Electromagnetic Transitions of Doubly Charmed Baryons of $J^P=3/2^+$ in Light-cone Sum Rules

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E-L Cui, etc., PRD 97, 034018 (2018)

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- **Introduction**
- Light-cone Sum Rules
- Numerical Analyses
- Summary and Discussions

Introduction

- The doubly heavy baryons provide an ideal platform for investigating the heavy quark symmetry, and have been studied both experimentally and theoretically.

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- In 2002 the SELEX reported the evidence of $\Xi_{cc}^{+}(3519)$ in the $\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+}$ process. However, searches from the FOCUS, BABAR and Belle did not confirm this state.

$$M_{\Xi_{cc}^{+}} = 3519 \pm 1 MeV$$

Introduction

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$$M_{\Xi_{cc}^{+}} = 3519 \pm 1 MeV$$

- Theoretically, various methods and models have been applied to study the doubly charmed baryons.

SELEX Collaboration, PRL 89, 112001 (2002)

Introduction

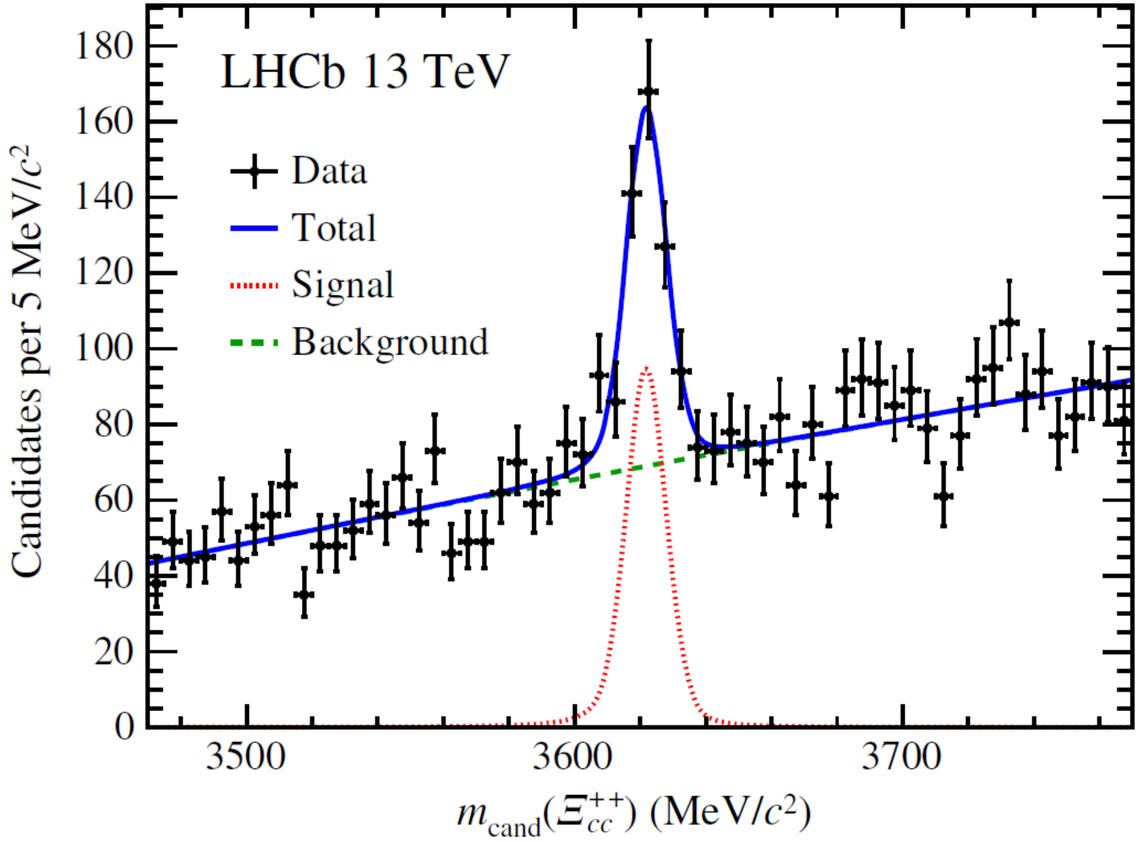
Table 19. Masses of the doubly charmed baryon $\Xi_{cc}(ccq)$ with $J^P = 1/2^+$ in various models.

Method	Reference	Mass (MeV)
Quark models	[54]	3550–3760
	[71]	3660
	[73]	3620
	[710]	3646 ± 12
	[557]	3678
	[720]	3627 ± 12
Potential models	[705]	3613
	[706]	3630
	[713]	3480 ± 50
	[716]	3643
Bag models	[705]	3516
	[715]	3520
Feynman–Hellmann theorem	[711]	3660 ± 70
Heavy quark effective theory	[566]	3610
Chiral perturbation theory	[719]	3665^{+93}_{-97}
Regge phenomenology	[455]	3520^{+41}_{-40}
Nonperturbative string	[714]	3690
Faddeev equations	[712]	3607
	[709]	3527
Bethe–Salpeter equations	[585]	3642
	[718]	3540 ± 20
QCD sum rules	[721]	4260 ± 190
	[724]	3570 ± 140
Lattice QCD	[578]	$3608(15)(^{13}_{35})$
	[593]	3549(13)(19)(92)
	[594]	$3665 \pm 17 \pm 14^{+0}_{-78}$
	[725]	3603(15)(16)
	[598]	3595(39)(20)(6)
	[726]	3568(14)(19)(1)
	[727]	3610(90)(120)
	[600]	3610(23)(22)

A review of open charm and open bottom systems, RPP 80 (2017) 076201

Introduction

- Recently, the LHCb collaboration reported the doubly charmed baryon $\Xi_{cc}^{++}(3621)$ in the mass spectrum of $\Lambda_c^+ K^- \pi^+ \pi^+$.



$$M_{\Xi_{cc}^{++}} = 3621.40 \pm 0.72 \pm 0.27 \pm 0.14 \text{MeV}$$

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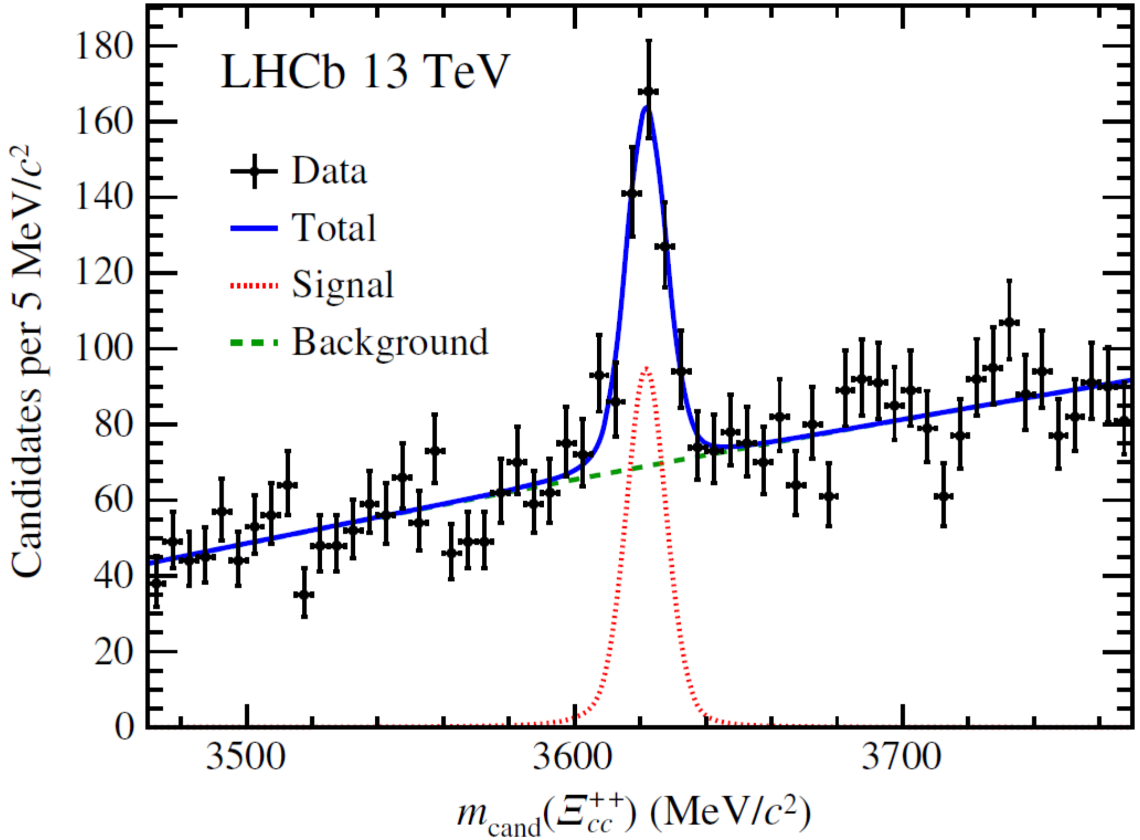

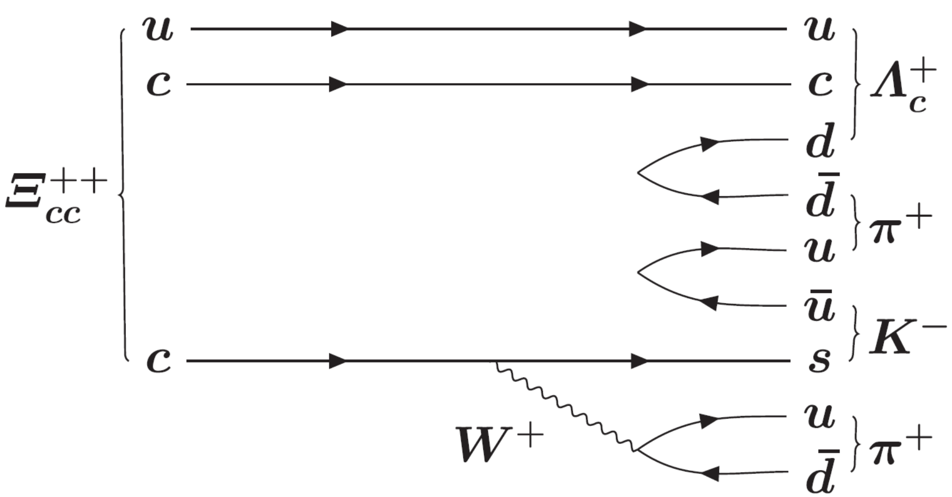

Example Feynman diagram contributing to the decay $\boxed{\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+}$

$$\boxed{M_{\Xi_{cc}^{++}} = 3621.40 \pm 0.72 \pm 0.27 \pm 0.14\,\text{MeV}}$$

LHCb Collaboration, PRL 119, 112001 (2017)
F-S Yu, etc., CPC 42 (2018) no.5, 051001

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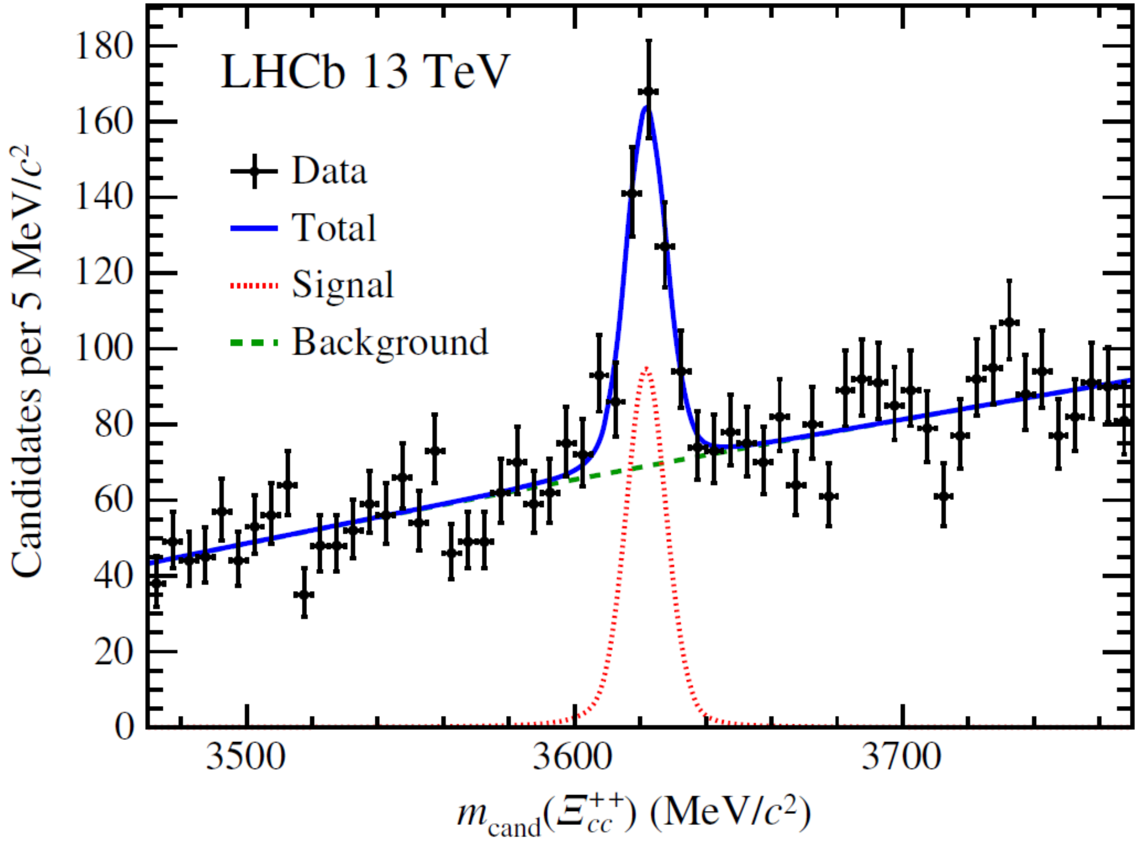

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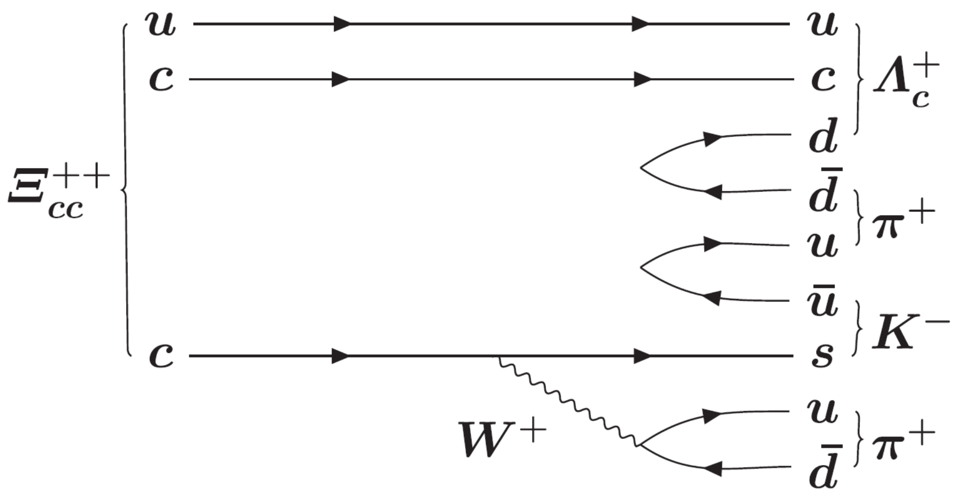

Example Feynman diagram contributing to the decay $\boxed{\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+}$

$$\Xi_{cc}^{++} \sim J^P = 1/2^+$$

$$\Xi_{cc}^{*++} \sim J^P = 3/2^+$$

$$\Xi_{cc}^{*++} \to \Xi_{cc}^{++}\gamma$$

LHCb Collaboration, PRL 119, 112001 (2017)
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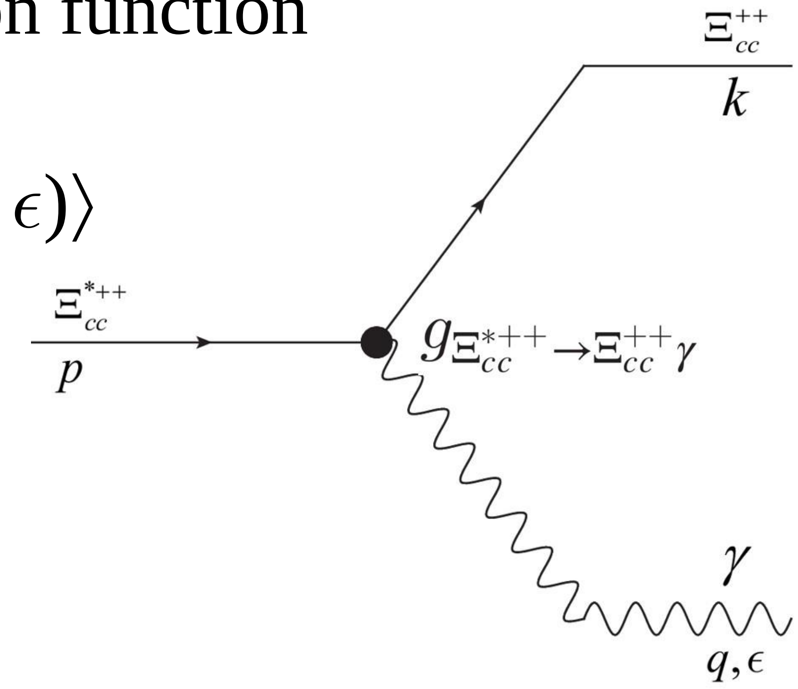
Light-cone sum rules

- We first investigate the following three-point correlation function

$$\Pi_{\alpha}(p,k,q,\epsilon)=\int d^4x e^{-ik\cdot x}\langle 0|J_{\Xi_{cc}^{*++},\alpha}(0)\bar{J}_{\Xi_{cc}^{++}}(x)|\gamma(q,\epsilon)\rangle$$



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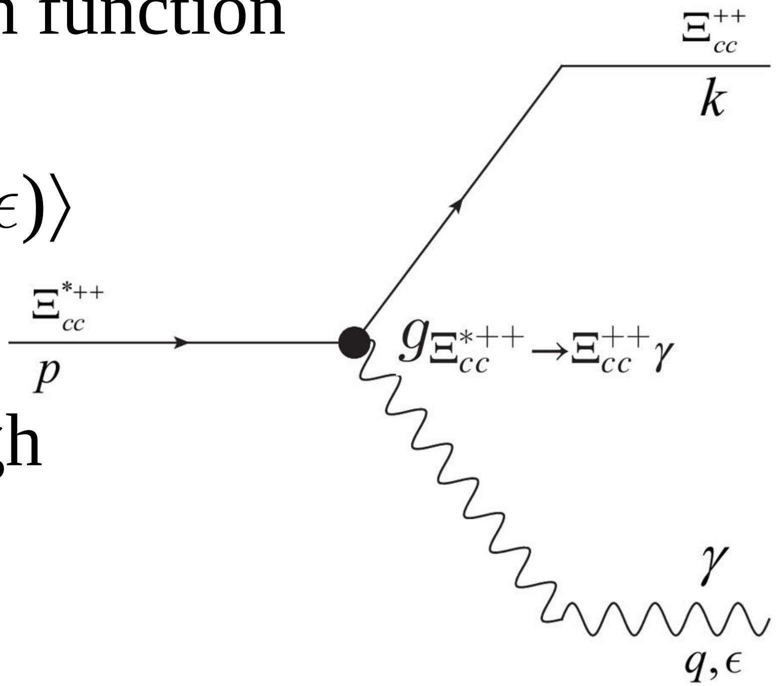

- The above two currents couple to the Ξ_{cc}^{++} and Ξ_{cc}^{*++} through

$\langle 0|J_{\Xi_{cc}^{++}}|\Xi_{cc}^{++}\rangle = f_{\Xi_{cc}^{++}}u_{\Xi_{cc}^{++}}(p)$ and $\langle 0|J_{\Xi_{cc}^{++}}|\Xi_{cc}^{*++}\rangle = f_{\Xi_{cc}^{*++}}u_{\Xi_{cc}^{*++}}(p)$.

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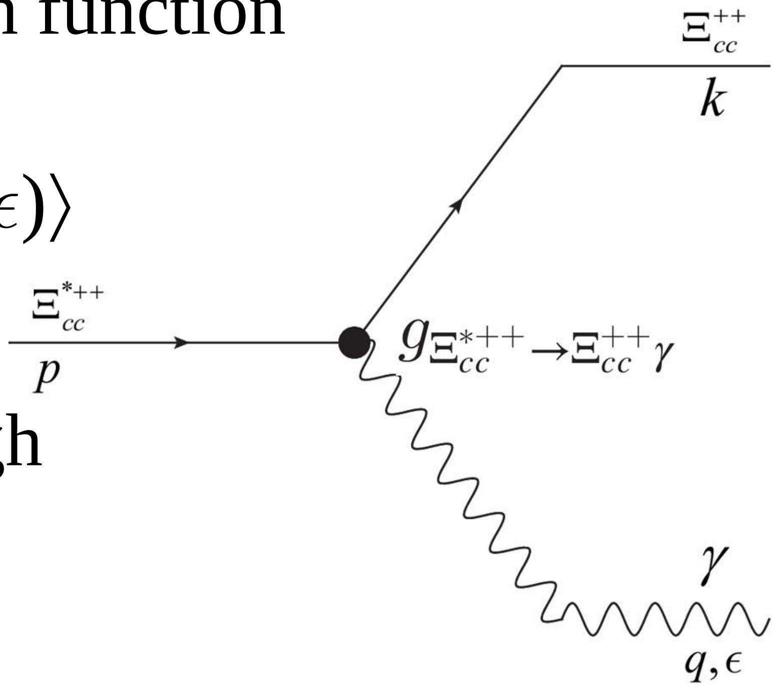

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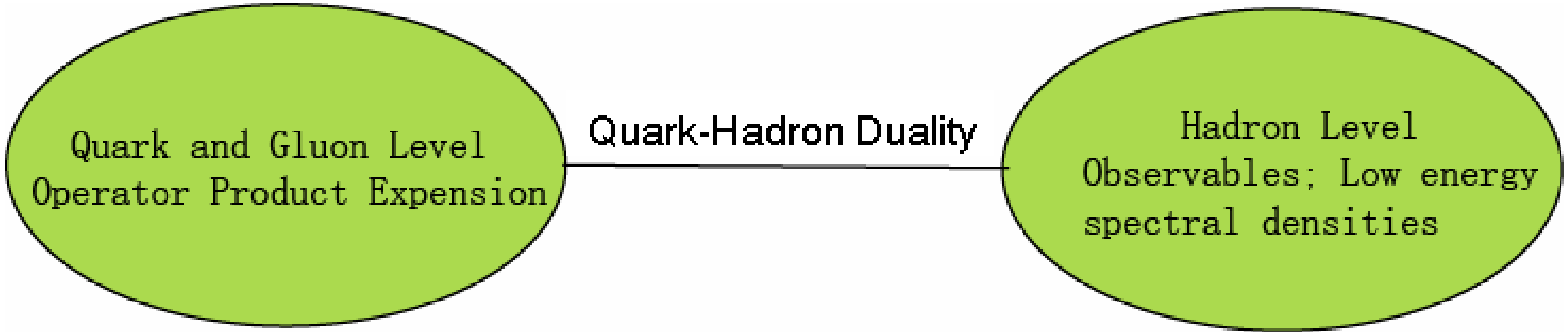
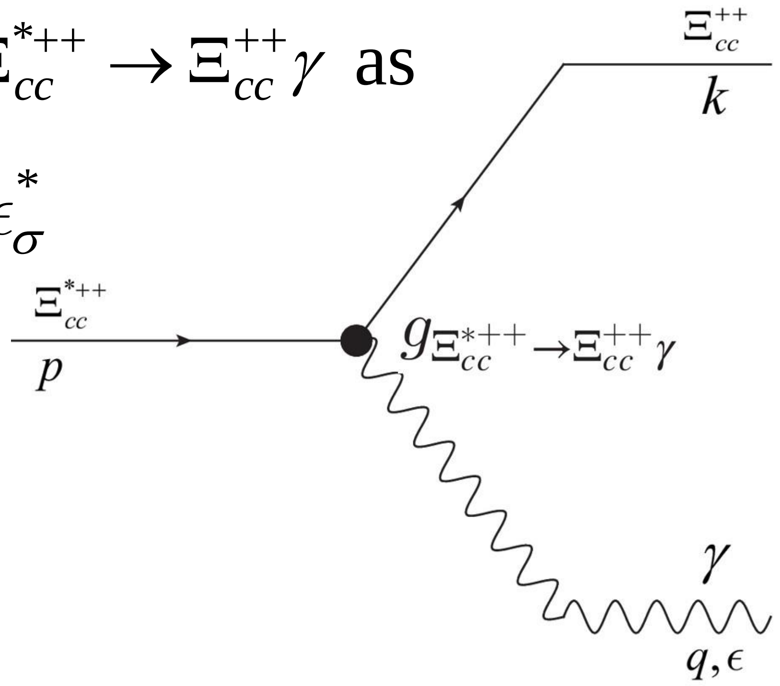


Light-cone sum rules

- At the hadronic level, we write the amplitude of the $\Xi_{cc}^{*++} \to \Xi_{cc}^{++}\gamma$ as

$$\mathcal{M}_{\Xi_{cc}^{*++}\to\Xi_{cc}^{++}\gamma} = e\, g\, \epsilon^{\mu\nu\rho\sigma}\, \bar{u}_{\Xi_{cc}^{++}}\, u_{\Xi_{cc}^{*++},\rho}\, p_\mu q_\nu \epsilon_\sigma^{*}$$



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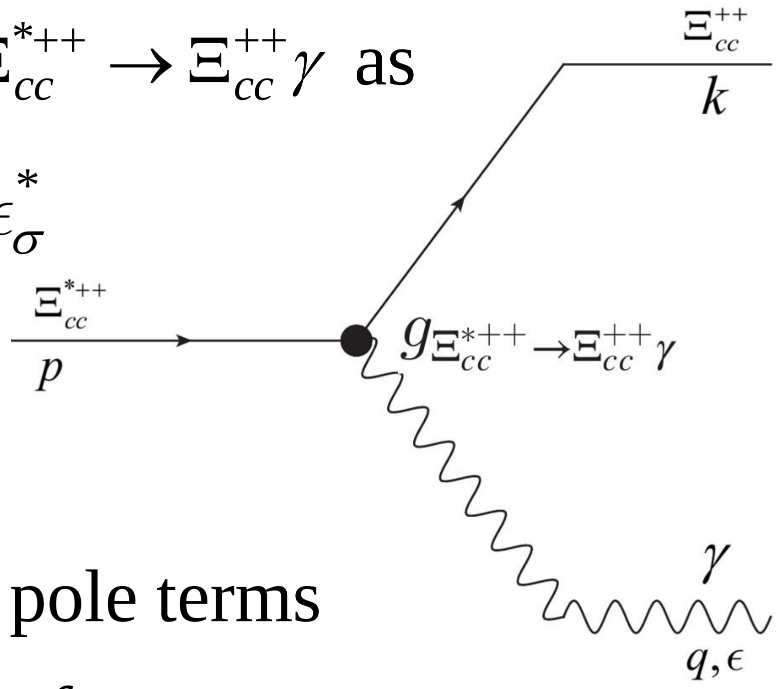

- Then we obtain the $\Pi_\alpha(p,k,q,\epsilon)$ having the following pole terms

$$\Pi_\alpha(p,k,q,\epsilon) \approx \frac{2e}{3} g\, \epsilon^{\alpha\nu\rho\sigma} p_\nu q_\rho \epsilon_\sigma \times \frac{f_{\Xi_{cc}^{*++}} f_{\Xi_{cc}^{++}}}{(p^2 - M^2)^2} \times \left(p^2 + M^2\right) + \cdots$$

Light-cone sum rules

- The currents $J_{\Xi_{cc}^{++}}$ and $J_{\Xi_{cc}^{*++}}$ write as

$$J_{\Xi_{cc}^{++}}(x) = \cos\theta_1 \times \epsilon^{abc}\left(c_a^T(x)C\gamma_\mu c_b(x)\right)\gamma^\mu\gamma_5 q_c(x) + \sin\theta_1 \times \epsilon^{abc}\left(q_a^T(x)C\gamma_5 c_b(x)\right)c_c(x)$$

$$= t_1 \times \epsilon^{abc}\left(c_a^T(x)C\gamma_\mu c_b(x)\right)\gamma^\mu\gamma_5 q_c(x) + t_2 \times \epsilon^{abc}\left(c_a^T(x)C\sigma_{\mu\nu} c_b(x)\right)\sigma^{\mu\nu}\gamma_5 q_c(x)$$

$$J_{\Xi_{cc}^{*++},\alpha}(x) = \cos\theta_2 \times \Gamma_{\alpha\mu}\epsilon^{abc}\left(c_a^T(x)C\gamma^\mu c_b(x)\right)q_c(x) + \sin\theta_2 \times \Gamma_{\alpha\mu}\epsilon^{abc}\left(q_a^T(x)C\gamma^\mu c_b(x)\right)c_c(x)$$

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- At the quark-gluon level, we calculate $\Pi_\alpha(p,k,q,\epsilon)$ using the method of operator product expansion(OPE).

Light-cone sum rules

$$
\begin{aligned}
\Pi^{\Xi_{cc}^{++}\gamma\to\Xi_{cc}^{*++}}_{\alpha,\mathrm{light}}(p,k,q,\epsilon) = & \int d^4x \int \frac{d^4p_1}{(2\pi)^4} \int \frac{d^4p_2}{(2\pi)^4} \int_0^1 du \times e^{-ikx} e^{-i(1-u)qx} \times \epsilon^{\alpha\nu\rho\sigma} q_\nu \epsilon_\rho \times e_u \\
& \times \Bigg\{ \cos\theta_1 t_1 \times \Bigg(-\frac{f_{3\gamma} x_\sigma (3m_c^2 + 2p_1\cdot p_2)}{2(p_1^2-m_c^2)(p_2^2-m_c^2)} \psi^{(a)}(u) + \frac{f_{3\gamma} x_\sigma p_1\cdot p_2}{72(p_1^2-m_c^2)^2(p_2^2-m_c^2)^2} \langle g_s^2 GG\rangle \psi^{(a)}(u) \\
& - \frac{f_{3\gamma} x_\sigma (3p_1^2 + 2p_1\cdot p_2)}{24(p_1^2-m_c^2)^4(p_2^2-m_c^2)} m_c^2 \langle g_s^2 GG\rangle \psi^{(a)}(u) - \frac{f_{3\gamma} x_\sigma (3p_2^2 + 2p_1\cdot p_2)}{24(p_1^2-m_c^2)(p_2^2-m_c^2)^4} m_c^2 \langle g_s^2 GG\rangle \psi^{(a)}(u) \Bigg) \\
& + \cos\theta_1 t_2 \times \Bigg(-\frac{10 i\chi (p_{1\sigma} + p_{2\sigma})}{(p_1^2-m_c^2)(p_2^2-m_c^2)} m_c \langle \bar{q}q\rangle \phi_\gamma(u) + \frac{5 i\chi (p_{1\sigma} + p_{2\sigma})}{72(p_1^2-m_c^2)^2(p_2^2-m_c^2)^2} m_c \langle \bar{q}q\rangle \langle g_s^2 GG\rangle \phi_\gamma(u) \\
& - \frac{5 i\chi (p_1^2 p_{2\sigma} + m_c^2 p_{1\sigma})}{6(p_1^2-m_c^2)^4(p_2^2-m_c^2)} m_c \langle \bar{q}q\rangle \langle g_s^2 GG\rangle \phi_\gamma(u) - \frac{5 i\chi (p_2^2 p_{1\sigma} + m_c^2 p_{2\sigma})}{6(p_1^2-m_c^2)(p_2^2-m_c^2)^4} m_c \langle \bar{q}q\rangle \langle g_s^2 GG\rangle \phi_\gamma(u) \Bigg) \\
& + \sin\theta_1 t_1 \times \Bigg(-\frac{f_{3\gamma} x_\sigma (3m_c^2 + 2p_1\cdot p_2)}{4(p_1^2-m_c^2)(p_2^2-m_c^2)} \psi^{(a)}(u) - \frac{3 i\chi (p_{1\sigma} + p_{2\sigma})}{(p_1^2-m_c^2)(p_2^2-m_c^2)} m_c \langle \bar{q}q\rangle \phi_\gamma(u) \\
& + \frac{f_{3\gamma} x_\sigma p_1\cdot p_2}{144(p_1^2-m_c^2)^2(p_2^2-m_c^2)^2} \langle g_s^2 GG\rangle \psi^{(a)}(u) + \frac{i\chi (p_{1\sigma} + p_{2\sigma})}{48(p_1^2-m_c^2)^2(p_2^2-m_c^2)^2} m_c \langle \bar{q}q\rangle \langle g_s^2 GG\rangle \phi_\gamma(u) \\
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& + \cdots
\end{aligned}
$$

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Numerical analyses

- To perform numerical analyses, we use the following values at $\mu = 1\text{GeV}$.

The parameters in distribution amplitude

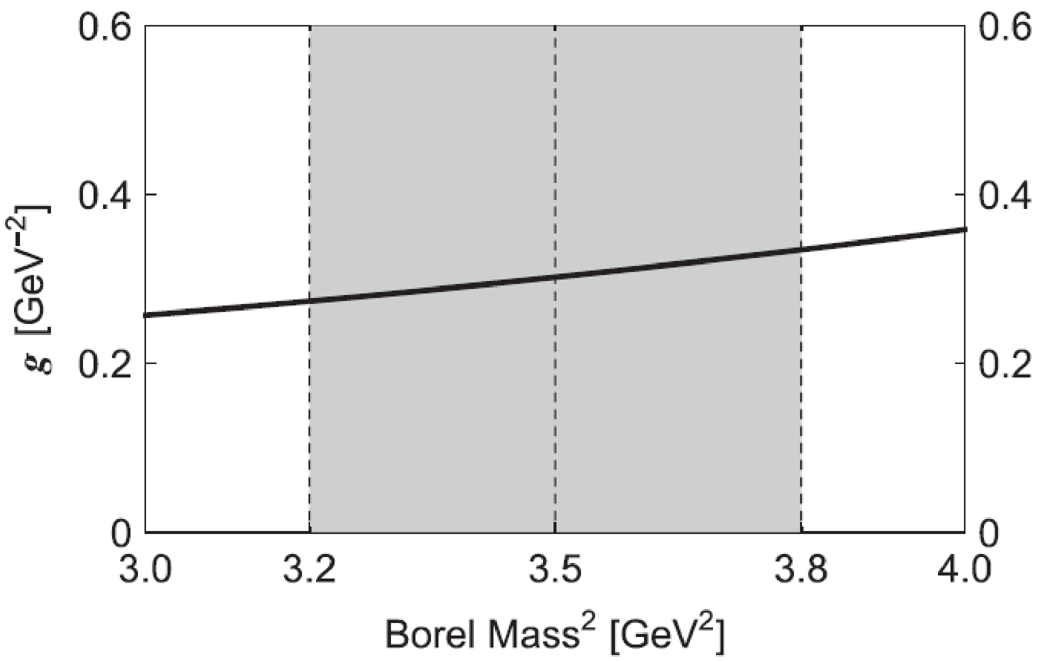
$$f_{3\gamma} = -(4 \pm 2) \times 10^{-3}\ \text{GeV}^2,$$
$$\omega_\gamma^V = 3.8 \pm 1.8,$$
$$\omega_\gamma^A = -2.1 \pm 1.0,$$
$$\chi = (3.15 \pm 0.10)\ \text{GeV}^{-2},$$
$$\kappa = 0.2,$$
$$\zeta_1 = 0.4,$$
$$\zeta_2 = 0.3,$$
$$\kappa^+ = \zeta_1^+ = \zeta_2^+ = 0.$$

The quark and gluon condensates

$$\langle \bar{q}q \rangle = -(0.24 \pm 0.01)^3\ \text{GeV}^3,$$
$$\langle \bar{s}s \rangle = 0.8 \times \langle \bar{q}q \rangle,$$
$$\langle g_s^2 GG \rangle = (0.48 \pm 0.14)\ \text{GeV}^4,$$
$$\langle g_s \bar{q}\sigma Gq \rangle = M_0^2 \times \langle \bar{q}q \rangle,$$
$$\langle g_s \bar{s}\sigma Gs \rangle = M_0^2 \times \langle \bar{s}s \rangle,$$
$$m_s = 96_{-4}^{+8}\ \text{MeV},$$
$$m_c = 1.23 \pm 0.09\ \text{GeV},$$
$$m_b = 4.18_{-0.03}^{+0.04}\ \text{GeV}.$$

Numerical analyses

- Then the coupling constant is evaluated to be



$$g_{\Xi_{cc}^{*++}\to\Xi_{cc}^{++}\gamma} = 0.30^{+0.16}_{-0.11}\,\mathrm{GeV}^{-2} = 0.304^{+0.024+0.007+0.033+0.093+0.118}_{-0.026-0.014-0.028-0.045-0.087}\,\mathrm{GeV}^{-2}$$

Numerical analyses

- Finally, we use the following decay formula,

$$\Gamma_{\Xi_{cc}^{*++}\to\Xi_{cc}^{++}\gamma} = \frac{|\vec{q}\,|}{8\pi M^2_{\Xi_{cc}^{*++}}} \times \left|\frac{1}{4}\sum_{spin}\mathcal{M}_{\Xi_{cc}^{*++}\to\Xi_{cc}^{++}\gamma}\right|^2$$

to obtain

$$\boxed{\Gamma_{\Xi_{cc}^{*++}\to\Xi_{cc}^{++}\gamma} = 13.7^{+17.7}_{-7.9}\ \mathrm{keV}}$$

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- Using the same approach, we calculate the following processes.

coupling constants

$$g_{\Xi_{cc}^{*+}\to\Xi_{cc}^{+}\gamma} = 0.23^{+0.13}_{-0.09}\ \text{GeV}^{-2},$$
$$g_{\Omega_{cc}^{*+}\to\Omega_{cc}^{+}\gamma} = 0.22^{+0.11}_{-0.08}\ \text{GeV}^{-2},$$
$$g_{\Xi_{bb}^{*0}\to\Xi_{bb}^{0}\gamma} = 0.050^{+0.026}_{-0.018}\ \text{GeV}^{-2},$$
$$g_{\Xi_{bb}^{*-}\to\Xi_{bb}^{-}\gamma} = 0.081^{+0.031}_{-0.020}\ \text{GeV}^{-2},$$
$$g_{\Omega_{bb}^{*-}\to\Omega_{bb}^{-}\gamma} = 0.053^{+0.015}_{-0.013}\ \text{GeV}^{-2},$$

relevant decay widths

$$\Gamma_{\Xi_{cc}^{*+}\to\Xi_{cc}^{+}\gamma} = 8.1^{+11.1}_{-4.9}\ \text{keV},$$
$$\Gamma_{\Omega_{cc}^{*+}\to\Omega_{cc}^{+}\gamma} = 5.4^{+6.9}_{-3.1}\ \text{keV},$$
$$\Gamma_{\Xi_{bb}^{*0}\to\Xi_{bb}^{0}\gamma} = 0.11^{+0.13}_{-0.07}\ \text{keV},$$
$$\Gamma_{\Xi_{bb}^{*-}\to\Xi_{bb}^{-}\gamma} = 0.28^{+0.24}_{-0.13}\ \text{keV},$$
$$\Gamma_{\Omega_{bb}^{*-}\to\Omega_{bb}^{-}\gamma} = 0.08^{+0.05}_{-0.04}\ \text{keV}.$$

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Summary and discussions

- We have investigated electromagnetic transitions of some doubly heavy baryons using the method of light-cone sum rules.

Electromagnetic transitions of doubly charmed baryons(in keV)

Process	Our results	Ref. [16]	Ref. [17]	Ref. [18]	Ref. [19]	Ref. [20]	Ref. [21]
$\Xi_{cc}^{*++} \to \Xi_{cc}^{++}\gamma$	$13.7_{-7.9}^{+17.7}$	4.35	1.43	16.7	23.46 ± 3.33	7.21	22.0
$\Xi_{cc}^{*+} \to \Xi_{cc}^{+}\gamma$	$8.1_{-4.9}^{+11.1}$	3.96	2.08	14.6	28.79 ± 2.51	3.90	9.57
$\Omega_{cc}^{*+} \to \Omega_{cc}^{+}\gamma$	$5.4_{-3.1}^{+6.9}$	1.35	0.95	6.93	2.11 ± 0.11	0.82	9.45
$\Xi_{bb}^{*0} \to \Xi_{bb}^{0}\gamma$	$0.11_{-0.07}^{+0.13}$	$\cdots$	$\cdots$	1.19	0.31 ± 0.06	0.98	$\cdots$
$\Xi_{bb}^{*-} \to \Xi_{bb}^{-}\gamma$	$0.28_{-0.13}^{+0.24}$	$\cdots$	$\cdots$	0.24	0.0587 ± 0.0142	0.21	$\cdots$
$\Omega_{bb}^{*-} \to \Omega_{bb}^{-}\gamma$	$0.08_{-0.04}^{+0.05}$	$\cdots$	$\cdots$	0.08	0.0226 ± 0.0045	0.04	$\cdots$

Our results are (slightly) larger than those obtained using the bag model[16-R. H. Hackman, etc. PRD 18, 2537 (1978), 17-A. Bernotas and V. Simonis, PRD 87, 074016 (2013)], but quite comparable with those obtained using the nonrelativistic constituent quark model [18-L. Y. Xiao, etc. PRD 96, 094005(2017)], the relativistic three-quark model including hyperfine mixing effects [19-T. Branz, etc. PRD 81, 114036 (2010)], the relativistic constituent quark model within the diquark picture[20-Q. F. Lü, etc. PRD, 114006(2017)], and the chiral perturbation theory [21-H. S. Li, etc. PLB 777, 169 (2018)].

Summary and discussions

- We propose to search for the doubly charmed baryon Ξ_{cc}^{*++} of $J^P = 3/2^+$ via its electromagnetic transition:

$$\boxed{\Gamma(\Xi_{cc}^{*++} \to \Xi_{cc}^{++}\gamma) = 13.7_{-7.9}^{+17.7}\,\mathrm{keV}}$$

Summary and discussions

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$$\boxed{\Gamma(\Xi_{cc}^{*++} \to \Xi_{cc}^{++}\gamma) = 13.7^{+17.7}_{-7.9}\,\mathrm{keV}}$$

- In the future work, we would like to calculate the axial coupling constant $g_{\Xi_{cc}^{++}\Xi_{cc}^{+}\pi}$ and look into decay properties of some excited doubly heavy baryons.

Thank you very much
谢谢