Charmonium Transitions and Decays

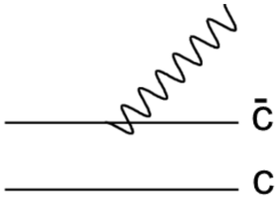
Jingzhi Zhang
(IHEP,Beijing)

Hiepa2018, Huairou,UCAS

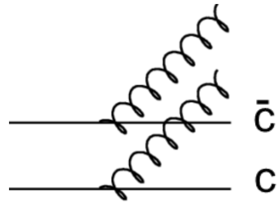
Outline

- Main processes of charmonium
- Radiative transition
- Hadronic decay
- Radiative decay
- Rare decay
- Summary

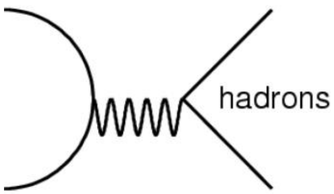
Main transition and decay processes of charmonium (e.g. $\psi(2S)$)



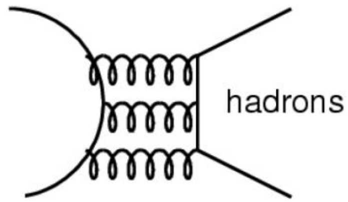
A) Radiative transition



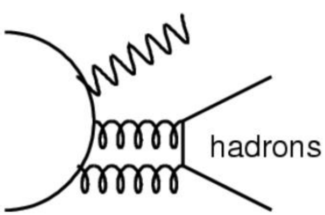
B) Hadonic transition



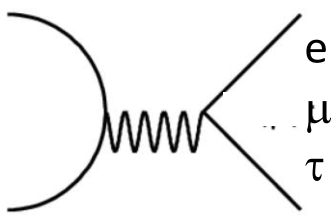
c) EM decay



D) Strong decay



E) Radiative decay



F) Leptonic decay

		$\psi(2S)$
Transitions	A)	29%
	B)	56%
Decays	C)	2%
	D)	11%
	E)	1%
	F)	2%

- & Others

Radiative transition

1. Radiative transitions are sensitive to inner structure of hadrons ;
2. E1 transition is well measured in general, but still no one model explains all the exp. results.

Eur. Phys. J.491 C76, 601 (2016)

Process	Quark Model				SU(2) with $\Lambda=$					SU(3) with $\Lambda=$					Ex
	[9]	[13]	[11](a)	[11](b)	0.8	0.9	1.0	1.1	1.2	0.8	0.9	1.0	1.1	1.2	PDG [18]
$\psi'' \to \chi_{c0}\gamma$	—	299	403	213	199	199	197	196	194	199	197	195	194	193	199 ± 26
$\psi'' \to \chi_{c1}\gamma$	—	99	125	77	64.5	64.8	65.6	66.6	67.4	64.8	66.0	67.2	67.8	68.0	73.4 ± 13.9
$\psi'' \to \chi_{c2}\gamma$	—	3.88	4.9	3.3	3.2	3.1	2.9	2.9	3.1	2.7	2.5	2.6	3.1	3.5	<24.5
$\psi' \to \chi_{c0}\gamma$	50	47	63	26	30.3	30.2	30.1	30.0	29.9	30.1	30.0	29.9	29.9	29.9	29.8 ± 1.1
$\psi' \to \chi_{c1}\gamma$	45.3	42.8	54	29	27.8	28.0	28.2	28.3	28.4	28.0	28.2	28.4	28.4	28.4	28.5 ± 1.2
$\psi' \to \chi_{c2}\gamma$	28.9	30.1	38	24	19.0	19.0	19.1	19.3	19.4	19.0	19.2	19.3	19.4	19.5	27.2 ± 1.2

NR and relativized Godfrey-Isgur model are quoted as (a) and (b)

- *Due to higher order contributions?*
- *The charmonium Dalitz decay (e.g. $\psi(2S) \to ee\chi_{cJ}$) can provide q^2 EM transition dependent form factor (TFF)*

- In the M1 transition, obvious differences between exp. and theory. It is experimentally difficult.

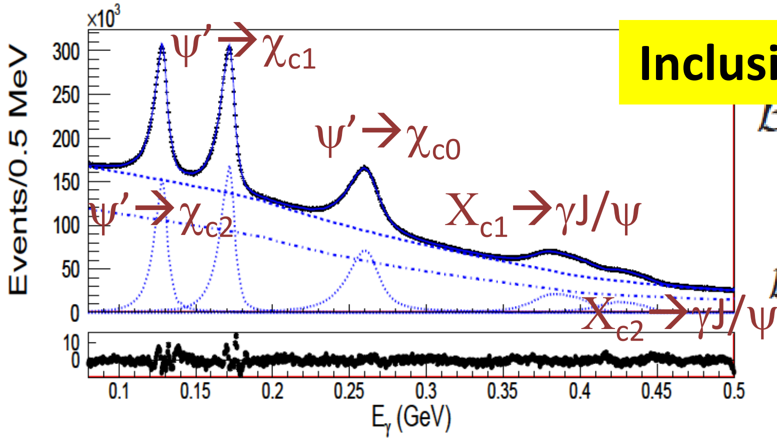
	NR(keV)	GI(keV)	LQCD (keV)	PDG(keV)
$\Gamma(\psi(1S)\rightarrow\gamma\eta_c)$	2.9	2.9	2.64(11)	1.58
$\Gamma(\psi(2S)\rightarrow\gamma\eta_c)$	4.6	9.6	0.4(8)	1.01

- Results from KEDR (with inclusive analysis method)

- Results from BESIII (exclusive analysis) using PWA, in process (will not show in this talk)

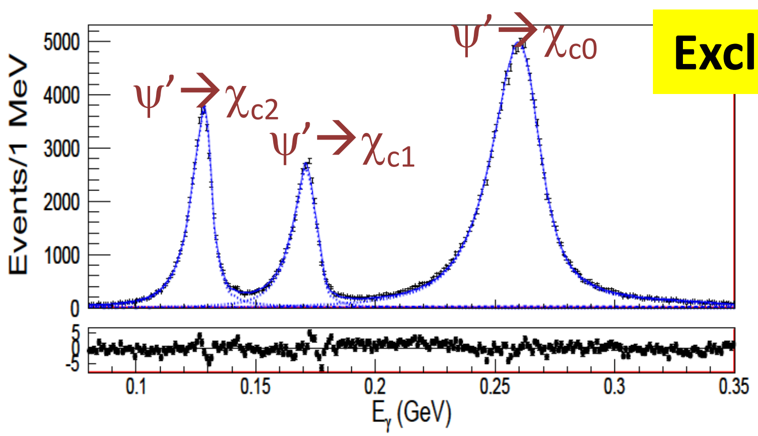
Updates of $\psi(2S) \to \gamma\chi_{cJ}$ at BESIII

With 106 M ψ(3686)



$$\mathcal{B}(\psi(3686) \to \gamma\chi_{cJ}) = \frac{N_{\psi(3686)\to\gamma\chi_{cJ}}}{\epsilon_{\psi(3686)\to\gamma\chi_{cJ}} \times N_{\psi(3686)}},$$

$$\mathcal{B}(\psi(3686) \to \gamma\chi_{cJ}) \times \mathcal{B}(\chi_{cJ} \to \gamma J/\psi) = \frac{N_{\chi_{cJ}\to\gamma J/\psi}}{\epsilon_{\chi_{cJ}\to\gamma J/\psi} \times N_{\psi(3686)}},$$



$$\mathcal{B}(\chi_{cJ} \to \gamma J/\psi) = \frac{\mathcal{B}(\psi(3686) \to \gamma\chi_{cJ}) \times \mathcal{B}(\chi_{cJ} \to \gamma J/\psi)}{\mathcal{B}(\psi(3686) \to \gamma\chi_{cJ})} = \frac{\epsilon_{\psi(3686)\to\gamma\chi_{cJ}} \times N_{\chi_{cJ}\to\gamma J/\psi}}{\epsilon_{\chi_{cJ}\to\gamma J/\psi} \times N_{\psi(3686)\to\gamma\chi_{cJ}}}.$$

Simultaneous fit to the inclusive and exclusive γ distribution

Inclusive: $\psi(2S) \to \gamma X$
Exclusicve: $\psi(2S) \to \gamma\chi_{cJ}$, $\chi_{cJ} \to$ 2/4 prong

Updates of $\psi(2S) \rightarrow \gamma\chi_{cJ}$ cont.

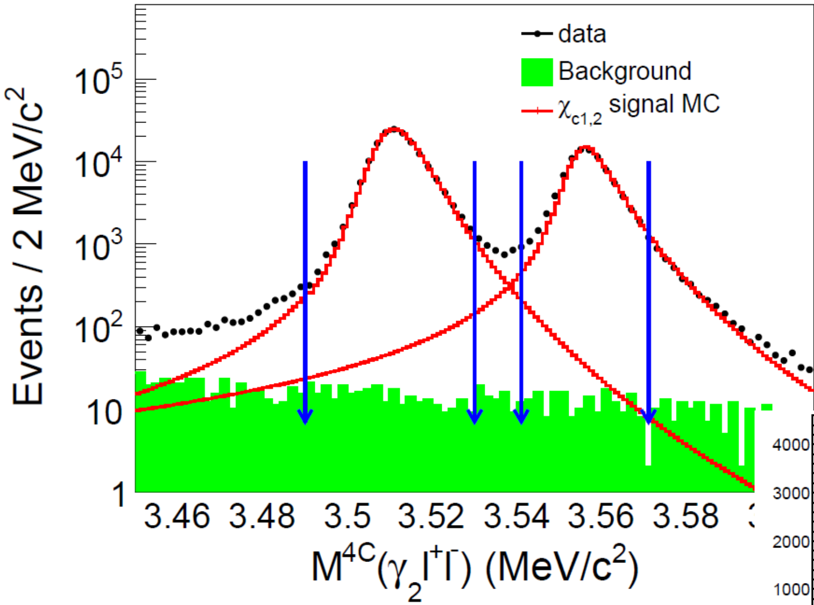
Branching Fraction	This analysis (%)	Other (%)	PDG [7] (%) Average	PDG [7] (%) Fit
$\mathcal{B}(\psi(3686) \to \gamma\chi_{c0})$	$9.389 \pm 0.014 \pm 0.332$	$9.22 \pm 0.11 \pm 0.46$ [9]	9.2 ± 0.4	9.99 ± 0.27
$\mathcal{B}(\psi(3686) \to \gamma\chi_{c1})$	$9.905 \pm 0.011 \pm 0.353$	$9.07 \pm 0.11 \pm 0.54$ [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

New results are consistent with previous measurements, but more precise

Phys. Rev. D 95, 072004

Higher order multipole?

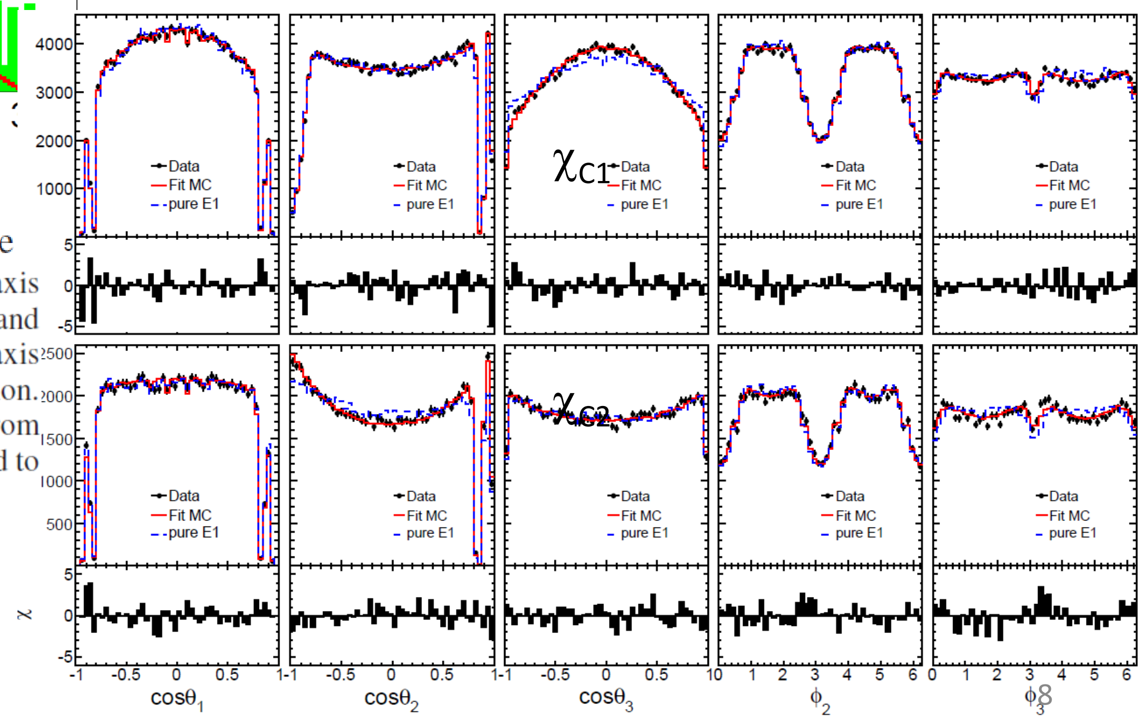
$\psi(2S) \rightarrow \chi_{cJ}$, $\chi_{cJ} \rightarrow \gamma\, J/\psi$



106 M $\psi(3686)$

Analyzed the high statistic & low backgronud $\chi_{c1,2}$ using five helicity angles in the FS.

θ_1 is the polar angle of γ_1 in the $\psi(3686)$ rest frame with the z axis in the electron-beam direction. θ_2 and ϕ_2 are the polar and azimuthal angles of γ_2 in the χ_{cJ} rest frame with the z axis in the γ_1 direction and $\phi_2 = 0$ in the electron-beam direction. θ_3 and ϕ_3 are the polar and azimuthal angles of ℓ^+ from $J/\psi \to \ell^+\ell^-$ in the J/ψ rest frame with the z axis aligned to the γ_2 direction and $\phi_3 = 0$ in the γ_1 direction.



PRD 95, 072004

The stat. signif. of non-pure E1 transition is 24.3σ for χ_{c1}; 13.4σ for χ_{c2}; and M2 is significant.

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}	$a_2^2 = -0.120 \pm 0.013 \pm 0.004$, $b_2^2 = 0.017 \pm 0.008 \pm 0.002$ $a_3^2 = -0.013 \pm 0.009 \pm 0.004$, $b_3^2 = -0.014 \pm 0.007 \pm 0.004$ $\rho^2_{a_2 b_2} = -0.605$, $\rho^2_{a_2 a_3} = 0.733$, $\rho^2_{a_2 b_3} = -0.095$ $\rho^2_{a_3 b_2} = -0.422$, $\rho^2_{b_2 b_3} = 0.384$, $\rho^2_{a_3 b_3} = -0.024$

$a_2^{1,2}$ (after) the normalized M2 contribution for $\chi_{c1,2} \to \gamma_2 J/\psi$
$b_2^{1,2}$ (before) the normalized M2 contribution for $\psi' \to \gamma_1 \chi_{c1,2}$

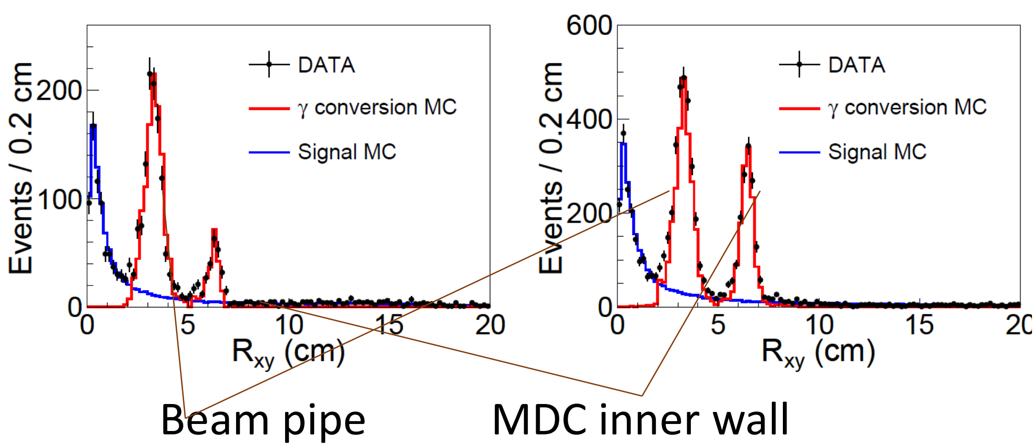
Similar analysis was performed using $\psi(2S) \to \gamma\chi_{c2} \to \gamma\pi\pi/\gamma KK$
M2=0.046±0.010±0.013 (4.4σ) *PRD 84,092006*

Yes. M2 component is significant. But this effect only changes the measured BF slightly.

$\psi(2S) \rightarrow e^+e^-\chi_{cJ},\ \chi_{cJ} \rightarrow \gamma J/\psi,\ \ J/\psi \rightarrow e^+e^-/\mu^+\mu^-$

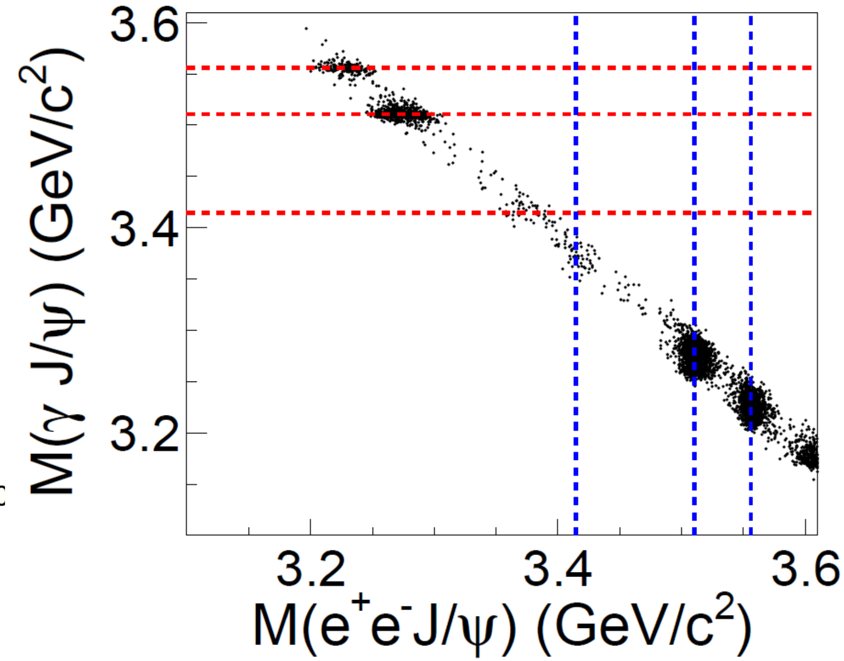
$\psi(2S) \rightarrow \gamma\chi_{cJ},\ \chi_{cJ} \rightarrow e^+e^- J/\psi,\ \ J/\psi \rightarrow e^+e^-/\mu^+\mu^-$

Major background:
$\psi(2S) \rightarrow \gamma\chi_{cJ}, \chi_{cJ} \rightarrow \gamma J/\psi$,
where one photon has conversion

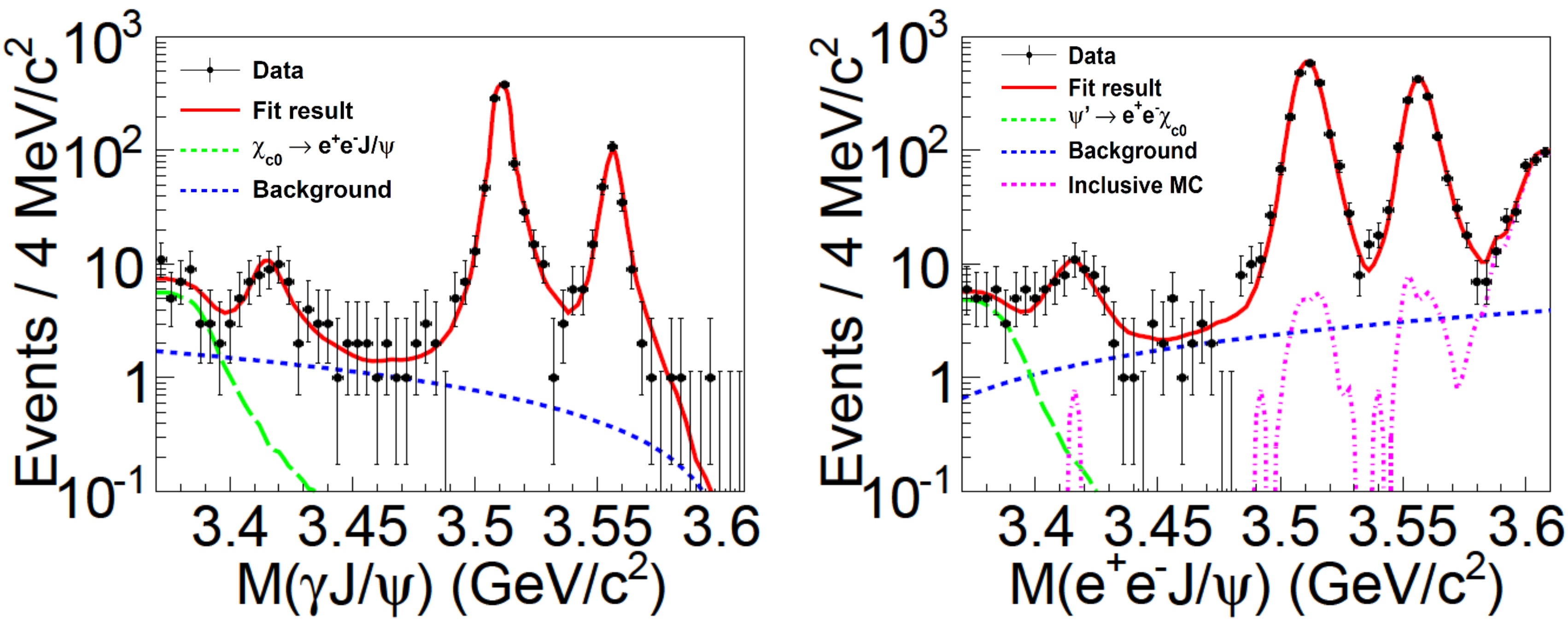


The reconstructed e^+e^- vertex

The Dalitz plot after selection



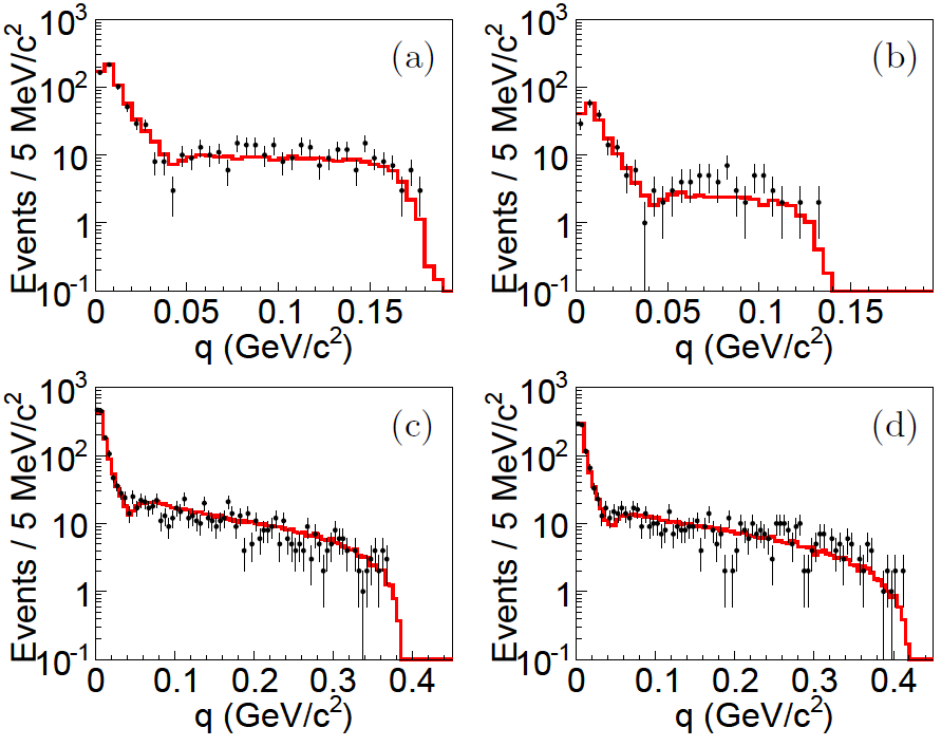
Invariant mass

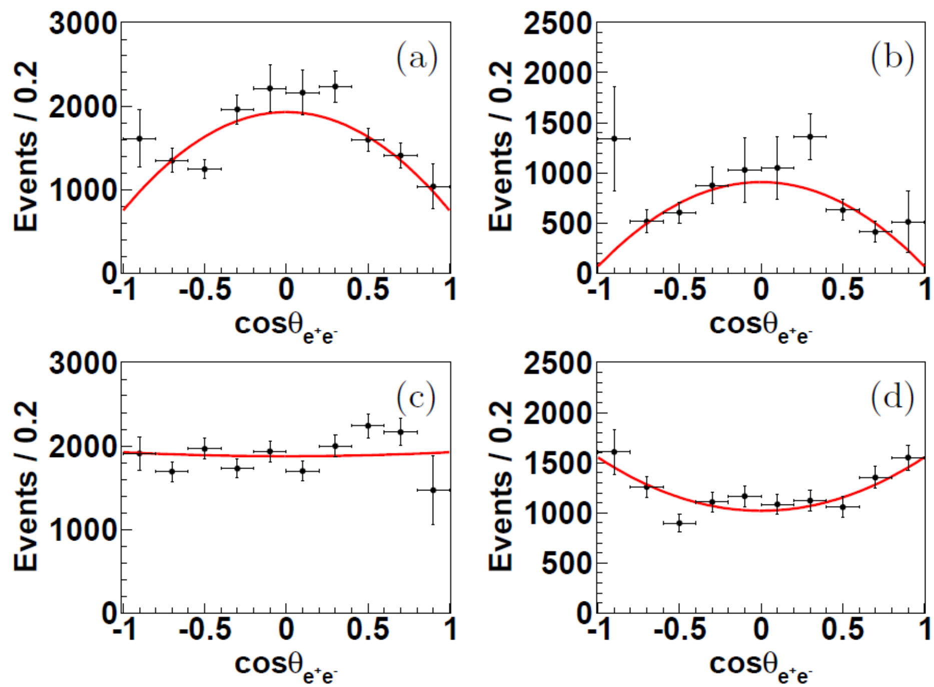


Mode	Yields	Efficiency(%)	Branching fraction	$\frac{\mathcal{B}(\psi(3686)\to e^+e^-\chi_{cJ})}{\mathcal{B}(\psi(3686)\to\gamma\chi_{cJ})}$	$\frac{\mathcal{B}(\chi_{cJ}\to e^+e^-J/\psi)}{\mathcal{B}(\chi_{cJ}\to\gamma J/\psi)}$
$\psi(3686)\to e^+e^-\chi_{c0}$	48 ± 10	6.06	$(11.7\pm2.5\pm1.0)\times10^{-4}$	$(9.4\pm1.9\pm0.6)\times10^{-3}$	–
$\psi(3686)\to e^+e^-\chi_{c1}$	873 ± 30	5.61	$(8.6\pm0.3\pm0.6)\times10^{-4}$	$(8.3\pm0.3\pm0.4)\times10^{-3}$	–
$\psi(3686)\to e^+e^-\chi_{c2}$	227 ± 16	3.19	$(6.9\pm0.5\pm0.6)\times10^{-4}$	$(6.6\pm0.5\pm0.4)\times10^{-3}$	–
$\chi_{c0}\to e^+e^-J/\psi$	56 ± 11	6.95	$(1.51\pm0.30\pm0.13)\times10^{-4}$	–	$(9.5\pm1.9\pm0.7)\times10^{-3}$
$\chi_{c1}\to e^+e^-J/\psi$	1969 ± 46	10.35	$(3.73\pm0.09\pm0.25)\times10^{-3}$	–	$(10.1\pm0.3\pm0.5)\times10^{-3}$
$\chi_{c2}\to e^+e^-J/\psi$	1354 ± 39	11.23	$(2.48\pm0.08\pm0.16)\times10^{-3}$	–	$(11.3\pm0.4\pm0.5)\times10^{-3}$

Q: $M(e^+e^-)$

Angular dist.





The comparison of data (dark) and MC(red)

Top : $\psi(2S) \rightarrow \gamma\chi$; bottom: $\chi \rightarrow \gamma J/\psi$
Left: for χ_{c1} ; right: for χ_{c2}

$$\alpha_{\psi' \to e^+e^-\chi_{c1}} = -0.6 \pm 0.2$$

$$\alpha_{\psi' \to e^+e^-\chi_{c2}} = -0.9 \pm 0.3$$

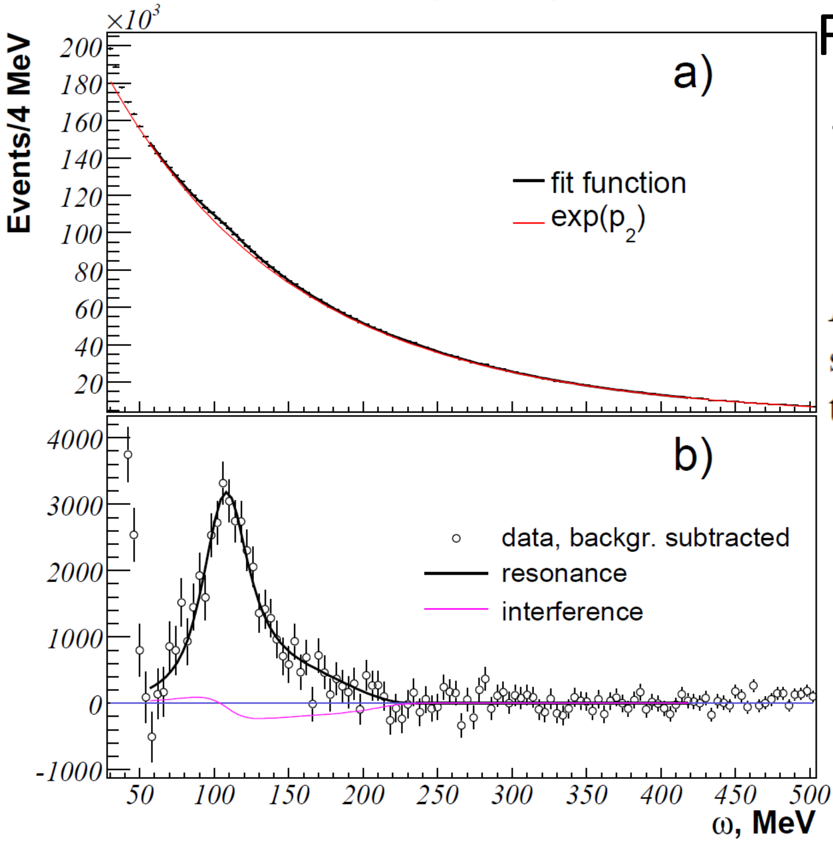
$$\alpha_{\chi_{c1} \to e^+e^-J/\psi} = 0.0 \pm 0.2$$

$$\alpha_{\chi_{c2} \to e^+e^-J/\psi} = 0.5 \pm 0.2$$

Note: The simulation assumed a point-like meson

KEDR results on $J/\psi \to \gamma\eta_c$ — using inclusive photon spectrum

arXiv: 1406.7644 (2014)



Firstly, they find the interference effects small in inclusive

$$\frac{d\Gamma(\omega)}{d\omega} \sim \left|S\,e^{i\gamma} + x^{1/2}N(\omega_0)e^{i\phi}\right|^2,$$

$N(\omega_0)$ is quite small, therefore interference changes the measured values only slightly. These shifts are considered as systematic uncertainties due to interference effects.

$X=\omega/\omega_0$, γ and ϕ are resonant and non-res phase

$$M_{\eta_c} = 2983.5 \pm 1.4\,^{+1.6}_{-3.6}\ \mathrm{MeV}/c^2,$$

$$\Gamma_{\eta_c} = 27.2 \pm 3.1\,^{+5.4}_{-2.6}\ \mathrm{MeV}.$$

$$\Gamma^0_{\gamma\eta_c} = 2.98 \pm 0.18\,^{+0.15}_{-0.33}\ \mathrm{keV}.$$

The results from BESIII inclusive decay are ongoing.

The results are consistent with the latest lattice QCD prediction.

Decays (to light hadrons)

To understand the charmonium decay dynamics

Test the 12% rule

The 12 % rule

- $Q_h = \frac{BF(psi(2S)\to h)}{BF(psi(1S)\to h)} = \frac{BF(psi(2S)\to ll)}{BF(psi(1S)\to ll)} = 12\%$

$$\Gamma_h = |M_h|^2 |\Psi(0)|^2$$

$$= (2/9\pi)(\pi^2 - 9)\tfrac{5}{18}\alpha_s{}^3(\tfrac{4}{3}\alpha_s)^3 m_{\psi'}.$$

The leptonic width via one photon into $\bar{l}l$ is

$$\Gamma_l = |M_l|^2 |\Psi(0)|^2 = \tfrac{1}{2}(\tfrac{2}{3}\alpha)^2(\tfrac{4}{3}\alpha_s)^3 m_{\psi'},$$

where $\alpha \approx \frac{1}{137}$. Although separately these calcul
tions are not trustworthy, the ratio

$$\frac{\Gamma_l}{\Gamma_h} = \frac{\frac{2}{9}\alpha^2}{(2/9\pi)(\pi^2 - 9)5/\alpha_s{}^3}$$

is independent of wave-function effects.

PRL34,43

Test the rule

Extensive study has done by BESII/CLEO

1. VP mode: e.g. $\rho\pi$, $K^{*+}K^{-}$, $k^{*0}K^{0}$, $\omega\pi^{0}$
2. PP mode: e.g. K_SK_L, $K^{+}K^{-}$, $\pi^{+}\pi^{-}$
3. BB mode: e.g. ppbar, $\Lambda\Lambda$bar
4. VT mode: e.g. $K^*K^*_2$, $\phi f_2'$, ρa_2 ,$\omega\phi_2$
5. 3 boby: e.g. w ppbar π^{0}, $\pi\pi\eta$, $\pi^{+}\pi^{-}\pi^{0}$
6. Multi-body: e.g. $K_SK_S$hh, $\pi^{+}\pi^{-}\pi^{0}K^{+}K^{-}$, $\pi\pi\pi\pi\pi\pi$

Some modes are suppressed, some are enhanced, while some others obey the 12% rule!

J/ψ, $\psi(2S) \to VP$

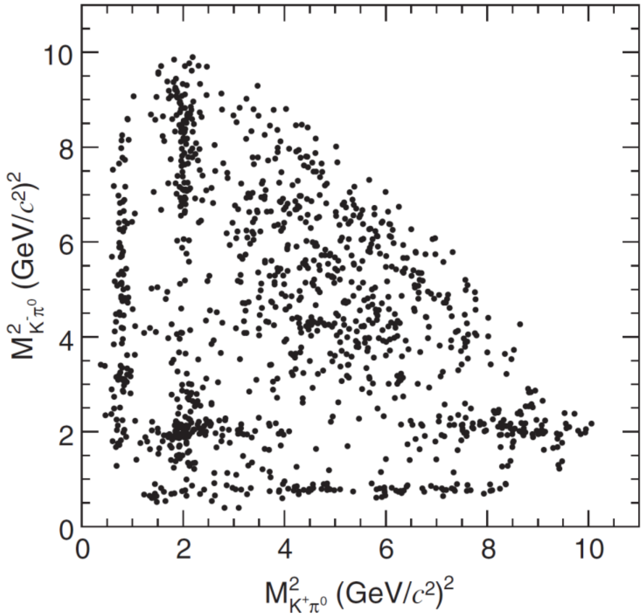
BESII : PLB614, 37 (2005); PRD73, 052007 (2006)
CLEOc: PRL94, 012005 (2005)
BESIII: arXiv:1202.2048

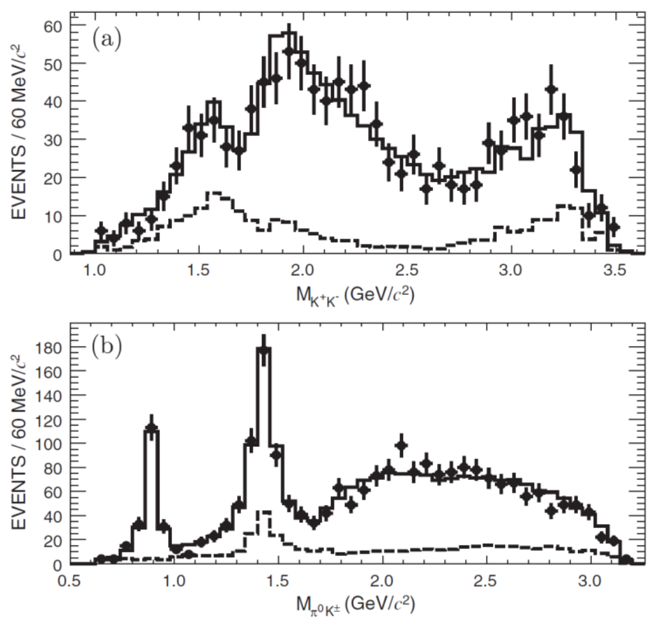
mode	BESII/III $B(\psi')(\times 10^{-5})$	CLEOc: $B(\psi')(\times 10^{-5})$	PDG/BESIII $B(J/\psi)(\times 10^{-4})$	$B(\psi')/B(J/\psi)$ (%)
$\rho\pi$	$5.1 \pm 0.7 \pm 1.1$	$2.4^{+0.8}_{-0.7} \pm 0.2$	169 ± 15	0.30 ± 0.04
$\pi^+\pi^-\pi^0$	$21.4 \pm 0.3 \pm 0.8 \pm 0.9$	$18.8^{+1.6}_{-1.5} \pm 2.8$	$21.37 \pm 0.04 \pm 0.58 \pm 0.27$	1.00 ± 0.06
$K^{*0}K^0$+c.c.	$13.3 \pm 2.7 \pm 1.7$	$9.2^{+2.7}_{-2.2} \pm 0.9$	43.9 ± 3.1	3 ± 0.6
$\omega\pi$	$1.87^{+0.68}_{-0.62} \pm 0.28$	$2.5^{+1.2}_{-1.0} \pm 0.2$	4.5 ± 0.5	4 ± 1.6
$\rho\eta$	$1.78^{+0.67}_{-0.62} \pm 0.17$	$3.0^{+1.1}_{-0.9} \pm 0.2$	1.93 ± 0.23	9 ± 3
$\rho\eta'$	$1.87^{+1.64}_{-1.11} \pm 0.33$	-	1.05 ± 0.18	18 ± 16
$\phi\eta'$	$3.1 \pm 1.4 \pm 0.7$	-	4.0 ± 0.7	7.8 ± 4.1
$\omega\eta$	<3.1	<1.1	17.4 ± 2.0	<0.53
$\omega\eta'$	$3.2^{+2.4}_{-2.0} \pm 0.7$	-	1.82 ± 0.21	18 ± 13

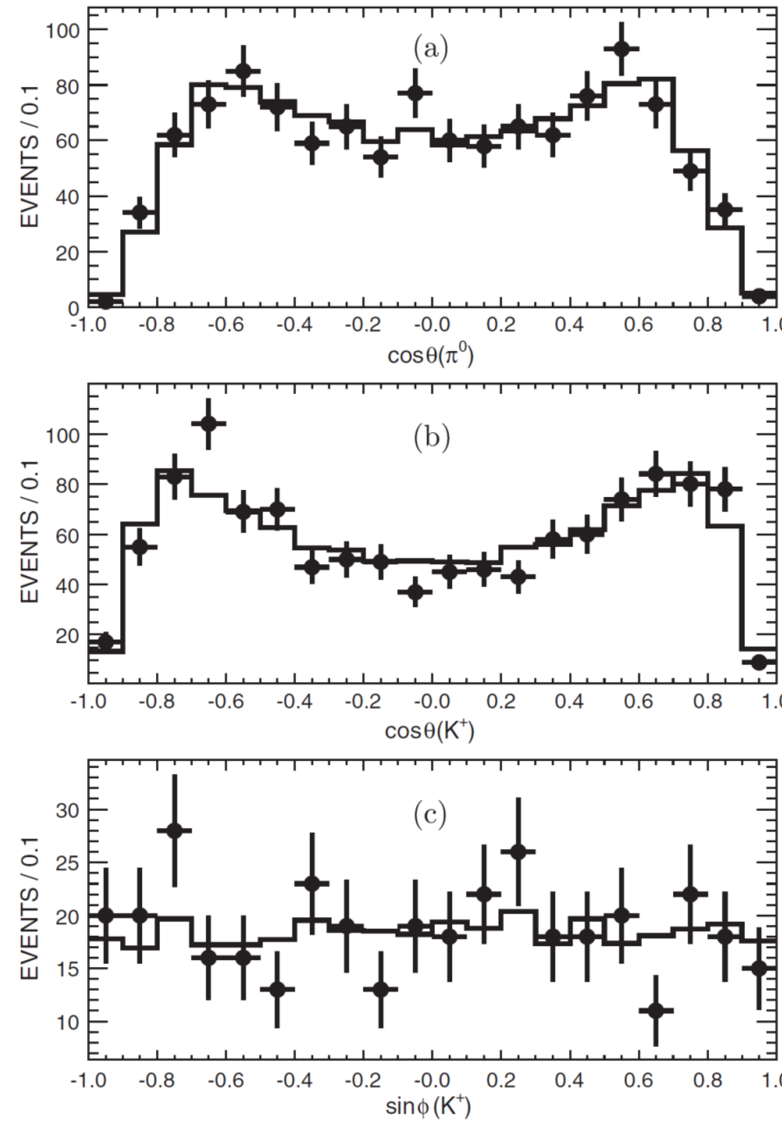
From Changzheng's talk

ψ(2S)→KKπ^0 : PWA is performed to 1158 →KKπ^0 events

Based on BSEIII 106 ψ'



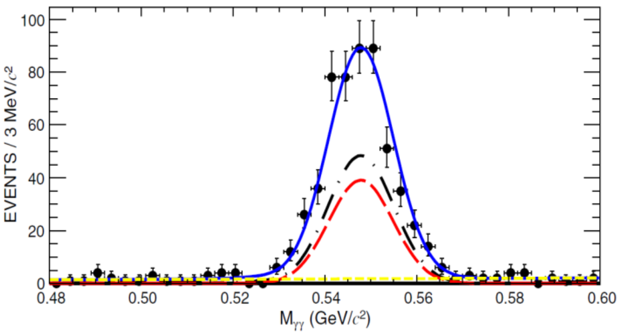




$\psi(2S) \rightarrow KK\eta$

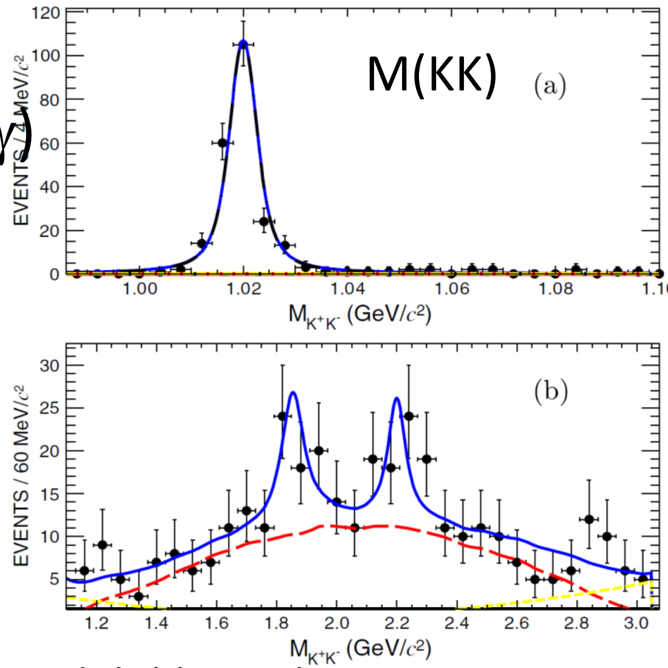
BESIII PRD 86, 072001
Base on 106M ψ'

2D fit to M(KK) vs.M ($\gamma\gamma$)



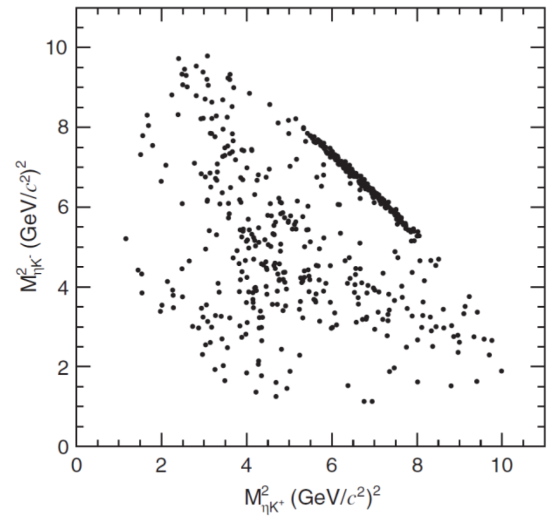
M($\gamma\gamma$)

M(KK)



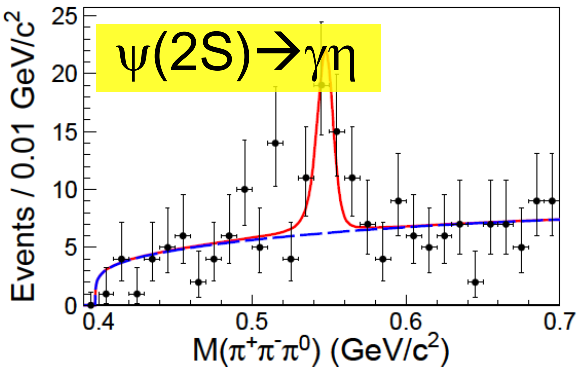
(a) ϕ(1020)
(b) ϕ(1850) and ϕ(2170)
dark dash: $\phi\eta$; red dash: ηKK

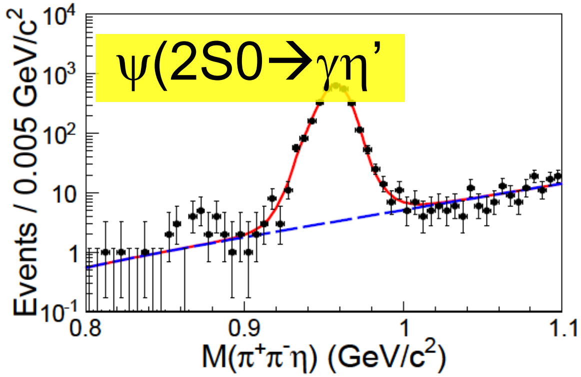
0.48<M($\gamma\gamma$)<0.6 GeV/C^2

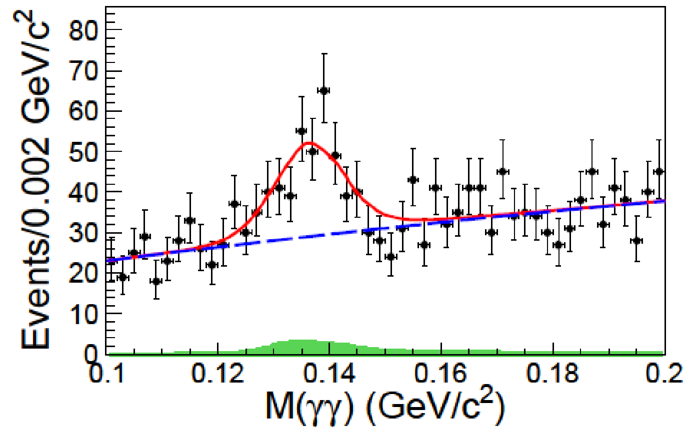


Mode ($\psi' \to$)	ϵ(%)	N^{obs}	$Br(\times 10^{-5})$	Q_h (%)	PDG ($\times 10^{-5}$)	CLEO ($\times 10^{-5}$)	BESII ($\times 10^{-5}$)
$\pi^0 K^+ K^-$(inclusive)	21.52	917 ± 37	4.07 ± 0.16 ± 0.26	···	<8.9 [2]	···	···
$K^*(892)^+ K^-$ + c.c.	20.25	224 ± 21	$3.18 \pm 0.30^{+0.26}_{-0.31}$	0.62 ± 0.09	$1.7^{+0.8}_{-0.9}$	1.3 ± 1.0 ± 0.3	2.9 ± 1.3 ± 0.4
$K_2^*(1430)^+ K^-$ + c.c.	20.28	251 ± 22	$7.12 \pm 0.62^{+1.13}_{-0.61}$	>2	···	···	···
$\eta K^+ K^-$($\eta\phi$ excluded)	22.10	284 ± 27	3.08 ± 0.29 ± 0.25	···	<13	<13	···
$\eta\phi$	33.53	216 ± 16	3.14 ± 0.23 ± 0.23	4.19 ± 0.61	$2.8^{+1.0}_{-0.8}$	2.0 ± 1.1 ± 0.4	3.3 ± 1.1 ± 0.5
$\pi^0\phi$	35.63	<10	<0.04	···	<0.4	0.7	0.4

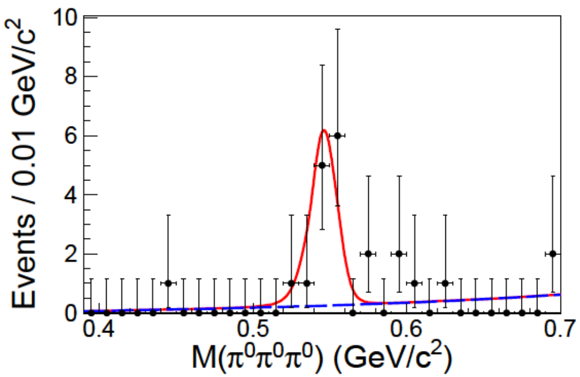
J/ψ & $\psi(2S)\to\gamma\pi^0$, $\gamma\eta$ & $\gamma\eta'$



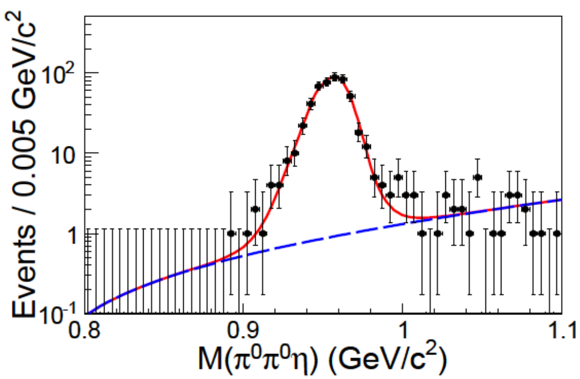




$M(\gamma\gamma)$



$M(\pi\pi\pi)$



$M(\pi^+\pi^-\eta)$

BESIII
PRD 96, 052003

Mode	$B(\psi(2S))$ [x10^{-6}]	$B(J/\psi)$ [x10^{-4}]	Q (%)
$\gamma\pi^0$	0.95±0.17	0.35±0.03	2.7± 0.5
$\gamma\eta$	0.85±0.18	11.04±0.34	0.08 ± 0.02
$\gamma\eta'$	125.1±6.6	52.8±1.5	2.4 ± 0.1

Multi-body ψ' decays

Mode h	$\mathcal{B}(\psi(2S)\to h)$ (units of10^{-4})	$\mathcal{B}$ (PDG) (units of10^{-4})	Q_h (%)
$2(\pi^+\pi^-)$	$2.2 \pm 0.2 \pm 0.2$	4.50 ± 1.00	5.55 ± 1.53
$\rho\pi^+\pi^-$	$2.0 \pm 0.2 \pm 0.4$	4.20 ± 1.50	—
$2(\pi^+\pi^-)\pi^0$	$26.1 \pm 0.7 \pm 3.0$	30.00 ± 8.00	7.76 ± 1.10
$\eta\pi^+\pi^-$	<1.6	—	—
$\omega\pi^+\pi^-$	$8.2 \pm 0.5 \pm 0.7$	4.80 ± 0.90	11.35 ± 1.94
$\eta 3\pi(\eta\to\gamma\gamma)$	$10.3 \pm 0.8 \pm 1.4$	—	—
$\eta 3\pi(\eta\to 3\pi)$	$8.1 \pm 1.4 \pm 1.6$	—	—
$\eta 3\pi$	$9.5 \pm 0.7 \pm 1.5$	—	—
$\eta' 3\pi$	$4.5 \pm 1.6 \pm 1.3$	—	—
$K^+K^-\pi^+\pi^-$	$7.1 \pm 0.3 \pm 0.4$	16.00 ± 4.00	9.85 ± 3.23
ρK^+K^-	$2.2 \pm 0.2 \pm 0.4$	—	—
$\phi\pi^+\pi^-$	$0.9 \pm 0.2 \pm 0.1$	1.50 ± 0.28	11.07 ± 3.30
$K^+K^-\pi^+\pi^-\pi^0$	$12.7 \pm 0.5 \pm 1.0$	—	10.59 ± 2.81
ηK^+K^-	<1.3	—	—
ωK^+K^-	$1.9 \pm 0.3 \pm 0.3$	1.50 ± 0.40	10.19 ± 2.96
$2(K^+K^-)$	$0.6 \pm 0.1 \pm 0.1$	—	6.71 ± 2.74
ϕK^+K^-	$0.8 \pm 0.2 \pm 0.1$	0.60 ± 0.22	5.14 ± 1.53
$2(K^+K^-)\pi^0$	$1.1 \pm 0.2 \pm 0.2$	—	—
$p\bar{p}\pi^+\pi^-$	$5.9 \pm 0.2 \pm 0.4$	8.00 ± 2.00	9.90 ± 1.16
$\rho p\bar{p}$	$0.5 \pm 0.1 \pm 0.2$	—	—
$p\bar{p}\pi^+\pi^-\pi^0$	$7.3 \pm 0.4 \pm 0.6$	—	18.70 ± 5.80
$\eta p\bar{p}$	$0.8 \pm 0.3 \pm 0.3$	—	3.80 ± 2.09
$\omega p\bar{p}$	$0.6 \pm 0.2 \pm 0.2$	0.80 ± 0.32	4.69 ± 2.22
$p\bar{p}K^+K^-$	$0.3 \pm 0.1 \pm 0.0$	—	—
$\phi p\bar{p}$	<0.24	<0.26	—
$\Lambda\bar{\Lambda}\pi^+\pi^-$	$2.8 \pm 0.4 \pm 0.5$	—	—
$\Lambda\bar{p}K^+$	$1.0 \pm 0.1 \pm 0.1$	—	10.92 ± 2.93
$\Lambda\bar{p}K^+\pi^+\pi^-$	$1.8 \pm 0.3 \pm 0.3$	—	—

CLEOc: PRL95, 062001 (2005)

BESII: PRD71, 072006 (2005)

$$Q_{p\bar{p}\pi^0} = \frac{\mathcal{B}(\psi'\to p\bar{p}\pi^0)}{\mathcal{B}(J/\psi\to p\bar{p}\pi^0)} = \frac{(13.2\pm1.0\pm1.5)\times10^{-5}}{(1.09\pm0.09)\times10^{-3}} = (12.1\pm1.9)\%,$$

$$Q_{p\bar{p}\eta} = \frac{\mathcal{B}(\psi'\to p\bar{p}\eta)}{\mathcal{B}(J/\psi\to p\bar{p}\eta)} = \frac{(5.8\pm1.1\pm0.7)\times10^{-5}}{(2.09\pm0.18)\times10^{-3}} = (2.8\pm0.7)\%.$$

BESII, PRD73, 052004 (2006)

$$B(\psi(2S)\to K^+K^-\pi^+\pi^-\pi^0) = (1.17\pm0.10\pm0.15)\times10^{-3},$$
$$B(\psi(2S)\to \omega K^+K^-) = (2.38\pm0.37\pm0.29)\times10^{-4},$$
$$B(\psi(2S)\to \omega f_0(1710), f_0(1710)\to K^+K^-) = (5.9\pm2.0\pm0.9)\times10^{-5},$$
$$B(\psi(2S)\to K^*(892)^0K^-\pi^+\pi^0 + \text{c.c.}) = (8.6\pm1.3\pm1.8)\times10^{-4},$$
$$B(\psi(2S)\to K^*(892)^+K^-\pi^+\pi^- + \text{c.c.}) = (9.6\pm2.2\pm1.7)\times10^{-4},$$
$$B(\psi(2S)\to K^*(892)^+K^-\rho^0 + \text{c.c.}) = (7.3\pm2.2\pm1.4)\times10^{-4},$$
$$B(\psi(2S)\to K^*(892)^0K^-\rho^+ + \text{c.c.}) = (6.1\pm1.3\pm1.2)\times10^{-4},$$

CLEOc: PRD72, 051108 (2005)

Modes	$\mathcal{B}(10^{-4})$
$p\overline{p}$	$2.87 \pm 0.12 \pm 0.15$
$\Lambda\overline{\Lambda}$	$3.28 \pm 0.23 \pm 0.25$
$\Sigma^+\overline{\Sigma^+}$	$2.57 \pm 0.44 \pm 0.68$
$\Sigma^0\overline{\Sigma^0}$	$2.63 \pm 0.35 \pm 0.21$
$\Xi^-\overline{\Xi^-}$	$2.38 \pm 0.30 \pm 0.21$
$\Xi^0\overline{\Xi^0}$	$2.75 \pm 0.64 \pm 0.61$
$\Xi(1530)^0\overline{\Xi(1530)^0}$	$0.72^{+1.48}_{-0.62} \pm 0.10(<3.2\ 90\%\ \text{CL})$
$\Omega^-\overline{\Omega^-}$	$0.70^{+0.55}_{-0.33} \pm 0.10(<1.6\ 90\%\ \text{CL})$

BESIII PRD 89 112006

$$Q_{\omega KK} = \frac{B(\psi(3686)\to\omega K^-K^+)}{B(J/\psi\to\omega K^-K^+)} = (18.4\pm3.7)$$

VT mode	$B_{\psi(2S)\to X}$ (10^{-4}) (BES-II)	$B_{J/\psi\to X}$ (10^{-3}) (PDG2002)	$Q_h(\%)$
$\omega\ f_2$	2.05± 0.41 ± 0.38	4.3±0.6	4.8±1.5
$\rho\ a_2$	2.55± 0.73± 0.47	10.9±2.2	2.3±1.1
$K^*\overline{K^*}_2$	1.86± 0.32 ± 0.43	6.7±2.6	2.8±1.3
$\phi\ f_2'$	0.44 ± 0.12 ± 0.11	1.23±0.21 †	3.6±1.5

PRD69,072001

AP Mode	$B_{\psi(2S)\to X}(10^{-4})$	$B_{J/\psi\to X}(10^{-3})$	Q_h (%)
$b_1\pi$	3.2±0.6±0.5	3.0±0.5	11±3
$KK_1(1270)$	10.0 ±1.8±2.1	<3.0	>24
$KK_1(1410)$	<3.1 (C.L. 90 %)	3.8±0.8 ±1.2	< 13

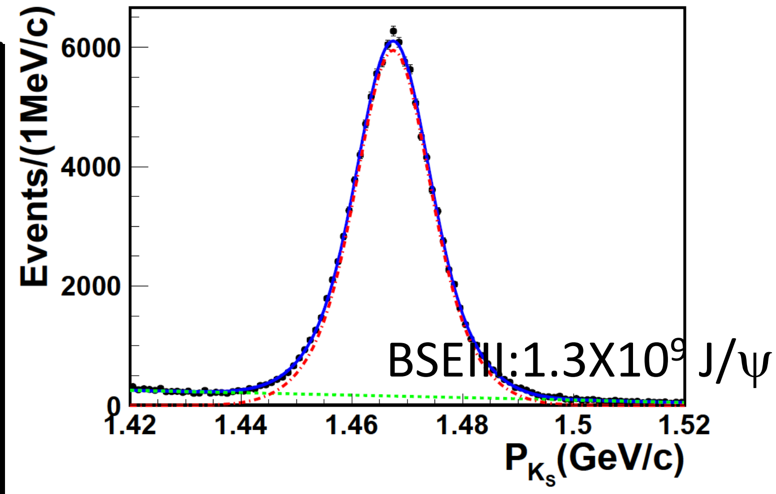
PRL 83,1918;PRD 67,52002

BB mode

$$\frac{\mathcal{B}(\psi(3686)\to p\bar{p})}{\mathcal{B}(J/\psi\to p\bar{p})} = (14.4\pm 0.6)\%$$

$$\frac{\mathcal{B}(\psi(3686)\to n\bar{n})}{\mathcal{B}(J/\psi\to n\bar{n})} = (14.8\pm 1.2)\%,$$

PP: $J/\psi \to K_S K_L$



G. 2: The momentum distribution of K_S in the e^+e^- rest me. The (black) crosses are from data, and the (blue) solid e is the fit result. The (red) dash-dotted line is the signal, l the (green) dashed line is background.

BF($\psi(2S)\to K_S K_L$)
$(5.24\pm 0.47 \pm 0.48)\times 10^{-5}$
BF($J/\psi \to K_S K_L$)
$(1.93\pm 0.01 \pm 0.05)\times 10^{-4}$

$$Q_h = \frac{BF(\psi(2S)\to K_S K_L)}{BF(J/\psi\to K_S K_L)} = (27.2\pm 3.5)\%$$

PRL 92, 052001; PRD 69, 012003

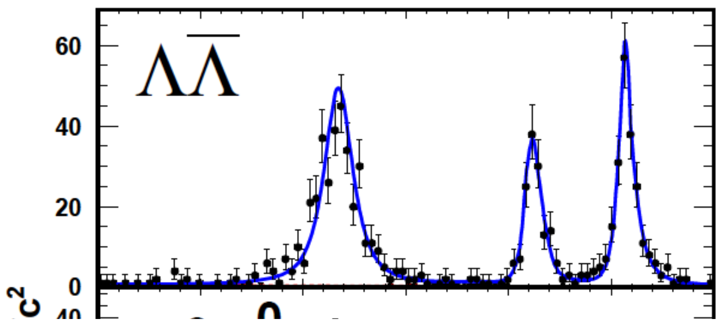
χ_{cJ} decays

Cannot be well described by the color-singlet contribution alone, although this works well in explaining S-Wave charmonium eg. the J/psi, psi(2S) decays

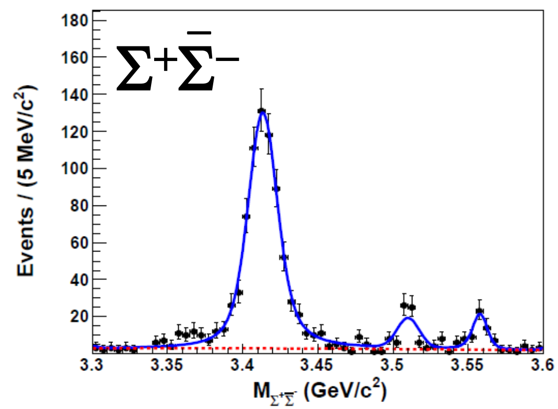
With the inclusion of the color-octet mechanism, the calculations of $\chi_{cJ} \rightarrow P\bar{P}, B\bar{B}$ come into more reasonable agreement with the experimental results, but with exceptions

Measure more decays.

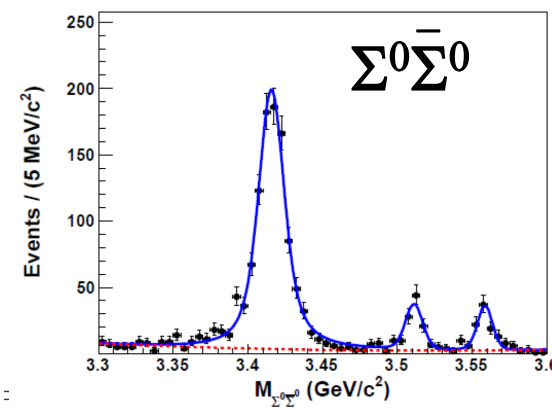
106M ψ(2S)



448M ψ(2S)



448Mψ(2S)



Mode		χ_{c0}	χ_{c1}	χ_{c2}
$\Lambda\bar{\Lambda}$	This work	$33.3 \pm 2.0 \pm 2.6$	$12.2 \pm 1.1 \pm 1.1$	$20.8 \pm 1.6 \pm 2.3$
	PDG	33.0 ± 4.0	11.8 ± 1.9	18.6 ± 2.7
	CLEO	$33.8 \pm 3.6 \pm 2.2 \pm 1.7$	$11.6 \pm 1.8 \pm 0.7 \pm 0.7$	$17.0 \pm 2.2 \pm 1.1 \pm 1.1$
	Theory	$(93.5 \pm 20.5^a, 22.1 \pm 6.1^b)$ [2]	–	$(15.2 \pm 1.7^a, 4.3 \pm 0.6^b)$ [2]
		$11.9 \sim 15.1$ [3]	3.9 [22]	3.5 [22]

PRD 87, 032007
arXiv:1710.07922

Throughout the table, the BFs are given in units of 10^{-5}.

Channel	This work	PDG	Previous BESIII [6]	CLEO [5]	Theory	$\mathcal{B}_{\rm prod}$
$\chi_{c0} \to \Sigma^+\bar{\Sigma}^-$	$50.4 \pm 2.5 \pm 2.7$	39 ± 7	$43.7 \pm 4.0 \pm 2.8$	$32.5 \pm 5.7 \pm 4.3$	5.5-6.9 [3]	$4.99 \pm 0.24 \pm 0.24$
$\chi_{c1} \to \Sigma^+\bar{\Sigma}^-$	$3.7 \pm 0.6 \pm 0.2$	< 6	$5.2 \pm 1.3 \pm 0.5 (< 8.3)$	< 6.5	3.3 [4]	$0.35 \pm 0.06 \pm 0.02$
$\chi_{c2} \to \Sigma^+\bar{\Sigma}^-$	$3.5 \pm 0.7 \pm 0.3$	< 7	$4.7 \pm 1.8 \pm 0.7 (< 8.4)$	< 6.7	5.0 [4]	$0.32 \pm 0.06 \pm 0.03$
$\chi_{c0} \to \Sigma^0\bar{\Sigma}^0$	$47.7 \pm 1.8 \pm 3.5$	44 ± 4	$46.0 \pm 3.3 \pm 3.7$	$44.1 \pm 5.6 \pm 4.7$	$(25.1 \pm 3.4, 18.7 \pm 4.5)$ [2]	$4.72 \pm 0.18 \pm 0.28$
$\chi_{c1} \to \Sigma^0\bar{\Sigma}^0$	$4.3 \pm 0.5 \pm 0.3$	< 4	$3.7 \pm 1.0 \pm 0.5 (< 6.0)$	< 4.4	3.3 [4]	$0.41 \pm 0.05 \pm 0.03$
$\chi_{c2} \to \Sigma^0\bar{\Sigma}^0$	$3.9 \pm 0.5 \pm 0.3$	< 6	$3.8 \pm 1.0 \pm 0.5 (< 6.2)$	< 7.5	$(38.9 \pm 8.8, 4.2 \pm 0.5)$ [2] 5.0 [4]	$0.35 \pm 0.05 \pm 0.02$

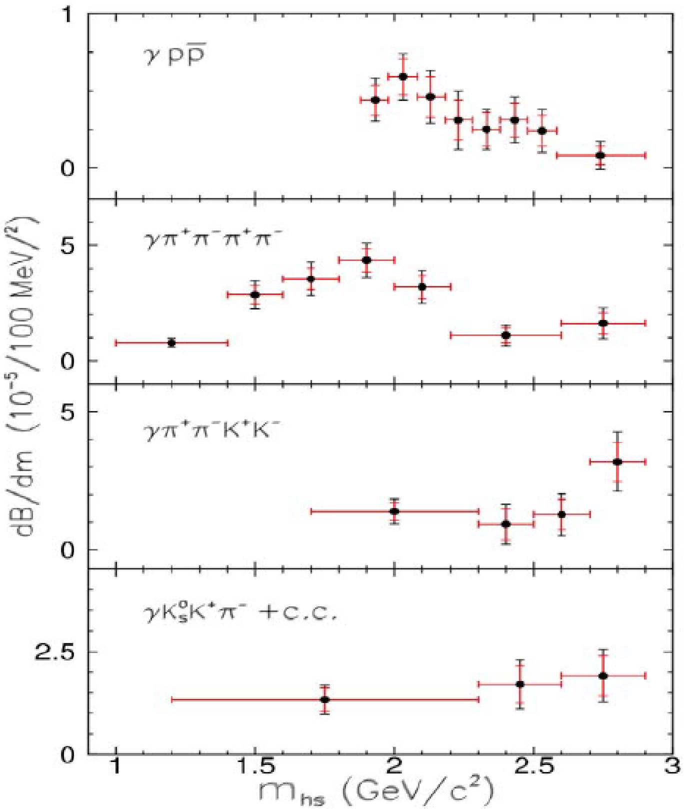
Radiative decay

- Old results
- $\psi(2S) \to \gamma\pi^0 / \gamma\eta / \gamma\eta'$
- $h_c \to \gamma\eta / \gamma\eta'$

ψ(2S) radiative decays

- Expected 1% BR, but only 0.05% observed.
- Potential channels for hadron spectroscopy study, including search for non-qqbar states, provided statistics is enough (BESIII?).
- ~ 0.1% more observed in this analysis.

Mode	BR ($\times 10^{-5}$) [$m<2.9$ GeV/c^2]
γ pp-bar	$2.9 \pm 0.4 \pm 0.4$
$\gamma\ \eta'$	$12.6 \pm 2.9 \pm 1.5$
$\gamma\ 2(\pi^+\pi^-)$	$39.6 \pm 2.8 \pm 5.0$
$\gamma\ K_S K^+\pi^-$+c.c.	$25.6 \pm 3.6 \pm 3.6$
$\gamma\ \pi^+\pi^- K^+K^-$	$19.1 \pm 2.7 \pm 4.3$
$\gamma\ \pi^+\pi^-$ppbar	$2.8 \pm 1.2 \pm 0.7$
$\gamma\ 2(K^+K^-)$	< 4.0
$\gamma\ 3(\pi^+\pi^-)$	< 17
$\gamma\ 2(\pi^+\pi^-)K^+K^-$	< 22



PRL99, 011802 (2007)

Take from Changzheng'talk

PRD 96 , 052003

ψ(2S) radiative decays cont.

BESIII has observed the signals for

$\psi(2S) \to \gamma\eta'$(>12σ) **$\psi(2S) \to \gamma\eta$(7.3σ)**

$\psi(2S) \to \gamma\pi^0$(6.7σ)

With 448 ψ(3686)

	this $(\times 10^{-6})$	Old Results $(\times 10^{-6})$	prediction $(\times 10^{-6})$
$\psi(3686) \to \gamma\eta'$	$(125.7 \pm 2.2 \pm 5.2)$	$(126 \pm 3 \pm 8)$	$(1.14 \sim 1.19) \times 10^{-4}$
$\psi(3686) \to \gamma\eta$	$(0.86 \pm 0.18 \pm 0.04)$	$(1.38 \pm 0.48 \pm 0.09)$	$(1.39 \sim 1.53) \times 10^{-6}$
$\psi(3686) \to \gamma\pi^0$	$(0.96 \pm 0.15 \pm 0.05)$	$(1.58 \pm 0.40 \pm 0.13)$	$(0.66 \sim 1.15) \times 10^{-7}$

Radiative decays cont.

$\mathcal{B}(\psi' \to \pi^0 h_c) = (8.6 \pm 1.3) \times 10^{-4}$

448M ψ(3686)

h_c~0.4M

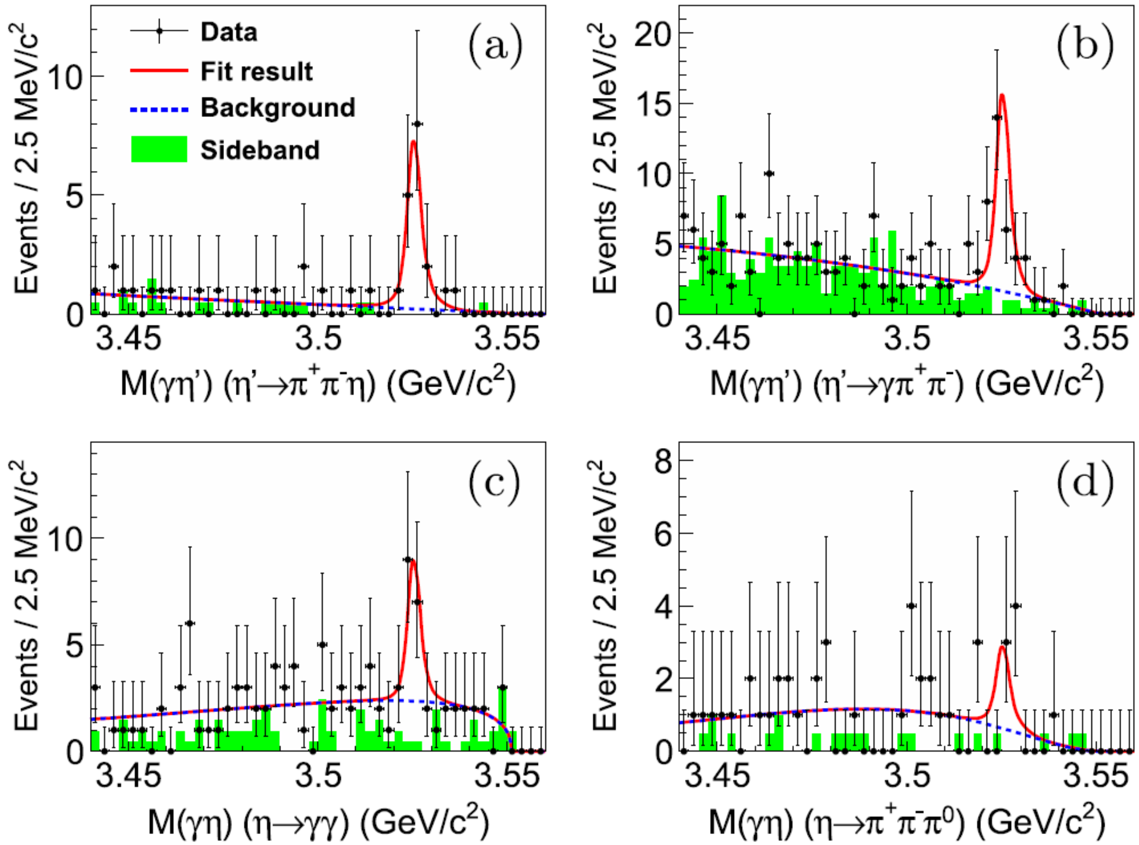
Reconstruct by

$h_c \to \gamma\eta',\ \eta' \to \pi^+\pi^-\eta,$
$\eta \to \gamma\gamma$

$h_c \to \gamma\eta',\ \eta' \to \gamma\pi^+\pi^-$

$h_c \to \gamma\eta,\ \eta \to \gamma\gamma$

$h_c \to \gamma\eta,\ \eta \to \pi^+\pi^-\pi^0$

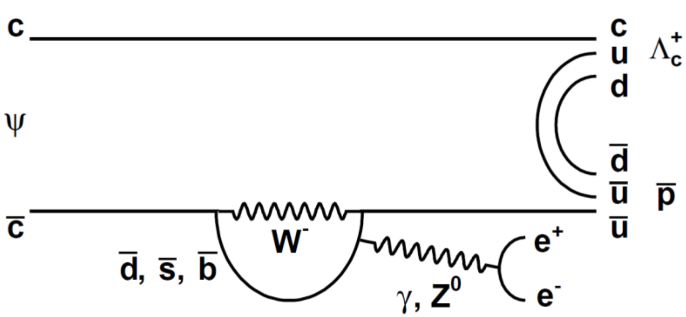


Mode	$N_{h_c\to\gamma\eta'(\eta)}$	$W_{\eta'(\eta)}(\times 10^{-2})$	$\mathcal{B}[h_c \to \gamma\eta'(\eta)]$	Significance	$[\mathcal{B}(h_c \to \gamma\eta)/\mathcal{B}(h_c \to \gamma\eta')](\%)$
$h_c \to \gamma\eta'$	44.3 ± 7.8(stat)	7.67 ± 0.38(sys)	$[1.52 \pm 0.27\text{(stat)} \pm 0.29\text{(sys)}] \times 10^{-3}$	8.4σ	30.7 ± 11.3(stat) ± 8.7(sys)
$h_c \to \gamma\eta$	18.1 ± 5.8(stat)	10.22 ± 0.55(sys)	$[4.7 \pm 1.5\text{(stat)} \pm 1.4\text{(sys.)}] \times 10^{-4}$	4.0σ	

Search for rare decays

$\psi' \to \Lambda_c^+ \bar{p} e^+ e^-$ with $\Lambda_c^+ \to p K^- \pi^+$

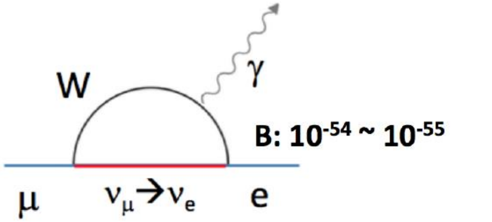
arXiv: 1802.04057

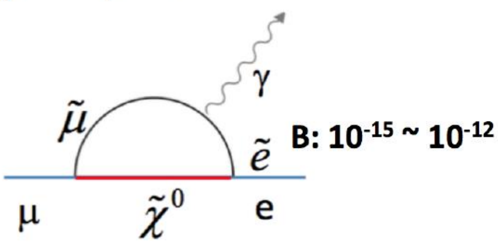


BESIII analyzed 448M $\psi(3686)$, found no signal candidates

UL: 1.6×10^{-6} @ 90% C.L.

Decay mode	BESII upper limit	BESIII upper limit
$J/\psi \to e\mu$	1.1×10^{-6} (58M)	1.6×10^{-7} (225M)
$J/\psi \to e\tau$	8.3×10^{-6} (58M)	-
$J/\psi \to \mu\tau$	2.0×10^{-6} (58M)	-

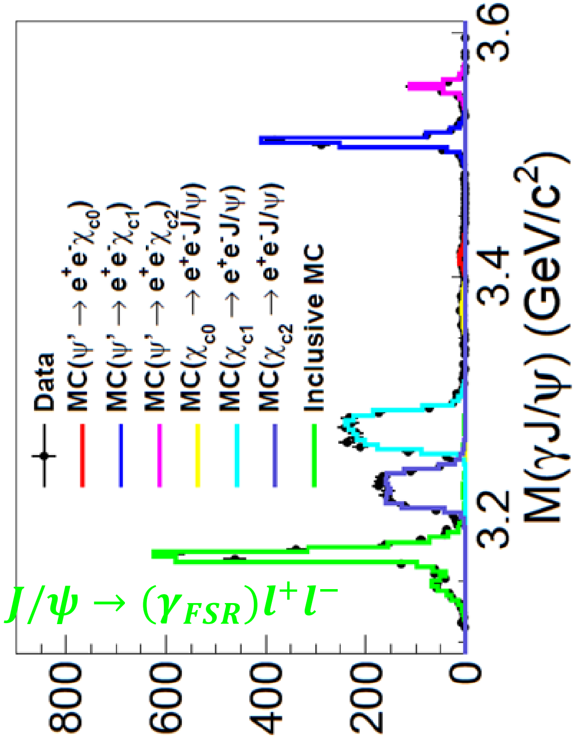




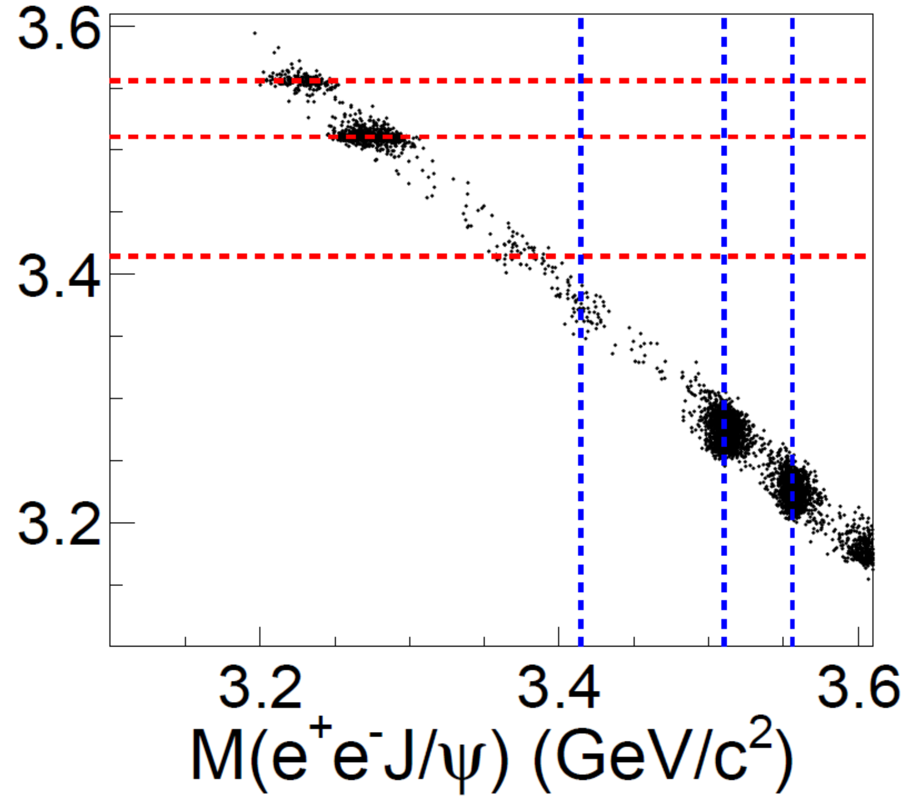
PRD 87 112007

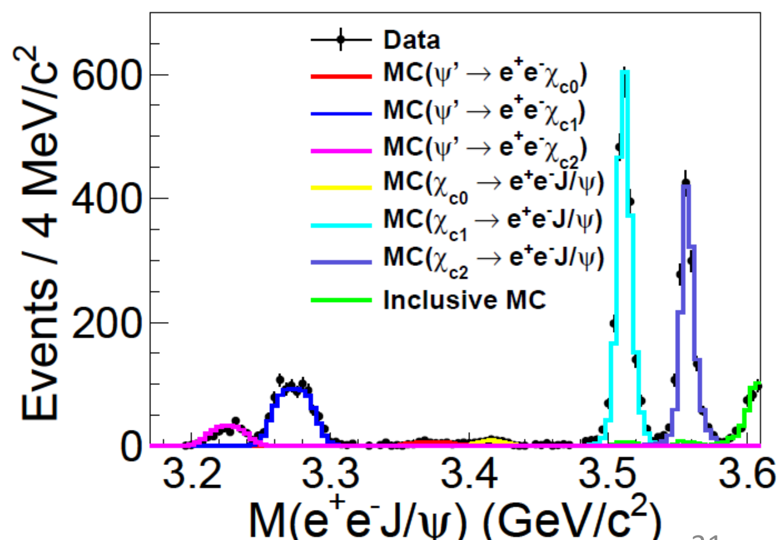
Summary

- Much knowledge has been gained in the past years; BESIII is producing more results, be patient.
- Some channels are statistically limited; need more data and better analysis techniques, a higher luminosity machine is desired.



$\psi' \rightarrow \pi^+\pi^- J/\psi, J/\psi \rightarrow (\gamma_{FSR}) l^+ l^-$



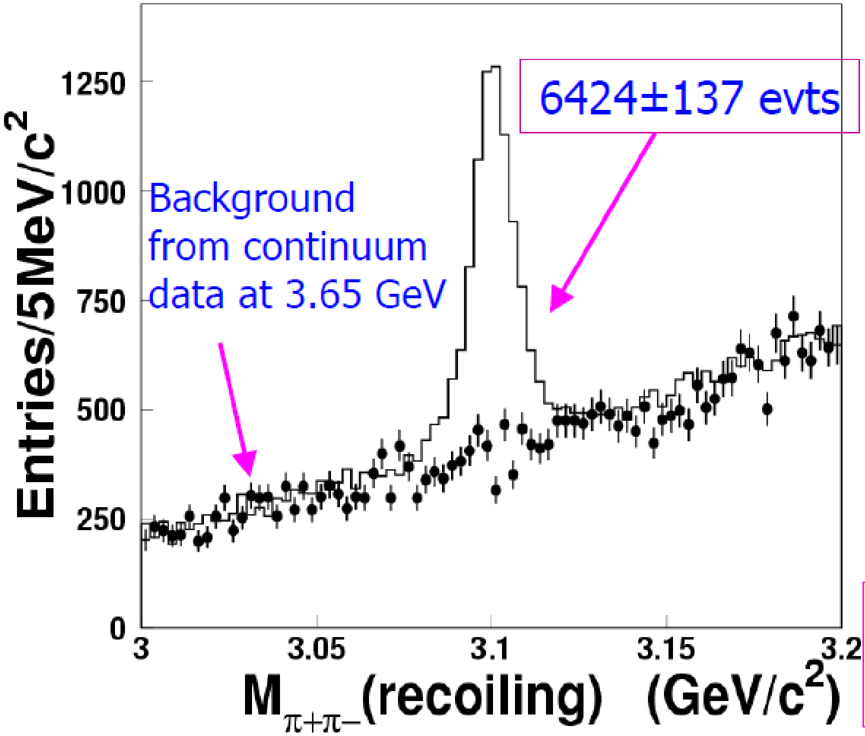


$J/\psi \rightarrow$ invisible

arXiv: 0710.0039 [hep-ex]
Published in PRL(2008)

- $\psi(2S) \rightarrow \pi^+\pi^- J/\psi$ as a J/ψ sample by tagging $\pi^+\pi^-$

Select two low momentum pions, and require no other particles in detector.



Peaking background

Background channel ($\psi(2S) \rightarrow \pi^+\pi^- J/\psi$, $J/\psi \rightarrow$)	expected N_{bg}
$\mu^+\mu^-$	2543 ± 254
e^+e^-	2393 ± 240
$n\bar{n}$	1011 ± 85
$p\bar{p}$	42 ± 13
$n\bar{n}\pi^0$	29 ± 10
Total	6018 ± 360

Lower limit of N_{bkg}

$$\frac{B(J/\psi \rightarrow \text{invisible})}{B(J/\psi \rightarrow \mu^+\mu^-)} < 0.010 \quad @90\% \text{ C.L.}$$

More stringent constraint on NEW physics parameters: (U-boson c-quark/LDM coupling)

P. Fayet, Phys. Rev. D **74**, 054034 (2006).
P. Fayet, Phys. Rev. D **75**, 115017 (2007).