A Review of χ_{cJ}(1P) Decays at BESIII and CLEO-c

Ryan Mitchell
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Charm 2012
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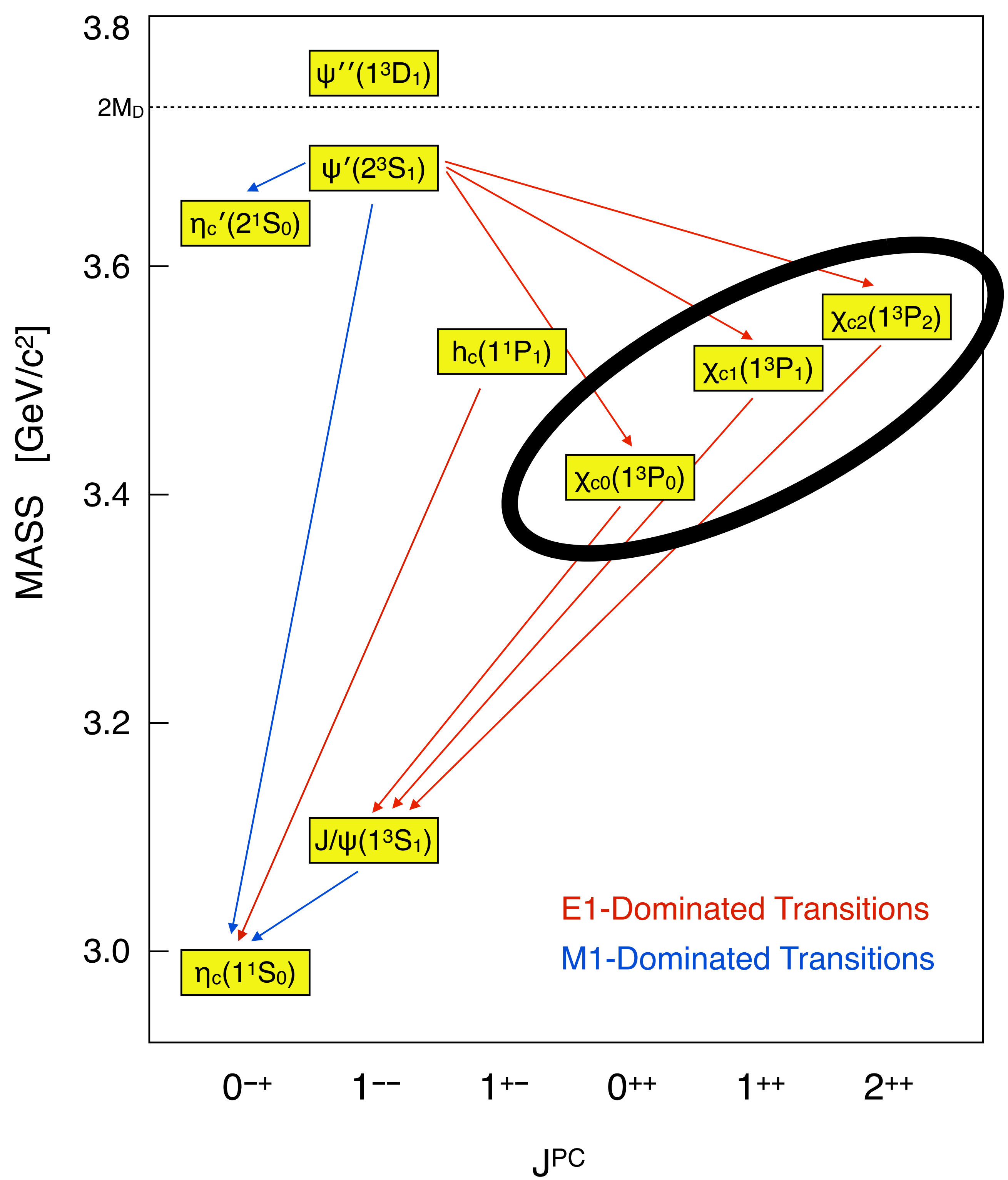
The $\chi_{cJ}(1P)$ States of Charmonium

The Charmonium System

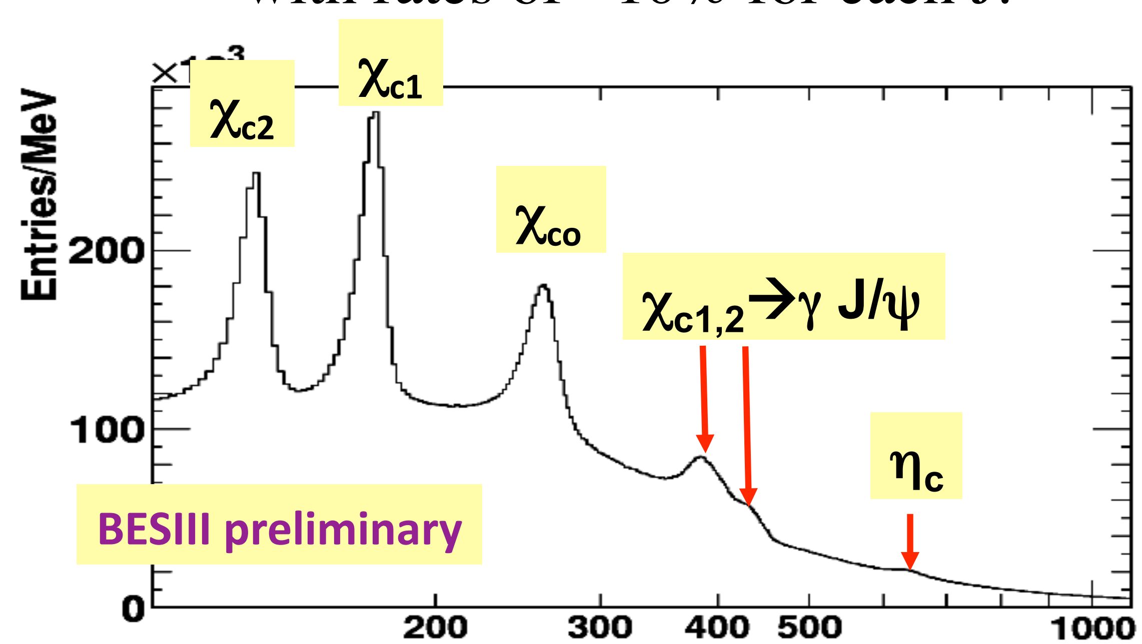


S = 1 *(spins aligned)* and

L = 1 *(P-wave)*

$\Rightarrow$ J = 0, 1, 2 ($\chi_{c0}(1P)$, $\chi_{c1}(1P)$, $\chi_{c2}(1P)$)

Produced through $\psi(2S) \rightarrow \gamma\chi_{cJ}(1P)$ with rates of ~10% for each J:



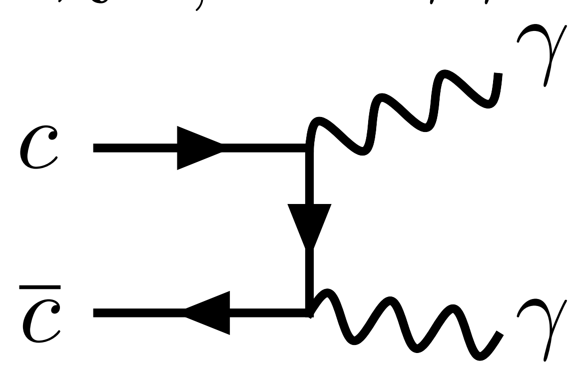
Inclusive energy spectrum of γ from ψ(2S)

CLEO-c number of ψ(2S): 26M

BESIII number of ψ(2S): 106M

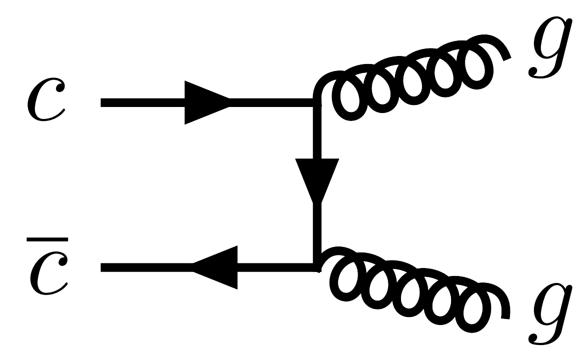
- $\chi_{cJ}(1P)$ decays can probe strong force dynamics, for example, through:

$\chi_{c0,2} \to \gamma\gamma$



corrections to EM processes

$\chi_{c0,2} \to gg$



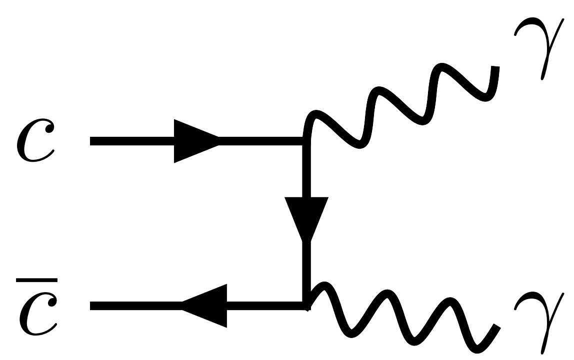
perturbative QCD considerations

- Exclusive $\chi_{cJ}(1P)$ decays are also a source of light quark states, useful for both meson and baryon spectroscopy -- a rich set of final states allows one to isolate quantum numbers.

Dynamics of $\chi_{cJ}(1P)$ Decays

ELECTROMAGNETIC

$$\chi_{c0,2} \to \gamma\gamma$$



Zeroth order is QED.

But the process is sensitive to QCD corrections.

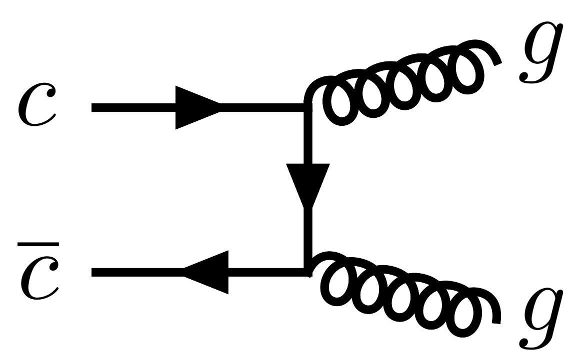
Some theoretical uncertainties cancel in the ratio:

$$R = \frac{\Gamma(\chi_{c2} \to \gamma\gamma)}{\Gamma(\chi_{c0} \to \gamma\gamma)}$$

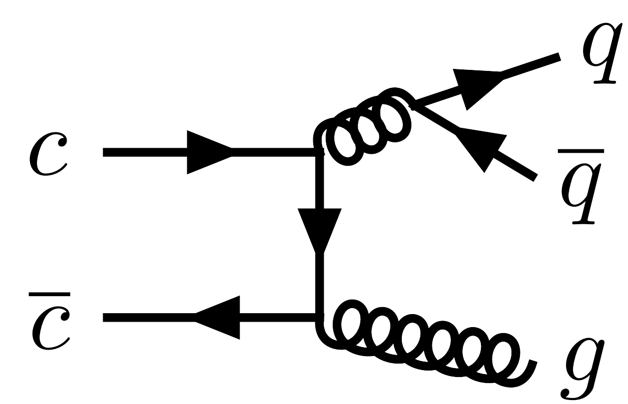
Also measure ratio of two helicity amplitudes for $\chi_{c2} \to \gamma\gamma$.

STRONG

$$\chi_{c0,2} \to gg$$



$$\chi_{c1} \to q\bar{q}g$$



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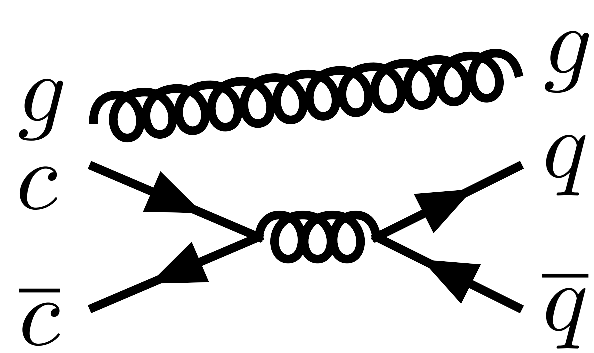

Use the "color octet model" to help explain large 2-body decay widths?

Dynamics of $\chi_{cJ}(1P)$ Decays

ELECTROMAGNETIC

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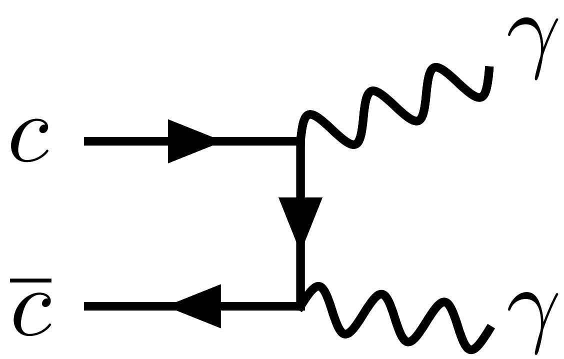

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$$\chi_{c0,2} \to gg \qquad \chi_{c1} \to q\bar{q}g$$

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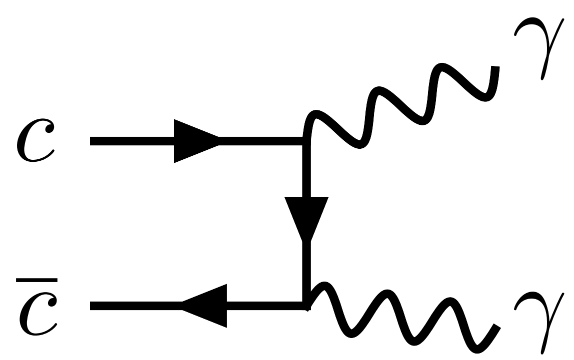

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Some theoretical uncertainties cancel in the ratio:

$$R = \frac{\Gamma(\chi_{c2} \rightarrow \gamma\gamma)}{\Gamma(\chi_{c0} \rightarrow \gamma\gamma)}$$

Also measure ratio of two helicity amplitudes for $\chi_{c2} \rightarrow \gamma\gamma$.

To lowest order (QED):

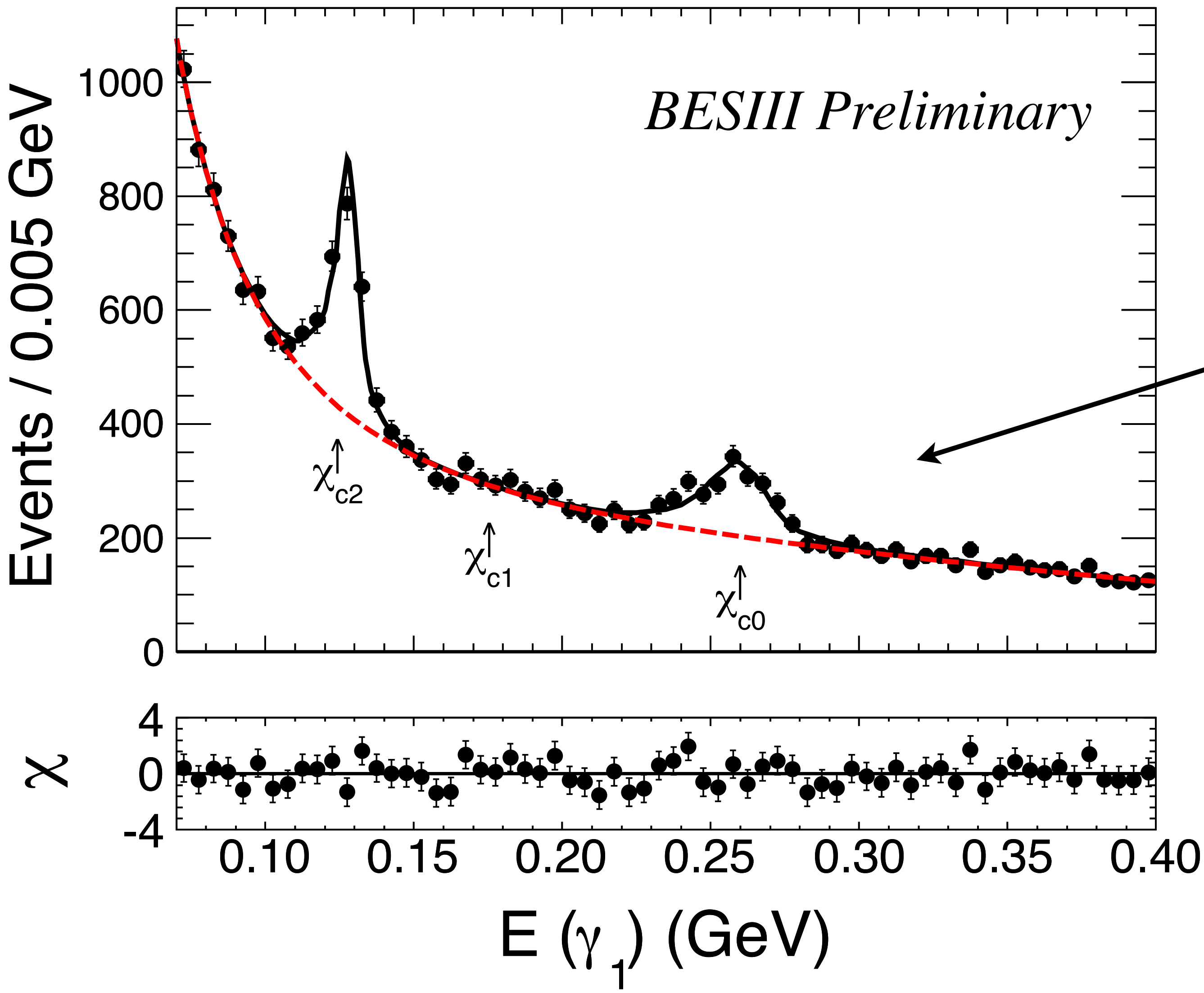
R = 4/15 ≈ 0.27

With corrections, predictions vary from:

R = 0.09 – 0.36

⇒ R is sensitive to higher order QCD effects (radiative corrections, relativistic corrections, etc)

Study of $\chi_{c0,2} \to \gamma\gamma$ at BESIII *(preliminary)*



Look for:

$\psi(2S) \to \gamma_1\chi_{c0,2};\ \chi_{c0,2} \to \gamma\gamma$

(3γ final state)

The energy of the lowest-energy photon tags the $\chi_{c0,2}$.

Derive the background shape (dominated by QED processes) from non-$\psi(2S)$ data.

Take the signal shapes from:

$\psi(2S) \to \gamma_1\chi_{c0,2};\ \chi_{c0,2} \to K^+K^-$

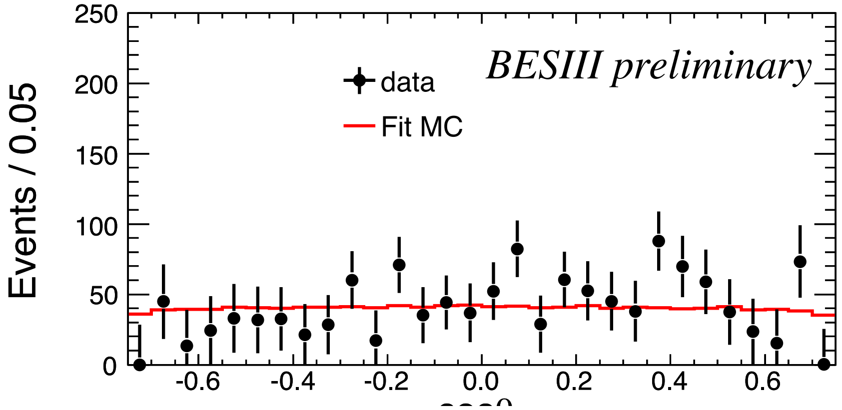
Quantity	χ_{c0}	χ_{c2}
$\mathcal{B}_1 \times \mathcal{B}_2 \times 10^5$	2.17±0.17±0.12	2.81±0.17±0.15
$\mathcal{B}_2 \times 10^4$	2.24±0.19±0.12±0.08	3.21±0.18±0.17±0.13
$\Gamma_{\gamma\gamma}$ (keV)	2.33±0.20±0.13±0.17	0.63±0.04±0.04±0.04
$\mathcal{R}$	0.271±0.029±0.013±0.027	

Results for R are consistent with the lowest order prediction!

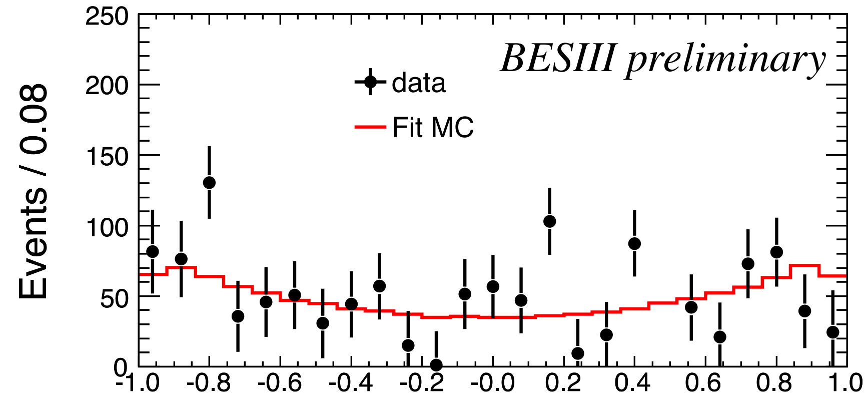
(but many calculations of higher order corrections deviate from this value...??...)

Study of $\chi_{c0,2} \to \gamma\gamma$ at BESIII *(preliminary)*

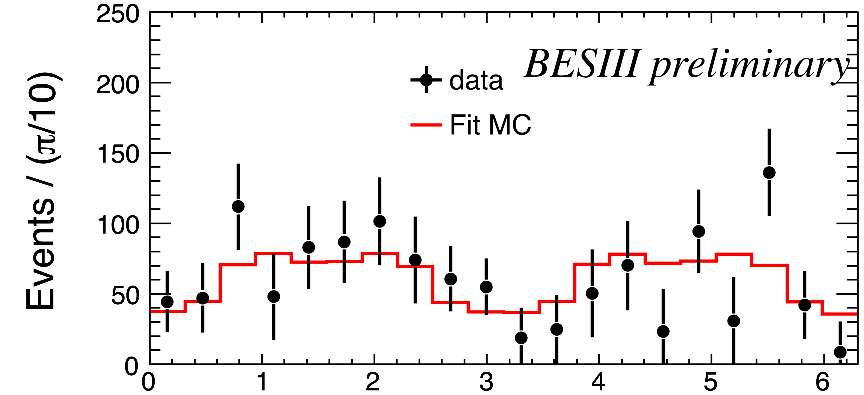
Also look at the two possible helicity states ($\lambda = 0, 2$) of the photons in $\chi_{c2} \to \gamma\gamma$:



$\cos\vartheta_1$ of transition γ



$\cos\vartheta_2$ of a γ from χ_{c2}



ϕ_2 of a γ from χ_{c2}

Fit angular distributions with fixed χ_{c2} helicity ratios ($x = A_1/A_0$ and $y = A_2/A_0$) and one free parameter ($f_{0/2}$, the fraction of $\lambda = 0$ / $\lambda = 2$):

$$
\begin{aligned}
W_2(\theta_1,\theta_2,\phi_2) \;=\; & f_{0/2}\Big[\frac{3}{2}y^2(1+\cos^2\theta_1)\sin^4\theta_2 + 3x^2\sin^2\theta_1\sin^2 2\theta_2 - \frac{3\sqrt{2}}{2}xy\sin 2\theta_1\sin^2\theta_2\sin 2\theta_2\cos\phi_2 \\
& + \sqrt{3}x\sin 2\theta_1\sin 2\theta_2(3\cos^2\theta_2-1)\cos\phi_2 + \sqrt{6}y\sin^2\theta_1\sin^2\theta_2(3\cos^2\theta_2-1)\cos 2\phi_2 + (1+\cos^2\theta_1)(3\cos^2\theta_2-1)^2\Big]_{\lambda=0} \\
& + \Big[\frac{1}{4}y^2(1+\cos^2\theta_1)(1+6\cos^2\theta_2+\cos^4\theta_2) + 2x^2\sin^2\theta_1(1+\cos^2\theta_2)\sin^2\theta_2 + \frac{\sqrt{2}}{4}xy\sin 2\theta_1\sin 2\theta_2(3+\cos^2\theta_2)\cos\phi_2 \\
& - \frac{\sqrt{3}}{2}x\sin 2\theta_1\sin^2\theta_2\sin 2\theta_2\cos\phi_2 + \frac{\sqrt{6}}{2}y\sin^2\theta_1(1-\cos^4\theta_2)\cos 2\phi_2 + \frac{3}{2}(1+\cos^2\theta_1)\sin^4\theta_2\Big]_{\lambda=2}, \qquad (5)
\end{aligned}
$$

Find $f_{0/2} = 0.00 \pm 0.02$ *(consistent with expectations, < 0.5%)* $\Rightarrow$ **dominantly $\lambda = 2$.**

Dynamics of $\chi_{cJ}(1P)$ Decays

ELECTROMAGNETIC

$$\chi_{c0,2} \rightarrow \gamma\gamma$$

Zeroth order is QED.

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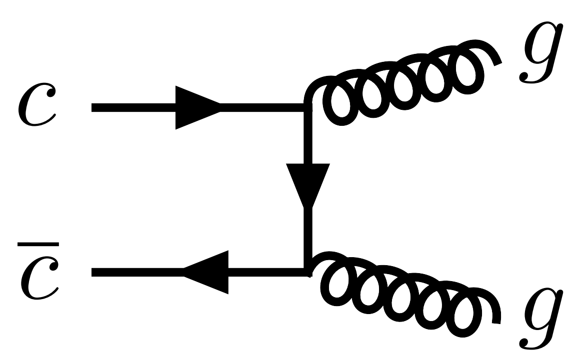
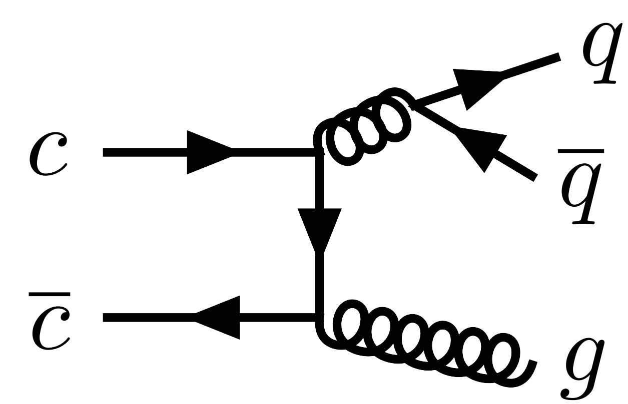
Also measure ratio of two helicity amplitudes for $\chi_{c2} \rightarrow \gamma\gamma$.

STRONG

$$\chi_{c0,2} \rightarrow gg \qquad \chi_{c1} \rightarrow q\bar{q}g$$





Start with perturbative QCD considerations *(but this picture appears to be too simple)*.

$$\chi_{cJ} \rightarrow q\bar{q}g$$

Use the "color octet model" to help explain large 2-body decay widths?

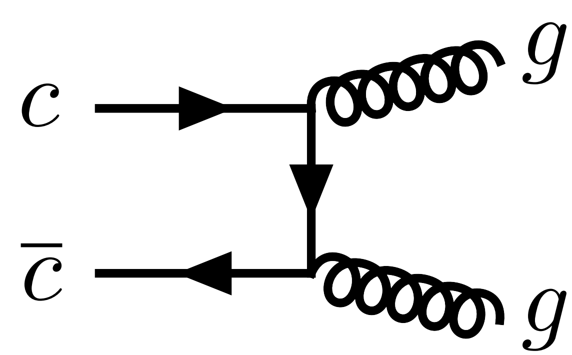
Study of $\chi_{cJ} \to \omega\omega, \phi\phi, \omega\phi$ at BESIII *(PRL 107, 092001 (2011))*

Three initial expectations:

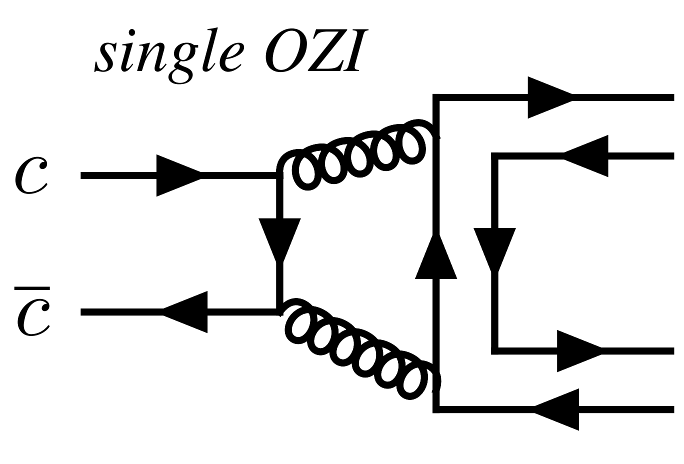
1. Perturbative QCD calculations suggest branching fractions much smaller than 10^{-3}.

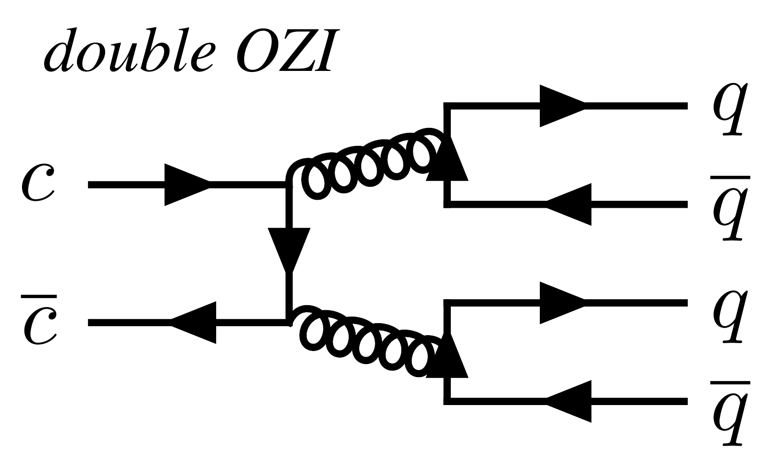
2. $\chi_{c1} \to VV$ ($\omega\omega, \phi\phi$) should be suppressed due to the "helicity selection rule":

$$\chi_{c0,2} \to gg$$



3. $\chi_{cJ} \to V'V$ ($\omega\phi$) should be suppressed since it is doubly OZI-violating:





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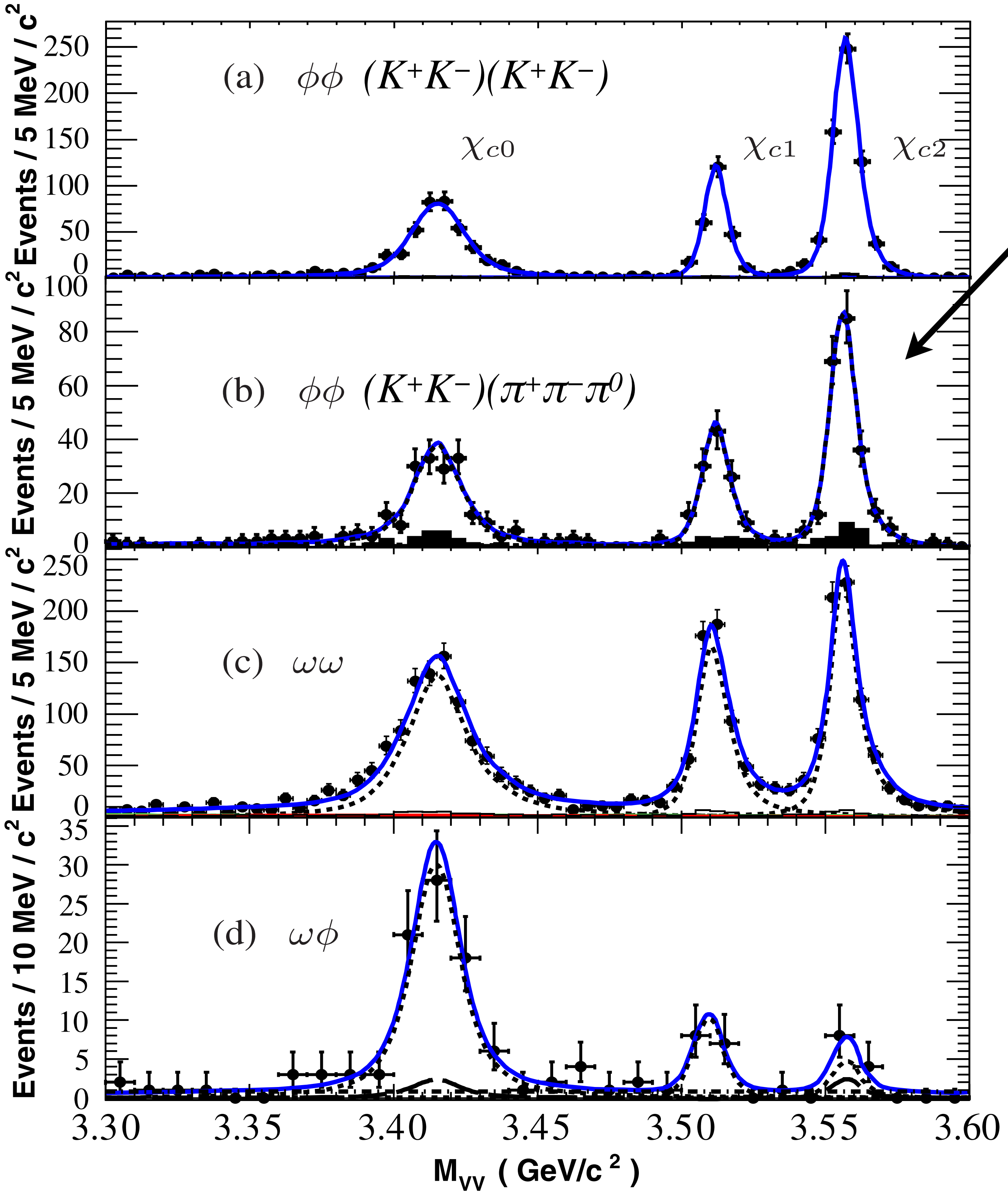

Fit signals while accounting for (small) peaking backgrounds from sidebands.

Find:

1. Branching fractions of $O(10^{-3})$ *(against perturbative QCD expectations)*.

2. Substantial rates for $\chi_{c1} \to VV$ *(against helicity expectations?)*.

3. Substantial rates for $\chi_{cJ} \to V'V$ $(\omega\phi)$ *(against double OZI expectations?)*.

Study of $\chi_{cJ} \to \omega\omega, \phi\phi, \omega\phi$ at BESIII *(PRL 107, 092001 (2011))*

Final numbers:

Mode	N_{net}	ϵ (%)	$\mathcal{B}(\times 10^{-4})$
$\chi_{c0} \to \phi\phi$	433 ± 23	22.4	$7.8 \pm 0.4 \pm 0.8$
$\chi_{c1} \to \phi\phi$	254 ± 17	26.4	$4.1 \pm 0.3 \pm 0.4$
$\chi_{c2} \to \phi\phi$	630 ± 26	26.1	$10.7 \pm 0.4 \pm 1.1$
$\to 2(K^+K^-)$			
$\chi_{c0} \to \phi\phi$	179 ± 16	12.8	$9.2 \pm 0.7 \pm 1.0$
$\chi_{c1} \to \phi\phi$	112 ± 12	15.3	$5.0 \pm 0.5 \pm 0.6$
$\chi_{c2} \to \phi\phi$	219 ± 16	14.9	$10.7 \pm 0.7 \pm 1.2$
$\to K^+K^-\pi^+\pi^-\pi^0$			
Combined:			
$\chi_{c0} \to \phi\phi$	···	···	$8.0 \pm 0.3 \pm 0.8$
$\chi_{c1} \to \phi\phi$	···	···	$4.4 \pm 0.3 \pm 0.5$
$\chi_{c2} \to \phi\phi$	···	···	$10.7 \pm 0.3 \pm 1.2$
$\chi_{c0} \to \omega\omega$	991 ± 38	13.1	$9.5 \pm 0.3 \pm 1.1$
$\chi_{c1} \to \omega\omega$	597 ± 29	13.2	$6.0 \pm 0.3 \pm 0.7$
$\chi_{c2} \to \omega\omega$	762 ± 31	11.9	$8.9 \pm 0.3 \pm 1.1$
$\to 2(\pi^+\pi^-\pi^0)$			
$\chi_{c0} \to \omega\phi$	76 ± 11	14.7	$1.2 \pm 0.1 \pm 0.2$
$\chi_{c1} \to \omega\phi$	15 ± 4	16.2	$0.22 \pm 0.06 \pm 0.02$
$\chi_{c2} \to \omega\phi$	<13	15.7	<0.2
$\to K^+K^-\pi^+\pi^-\pi^0$			

Find:

1. Branching fractions of $O(10^{-3})$ *(against perturbative QCD expectations)*.

2. Substantial rates for $\chi_{c1} \to VV$ *(against helicity expectations?)*.

3. Substantial rates for $\chi_{cJ} \to V'V$ ($\omega\phi$) *(against double OZI expectations?)*.

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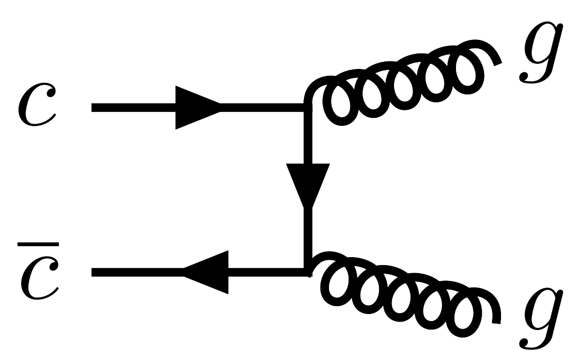

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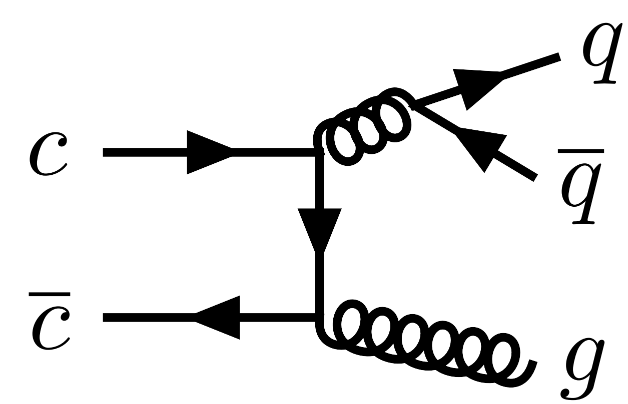

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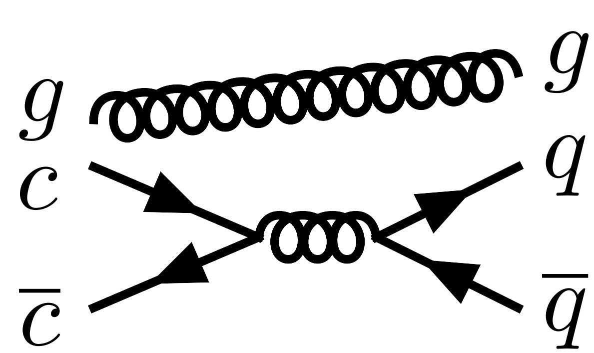

Use the “color octet model” to help explain large 2-body decay widths?

The “Color Octet Model” and χ_{cJ} di-Baryon Decays

Using only the color singlet model:

$$\mathcal{B}(\chi_{c0} \to p\bar{p}) = 0.29 \times 10^{-5}$$
$$\mathcal{B}(\chi_{c2} \to p\bar{p}) = 0.84 \times 10^{-5}$$

which are far lower than the experimental values.

Use color octet contributions to correct the discrepancy and predict other di-baryon rates:

predictions (COM) from EPJ. C 14, 643 (2000)

(in units of 10^{-5})

	Branching Fractions of χ_{c1}			**Branching Fractions of χ_{c2}**		
Decay Mode	COM	PDG	NEW from BESIII	COM	PDG	NEW from BESIII
$p\bar{p}$	6.5	7.3 ± 0.4	–	7.8	7.2 ± 0.4	–
$n\bar{n}$	6.5	–	–	7.8	–	–
$\Lambda\bar{\Lambda}$	3.9	11.8 ± 1.9	$12.2 \pm 1.1 \pm 1.1$	3.5	18.6 ± 2.7	$20.8 \pm 1.6 \pm 2.2$
$\Sigma^0\bar{\Sigma}^0$	3.3	< 4	$3.8 \pm 1.0 \pm 0.5$	5.0	< 8	$4.0 \pm 1.1 \pm 0.4$
$\Sigma^+\bar{\Sigma}^-$	3.3	< 6	$5.4 \pm 1.5 \pm 0.4$	5.0	< 7	$4.9 \pm 1.9 \pm 0.6$
$\Xi^0\bar{\Xi}^0$	2.5	< 6	–	3.7	< 11	–
$\Xi^-\bar{\Xi}^+$	2.5	8.4 ± 2.3	–	3.7	15.5 ± 3.5	–
$\Delta\bar{\Delta}$	3.9	–	–	6.3	–	–
$\Sigma^{+*}(1385)\bar{\Sigma}^{-*}(1385)$	2.1	–	$4.6 \pm 2.7 \pm 1.0$ (< 9.3)	3.6	–	$8.1 \pm 4.4 \pm 1.8$ (< 16)
$\Sigma^{-*}(1385)\bar{\Sigma}^{+*}(1385)$	2.1	–	$1.7 \pm 2.0 \pm 0.3$ (< 5.4)	3.6	–	$0.1 \pm 3.7 \pm 0.3$ (< 7.2)
$\Xi^*\bar{\Xi}^*$	1.1	–	–	2.1	–	–
$\Lambda(1520)\bar{\Lambda}(1520)$	–	–	< 8.6	–	–	51 ± 13

(Note that χ_{c0} decays are suppressed by the “helicity selection rule.”)

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$n\overline{n}$	6.5	–	–	7.8	–	–
$\Lambda\overline{\Lambda}$	3.9	11.8 ± 1.9	$12.2 \pm 1.1 \pm 1.1$	3.5	18.6 ± 2.7	$20.8 \pm 1.6 \pm 2.2$
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$\Sigma^+\overline{\Sigma}^-$	3.3	< 6	$5.4 \pm 1.5 \pm 0.4$	5.0	< 7	$4.9 \pm 1.9 \pm 0.6$
$\Xi^0\overline{\Xi}^0$	2.5	< 6	–	3.7	< 11	–
$\Xi^-\overline{\Xi}^+$	2.5	8.4 ± 2.3	–	3.7	15.5 ± 3.5	–
$\Delta\overline{\Delta}$	3.9	–	–	6.3	–	–
$\Sigma^{+*}(1385)\overline{\Sigma}^{-*}(1385)$	2.1	–	$4.6 \pm 2.7 \pm 1.0$ (< 9.3)	3.6	–	$8.1 \pm 4.4 \pm 1.8$ (< 16)
$\Sigma^{-*}(1385)\overline{\Sigma}^{+*}(1385)$	2.1	–	$1.7 \pm 2.0 \pm 0.3$ (< 5.4)	3.6	–	$0.1 \pm 3.7 \pm 0.3$ (< 7.2)
$\Xi^*\overline{\Xi}^*$	1.1	–	–	2.1	–	–
$\Lambda(1520)\overline{\Lambda}(1520)$	–	–	< 8.6	–	–	51 ± 13

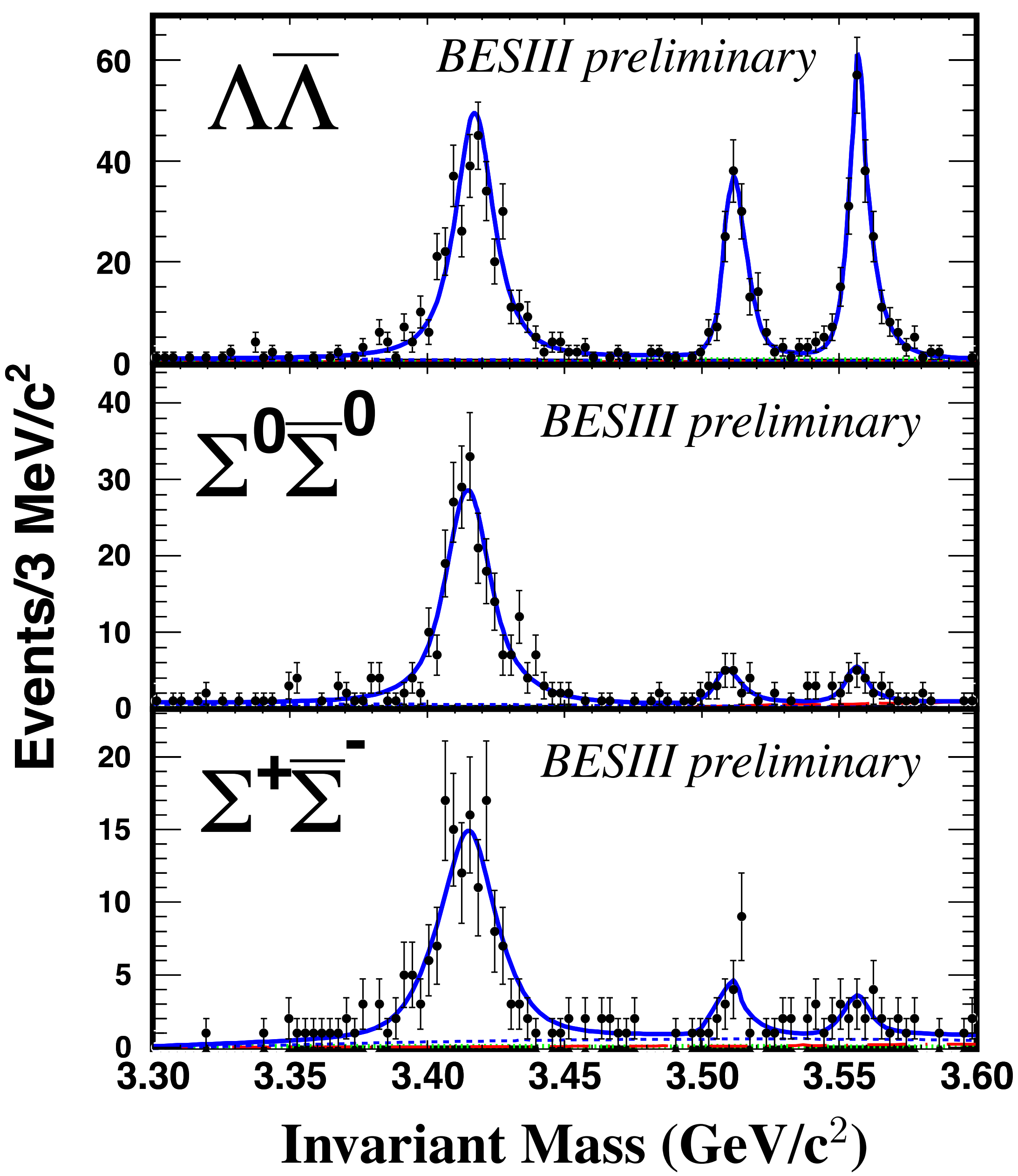
(Note that χ_{c0} decays are suppressed by the "helicity selection rule.")

1. χ_{cJ} di-Baryon Decays at BESIII *(preliminary)*

Select clean samples of χ_{cJ} decays using:

$\Lambda \to p\pi^-$ $\Sigma^0 \to \gamma\Lambda$ $\Sigma^+ \to p\pi^0$

$\bar{\Lambda} \to \bar{p}\pi^+$ $\bar{\Sigma}^0 \to \gamma\bar{\Lambda}$ $\bar{\Sigma}^- \to \bar{p}\pi^0$



Results *(preliminary)* *(in units of 10^{-5})*

Mode		χ_{c0}	χ_{c1}	χ_{c2}
$\Lambda\bar{\Lambda}$	This work	33.3±2.0±2.6	12.2±1.1±1.1	20.8±1.6±2.2
	PDG	33.0±4.0	11.8±1.9	18.6±2.7
	CLEO [18]	33.8± 3.6±2.2±1.7	11.6±1.8±0.7±0.7	17.0±2.2±1.1±1.1
	Theory [4, 19]	11.9∼15.1	3.9	3.5
$\Sigma^0\bar{\Sigma}^0$	This work	47.8±3.4±3.8	3.8±1.0±0.5 (< 6.1)	4.0±1.1±0.4 (< 6.4)
	PDG	42.0±7.0	<4.0	<8.0
	CLEO [18]	44.1±5.6±4.2±2.2	<4.4	<7.5
	Theory [4]	–	3.3	5.0
$\Sigma^+\bar{\Sigma}^-$	This work	45.4±4.2±2.5	5.4±1.5±0.4 (< 8.5)	4.9±1.9±0.6 (<8.6)
	PDG	31.0±7.0	<6.0	<7.0
	CLEO [18]	32.5±5.7±4.0±1.7	<6.5	<6.7
	Theory [4]	–	3.3	5.0

90% C.L.

$\mathcal{B}(\chi_{c1,2} \to \Lambda\bar{\Lambda})$: still larger than COM predictions

$\mathcal{B}(\chi_{c1,2} \to \Sigma\bar{\Sigma})$: UL's agree with COM predictions

$\mathcal{B}(\chi_{c0} \to \Lambda\bar{\Lambda}, \Sigma\bar{\Sigma})$: large violation of the helicity selection rule

The "Color Octet Model" and χ_{cJ} di-Baryon Decays

Using only the color singlet model:

$$\mathcal{B}(\chi_{c0} \to p\bar{p}) = 0.29 \times 10^{-5}$$
$$\mathcal{B}(\chi_{c2} \to p\bar{p}) = 0.84 \times 10^{-5}$$

which are far lower than the experimental values.

Use color octet contributions to correct the discrepancy and predict other di-baryon rates:

predictions (COM) from EPJ. C 14, 643 (2000)

(in units of 10^{-5})

	Branching Fractions of χ_{c1}			**Branching Fractions of χ_{c2}**		
Decay Mode	COM	PDG	NEW from BESIII	COM	PDG	NEW from BESIII
$p\bar{p}$	6.5	7.3 ± 0.4	–	7.8	7.2 ± 0.4	–
$n\bar{n}$	6.5	–	–	7.8	–	–
$\Lambda\bar{\Lambda}$	3.9	11.8 ± 1.9	$12.2 \pm 1.1 \pm 1.1$	3.5	18.6 ± 2.7	$20.8 \pm 1.6 \pm 2.2$
$\Sigma^0\bar{\Sigma}^0$	3.3	< 4	$3.8 \pm 1.0 \pm 0.5$	5.0	< 8	$4.0 \pm 1.1 \pm 0.4$
$\Sigma^+\bar{\Sigma}^-$	3.3	< 6	$5.4 \pm 1.5 \pm 0.4$	5.0	< 7	$4.9 \pm 1.9 \pm 0.6$
$\Xi^0\bar{\Xi}^0$	2.5	< 6	–	3.7	< 11	–
$\Xi^-\bar{\Xi}^+$	2.5	8.4 ± 2.3	–	3.7	15.5 ± 3.5	–
$\Delta\bar{\Delta}$	3.9	–	–	6.3	–	–
$\Sigma^{+*}(1385)\bar{\Sigma}^{-*}(1385)$	2.1	–	$4.6 \pm 2.7 \pm 1.0$ (< 9.3)	3.6	–	$8.1 \pm 4.4 \pm 1.8$ (< 16)
$\Sigma^{-*}(1385)\bar{\Sigma}^{+*}(1385)$	2.1	–	$1.7 \pm 2.0 \pm 0.3$ (< 5.4)	3.6	–	$0.1 \pm 3.7 \pm 0.3$ (< 7.2)
$\Xi^*\bar{\Xi}^*$	1.1	–	–	2.1	–	–
$\Lambda(1520)\bar{\Lambda}(1520)$	–	–	< 8.6	–	–	51 ± 13

(Note that χ_{c0} decays are suppressed by the "helicity selection rule.")

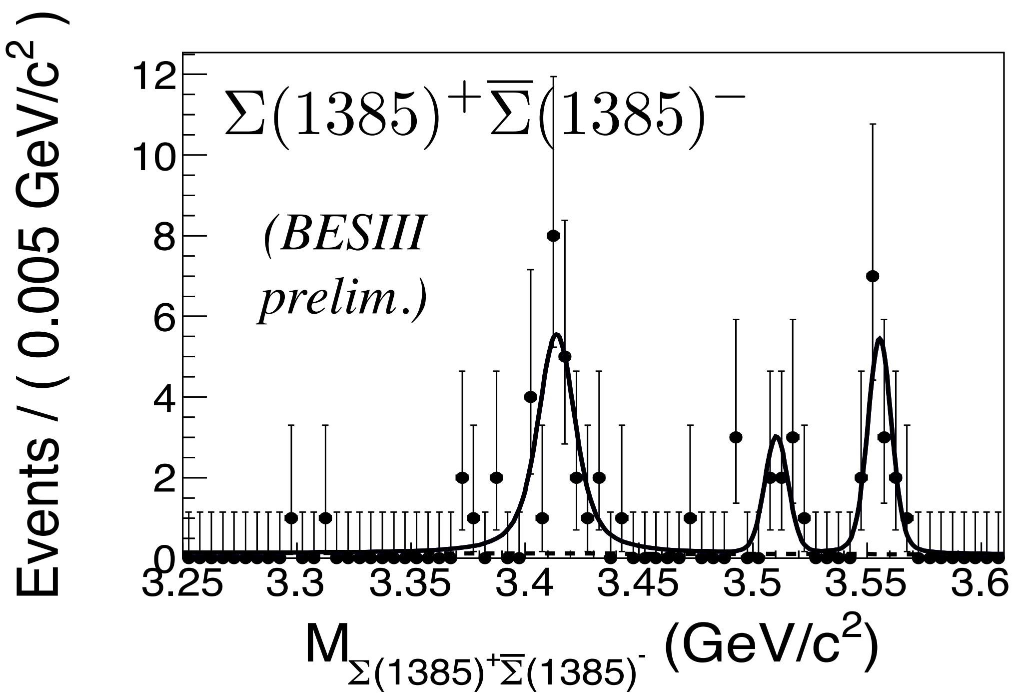
2. χ_{cJ} di-Baryon Decays at BESIII *(preliminary)*

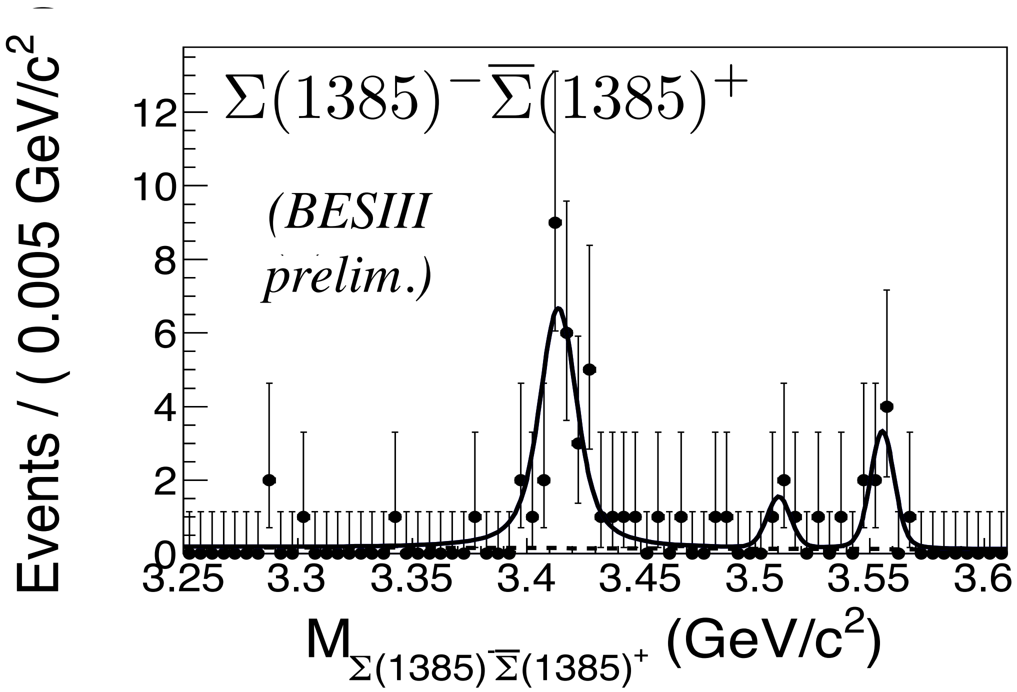
Search for:

$$\chi_{cJ} \to \Sigma(1385)^{\pm}\overline{\Sigma}(1385)^{\mp}$$

through:

$$\chi_{cJ} \to \pi^+\pi^-\Lambda\overline{\Lambda}$$





Divide the four-body phase space into five regions, study the cross-feed between regions using MC, then unfold the five different processes.

Results *(preliminary)*: *(UL's at 90% C.L.)* *(in units of 10^{-5})*

	χ_{cJ} decay mode	χ_{c0}		χ_{c1}		χ_{c2}	
		$\mathcal{B}$	UL	$\mathcal{B}$	UL	$\mathcal{B}$	UL
1	$\chi_{cJ} \to \Lambda\bar{\Lambda}\pi^+\pi^-$ (w/o $\Sigma(1385)$)	29.9±13.6±7.4	< 57	27.4±8.5±2.7		75.9±14.9±6.9	
2	$\chi_{cJ} \to \Sigma(1385)^+\bar{\Lambda}\pi^- + c.c.$	35.4±14.7±7.0		1.4±7.3±9.0	< 12	23.9±13.6±4.1	< 43
3	$\chi_{cJ} \to \Sigma(1385)^-\bar{\Lambda}\pi^+ + c.c.$	25.0±14.3±5.9	< 45	0.0±7.2±0.0	< 11	38.8±14.4±4.3	
4	$\chi_{cJ} \to \Sigma(1385)^+\bar{\Sigma}(1385)^-$	17.0±6.0±2.0		4.6±2.7±1.0	< 9.3	8.1±4.4±1.8	< 16
5	$\chi_{cJ} \to \Sigma(1385)^-\bar{\Sigma}(1385)^+$	24.0±6.3±3.1		1.7±2.0±0.3	< 5.4	0.1±3.7±0.3	< 7.2
	$\chi_{cJ} \to \Lambda\bar{\Lambda}\pi^+\pi^-$(total)	129±7±12		32.5±3.6±4.1		163±9±19	

$\mathcal{B}(\chi_{c1,2} \to \Sigma(1385)\overline{\Sigma}(1385))$: UL's agree with COM

$\mathcal{B}(\chi_{c0} \to \Sigma(1385)\overline{\Sigma}(1385))$: large violation of helicity selection rule

The "Color Octet Model" and χ_{cJ} di-Baryon Decays

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which are far lower than the experimental values.

Use color octet contributions to correct the discrepancy and predict other di-baryon rates:

(in units of 10^{-5})

	Branching Fractions of χ_{c1}			**Branching Fractions of χ_{c2}**		
Decay Mode	COM	PDG	NEW from BESIII	COM	PDG	NEW from BESIII
$p\bar{p}$	6.5	7.3 ± 0.4	–	7.8	7.2 ± 0.4	–
$n\bar{n}$	6.5	–	–	7.8	–	–
$\Lambda\bar{\Lambda}$	3.9	11.8 ± 1.9	$12.2 \pm 1.1 \pm 1.1$	3.5	18.6 ± 2.7	$20.8 \pm 1.6 \pm 2.2$
$\Sigma^0\bar{\Sigma}^0$	3.3	< 4	$3.8 \pm 1.0 \pm 0.5$	5.0	< 8	$4.0 \pm 1.1 \pm 0.4$
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$\Delta\bar{\Delta}$	3.9	–	–	6.3	–	–
$\Sigma^{+*}(1385)\bar{\Sigma}^{-*}(1385)$	2.1	–	$4.6 \pm 2.7 \pm 1.0$ (< 9.3)	3.6	–	$8.1 \pm 4.4 \pm 1.8$ (< 16)
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$\Xi^*\bar{\Xi}^*$	1.1	–	–	2.1	–	–
$\Lambda(1520)\bar{\Lambda}(1520)$	–	–	< 8.6	–	–	51 ± 13

predictions (COM) from EPJ. C 14, 643 (2000)

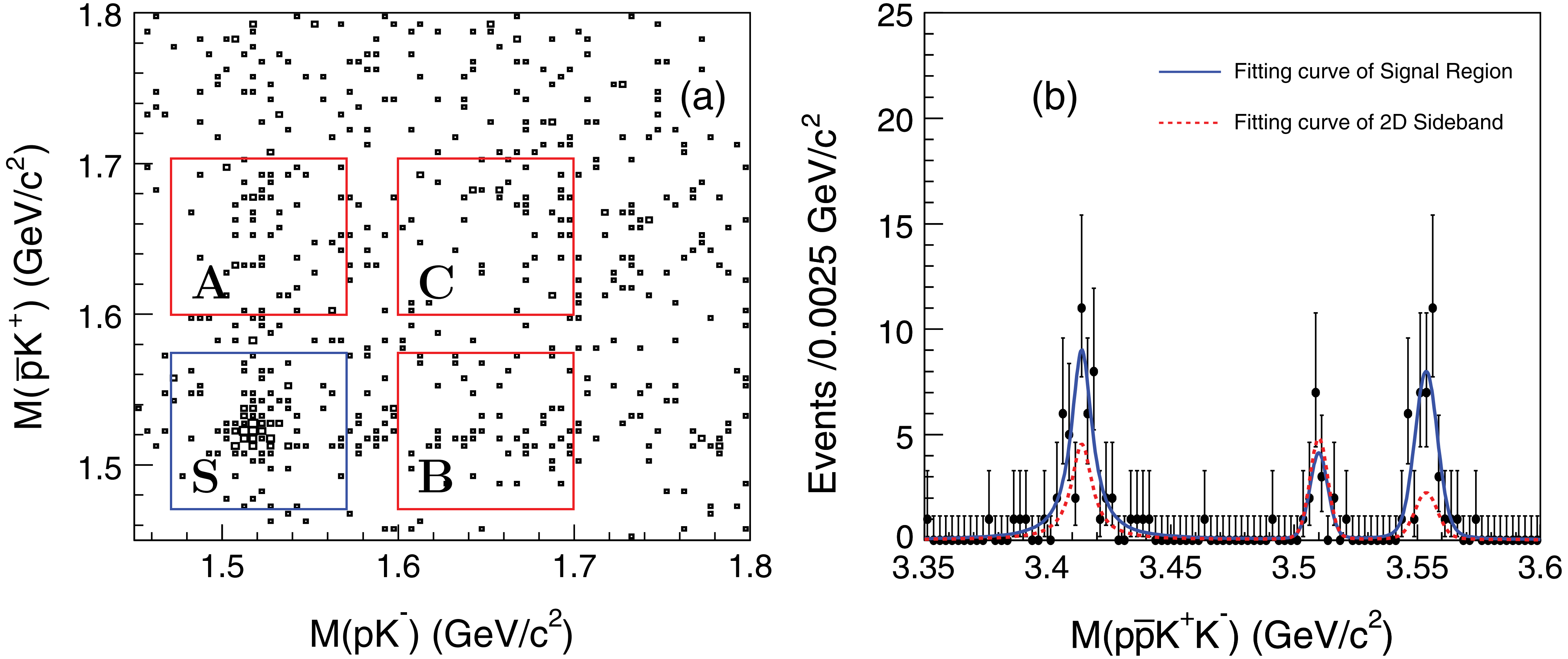
(Note that χ_{c0} decays are suppressed by the "helicity selection rule.")

3. χ_{cJ} di-Baryon Decays at BESIII *(PRD 83, 112009 (2011))*

Search for $\chi_{cJ} \to \Lambda(1520)\overline{\Lambda}(1520)$ through $\chi_{cJ} \to K^+K^-p\bar{p}$.

Isolate $\Lambda(1520) \to pK^-$ and c.c.:

Perform a simultaneous fit to the signal and sidebands:



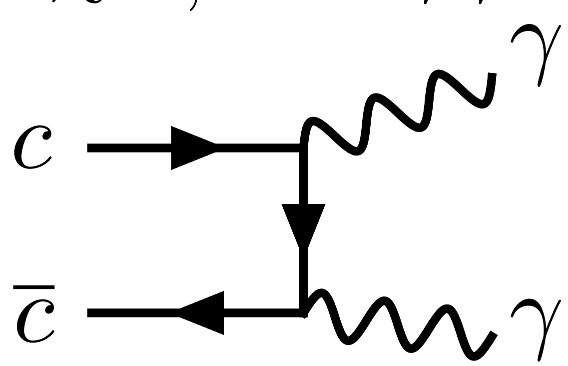
	χ_{c0}	χ_{c1}	χ_{c2}
$\mathcal{B}(\chi_{cJ} \to p\bar{p}K^+K^-)$ (10^{-4})	$1.24 \pm 0.20 \pm 0.18$	$1.35 \pm 0.15 \pm 0.19$	$2.08 \pm 0.19 \pm 0.30$
$\mathcal{B}(\chi_{cJ} \to \bar{p}K^+\Lambda(1520)$ + c.c.) (10^{-4})	$3.00 \pm 0.58 \pm 0.50$	$1.81 \pm 0.38 \pm 0.28$	$3.06 \pm 0.50 \pm 0.54$
$\mathcal{B}(\chi_{cJ} \to \Lambda(1520)\bar{\Lambda}(1520))$ (10^{-4})	$3.18 \pm 1.11 \pm 0.53$	<1.00 *(UL's at*	$5.05 \pm 1.29 \pm 0.93$
$\mathcal{B}(\chi_{cJ} \to p\bar{p}\phi)$ (10^{-5})	$6.12 \pm 1.18 \pm 0.86$	<1.82 *90% C.L.)*	$3.04 \pm 0.85 \pm 0.43$

$\mathcal{B}(\chi_{cJ} \to \Lambda(1520)\overline{\Lambda}(1520))$ rates are perhaps surprisingly large, comparable to $\mathcal{B}(\chi_{cJ} \to \Lambda\overline{\Lambda})$

Importance of the $\chi_{cJ}(1P)$ States

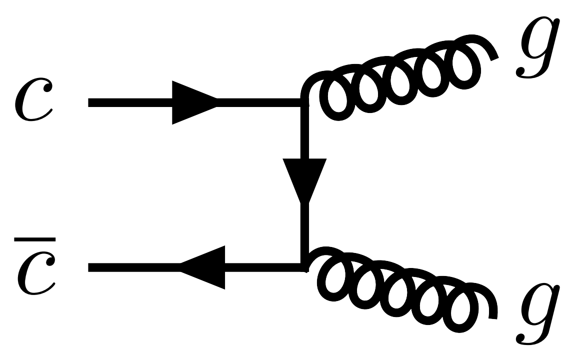
- $\chi_{cJ}(1P)$ decays can probe strong force dynamics, for example, through:

$$\chi_{c0,2} \to \gamma\gamma$$



corrections to EM processes

$$\chi_{c0,2} \to gg$$



perturbative QCD considerations

- Exclusive $\chi_{cJ}(1P)$ decays are also a source of light quark states, useful for both meson and baryon spectroscopy -- a rich set of final states allows one to isolate quantum numbers.

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Amplitude Analysis of $\chi_{c1} \to \eta^{(\prime)}\pi^+\pi^-$ at CLEO-c

(PRD 83, 112009 (2011))

***Search for states with exotic J^{PC}** (i.e. J^{PC} forbidden in the quark model).*

Possible substructure in $\chi_{c1} \to \eta^{(\prime)}\pi^+\pi^-$

χ_{c1} Decay Mode	L	Isobar J^{PC}
$a_0\pi;\ a_0 \to \eta^{(\prime)}\pi$	P	0^{++}
$\pi_1\pi;\ \pi_1 \to \eta^{(\prime)}\pi$	S, D	1^{-+}
$a_2\pi;\ a_2 \to \eta^{(\prime)}\pi$	P, F	2^{++}
$a_4\pi;\ a_4 \to \eta^{(\prime)}\pi$	F, H	4^{++}
$f_0\eta^{(\prime)};\ f_0 \to \pi\pi$	P	0^{++}
$f_2\eta^{(\prime)};\ f_2 \to \pi\pi$	P, F	2^{++}
$f_4\eta^{(\prime)};\ f_4 \to \pi\pi$	F, H	4^{++}

Advantages of these χ_{c1} decays:

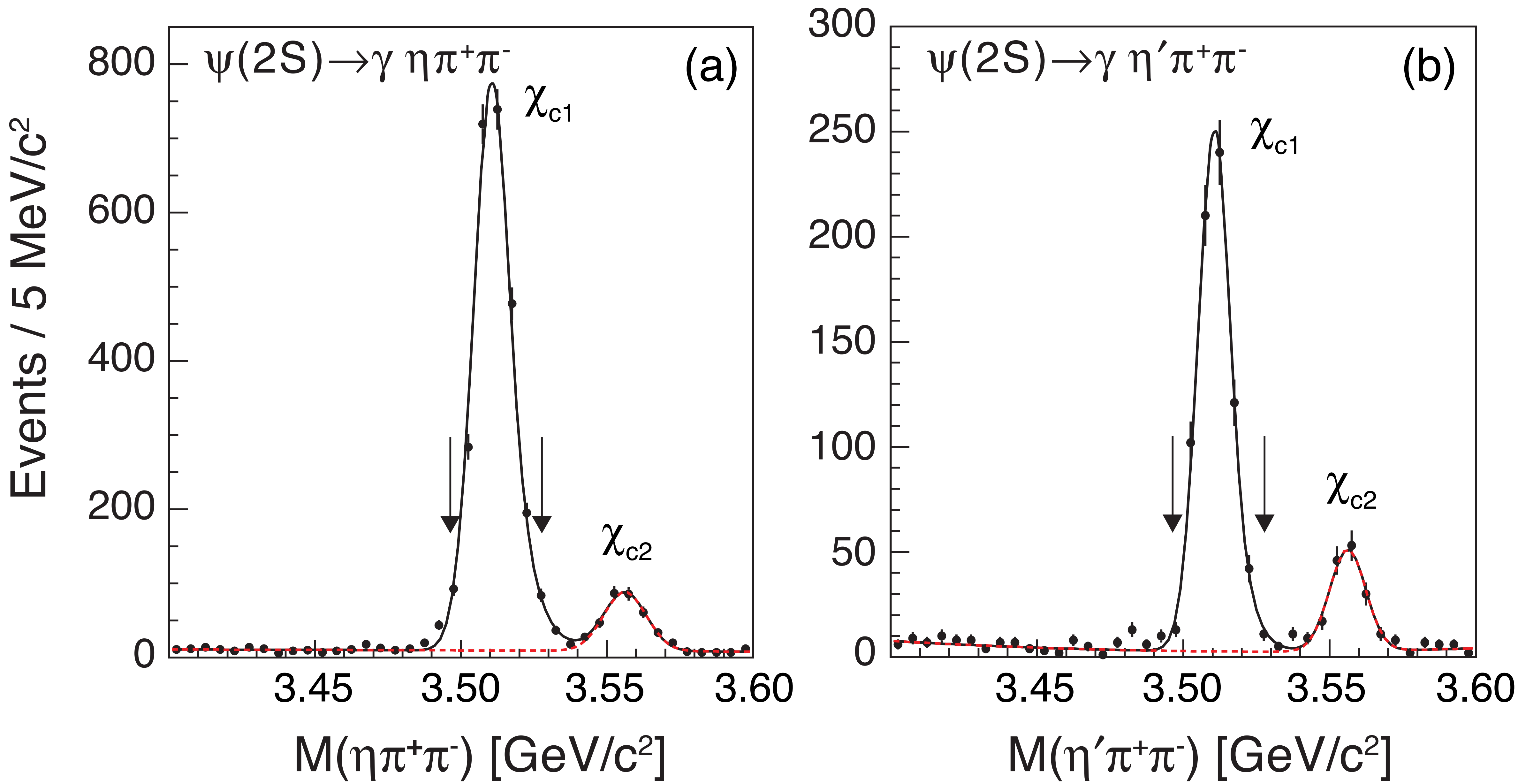
$\Rightarrow$ the only χ_{c1} S-wave decay is through $\pi_1\pi$ *(the π_1 has exotic $J^{PC} = 1^{-+}$)*

$\Rightarrow$ the "$\pi_1(1600)$" has been observed by BNL's E852 in $\pi^- p \to \eta'\pi^- p$ *(PRL 86, 3977 (2001))*

Amplitude Analysis of $\chi_{c1} \to \eta^{(\prime)}\pi^+\pi^-$ at CLEO-c

(PRD 83, 112009 (2011))

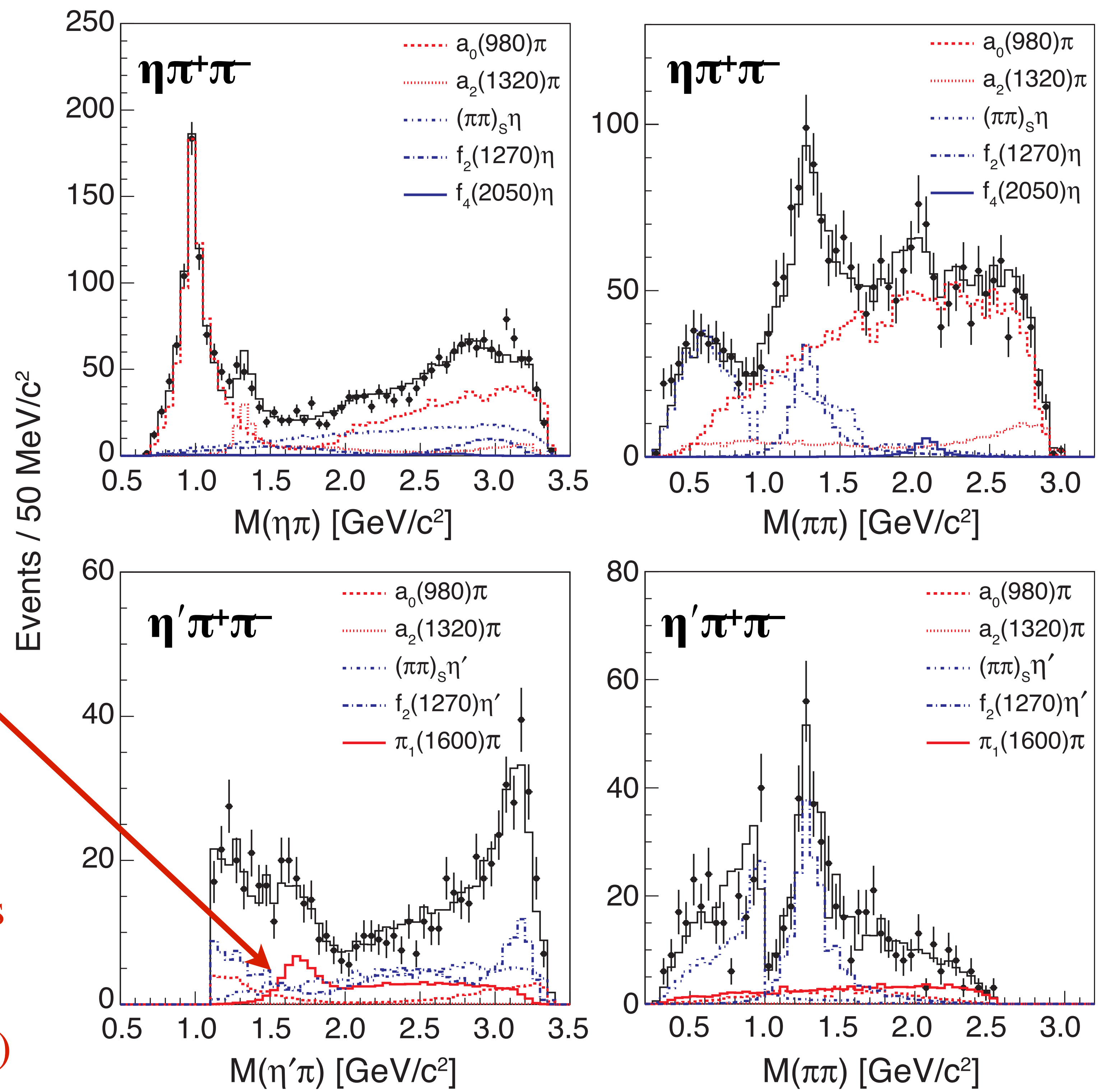
Select clean samples of $\chi_{c1} \to \eta\pi^+\pi^-$ and $\chi_{c1} \to \eta'\pi^+\pi^-$:



Amplitude Analysis of $\chi_{c1} \to \eta^{(\prime)}\pi^+\pi^-$ at CLEO-c

(PRD 83, 112009 (2011))

Perform an amplitude analysis of the $\eta\pi^+\pi^-$ and $\eta'\pi^+\pi^-$ systems:



first evidence for an exotic J^{PC} state in charmonium decays:

- 1^{-+} has significance $>4.7\sigma$ over all other J^{PC} and all other hypotheses
- mass and width consistent with $\pi_1(1600)$

Amplitude Analysis of $\chi_{c1} \to \eta^{(\prime)}\pi^+\pi^-$ at CLEO-c

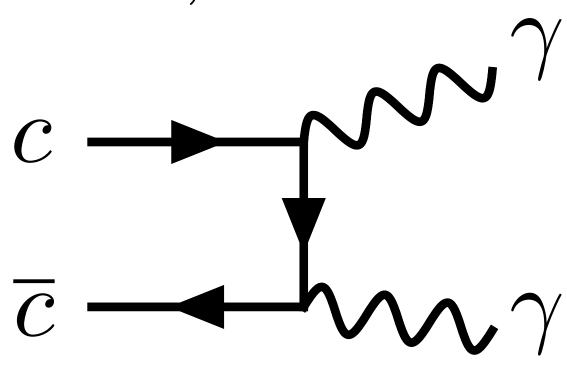
(PRD 83, 112009 (2011))

χ_{c1} Decay Mode	$\mathcal{F}$ [%]	$\mathcal{B}(\chi_{c1} \to \eta^{(\prime)}\pi^+\pi^-) \times \mathcal{F}$ [10^{-3}]	N_σ
$\eta\pi^+\pi^-$	⋯	4.97 ± 0.08 ± 0.21 ± 0.22	⋯
$a_0(980)\pi$	66.2 ± 1.2 ± 1.1	3.29 ± 0.09 ± 0.14 ± 0.15	>10
$a_2(1320)\pi$	9.8 ± 0.8 ± 1.0	0.49 ± 0.04 ± 0.05 ± 0.02	9.7
$(\pi^+\pi^-)_S\eta$	22.5 ± 1.3 ± 2.5	1.12 ± 0.06 ± 0.13 ± 0.05	>10
$S^0_{\pi\pi}\eta$	12.1 ± 1.7 ± 5.6	0.60 ± 0.08 ± 0.28 ± 0.03	>10
$S^1_{\pi\pi}\eta$	3.4 ± 0.9 ± 1.5	0.17 ± 0.05 ± 0.07 ± 0.01	6.0
$S_{KK}\eta$	3.1 ± 0.6 ± 0.4	0.15 ± 0.03 ± 0.02 ± 0.01	9.4
$f_2(1270)\eta$	7.4 ± 0.8 ± 0.6	0.37 ± 0.04 ± 0.04 ± 0.02	>10
$f_4(2050)\eta$	1.0 ± 0.3 ± 0.3	0.05 ± 0.01 ± 0.02 ± 0.00	5.2
$^*\pi_1(1600)\pi$	⋯	<0.031	0.7
$\eta'\pi^+\pi^-$	⋯	1.90 ± 0.07 ± 0.08 ± 0.09	⋯
$a_0(980)\pi$	11.0 ± 2.3 ± 1.8	0.21 ± 0.04 ± 0.04 ± 0.01	8.4
$a_2(1320)\pi$	0.4 ± 0.5 ± 0.6	<0.031	1.4
$(\pi^+\pi^-)_S\eta$	21.6 ± 2.7 ± 1.2	0.41 ± 0.05 ± 0.03 ± 0.02	10.2
$S^0_{\pi\pi}\eta'$	7.0 ± 2.2 ± 2.3	0.13 ± 0.04 ± 0.04 ± 0.01	6.6
$S_{KK}\eta'$	8.4 ± 1.5 ± 1.3	0.16 ± 0.03 ± 0.02 ± 0.01	7.5
$f_2(1270)\eta'$	27.0 ± 2.9 ± 1.7	0.51 ± 0.06 ± 0.04 ± 0.03	>10
$^*f_4(2050)\eta'$	⋯	<0.010	0.4
$\pi_1(1600)\pi$	15.1 ± 2.7 ± 3.2	0.29 ± 0.05 ± 0.06 ± 0.01	7.2

Summary

- χ_{cJ}(1P) decays can probe strong force dynamics, for example, through:

$\chi_{c0,2} \to \gamma\gamma$



corrections to EM processes

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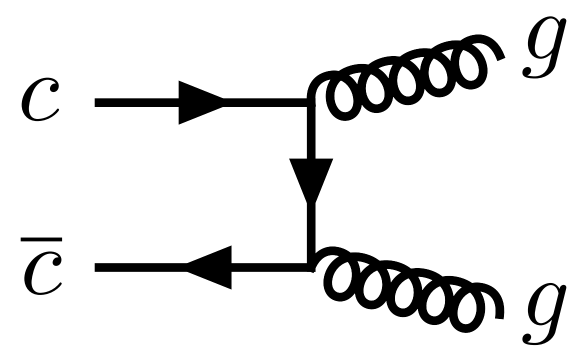

perturbative QCD considerations

- Exclusive χ_{cJ}(1P) decays are also a source of light quark states, useful for both meson and baryon spectroscopy -- a rich set of final states allows one to isolate quantum numbers.

Summary

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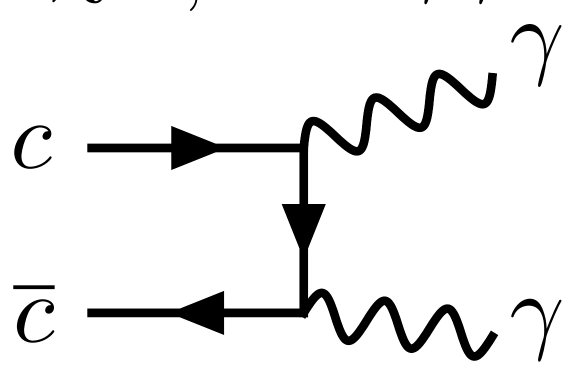
BESIII measurement of B($\chi_{c0,2} \to \gamma\gamma$)
(R consistent with lowest order expectations)

$$\chi_{c0,2} \to \gamma\gamma$$



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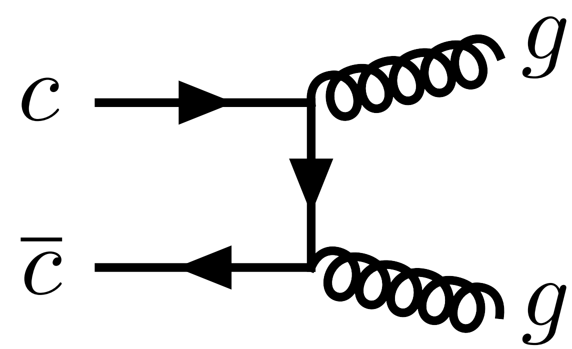

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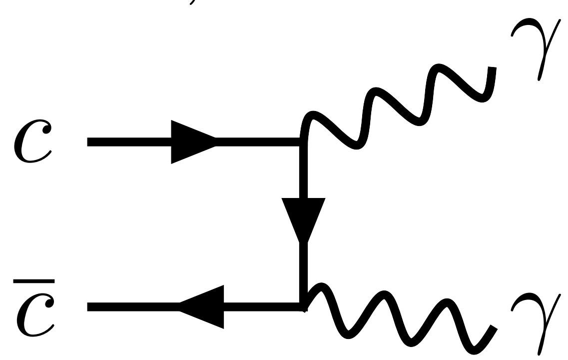

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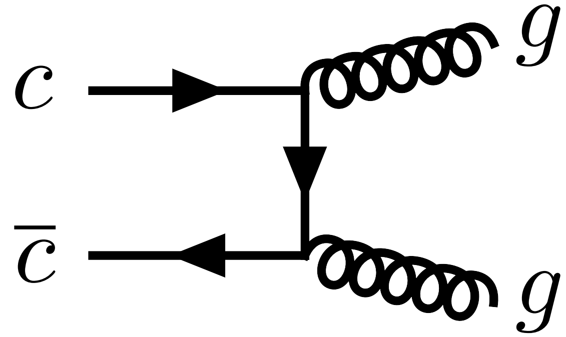

perturbative QCD considerations

BESIII measurement of $B(\chi_{cJ} \rightarrow VV)$ *(large rates, χ_{c1} decays, double OZI violation)*

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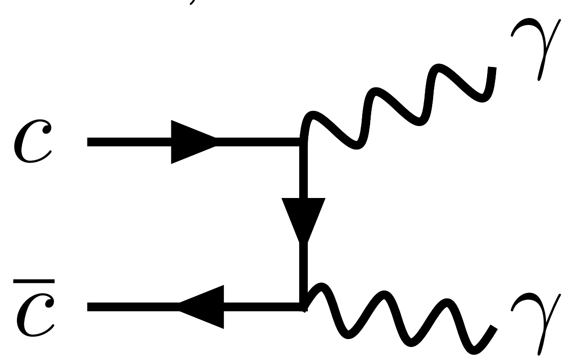

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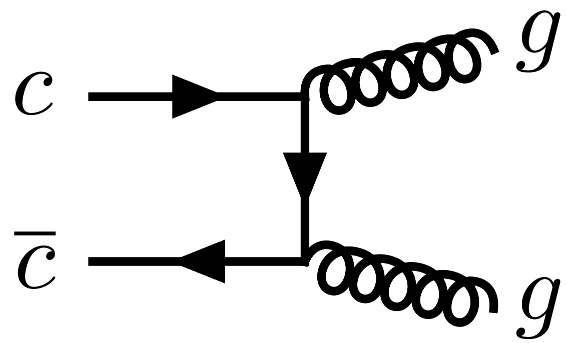

perturbative QCD considerations

BESIII measurement of B($\chi_{cJ} \rightarrow$ VV) *(large rates, χ_{c1} decays, double OZI violation)*

BESIII measurement of B($\chi_{cJ} \rightarrow B\bar{B}$) *(mixed reviews for COM, large violation of helicity selection rule)*

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- χ_{cJ}(1P) decays can probe strong force dynamics, for example, through:

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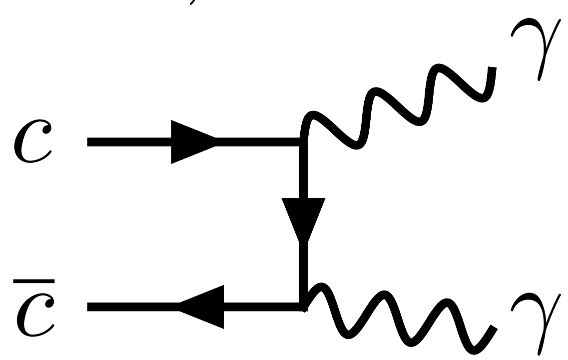

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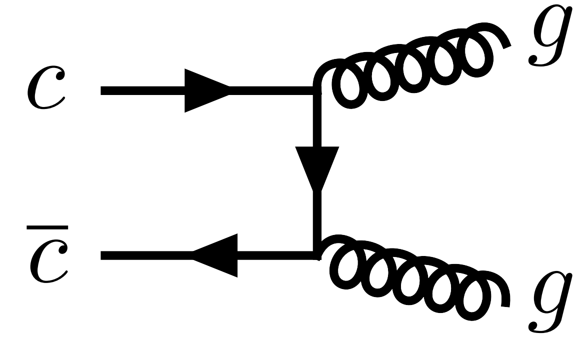

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CLEO-c observation of exotic J^{PC} in $\chi_{c1} \to \eta'\pi^+\pi^-$

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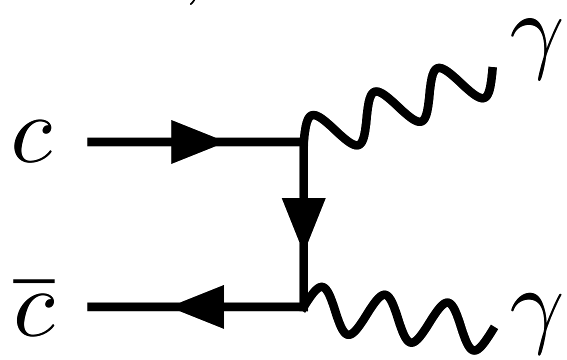

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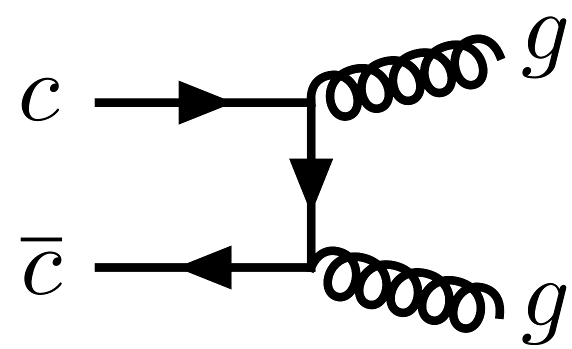

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BESIII measurement of $B(\chi_{cJ} \to B\overline{B})$ *(mixed reviews for COM, large violation of helicity selection rule)*

BESIII now has ~3× more $\psi(2S)$, therefore ~3× more χ_{cJ} decays... Expect more results soon!