Charmonium transitions at BESIII

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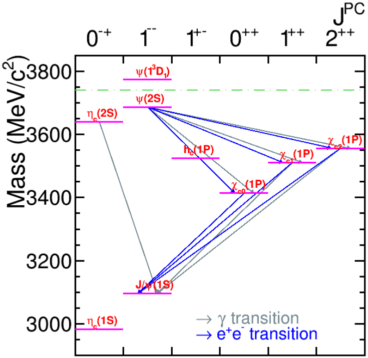
(On behalf of BESIII Collaboration)

The 12^{th} International Workshop on Heavy Quarkonium

Nov.6^{th}-10^{th}, 2017

BESIII

- World largest J/ψ and $\psi(3686)$ data sets via e^+e^- annihilation
  - 1.3 billion J/ψ events collected in 2009 and 2012
  - 0.5 billion $\psi(3686)$ events collected in 2009 and 2012
- An ideal laboratory to study charmonium decays
  - High statistic
  - Low background
- Many other data sets from 2 - 4.6 GeV



- Sensitive to the inner structure
- Untangle charmonium states

- $\psi(3686) \to \gamma \chi_{cJ}$
- $\psi(3686) \to e^+ e^- \chi_{cJ}$
- $\chi_{cJ} \to e^+ e^- J/\psi$
- $\eta_c(2S) \to \gamma J/\psi$

Recent charmonium transition results

- Higher-order multipole amplitudes in $\psi(3686) \to \gamma\chi_{c1,2}$ with $\chi_{c1,2} \to \gamma J/\psi$ and search for the transition $\eta_c(2S) \to \gamma J/\psi$

- Branching fraction measurements of $\psi(3686) \to \gamma\chi_{cJ}$

- Observation of $\psi(3686) \to e^+e^-\chi_{cJ}$ and $\chi_{cJ} \to e^+e^- J/\psi$

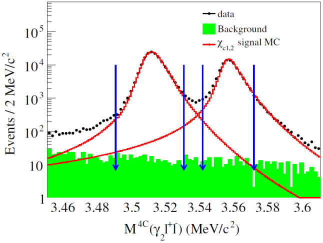
Motivation

PRD 95 072004 (2017)

- E1 (electric-dipole) amplitude dominated transitions $\psi(3686) \to \gamma\chi_{c1,2}$ and $\chi_{c1,2} \to \gamma J/\psi$ allow for higher multipole amplitudes
  - M2 (magnetic-quadrupole) transition
  - E3 (electric-octupol) transition
- Contributions of these higher multipole amplitudes give information on the anomalous magnetic moment of the charm quark and on the admixture of S- and D-wave states
- M2 contributions of $\psi(3686) \to \gamma\chi_{c1,2}$ have been predicted in PRL 45 215 (1980)

Mass distributions for $\psi(3686) \to \gamma\chi_{c1,2}$

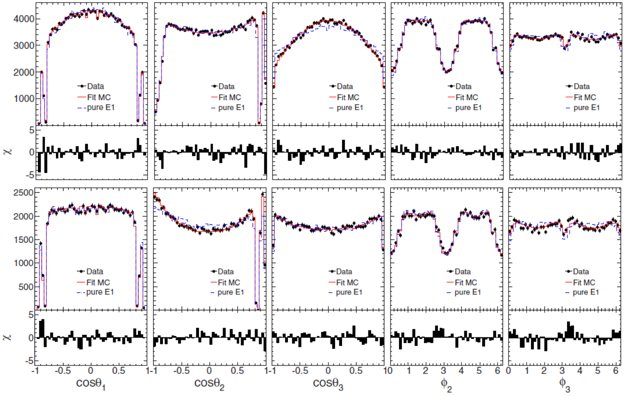
- Select two good charged tracks with MDC information (net charge is zero)
- Select photons with EMC information (at least two photons)
- Identify the electron and muon by E/p
- Improve the resolution and reduce backgrounds with four-constraint kinematic fit
- Mass windows are performed to repress backgrounds



106 M $\psi(3686)$ events

Angular distributions for $\psi(3686) \to \gamma\chi_{c1,2}$

- Higher-order multipole amplitudes can be obtained by investigating the angular distributions of the finial states.



Results of the multidimensional fit on the joint angular distribution ($\chi = (N_{data} - N_{fit})/\sqrt{N_{data}}$). upper figures are χ_{c1}, down figures are χ_{c2}

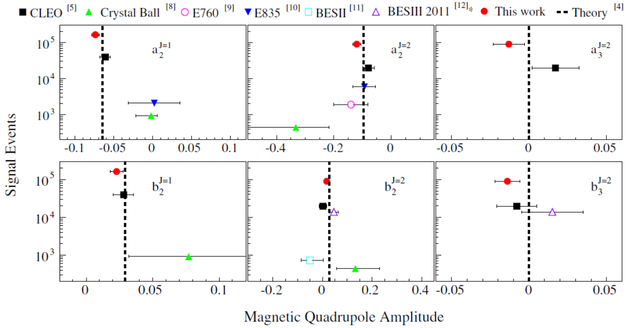
Higher-order multipole amplitudes

χ_{c1}	$a_2^1 = -0.0740 \pm 0.0033 \pm 0.0034$, $b_2^1 = 0.0229 \pm 0.0039 \pm 0.0027$ $\rho^1_{a_2 b_2} = 0.133$
χ_{c2}	$a_2^2 = -0.120 \pm 0.013 \pm 0.004$, $b_2^2 = 0.017 \pm 0.008 \pm 0.002$ $a_3^2 = -0.013 \pm 0.009 \pm 0.004$, $b_3^2 = -0.014 \pm 0.007 \pm 0.004$ $\rho^2_{a_2 b_2} = -0.605$, $\rho^2_{a_2 a_3} = 0.733$, $\rho^2_{a_2 b_3} = -0.095$ $\rho^2_{a_3 b_2} = -0.422$, $\rho^2_{b_2 b_3} = 0.384$, $\rho^2_{a_3 b_3} = -0.024$

The normalized M2 and E3 contributions and correlation coefficients.

- Statistical significance of nonpure E1 transition is 24.5σ for χ_{c1}
- Statistical significance of nonpure E1 transition is 13.5σ for χ_{c2}
- Statistical significance of the E3 contribution for χ_{c2} is 2.3σ
- Pearson-χ^2 test are performed with $\chi^2/ndf = 1.02$ for $\chi_{c1,2}$

Higher-order multipole amplitudes

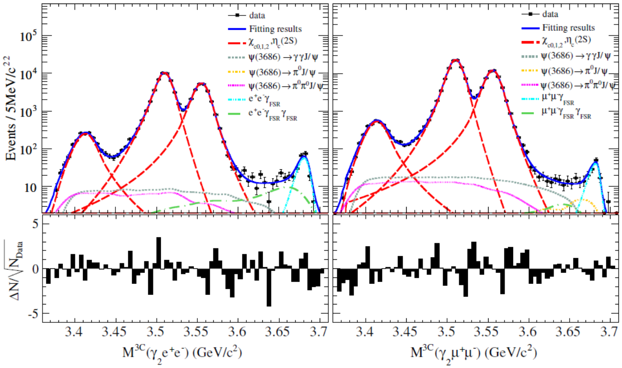


Normalized M2 and E3 amplitudes from this analysis compared with previous experimental results and theoretical predictions

- Consistent with and more precise than the results obtained by CLEO-c
- Confirm theoretical predictions in PRD 78 114011 (2008) and PRD 45 3163 (1992)

Fit results

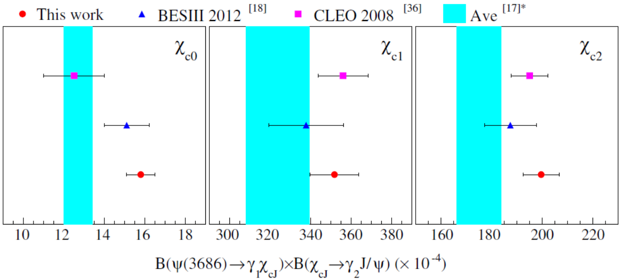
- Simultaneous maximum likelihood fit
- Signal line shapes of the $\chi_{c0,1,2}$: $(E^3_{\gamma_1} \times E^3_{\gamma_2} \times (BW(m) \otimes R \times \epsilon(m))) \otimes G(\mu,\ \sigma)$
- Signal line shapes of the $\eta_c(2S)$: $(E^3_{\gamma_1} \times E^7_{\gamma_2} \times (BW(m) \otimes R \times \epsilon(m))) \otimes G(\mu,\ \sigma)$



Fit results (top) and corresponding relative residual (bottom)

Results

Mode	Branching fraction measurement ($\times 10^{-4}$)
$\mathcal{B}_{\psi(3686)\to\gamma\chi_{c0}} \cdot \mathcal{B}_{\chi_{c0}\to\gamma J/\psi}$	$15.6 \pm 0.3 \pm 0.6$
$\mathcal{B}_{\psi(3686)\to\gamma\chi_{c1}} \cdot \mathcal{B}_{\chi_{c1}\to\gamma J/\psi}$	$351.8 \pm 1.0 \pm 12.0$
$\mathcal{B}_{\psi(3686)\to\gamma\chi_{c2}} \cdot \mathcal{B}_{\chi_{c2}\to\gamma J/\psi}$	$199.6 \pm 0.8 \pm 7.0$
$\mathcal{B}_{\psi(3686)\to\gamma\eta_c(2S)} \cdot \mathcal{B}_{\eta_c(2S)\to\gamma J/\psi}$	< 0.097



More precise and consistent with BESIII's previous results

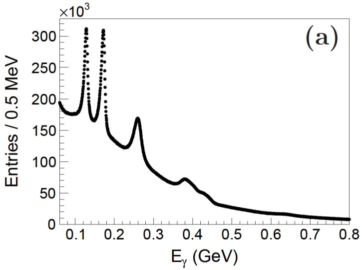
Recent charmonium transition results

- Higher-order multipole amplitudes in $\psi(3686) \to \gamma\chi_{c1,2}$ with $\chi_{c1,2} \to \gamma J/\psi$ and search for the transition $\eta_c(2S) \to \gamma J/\psi$
- Branching fraction measurements of $\psi(3686) \to \gamma\chi_{cJ}$
- Observation of $\psi(3686) \to e^+e^-\chi_{cJ}$ and $\chi_{cJ} \to e^+e^-J/\psi$

Inclusive photon energy distributions for $\psi(3686) \to \gamma X$

PRD 96 032001 (2017)

- Inclusive photon energy distribution of decays $\psi(3686) \to \gamma X$ (106 M $\psi(3686)$)

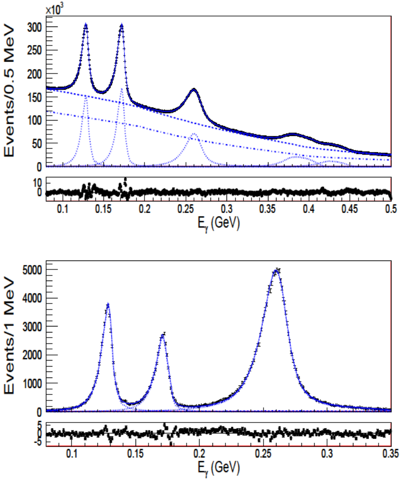


Data

Include MC

- Clear peak for $\psi(3686) \to \gamma\chi_{c2}/\gamma\chi_{c1}/\gamma\chi_{c0}$, and $\chi_{c1}/\chi_{c2} \to \gamma J/\psi$
- $\chi_{c0} \to \gamma J/\psi$ is not visible
- Small peak around 0.65 GeV is $\psi(3686) \to \gamma\eta_c$

Branching fraction measurements of $\psi(3686) \to \gamma\chi_{cJ}$



(Top set) Inclusive distribution fit and corresponding pulls, and (Bottom set) exclusive distribution fit and pull distribution

- Unbinned maximum simultaneous fits to the photon energy distributions of data.
- $\mathcal{B}_{\psi(3686)\to\gamma\chi_{cJ}} = \frac{N_{\psi(3686)\to\gamma\chi_{cJ}}}{\epsilon_{\psi(3686)\to\gamma\chi_{cJ}} \cdot N_{\psi(3686)}}$
- $\mathcal{B}_{\psi(3686)\to\gamma\chi_{cJ}} \cdot \mathcal{B}_{\chi_{cJ}\to\gamma J/\psi} = \frac{N_{\chi_{cJ}\to\gamma J/\psi}}{\epsilon_{\chi_{cJ}\to\gamma J/\psi} \cdot N_{\psi(3686)}}$
- $\mathcal{B}_{\chi_{cJ}\to\gamma J/\psi} = \frac{\epsilon_{\psi(3686)\to\gamma\chi_{cJ}} \cdot N_{\chi_{cJ}\to\gamma J/\psi}}{\epsilon_{\chi_{cJ}\to\gamma J/\psi} \cdot N_{\psi(3686)\to\gamma\chi_{cJ}}}$

BRs for $\psi(3686) \to \gamma\chi_{cJ}$ and $\chi_{cJ} \to \gamma J/\psi$

Branching Fraction	This analysis (%)	Other (%)	PDG [7] (%) Average	PDG [7] (%) Fit
$\mathcal{B}(\psi(3686) \to \gamma\chi_{c0})$	$9.389 \pm 0.014 \pm 0.332$	$9.22 \pm 0.11 \pm 0.46$ [9]	9.2 ± 0.4	9.99 ± 0.27
$\mathcal{B}(\psi(3686) \to \gamma\chi_{c1})$	$9.905 \pm 0.011 \pm 0.353$	$9.07 \pm 0.11 \pm 0.54$ [9]	8.9 ± 0.5	9.55 ± 0.31
$\mathcal{B}(\psi(3686) \to \gamma\chi_{c2})$	$9.621 \pm 0.013 \pm 0.272$	$9.33 \pm 0.14 \pm 0.61$ [9]	8.8 ± 0.5	9.11 ± 0.31
$\mathcal{B}(\psi(3686) \to \gamma\chi_{c0}) \times \mathcal{B}(\chi_{c0} \to \gamma J/\psi)$	$0.024 \pm 0.015 \pm 0.205$	$0.125 \pm 0.007 \pm 0.013$ [31] $0.151 \pm 0.003 \pm 0.010$ [15] $0.158 \pm 0.003 \pm 0.006$ [16]	0.131 ± 0.035	0.127 ± 0.006
$\mathcal{B}(\psi(3686) \to \gamma\chi_{c1}) \times \mathcal{B}(\chi_{c1} \to \gamma J/\psi)$	$3.442 \pm 0.010 \pm 0.132$	$3.56 \pm 0.03 \pm 0.12$ [31] $3.377 \pm 0.009 \pm 0.183$ [15] $3.518 \pm 0.01 \pm 0.120$ [16]	2.93 ± 0.15	3.24 ± 0.07
$\mathcal{B}(\psi(3686) \to \gamma\chi_{c2}) \times \mathcal{B}(\chi_{c2} \to \gamma J/\psi)$	$1.793 \pm 0.008 \pm 0.163$	$1.95 \pm 0.02 \pm 0.07$ [31] $1.874 \pm 0.007 \pm 0.102$ [15] $1.996 \pm 0.008 \pm 0.070$ [16]	1.52 ± 0.15	1.75 ± 0.04
$\mathcal{B}(\chi_{c0} \to \gamma J/\psi)$	$0.25 \pm 0.16 \pm 2.15$	$2 \pm 0.2 \pm 0.2$ [32]		1.27 ± 0.06
$\mathcal{B}(\chi_{c1} \to \gamma J/\psi)$	$34.75 \pm 0.11 \pm 1.70$	$37.9 \pm 0.8 \pm 2.1$ [32]		33.9 ± 1.2
$\mathcal{B}(\chi_{c2} \to \gamma J/\psi)$	$18.64 \pm 0.08 \pm 1.69$	$19.9 \pm 0.5 \pm 1.2$ [32]		19.2 ± 0.7

Most precise measurements for $\psi(3686) \to \gamma\chi_{cJ}$

$$\mathcal{B}(\psi(3686) \to \gamma\chi_{c0})/\mathcal{B}(\psi(3686) \to \gamma\chi_{c1}) = 0.948 \pm 0.002 \pm 0.044$$
$$\mathcal{B}(\psi(3686) \to \gamma\chi_{c0})/\mathcal{B}(\psi(3686) \to \gamma\chi_{c2}) = 0.976 \pm 0.002 \pm 0.040$$
$$\mathcal{B}(\psi(3686) \to \gamma\chi_{c2})/\mathcal{B}(\psi(3686) \to \gamma\chi_{c1}) = 0.971 \pm 0.002 \pm 0.040$$

- Common systematic uncertainties of the ratios of branching fractions are canceled

Partial widths for $\psi(3686) \to \gamma\chi_{cJ}$ and $\chi_{cJ} \to \gamma J/\psi$

Initial state	Final state	Γ_{E1} (keV) RQM [33]	NR/GI [34]	$\text{SNR}_{0/1}$ [35]	LP [8]	SP [8]	Γ_{EM} (keV) LP [8]	SP [8]	This analysis
$\psi(3686)$	χ_{c0}	26.3	63/26	74/25	27	26	22	22	26.9 ± 1.8
	χ_{c1}	22.9	54/29	62/36	45	48	42	45	28.3 ± 1.9
	χ_{c2}	18.2	38/24	43/34	36	44	38	46	27.5 ± 1.7
χ_{c0}	J/ψ	121	152/114	167/117	141	146	172	179	
χ_{c1}		265	314/239	354/244	269	278	306	319	306 ± 23
χ_{c2}		327	424/313	473/309	327	338	284	292	363 ± 41

Partial widths for $\psi(3686) \to \gamma\chi_{cJ}$ and $\chi_{cJ} \to \gamma J/\psi$.

- Experimental results have become accurate enough to become sensitive to fine details of the potentials, e.g. relativistic effects, screening effects, and higher partial waves.

Recent charmonium transition results

- Higher-order multipole amplitudes in $\psi(3686) \to \gamma\chi_{c1,2}$ with $\chi_{c1,2} \to \gamma J/\psi$ and search for the transition $\eta_c(2S) \to \gamma J/\psi$
- Branching fraction measurements of $\psi(3686) \to \gamma\chi_{cJ}$
- Observation of $\psi(3686) \to e^+e^-\chi_{cJ}$ and $\chi_{cJ} \to e^+e^- J/\psi$

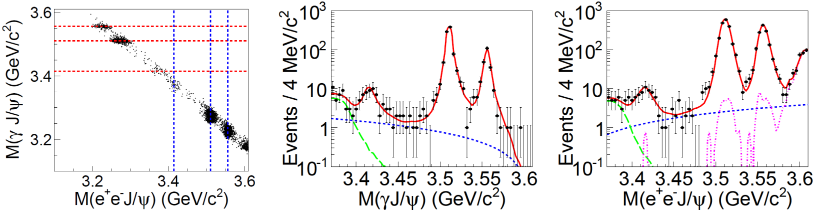
Motivation

PRL 118 221802 (2017)

- A virtual photon is internally converted into an e^+e^- pair in electromagnetic (EM) Dalitz decays
- Study of EM Dalitz decays plays an important role in revealing the structure of hadrons and the interactions between photons and hadrons
- The EM Dalitz decays in charmonium transitions have access to the EM transition form factors (TFFs) of charmonium states

Observation of $\psi(3686) \to e^+e^-\chi_{cJ}$ and $\chi_{cJ} \to e^+e^-J/\psi$

- Cascade decays $\psi(3686) \to e^+e^-\chi_{cJ} \to e^+e^-\gamma J/\psi$ and $\psi(3686) \to \gamma\chi_{cJ} \to \gamma e^+e^-J/\psi$ (447.9 M $\psi(3686)$ events)

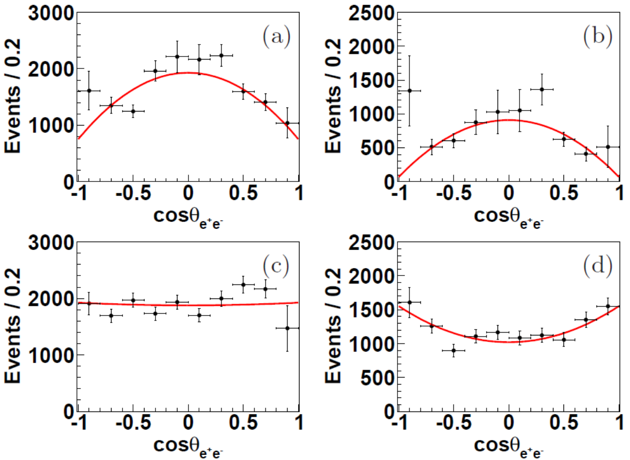


Clear χ_{cJ} signals

Fit results

Mode	Yields	Efficiency(%)	Branching fraction	$\frac{\mathcal{B}(\psi(3686)\to e^+e^-\chi_{cJ})}{\mathcal{B}(\psi(3686)\to\gamma\chi_{cJ})}$	$\frac{\mathcal{B}(\chi_{cJ}\to e^+e^-J/\psi)}{\mathcal{B}(\chi_{cJ}\to\gamma J/\psi)}$
$\psi(3686) \to e^+e^-\chi_{c0}$	48 ± 10	6.06	$(11.7 \pm 2.5 \pm 1.0) \times 10^{-4}$	$(9.4 \pm 1.9 \pm 0.6) \times 10^{-3}$	–
$\psi(3686) \to e^+e^-\chi_{c1}$	873 ± 30	5.61	$(8.6 \pm 0.3 \pm 0.6) \times 10^{-4}$	$(8.3 \pm 0.3 \pm 0.4) \times 10^{-3}$	–
$\psi(3686) \to e^+e^-\chi_{c2}$	227 ± 16	3.19	$(6.9 \pm 0.5 \pm 0.6) \times 10^{-4}$	$(6.6 \pm 0.5 \pm 0.4) \times 10^{-3}$	–
$\chi_{c0} \to e^+e^-J/\psi$	56 ± 11	6.95	$(1.51 \pm 0.30 \pm 0.13) \times 10^{-4}$	–	$(9.5 \pm 1.9 \pm 0.7) \times 10^{-3}$
$\chi_{c1} \to e^+e^-J/\psi$	1969 ± 46	10.35	$(3.73 \pm 0.09 \pm 0.25) \times 10^{-3}$	–	$(10.1 \pm 0.3 \pm 0.5) \times 10^{-3}$
$\chi_{c2} \to e^+e^-J/\psi$	1354 ± 39	11.23	$(2.48 \pm 0.08 \pm 0.16) \times 10^{-3}$	–	$(11.3 \pm 0.4 \pm 0.5) \times 10^{-3}$

α values of helicity angular distributions



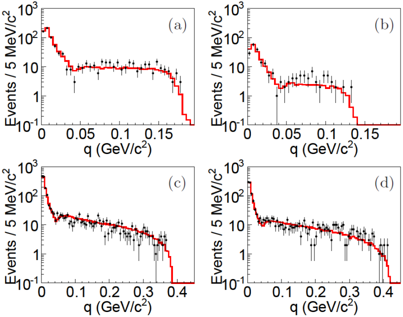
$$1 + \alpha \cos^2 \theta_{e^+e^-}$$

(a) $\psi(3686) \to e^+e^-\chi_{c1}$ (b) $\psi(3686) \to e^+e^-\chi_{c2}$ (c) $\chi_{c1} \to e^+e^- J/\psi$ (d) $\chi_{c2} \to e^+e^- J/\psi$

BESIII

q^2-dependent of charmonium EM transition form factors

- Provide additional information on the interactions between the charmonium states and the electromagnetic field
- Possibly distinguish the transition mechanisms based on the $c\bar{c}$ scenario
- Serve as a useful probe for χ_{cJ} internal structures and exotic hadron structures



Measured q^2 distributions are consistent with assumption of a point-like meson

(a) $\psi(3686) \to e^+e^-\chi_{c1}$ (b) $\psi(3686) \to e^+e^-\chi_{c2}$ (c) $\chi_{c1} \to e^+e^-J/\psi$ (d) $\chi_{c2} \to e^+e^-J/\psi$

Summary

- M2 contributions for $\psi(3686) \to \gamma\chi_{c1,2}$ and E3 contributions for $\psi(3686) \to \gamma\chi_{c2}$ were measured
- Branching fractions and partial widths for $\psi(3686) \to \gamma\chi_{cJ}$ and $\chi_{cJ} \to \gamma J/\psi$ were determined
- Searching for $\psi(3686) \to \gamma\eta_c(2S)$ are performed with an upper limit
- Observe the decays $\psi(3686) \to e^+e^-\chi_{cJ}$ and $\chi_{cJ} \to e^+e^-J/\psi$
- BESIII published many other interesting results (just a few of them about charmonium transitions is covered here), also many analysis are ongoing.
- With more data will be collected, more interesting and detailed studies will be performed.

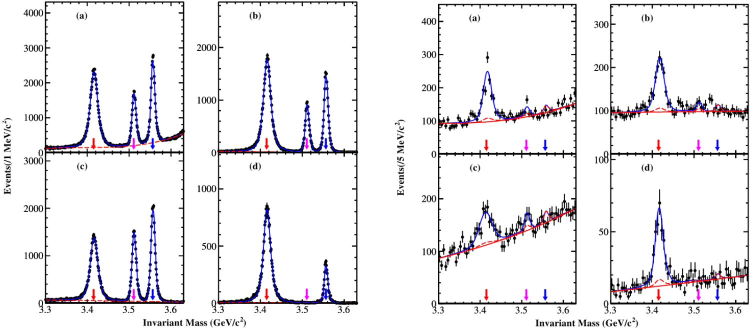
Thanks for your attention

Backup

Mass distributions for $\psi(3770) \to \gamma\chi_{c0}$

PLB 753 103 (2016)

- Based on S-D mixing model, many predictions have been made.
- Largest variations in predictions for the partial width of $\psi(3770) \to \gamma\chi_{c0}$.



106 M $\psi(3686)$ 2.92 fb^{-1} $\psi(3770)$

(a) $2(\pi^+\pi^-)$, (b) $K^+K^-\pi^+\pi^-$, (c) $3(\pi^+\pi^-)$, (d) K^+K^-

Ratios of BFs between $\psi(3770)$ and $\psi(3686)$ to $\gamma\chi_{cJ}$

$\chi_{cJ} \to LH$		$J=0$	$J=1$
$2(\pi^+\pi^-)$	$N_{\psi(3770)}$	756 ± 51	80 ± 26
	$\epsilon_{\psi(3770)}$	24.1 ± 0.2	25.7 ± 0.2
	$N_{\psi(3686)}$	59976 ± 318	19712 ± 175
	$\epsilon_{\psi(3686)}$	24.9 ± 0.2	26.5 ± 0.2
	R_{cJ}	6.64 ± 0.45	2.13 ± 0.69
$K^+K^-\pi^+\pi^-$	$N_{\psi(3770)}$	716 ± 54	46 ± 24
	$\epsilon_{\psi(3770)}$	24.0 ± 0.2	25.4 ± 0.2
	$N_{\psi(3686)}$	46929 ± 240	11576 ± 115
	$\epsilon_{\psi(3686)}$	23.3 ± 0.2	24.9 ± 0.2
	R_{cJ}	7.56 ± 0.57	2.00 ± 1.04
$3(\pi^+\pi^-)$	$N_{\psi(3770)}$	502 ± 54	76 ± 27
	$\epsilon_{\psi(3770)}$	18.5 ± 0.2	20.0 ± 0.2
	$N_{\psi(3686)}$	36536 ± 237	19593 ± 153
	$\epsilon_{\psi(3686)}$	18.1 ± 0.2	19.6 ± 0.2
	R_{cJ}	6.86 ± 0.74	1.94 ± 0.69
K^+K^-	$N_{\psi(3770)}$	283 ± 24	-
	$\epsilon_{\psi(3770)}$	32.5 ± 0.2	-
	$N_{\psi(3686)}$	21452 ± 154	-
	$\epsilon_{\psi(3686)}$	32.1 ± 0.2	-
	R_{cJ}	6.65 ± 0.57	-
Averaged R_{cJ}		6.89 ± 0.28	2.03 ± 0.44

$$R_{cJ} = \frac{B_{\psi(\mathbf{3770})\to\gamma\chi_{cJ}}}{B_{\psi(\mathbf{3686})\to\gamma\chi_{cJ}}} \ (\sigma_{sys.} = 0.66\%)$$

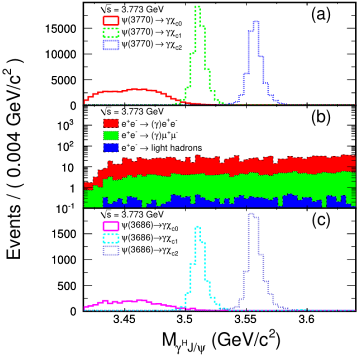
Experiments	$J=0$	$J=1$
$\mathcal{B}^{\mathrm{BESIII}}(\times 10^{-3})$	$6.88 \pm 0.28 \pm 0.67$	$1.94 \pm 0.42 \pm 0.64$
$\mathcal{B}^{\mathrm{BESIII}}(\times 10^{-3})$ [10]	–	$2.48 \pm 0.15 \pm 0.23$
Γ^{BESIII}	$187 \pm 8 \pm 19$	$53 \pm 12 \pm 18$
Γ^{BESIII} [10]	–	$67.5 \pm 4.1 \pm 6.7$
Γ^{CLEO} [7, 8]	172 ± 30	70 ± 17
$\Gamma^{\mathrm{CLEO}}_{\mathrm{corrected}}$	192 ± 24	72 ± 16
Theories		
Rosner [2] (non-relativistic)	523 ± 12	73 ± 9
Ding-Qing-Chao [3]		
non-relativistic	312	95
relativistic	199	72
Eichten-Lane-Quigg [4]		
non-relativistic	254	183
with coupled channels corrections	225	59
Barnes-Godfrey-Swanson [5]		
non-relativistic	403	125
relativistic	213	77
NRCQM [6]	218	70

Comparisons of partial widths for $\psi(3770) \to \gamma\chi_{cJ}$ (keV)

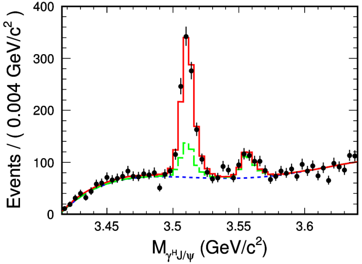
- A relativistic assumption or a coupled-channel correction agree quantitatively better with the experimental data
- Non-relativistic calculations overestimate the partial width of $\psi(3770) \to \gamma\chi_{cJ}$
- Contribute to a deeper understanding of the dynamics of charmonium decays above the open-charm threshold.

Mass distributions for $\psi(3770) \to \gamma\chi_{cJ}$

PRD 91 092009 (2015)



Mass distribution from MC



Mass distribution from $\psi(3770)$ data

- Clear peaks on $\chi_{c1,2}$
- Green long-dashed line is sum of the smooth background and the contribution $e^+e^- \to (\gamma_{ISR})\psi(3686)$ production

- Backgrounds from $\psi(3686)$ have been estimated

BESIII

Results

- $\psi(3770) \to \gamma\chi_{c1}$:
  $\mathcal{B} = (2.48 \pm 0.15 \pm 0.23) \times 10^{-3}$
  $\sigma = (24.6 \pm 1.5 \pm 3.0)$ pb
- $\psi(3770) \to \gamma\chi_{c2}$:
  $\mathcal{B} < 0.64 \times 10^{-3}$
  $\sigma < 6.4$ pb

Experiment/theory	$\Gamma(\psi(3770) \to \gamma\chi_{cJ})$ (keV) $J = 1$	$J = 2$
This work	$67.5 \pm 4.1 \pm 6.7$	< 17.4
Ding-Qin-Chao [12]		
nonrelativistic	95	3.6
relativistic	72	3.0
Rosner S-D mixing [13]		
$\phi = 12^\circ$ [13]	73 ± 9	24 ± 4
$\phi = (10.6 \pm 1.3)^\circ$ [32]	79 ± 6	21 ± 3
$\phi = 0^\circ$ (pure 1^3D_1 state) [32]	133	4.8
Eichten-Lane-Quigg [14]		
nonrelativistic	183	3.2
with coupled-channel corr.	59	3.9
Barnes-Godfrey-Swanson [15]		
nonrelativistic	125	4.9
relativistic	77	3.3

ϕ is the mixing angle of S-D mixing model

- Consistent with CLEO-c's results within error
- More precise

Mass distribution and results for $\psi(3770) \to \gamma\eta_c(\eta_c(2S))$

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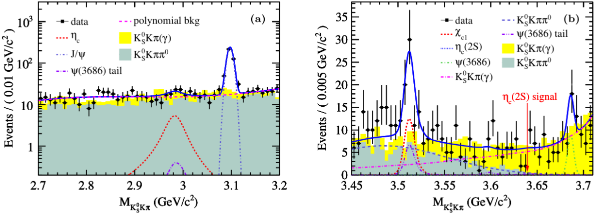

$$\mathcal{B}(\psi(3770) \to \gamma\eta_c(\eta_c(2S)) \to \gamma K_S^0 K^\pm \pi^\mp) < \frac{N_{\rm up}/(1-\sigma_{\rm syst.})}{\epsilon \cdot \mathcal{L} \cdot \sigma^0_{\psi(3770)} \cdot (1+\delta) \cdot \mathcal{B}(K_S^0 \to \pi^+\pi^-)},$$

$$\mathcal{B}(\psi(3770) \to \gamma\chi_{c1} \to \gamma K_S^0 K^\pm \pi^\mp) = \frac{N_{\rm obs}}{\epsilon \cdot \mathcal{L} \cdot \sigma^0_{\psi(3770)} \cdot (1+\delta) \cdot \mathcal{B}(K_S^0 \to \pi^+\pi^-)},$$

$$(1+\delta) = 0.718$$

2.92 fb^{-1} $\psi(3770)$ data

Quantity	η_c	$\eta_c(2S)$	χ_{c1}
$N_{\rm obs}$	29.3 ± 18.2	0.4 ± 8.5	34.9 ± 9.8
$N_{\rm up}$	56.8	16.1	...
ϵ (%)	27.87	25.24	28.46
$\mathcal{B}(\psi(3770) \to \gamma X \to \gamma K_S^0 K^\pm \pi^\mp)$ $(\times 10^{-6})$	< 16	< 5.6	$8.51 \pm 2.39 \pm 1.42$
$\mathcal{B}(\psi(3770) \to \gamma X)$ $(\times 10^{-3})$	< 0.68	< 2.0	$2.33 \pm 0.65 \pm 0.43$
$\mathcal{B}_{\rm CLEO}(\psi(3770) \to \gamma X)$ $(\times 10^{-3})$	...	...	$2.9 \pm 0.5 \pm 0.4$
$\Gamma(\psi(3770) \to \gamma X)$ (keV)	< 19	< 55	...
$\Gamma_{\rm IML}$ (keV)	$17.14^{+22.93}_{-12.03}$	$1.82^{+1.95}_{-1.19}$	...
$\Gamma_{\rm LQCD}$ (keV)	10 ± 11	...	...

- Measured $\mathcal{B}_{\psi(3770)\to\gamma\eta_c}$ is just within the error range of theoretical predictions
- Measured $\mathcal{B}_{\psi(3770)\to\gamma\eta_c(2S)}$ is larger than the prediction based on intermediate meson loop mechanism a lot