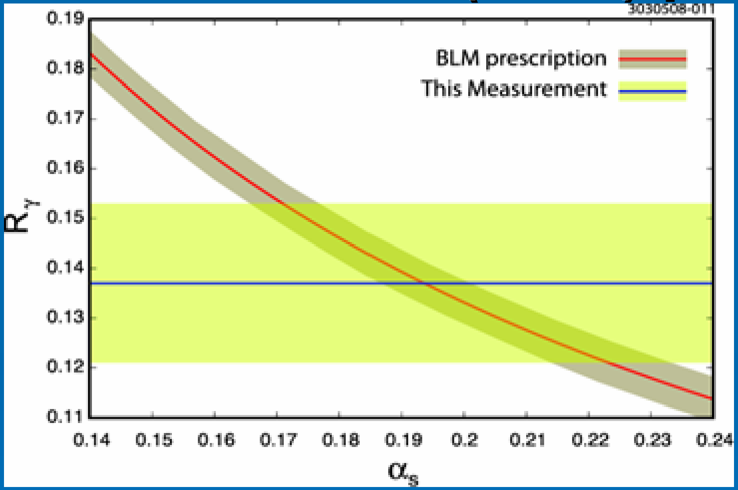
Experiment	R_γ
MARK-II [14]	0.041 ± 0.008 ($z_\gamma > 0.6$ only)
	0.146 ± 0.028 (all z_γ, estimated)
This measurement	$R_\gamma = 0.137 \pm 0.001 \pm 0.016 \pm 0.004$

PRD 78, 032012 (2008)

Measured R_γ & QCD

- Systematic error (11%) dominated by
  - Background subtraction uncertainty
  - Signal shape uncertainty
- Brodsky, Lepage, Mackenzie PRD 28, 228 (1983) predict

$$R_\gamma = \frac{36}{5} q_c^2 \frac{\alpha_{em}}{\alpha_s}[1 + (2.2 \pm 0.6)\alpha_s/\pi]$$

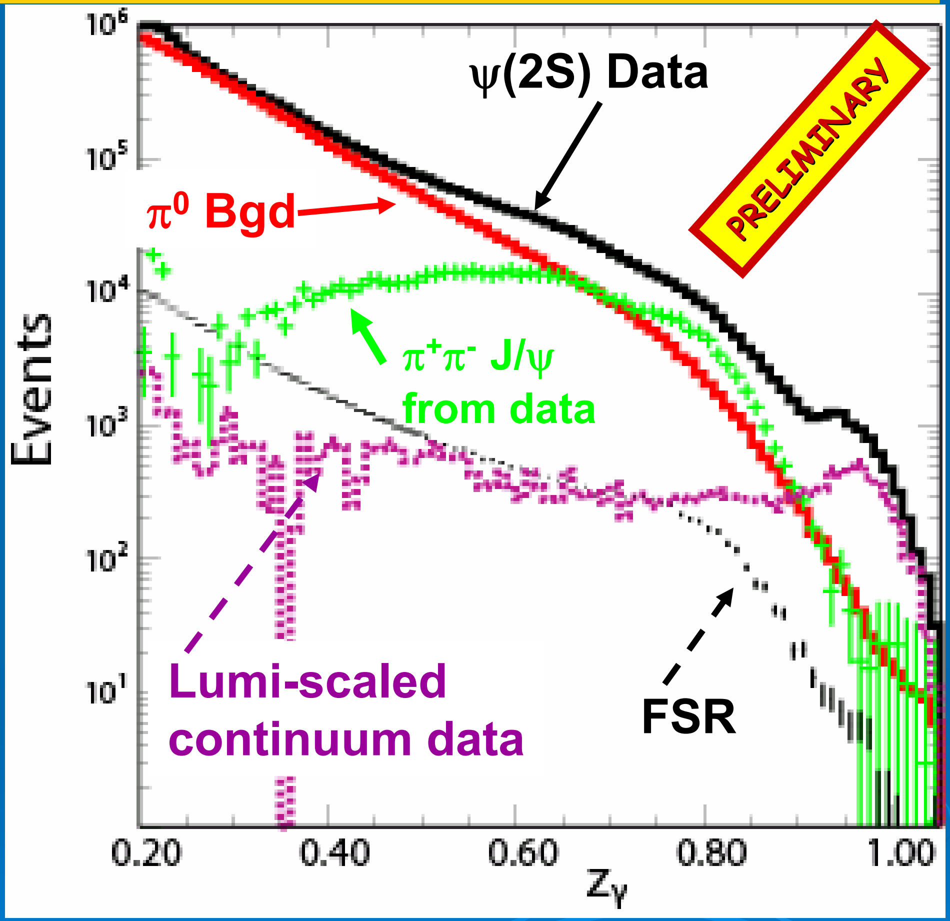


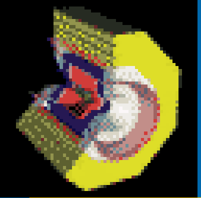
- Also can be expressed as $B(J/\psi \rightarrow \gamma gg) = (9.0 \pm 1.0)\%$
  - Somewhat larger than Voloshin [PPNP 61, 455 (2008)] estimate of 6.7% based on $\alpha_S(m_c)$=0.19 & known $\Gamma_{ee}(J/\psi)$

$\psi(2S) \to \gamma\, gg$

$\psi(2S) \to \gamma\, gg$

- Similar approach, but…
- Must subtract spectrum from below-$\psi(2S)$ continuum data to suppress ISR effects
- Must subtract contribution from $J/\psi \to \gamma gg$ & its bgd
  - Use shape from dipion tags: $\psi(2S) \to \pi^+\pi^- J/\psi$
  - Correct for ε, $B(\text{any } J/\psi)$ / B_{+-}
- FSR from MC
- Model remaining backgrounds 3 different ways (both MC and data-driven methods)



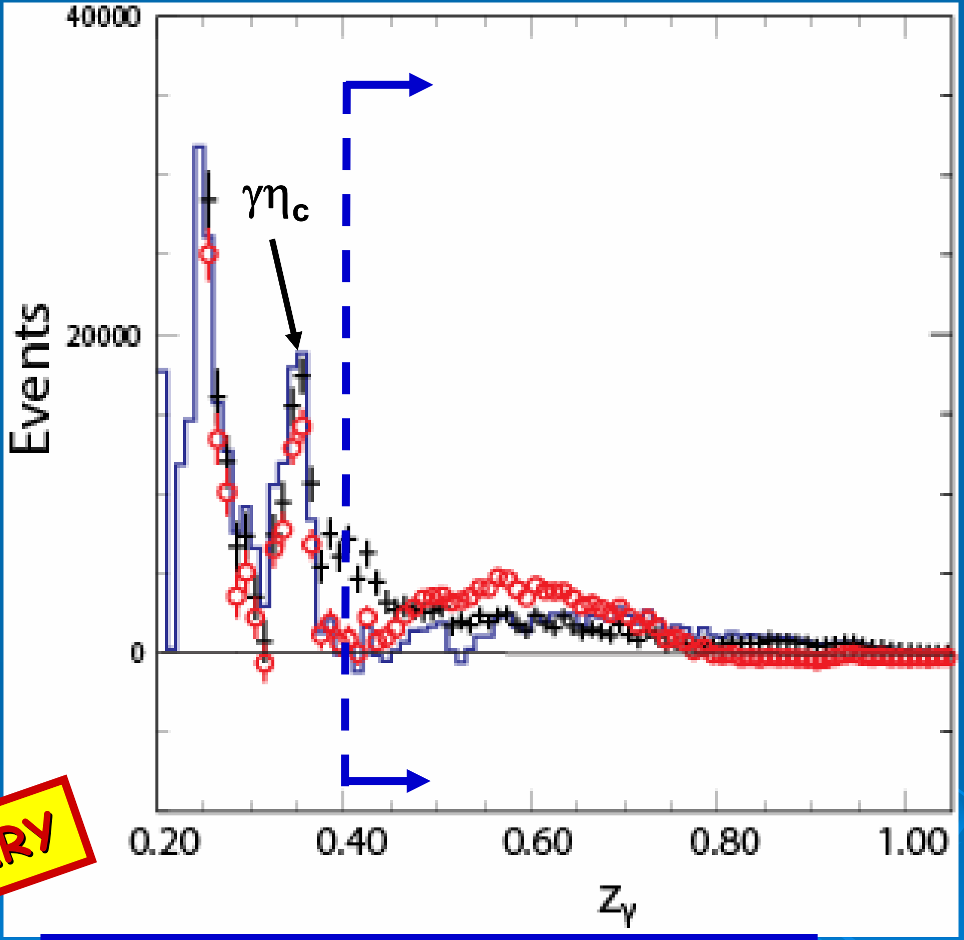


Results for $\psi(2S) \rightarrow \gamma\, gg$

- Integrate data for z_γ>0.4
  - spread among bgd methods indicates systematics
  - Correct for ε
  - Correct for z_γ<0.4 / z_γ>0.4
    - ~30% of spectrum is z_γ<0.4
- Σ B[$\psi(2S) \rightarrow$
  - e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$ (PDG)
  - $\gamma^* \rightarrow q\bar{q}$ (PDG)
  - $\pi^+\pi^- J/\psi$, $\pi^0\pi^0 J/\psi$, $\eta/\pi^0 J/\psi$
  - $\gamma\, \chi_{cJ}$, $\gamma\, \eta_c$, $\pi^0\, h_c$

$\approx$ 87%.

  - Leaves ~13% for γ gg, 3g
  - We know total #$\psi(2S)$
  - B(γgg) $\approx$ 0.9 %
  - B(ggg) $\approx$ 12 %



PRELIMINARY

$\Rightarrow R_\gamma$= 0.065 ± 0.010 ± 0.023

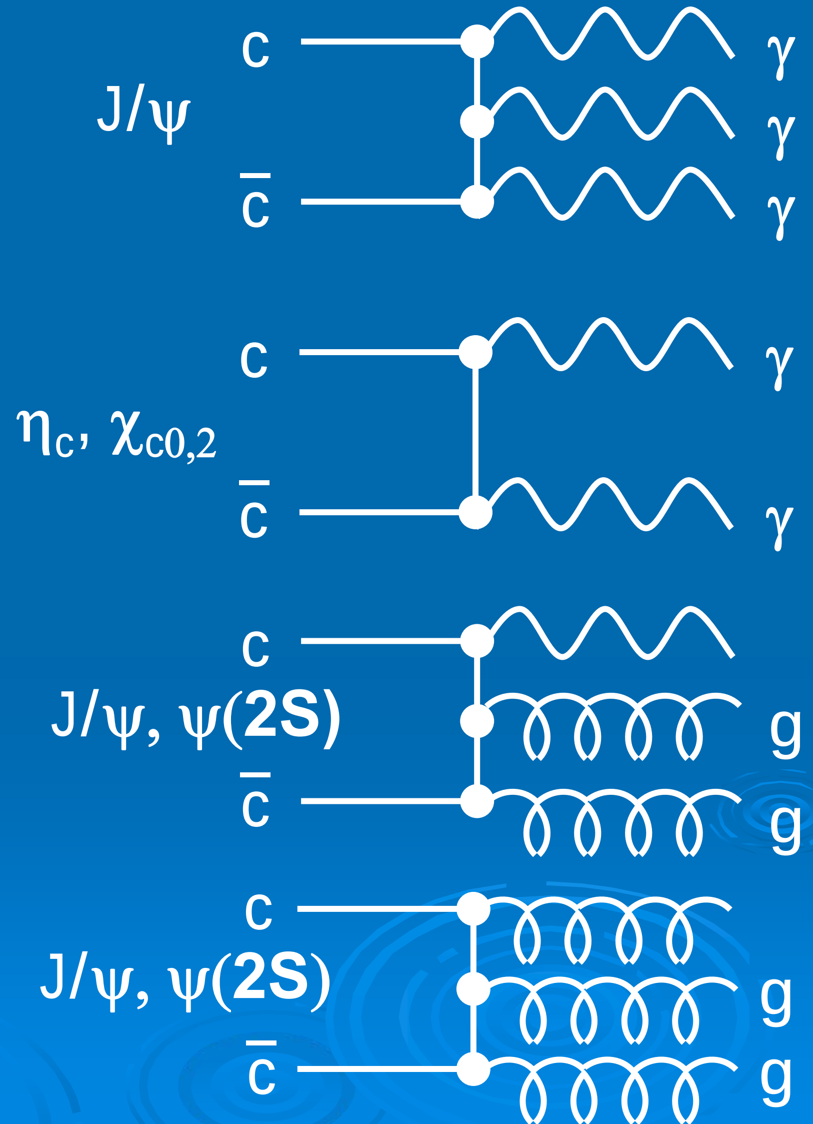
- ~Half of J/ψ R_γ (~3σ below)

Reminder: for Υ(1S,2S,3S)$\rightarrow\gamma$gg, CLEO measurements yielded $R_\gamma \approx$ 0.03 within ~10-15% errors [PRD74 (2006) 012003]

Charmonium Annihilation Summary

Many measured annihilation rates!

- CLEO has measured several important & fundamental rates
- Various ratios can be taken to cancel out wave function terms & other common factors
- Lowest order PQCD predictions known, up to choice of the mass scale at which to evaluate α_s
- 1st order α_s corrections to these ratios are also known
  - Most are large (>~20%)
  - Some are unphysical
- Fodder for postdictions!



Charmonium Annihilation Γ Ratios

System	Ratio	Lowest order	L.O. Value	Msd by CLEO
η_c	$\gamma\gamma$ / gg	$(8/9)(\alpha/\alpha_S)^2$	5.3×10^{-4}	$<2.6 \times 10^{-4}$ (90%CL)
J/ψ	$\gamma\gamma\gamma / e^+e^-$	$[64(\pi^2-9)/(243\pi)]\,\alpha$	5.3×10^{-4}	$(2.0\pm0.7) \times 10^{-4}$
J/ψ	$\gamma\gamma\gamma$ / γgg	$(8/27)(\alpha/\alpha_S)^2$	1.8×10^{-4}	$(1.3\pm0.4) \times 10^{-4}$
J/ψ	$\gamma\gamma\gamma$ / ggg	$(128/135)(\alpha/\alpha_S)^3$	1.4×10^{-5}	$(1.8\pm0.4) \times 10^{-5}$
J/ψ, ψ(2S)	γgg / ggg	$(16/5)(\alpha/\alpha_S)$	0.078	0.137±0.017 0.065±0.025
χ_{c0}	$\gamma\gamma$ / gg	$(8/9)(\alpha/\alpha_S)^2$	5.3×10^{-4}	$(2.3\pm0.4) \times 10^{-4}$
χ_{c2}	$\gamma\gamma$ / gg	$(8/9)(\alpha/\alpha_S)^2$	5.3×10^{-4}	$(4.3\pm0.6) \times 10^{-4}$
$\chi_{c0,2}$	$\gamma\gamma_2 / \gamma\gamma_0$	4 / 15	0.27	0.28±0.06

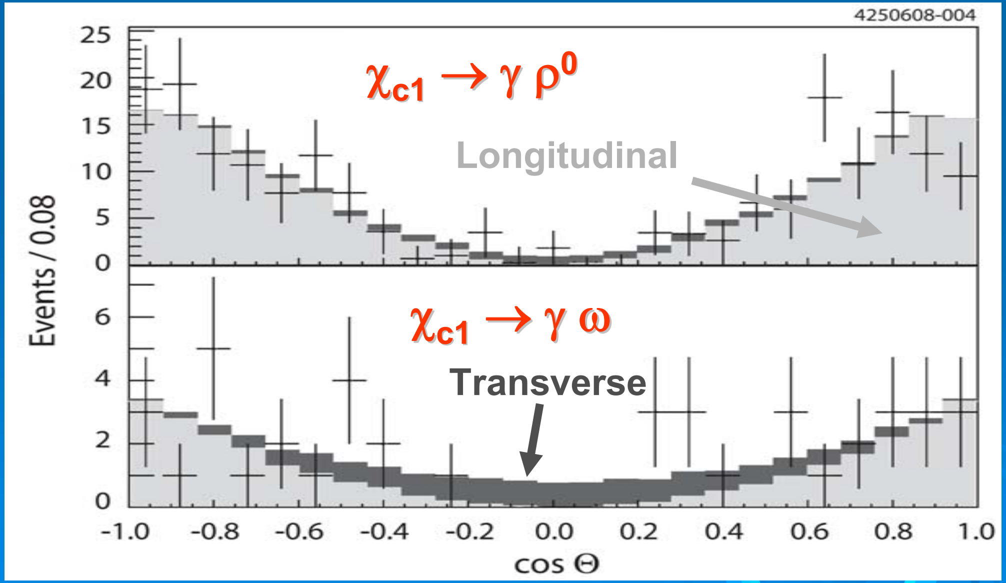
Kwong, et al., PRD 37, 3210 (1988)

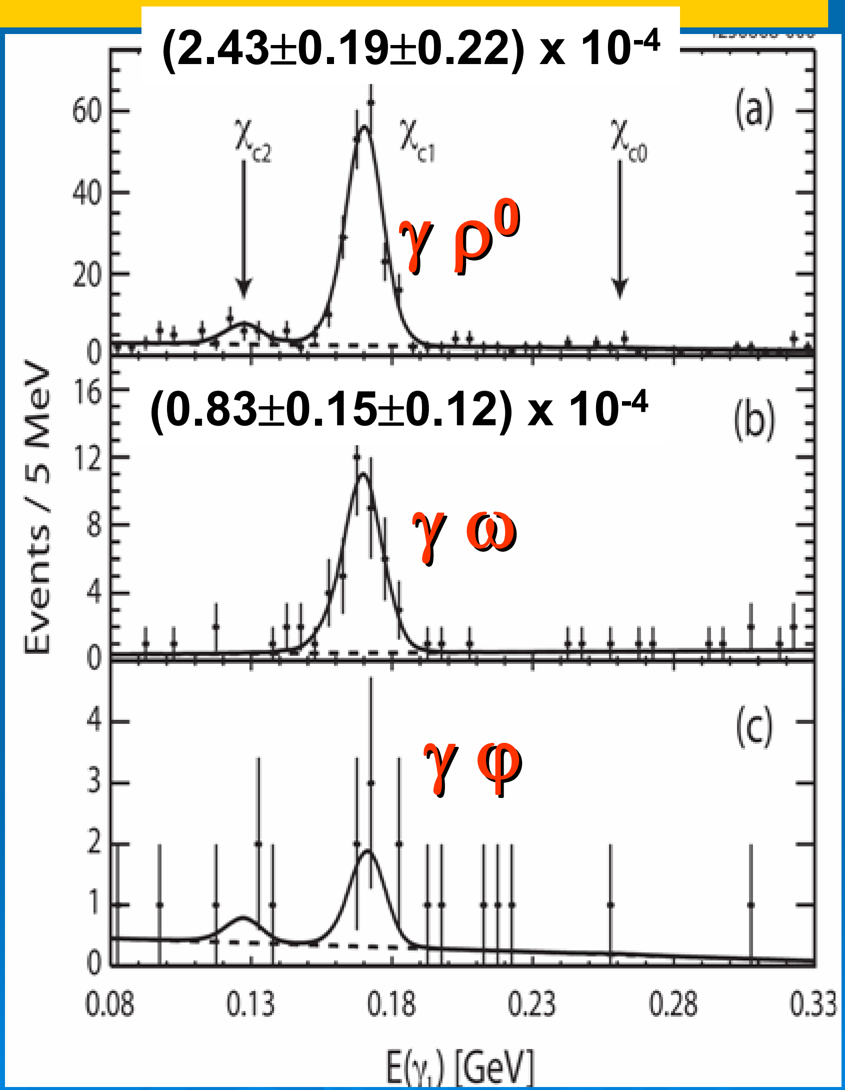
Using α_S=0.3

$\chi_{cJ} \to \gamma\ (\rho^0, \omega, \varphi)$

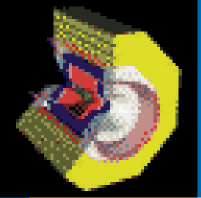
$\chi_{cJ} \rightarrow \gamma\ (\rho^0, \omega, \varphi)$

- Glue-rich system recoils against γ
- Clean experimental signatures
- ULs for $B[\chi_{c0,2} \rightarrow \gamma\ (\rho^0, \omega, \varphi)]$
- Observe $B[\chi_{c1} \rightarrow \gamma\ (\rho^0, \omega)] \sim 10^{-4}$
  - Factors of ~(15,50) higher than prediction of Gao, Zhang, & Chao, CPL 23, 2376 (2006)
- $\chi_{c1} \rightarrow \gamma\ \rho^0$ has ~full long. polarization
  - Like $f_1(1285) \rightarrow \gamma\rho^0$ [VES, ZPC66, 71 (1995)]

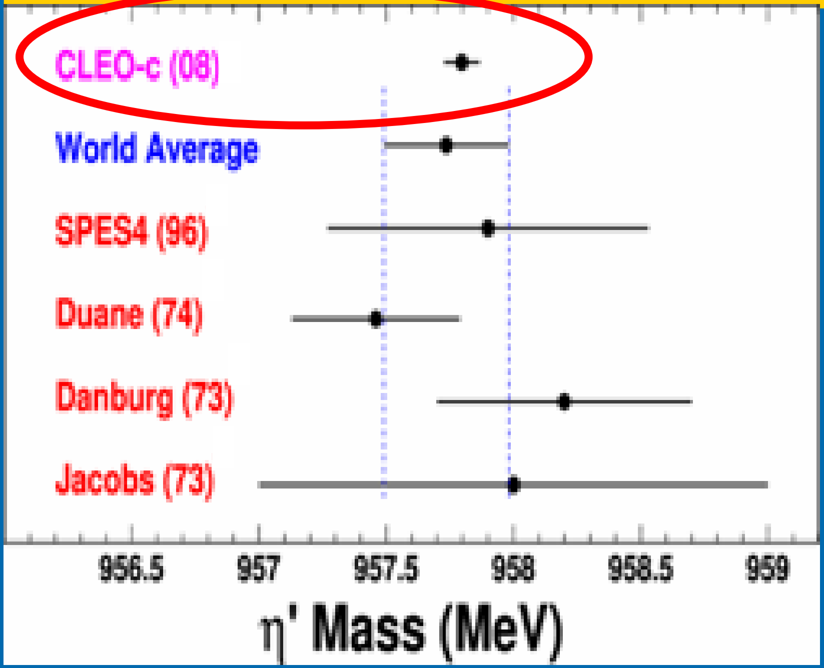


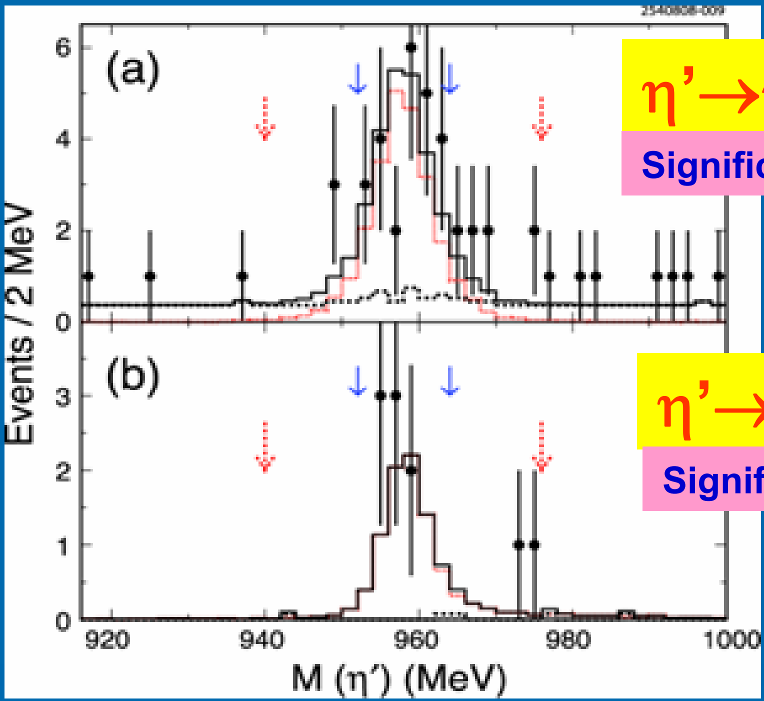


PRL 101, 151801 (2008)



η’ Properties





$\eta' \to \pi^+\pi^-\pi^0$

Significance: $>6\sigma$

$\eta' \to \pi^+\pi^- e^+e^-$

Significance: $>6\sigma$

- **CLEO has studied η’ properties via $J/\psi \to \gamma\,\eta'$**
  - **Mass error improved by factor of 5**
  - **Limits on rare hadronic modes**
  - **1st observation of $\eta' \to \pi^+\pi^-\pi^0$, $\pi^+\pi^- e^+e^-$**

PRL101, 182002 (2008)

Summary & Conclusions

- **CLEO has measured a large number of charmonium annihilation rates**
  - $B(J/\psi \to \gamma\gamma\gamma) = (12 \pm 3 \pm 2) \times 10^{-6}$
  - $B(J/\psi \to \gamma\,\eta_c) \times B(\eta_c \to \gamma\gamma) = (1.2\,^{+2.7}_{-1.1} \pm 0.3) \times 10^{-6}$
  - χ_{cJ} : $\Gamma_2(\gamma\gamma) / \Gamma_0(\gamma\gamma) = 0.278 \pm 0.050 \pm 0.018 \pm 0.031$
  - $J/\psi \to \gamma\,gg$: $R_\gamma = 0.137 \pm 0.001 \pm 0.016 \pm 0.004$
  - $\psi(2S) \to \gamma\,gg$: $R_\gamma = 0.065 \pm 0.010 \pm 0.023$
- **$\chi_{cJ} \to \gamma\,(\rho^0, \omega, \varphi)$ rates measured**
  - $\chi_{c1} \to \gamma\,(\rho^0, \omega)$ BRs exceed prediction by factor of (15,50)
- **CLEO has studied η' properties via $J/\psi \to \gamma\,\eta'$**
  - Mass error improved by factor of 5
  - Limits on rare hadronic modes
  - 1st observation of $\eta' \to \pi^+\pi^-\pi^0$, $\pi^+\pi^-e^+e^-$

Charmonium Decay Analyses in Progress

- η_c exclusive branching fractions
- h_c decays to light hadrons
- $J/\psi \to \gamma$ + invisible
- $J/\psi \to$ invisible
- J/ψ, $\psi(2S) \to \gamma/\pi^0\, pp$
- J/ψ, $\psi(2S) \to \gamma\, f_J \to \gamma\, (\pi\pi$, KK, $\eta\eta)$ [glueball search]
- $J/\psi \to \pi\pi$, KK, pp
- J/ψ, $\psi(2S) \to$ baryon-antibaryon
- $\psi(4160) \to \gamma\, \chi_c(2P)$ search

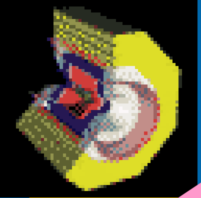
Backup Slides

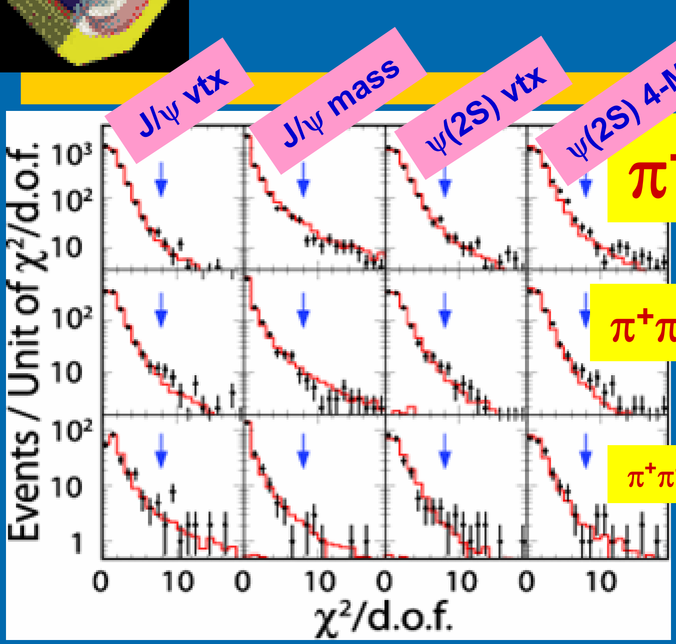
η’ Properties

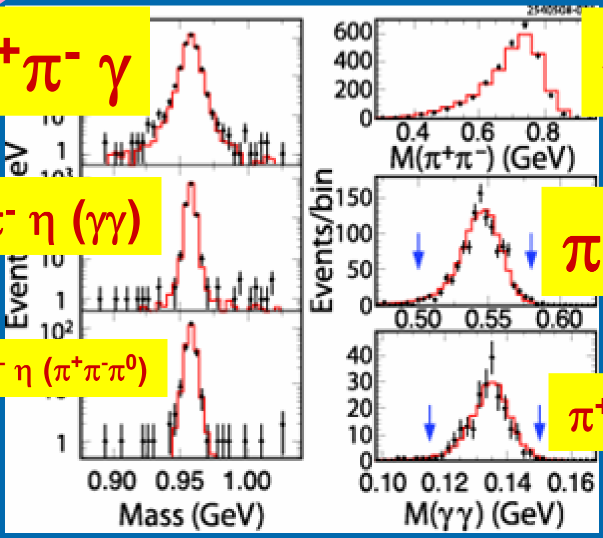
η' Properties

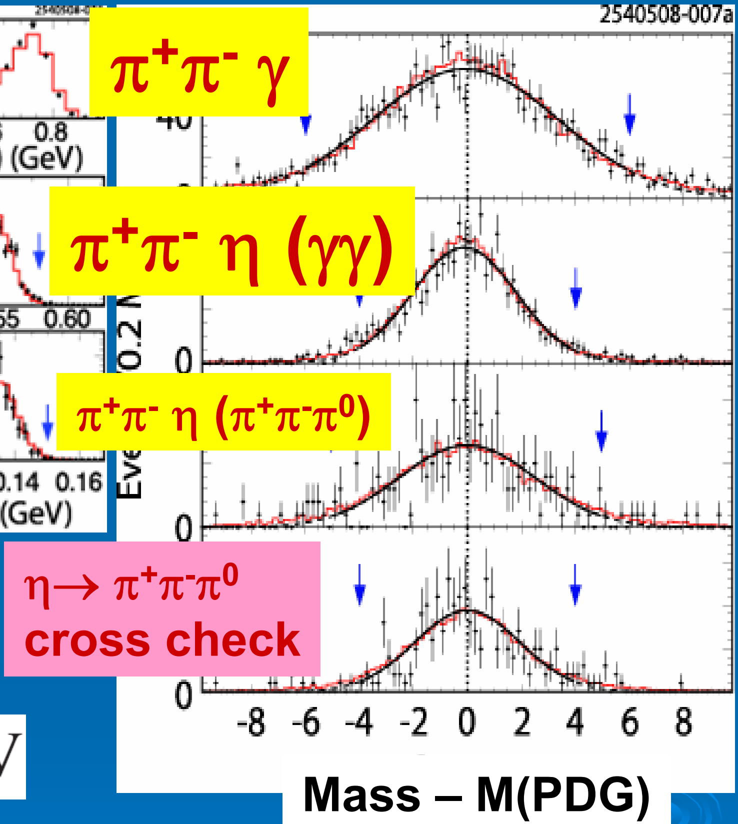
- Some properties of $\eta'(958)$ are not so well known
- M(PDG08) = 957.66 ± 0.24 MeV
  - Best msmt 1974: MMS 957.46 ± 0.33 MeV
  - Compare to η mass error of 24 keV:
    η' is less precise by a factor of 10
- Rare BRs: many mode limits of order 1-5%
  - $B(\eta' \to \pi^+\pi^-\pi^0) < 5\%$
    - Of interest because $B(\eta' \to \pi^+\pi^-\pi^0) \propto m_u - m_d$ (or not!)
    - Predictions vary from 0.1%-3%.
    - Rate sensitive to level of η-η'-π^0 mixing, final state rescattering
  - $B(\eta' \to \pi^+\pi^- e^+e^-) < 0.6\%$. Predicted to be ~0.2%.
  - $\eta' \to 2(\pi^+\pi^-)\,\pi^0$, $\eta' \to 3(\pi^+\pi^-)$, $\eta' \to 2(\pi^+\pi^-)$ each has a B < 1%
- Turns out that we can produce many η' mesons in $\psi(2S) \to \pi^+\pi^- J/\psi$, $J/\psi \to \gamma\,\eta'$: ~40K in CLEO-c data.
- Use common decay modes for mass measurement & search for some rare modes
  - Exclusive reconstruction & constrained fitting

η' Mass



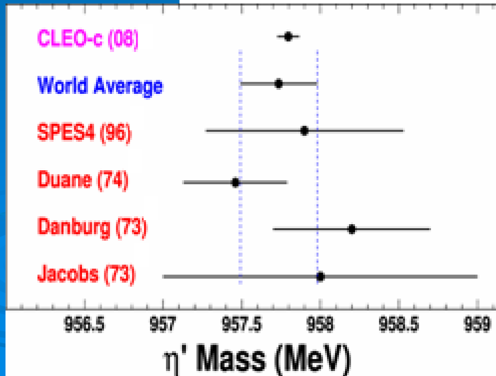






- ~4K reconstructed decays
- $M_{\eta'} = 957.793 \pm 0.054 \pm 0.036$ MeV
- Factor of 5 in mass precision

PRL101, 182002 (2008)



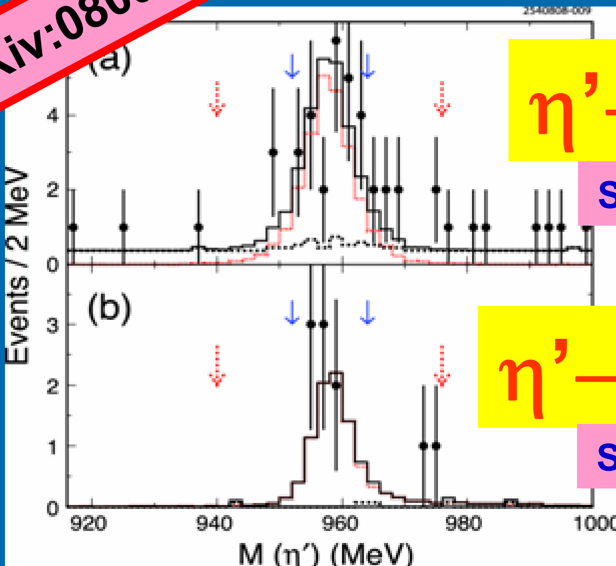
η' Mass

- **Systematic errors**

Source	Variation	A	B	C	All
Fit mass window		11	9	31	7
$M_{\psi(2S)}$	34 keV	9	2	3	5
$M_{J/\psi}$	11 keV	3	2	2	2
Bias	$(\lvert\beta_i\rvert + \Delta\beta_i)/3$	27	51	30	27
$p_{\pi^\pm}$ scale	0.01%	28	17	25	15
E_γ scale	0.6%	13	22	28	12
M_η	24 keV		23		11
Systematic sum		44	63	57	36
Statistical		87	70	208	54

Rare η' Decays

arXiv:0809.2587

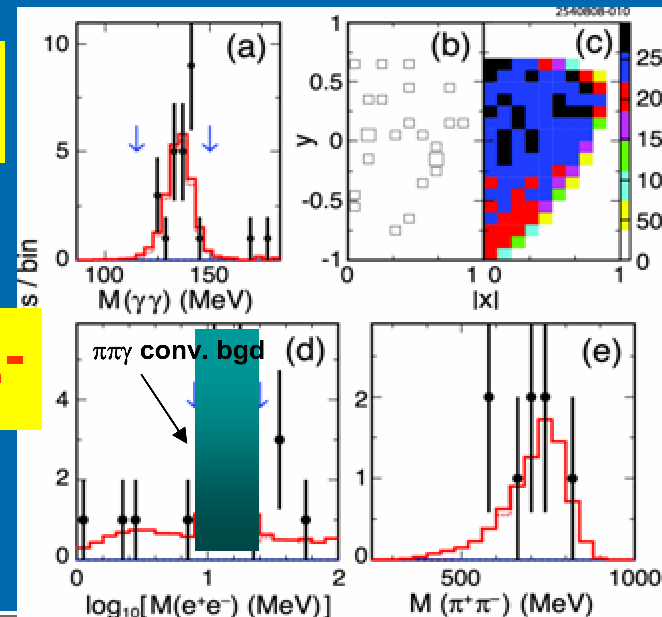


$\eta' \to \pi^+\pi^-\pi^0$

Significance: >6σ

$\eta' \to \pi^+\pi^- e^+e^-$

Significance: >6σ

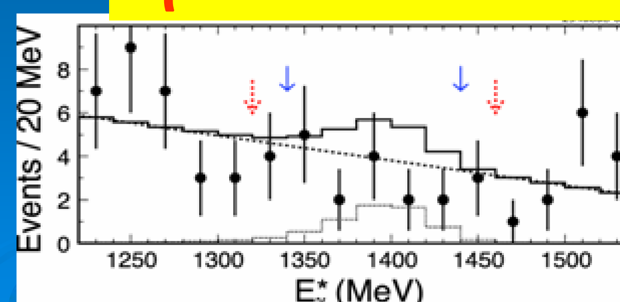


Mode X	ϵ/ϵ_0	N	$B(10^{-4})$	PDG (10^{-4})
$\pi^+\pi^-\pi^0$	0.55	$20.2^{+6.1}_{-4.8}$	$37^{+11}_{-9}\pm4$	<500
$\pi^+\pi^-e^+e^-$	0.31	$7.9^{+3.9}_{-2.7}$	$25^{+12}_{-9}\pm5$	<60
$\pi^+\pi^-\mu^+\mu^-$	2.14	<4.8	<2.4	-
$2(\pi^+\pi^-)$	1.02	<2.3	<2.4	<100
$\pi^+\pi^-2\pi^0$	0.18	<4.1	<27	-
$2(\pi^+\pi^-)\pi^0$	0.21	<3.6	<20	<100
$3(\pi^+\pi^-)$	0.47	<2.3	<5.3	<100
Invisible	0.74	<5.8	<9.5	<14

1st Obs.

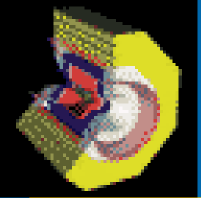
Improved/ 1st Limits

$\eta' \to$ invisible



Results for $J/\psi \to n\gamma$

	2γ	3γ	4γ	5γ	$\gamma\eta_c, \gamma\eta_c \to \gamma\gamma$
Signal candidates (events)	9	37	5	0	2
Background (events)					
J/ψ backgrounds	6.2	11.9	3.2	0.5	0.8
Non-J/ψ backgrounds	0.9	0.9	0.5	0	0
Background sum (events)	7.1	12.8	3.7	0.5	0.8
Statistical significance (σ)	1.1	6.3	1.0	0.0	1.0
Net yield (68% C.L. interval) (events)	$1.9^{+4.7}_{-1.6}$	$24.2^{+7.2}_{-6.0}$	$1.3^{+2.4}_{-1.3}$	$0^{+1.2}_{-0}$	$1.2^{+2.8}_{-1.1}$
UL @ 90% C.L.	<7.7	<33.5	<6.0	<2.3	<4.7
Efficiency (%)	19.2	21.8	8.71	1.90	10.9
Systematic errors (%)					
Matrix element	0	15	15	15	15
J/ψ background	15	5	10	0	15
$\pi^+\pi^- J/\psi$ counting	0.7	0.7	0.7	0.7	0.7
Detector modeling	4.5	6.4	8.3	10	6.4
$\Gamma(\eta_c)$	0	0	0	0	12
Quadrature sum (%)	16	17	20	18	25
$\mathcal{B}(J/\psi \to X)$ $[10^{-6}]$		$12 \pm 3 \pm 2$			$1.2^{+2.7}_{-1.1} \pm 0.3$
UL on $\mathcal{B}(J/\psi \to X)$ @ 90% C.L. $[10^{-6}]$	<5	<19	<9	<15	<6



Matrix element for $J/\psi \to 3\gamma$

- Lowest order for ortho-positronium 3γ decay: *Ore & Powell, Phys. Rev. 75, 1696 (1949).*

$$\langle |M|^2 \rangle = (512/3)\, \pi^2 \alpha^6 \sum_{i=1}^{3} \left[(1 - x_i) / (x_j\, x_k) \right]^2$$

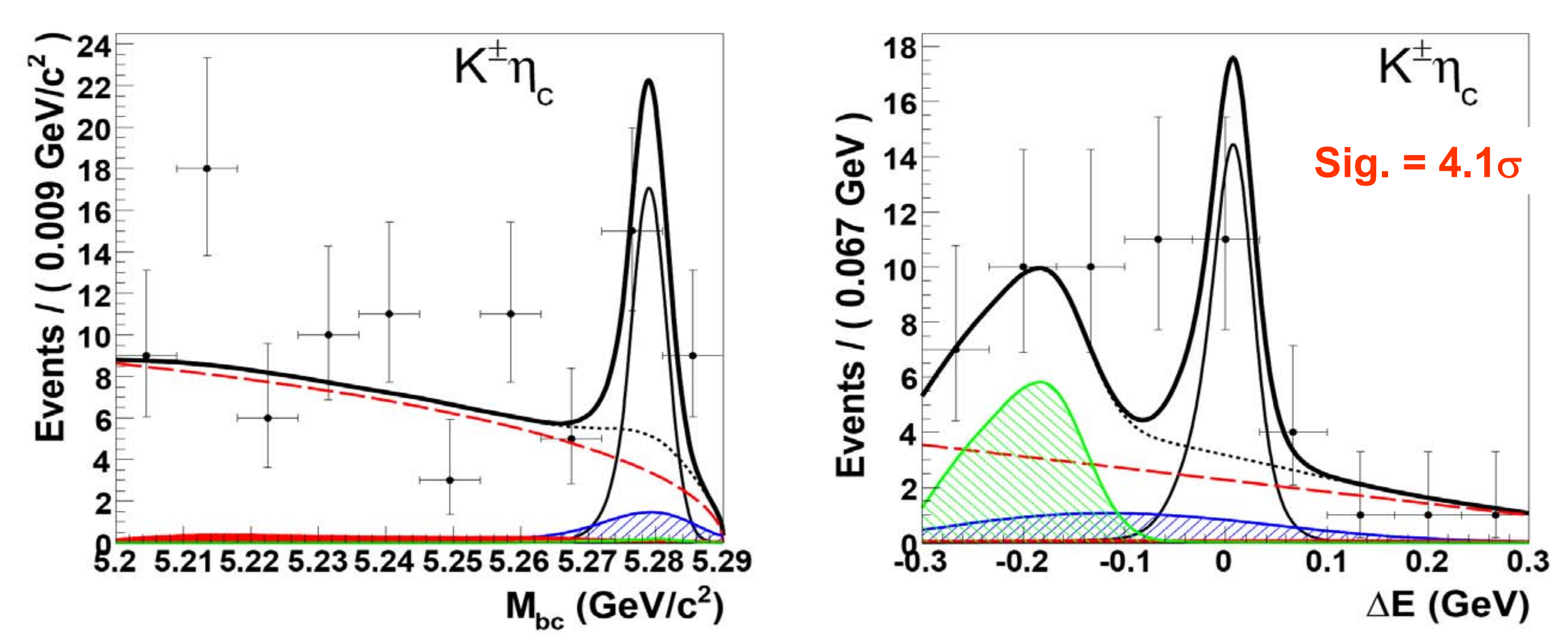
where $x_i = 2E_i^* / M_{J/\psi}$, E_i=c.o.m. γ_i energy, $i \neq j, k$

- Weight the phase space events by this factor to sculpt the distributions
- Is a very gentle sculpting
- Makes (0.2 ± 0.1)% relative difference in efficiency compared to pure phase space

Belle evidence for $\eta_c \to \gamma\gamma$

Belle PLB 662 (2008) 323

$B^\pm \to K^\pm \gamma\gamma$

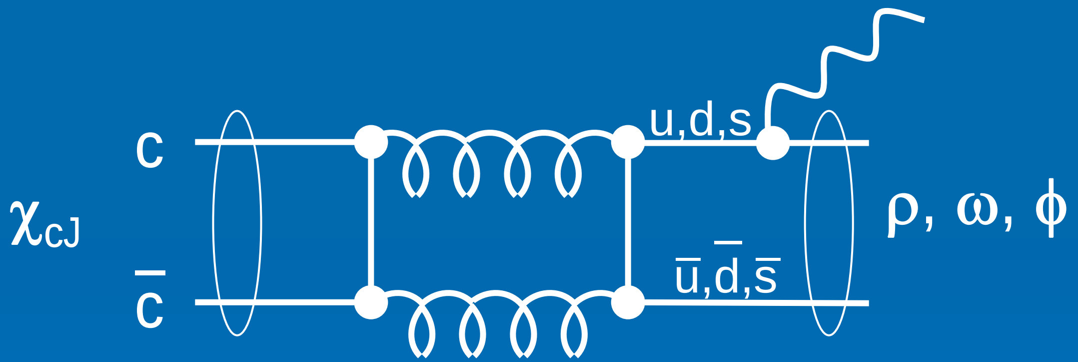


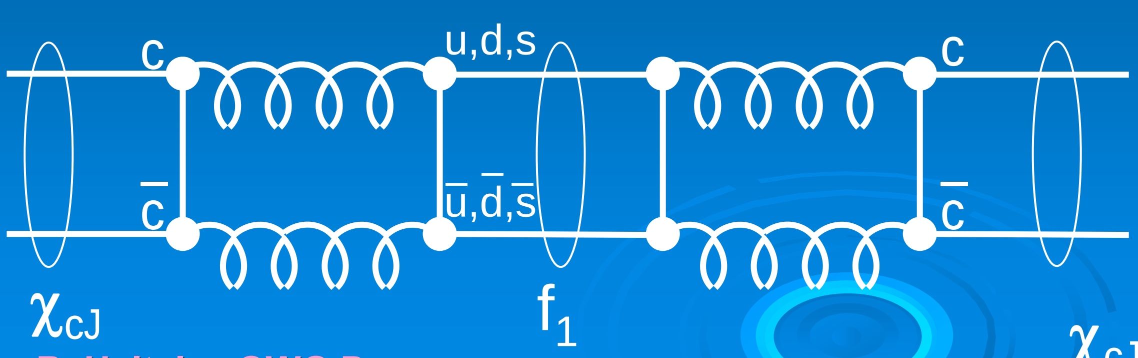
$$B(\eta_c \to \gamma\gamma) = (2.4^{+0.9}_{-0.8}{}^{+0.7}_{-0.4}) \times 10^{-4}$$

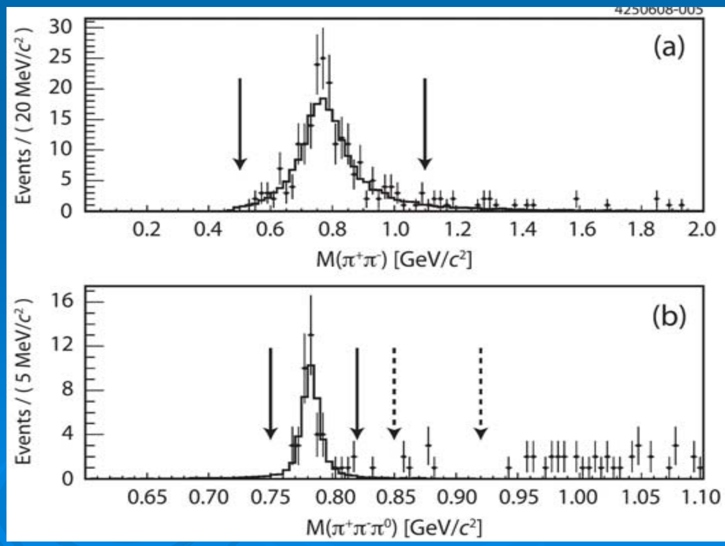
$\chi_{cJ} \rightarrow \gamma\,(\rho, \omega, \phi)$

TABLE I. Summary of the fitted yield, efficiency, and branching fraction ($\mathcal{B}$) or upper limit (U.L.) at 90% confidence level for each of the $\chi_{cJ} \rightarrow \gamma V$ transitions. Also listed is the total systematic error and the portion of the systematic error due to uncertainty in the backgrounds that might bias the signal yield. The efficiencies include the vector meson branching fractions [5] and the probability of detecting the $\psi(2S) \rightarrow \gamma\chi_{cJ}$ transition photon. Finally, we list the pQCD predictions of Ref. [1].

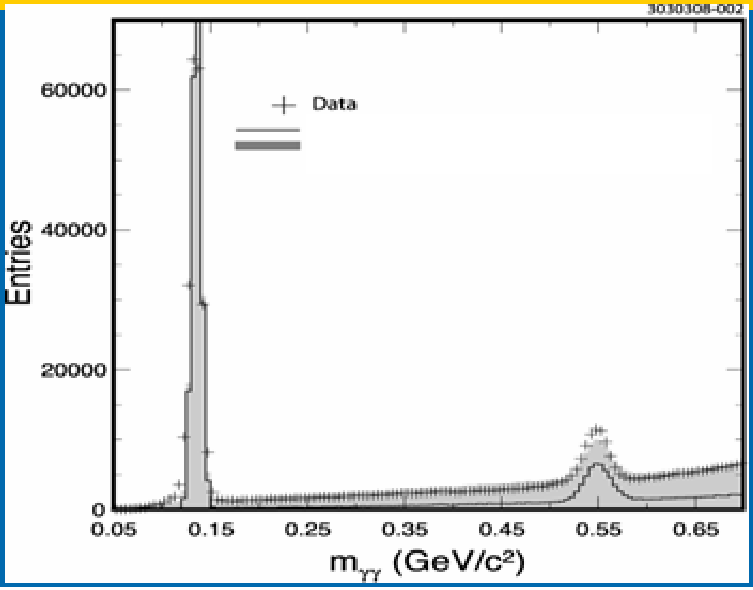
Mode	Yield [Events]	Efficiency [%]	Bias Uncert. [%]	Syst. Error [%]	$\mathcal{B} \times 10^6$	U.L. [10^{-6}]	pQCD [10^{-6}]
$\chi_{c0} \rightarrow \gamma\rho^0$	1.2 ± 4.5	30	···	± 10		<9.6	1.2
$\chi_{c1} \rightarrow \gamma\rho^0$	186 ± 15	32	± 2	± 9	$243 \pm 19 \pm 22$		14
$\chi_{c2} \rightarrow \gamma\rho^0$	17.2 ± 6.8	31	$^{-50}_{+20}$	$^{-57}_{+34}$	$25 \pm 10^{+8}_{-14}$	<50	4.4
$\chi_{c0} \rightarrow \gamma\omega$	0.0 ± 2.8	17	···	± 16		<8.8	0.13
$\chi_{c1} \rightarrow \gamma\omega$	39.2 ± 7.1	20	± 8	± 15	$83 \pm 15 \pm 12$		1.6
$\chi_{c2} \rightarrow \gamma\omega$	0.0 ± 1.8	18	···	± 16		<7.0	0.50
$\chi_{c0} \rightarrow \gamma\phi$	0.1 ± 1.6	15	···	± 12		<6.4	0.46
$\chi_{c1} \rightarrow \gamma\phi$	5.2 ± 3.1	17	···	± 12	$12.8 \pm 7.6 \pm 1.5$	<26	3.6
$\chi_{c2} \rightarrow \gamma\phi$	1.3 ± 2.5	16	···	± 12		<13	1.1

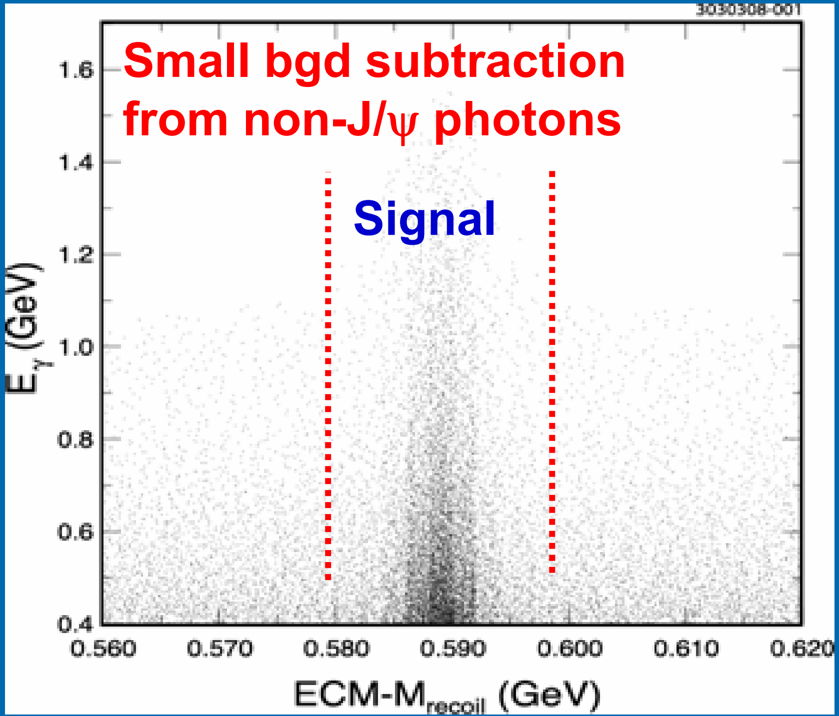






$J/\psi \to \gamma\, gg$





Source	Assigned systematic error
Photon angular distribution	3%
Nonphoton showers	1.5%
Number of three-gluon events	2%
Trigger efficiency	1%
Background subtraction	7%
Photon-finding efficiency	2%
J/ψ signal/sideband definition	2%
π^0 veto	3%
QED contamination	1%
Fitting systematics	6%
TOTAL	11.2%