Doubly heavy tetraquark and $\bar{D}^{(*)}\Xi_{cc}^{(*)}$ and $\Xi_{cc}^{(*)}\Xi_{cc}^{(*)}$ as partners of doubly charmed tetraquark

M. Sakai, Y. Yamaguchi, in preparation

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Nagoya Univ.

November 13, 2025

Outline

- Introduction
- $\bar{D}^{(*)}\Xi_{cc}^{(*)}$ and $\Xi_{cc}^{(*)}\Xi_{cc}^{(*)}$
- Summary

Introduction

$T_{cc}(cc\bar{u}\bar{d})^+$

- T_{cc} has been reported by LHCb in 2022.
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  $\rightarrow$ **Genuine exotic!**
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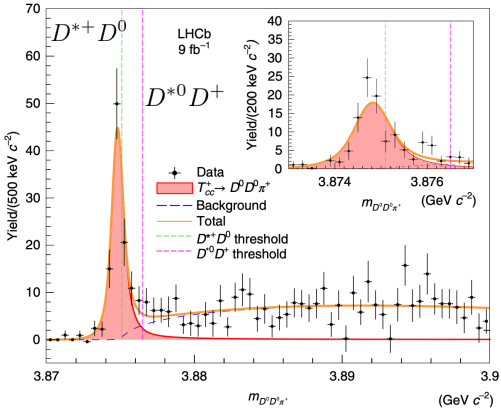

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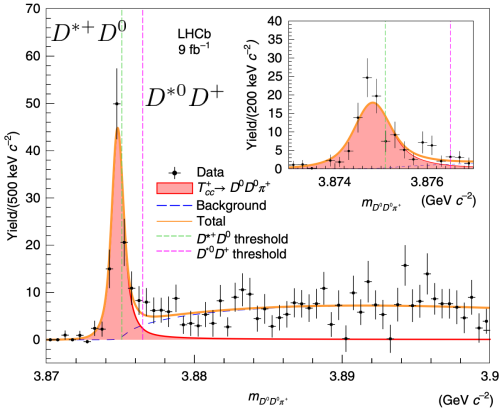

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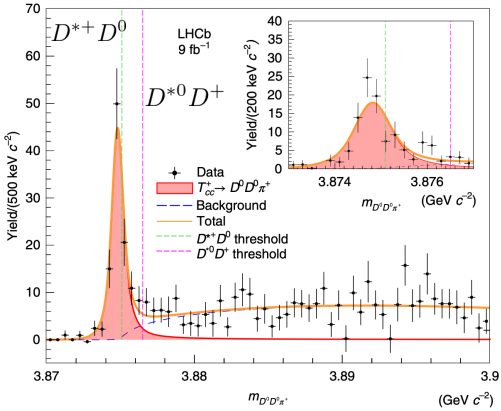

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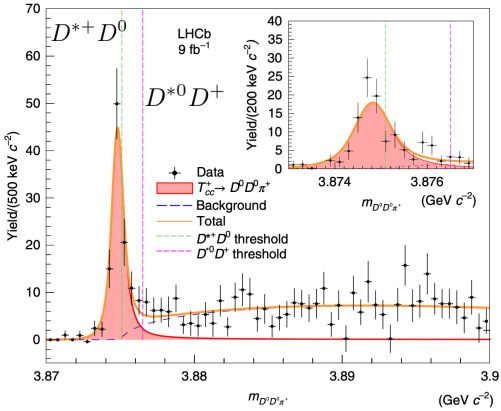
$\Rightarrow$ T_{cc} **can be considered as a** DD^* **molecule.**



Our previous study M.S., Yasuhiro Yamaguchi, PRD 109 (2024) 5, 054016, PRD 112 (2025) 3, 034038

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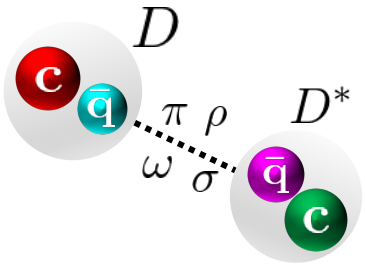

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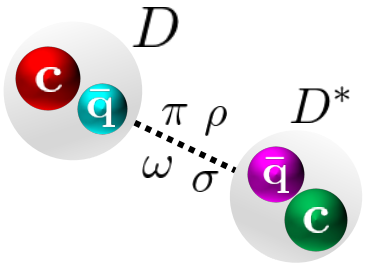

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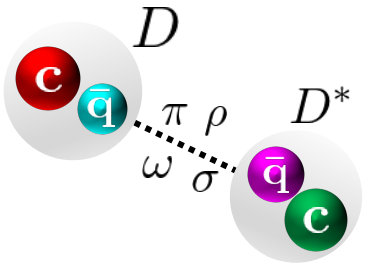

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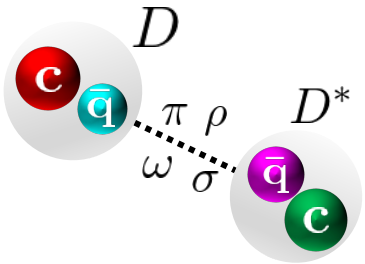

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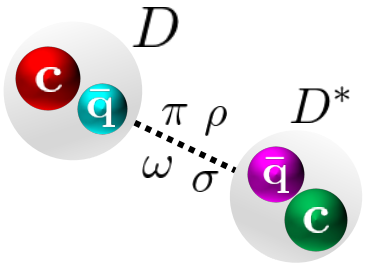

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  - ▷ **Coupled channel system** ($D - D^*$ and $S - D$ mixings).

$\bar{D}^{(*)}\Xi_{cc}^{(*)}$ and $\Xi_{cc}^{(*)}\Xi_{cc}^{(*)}$

Super Flavor Symmetry

- Subjects in our study:
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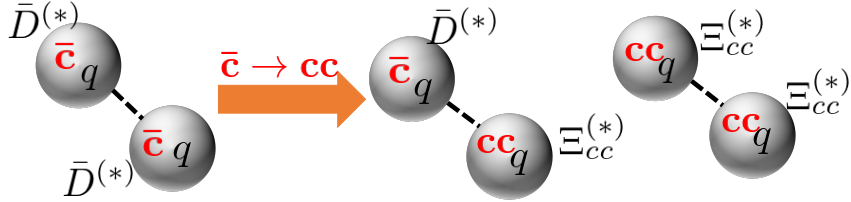

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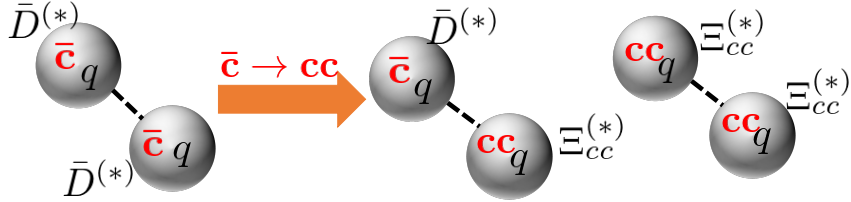

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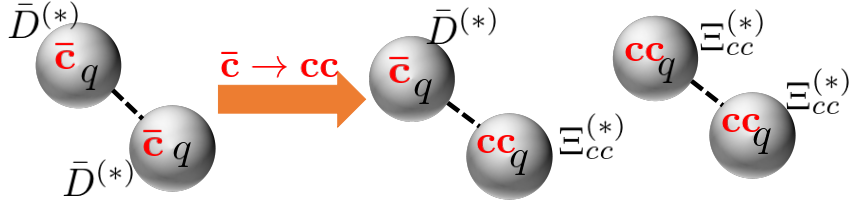

- ▷ Interaction: One boson exchange potential
- ▷ Parameters: Same parameters (Coupling const. and Cutoff) are employed due to the superflavor symmetry.

Other studies on $\bar{D}^{(*)}\Xi_{cc}^{(*)}$ and $\Xi_{cc}\Xi_{cc}$

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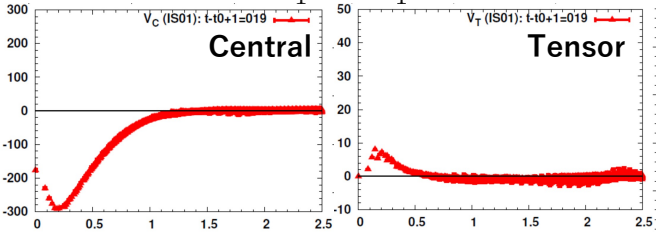

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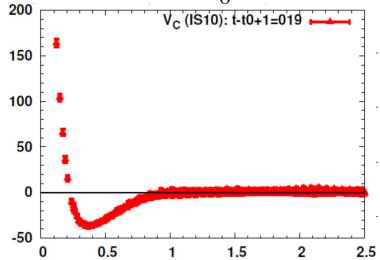

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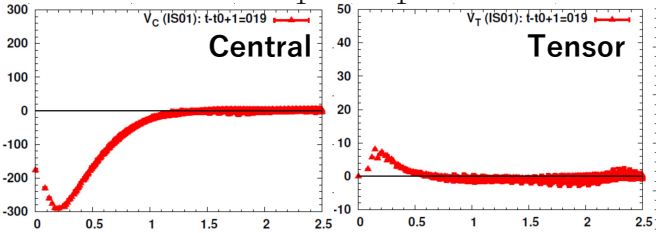

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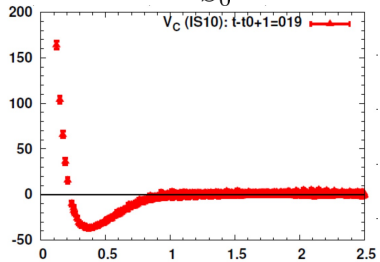

⇒ We study $\Xi_{cc}^{(*)}\Xi_{cc}^{(*)}$ using the effective model and try to compare our results with the HAL QCD results.

Coupled channels of $\bar{D}^{(*)}\Xi_{cc}^{(*)}$ and $\Xi_{cc}^{(*)}\Xi_{cc}^{(*)}$

- The mass differences between $(\bar{D},\ \bar{D}^*)$ and (Ξ_{cc}, Ξ_{cc}^*) are small because of the heavy quark spin symmetry:

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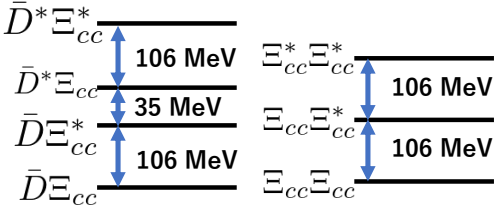

$\bar{D}$: 1868 MeV (Assumming isospin sym.)

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N. Brambilla, et al PRD 72 (2005) -34021,
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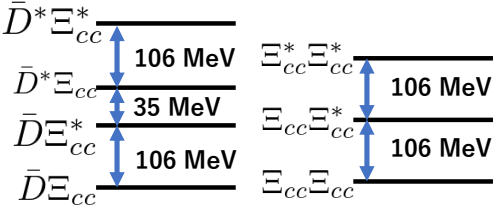

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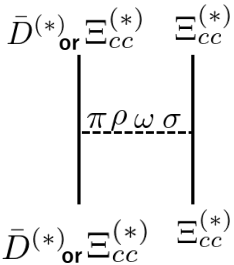
  - $\bar{D}\Xi_{cc}(^2S)$, $\bar{D}\Xi^*(^4D)$, $\bar{D}^*\Xi_{cc}(^2S, ^4D)$, $\bar{D}^*\Xi_{cc}^*(^2S, ^4D, ^6D)$
- Channels of $\Xi_{cc}^{(*)}\Xi_{cc}^{(*)}$ with $I(J^P) = 0(1^+)$ $([\Xi_{cc}\Xi_{cc}]_\pm = \frac{1}{\sqrt{2}}(\Xi_{cc}\Xi_{cc}^* \pm \Xi_{cc}^*\Xi_{cc}))$:
  - $\Xi_{cc}\Xi_{cc}(^3S, ^3D)$, $[\Xi_{cc}\Xi_{cc}^*]_-(^3S, ^3D)$, $[\Xi_{cc}\Xi_{cc}]_+(^5D)$, $\Xi_{cc}^*\Xi_{cc}^*(^3S, ^3D, ^7D, ^7G)$

One boson exchnage potential for $\bar{D}^{(*)}\Xi_{cc}^{(*)}$ and $\Xi_{cc}^{(*)}\Xi_{cc}^{(*)}$

- OBEP for $\bar{D}^{(*)}\Xi_{cc}^{(*)}$ and $\Xi_{cc}^{(*)}\Xi_{cc}^{(*)}$



$$\pi:\ V^{\pi}(r) = k_{\pi}\frac{1}{3}\left(\frac{g}{2f_{\pi}}\right)^2 [\vec{\mathcal{O}}_1\cdot\vec{\mathcal{O}}_2 C(r;m_{\pi}) + S_{12}(r)T(r;m_{\pi})]\vec{\tau}_1\cdot\vec{\tau}_2$$

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$$\sigma:\ V^{\sigma}(r) = -\left(\frac{g_{\sigma}}{m_{\sigma}}\right)^2 C(r;m_{\sigma})$$

- Form factor:

$$F(\vec{q};m) = \frac{\Lambda^2 - m^2}{\Lambda^2 + \vec{q}^{\,2}}$$

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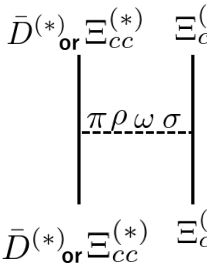

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- Coupling constant (Λ is determined to reproduce the binding energy of T_{cc}):
  $g = 0.59$ ($D^* \to D\pi$ decay), $\beta = 0.9$ (Lattice QCD), $\lambda = 0.59\,\mathrm{GeV}^{-1}$ (B meson decay)
  $g_{\sigma} = \frac{g_{\sigma NN}}{3} = 3.4$ ($\Lambda = 1075.4$ MeV), $g_{\sigma} = \frac{g_{\pi}}{2\sqrt{6}} = 0.76$ ($\Lambda = 1682.4$ MeV)

S. Ahmed et al., CLEO Collaboration, PRL. 87, 251801 (2001) Ming-Zhu Liu et al., PRD 99 094018 (2019), C. Isola, PRD 68, 114001(2003), W.A. Bardeen et al., PRD 68, 054024(2003)

Bound state of $\bar{D}^{(*)}\Xi_{cc}^{(*)}$

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  - Binding energy: **7.78 MeV** for $g_\sigma = 3.4$, **20.5 MeV** for $g_\sigma = 0.76$
  - Mixing ratio for each channel:

Mixing ratio	$g_\sigma = 3.4$	$g_\sigma = 0.76$
$\bar{D}\Xi_{cc}(^2S)$	$98.8\,\%$	$93.5\,\%$
$\bar{D}\Xi_{cc}^*(^4D)$	$0\,\%$	$0\,\%$
$\bar{D}^*\Xi_{cc}(^2S)$	$0.103\,\%$	$1.19\,\%$
$\bar{D}^*\Xi_{cc}(^4D)$	$0.136\,\%$	$0.378\,\%$
$\bar{D}^*\Xi_{cc}^*(^2S)$	$0.285\,\%$	$2.78\,\%$
$\bar{D}^*\Xi_{cc}^*(^4D)$	$0.0601\,\%$	$0.169\,\%$
$\bar{D}^*\Xi_{cc}^*(^6D)$	$0.585\,\%$	$2.02\,\%$
r.m.s	$1.40\,\mathrm{fm}$	$0.884\,\mathrm{fm}$

Bound state of $\bar{D}^{(*)}\Xi_{cc}^{(*)}$

- Bound states of $\bar{D}^{(*)}\Xi_{cc}^{(*)}$ with $J^P = \frac{1}{2}^-$ are obtained in both cases of $g_\sigma = 3.4, 0.76$:
  - ▷ Binding energy: **7.78 MeV** for $g_\sigma = 3.4$, **20.5 MeV** for $g_\sigma = 0.76$
  - ▷ Mixing ratio for each channel:

Mixing ratio	$g_\sigma = 3.4$	$g_\sigma = 0.76$
$\bar{D}\Xi_{cc}(^2S)$	$98.8\,\%$	$93.5\,\%$
$\bar{D}\Xi_{cc}^*(^4D)$	$0\,\%$	$0\,\%$
$\bar{D}^*\Xi_{cc}(^2S)$	$0.103\,\%$	$1.19\,\%$
$\bar{D}^*\Xi_{cc}(^4D)$	$0.136\,\%$	$0.378\,\%$
$\bar{D}^*\Xi_{cc}^*(^2S)$	$0.285\,\%$	$2.78\,\%$
$\bar{D}^*\Xi_{cc}^*(^4D)$	$0.0601\,\%$	$0.169\,\%$
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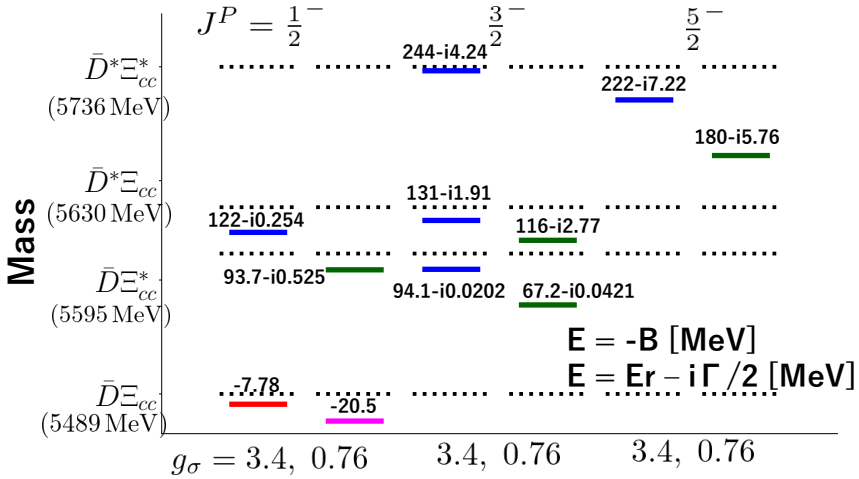
$\bar{D}^{(*)}\Xi_{cc}^{(*)}$ with some quantum numbers



- The bound states of $\bar{D}^{(*)}\Xi_{cc}^{(*)}$ with only $J^P = \frac{1}{2}^-$ appear.
- For higher-spin states, many resonant states appear because of the coupled channel effect.

Bound state of $\Xi_{cc}^{(*)}\Xi_{cc}^{(*)}$ with $I(J^P) = 0(1^+)$

- Bound states of $\Xi_{cc}^{(*)}\Xi_{cc}^{(*)}$ with $I(J^P) = 0(1^+)$ are obtained in both cases of $g_\sigma = 3.4, 0.76$:

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- Bound states of $\Xi_{cc}^{(*)}\Xi_{cc}^{(*)}$ with $I(J^P) = 0(1^+)$ are obtained in both cases of $g_\sigma = 3.4, 0.76$:
  - ▷ Binding energy: **24.7 MeV** for $g_\sigma = 3.4$, **67.4 MeV** for $g_\sigma = 0.76$

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  - Binding energy: **24.7 MeV** for $g_\sigma = 3.4$, **67.4 MeV** for $g_\sigma = 0.76$
  - Mixing ratio for dominant and non-negligible channels ($^{2S+1}L_{(1)}$):

Mixing ratio	$g_\sigma = 3.4$	$g_\sigma = 0.76$
$\Xi_{cc}\Xi_{cc}(^3S)$	$96.6\,\%$	$85.9\,\%$
$\Xi_{cc}\Xi_{cc}^*(^3S)$	$0.834\,\%$	$5.92\,\%$
$\Xi_{cc}\Xi_{cc}^*(^5D)$	$0.475\,\%$	$1.10\,\%$
$\Xi_{cc}^*\Xi_{cc}^*(^3S)$	$0.538\,\%$	$3.09\,\%$
$\Xi_{cc}^*\Xi_{cc}^*(^7D)$	$1.34\,\%$	$3.80\,\%$
r.m.s	$0.827\,\mathrm{fm}$	$0.531\,\mathrm{fm}$

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  - ◇ In both cases of g_σ, $\Xi_{cc}\Xi_{cc}(^3S)$ is dominant.

⇒ $\langle \boldsymbol{\Xi_{cc}\Xi_{cc}(^3S)|V^\sigma|\Xi_{cc}\Xi_{cc}(^3S)}\rangle$ and $\langle \boldsymbol{\Xi_{cc}\Xi_{cc}(^3S)|V^\rho|\Xi_{cc}\Xi_{cc}(^3S)}\rangle$ are important.

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- ◇ For $g_\sigma = 3.4$, $\Xi_{cc}^*\Xi_{cc}^*(^7D)$ is second "important".

⇒ $\langle \boldsymbol{\Xi_{cc}\Xi_{cc}(^3S)}|\boldsymbol{V^\pi}|\boldsymbol{\Xi_{cc}^*\Xi_{cc}^*(^7D)}\rangle$ is important.

Bound state of $\Xi_{cc}^{(*)}\Xi_{cc}^{(*)}$ with $I(J^P) = 0(1^+)$

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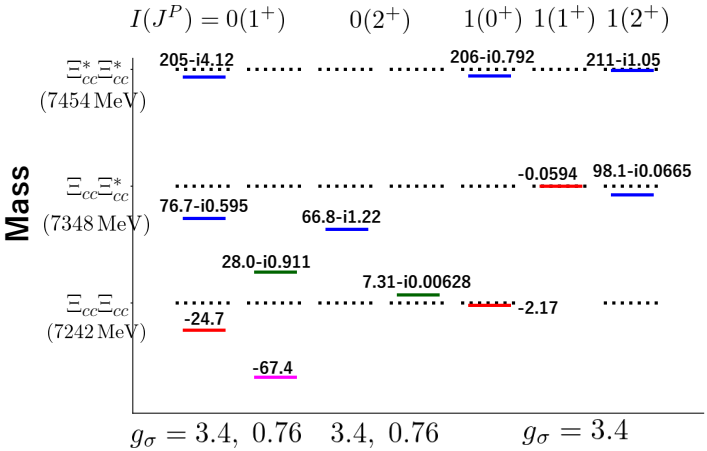
- ◇ For $g_\sigma = 0.76$, $\Xi_{cc}\Xi_{cc}(^3S)$ is dominant and 4 other components are non-negligible.

⇒ One $\pi\rho$ exchanges are important (Off-diagonal components).

$\Xi_{cc}^{(*)}\Xi_{cc}^{(*)}$ with some quantum numbers



- For $g_\sigma = 3.4$, $\Xi_{cc}^{(*)}\Xi_{cc}^{(*)}$ with not only $I = 0$ but also $I = 1$ are obtained.
- For $g_\sigma = 0.76$, $\Xi_{cc}^{(*)}\Xi_{cc}^{(*)}$ with only $I = 0$ are obtained.

Summary and Outlook

- Analysis of $\bar{D}^{(*)}\Xi_{cc}^{(*)}$ and $\Xi_{cc}^{(*)}\Xi_{cc}^{(*)}$
  - ▷ We constructed the one boson exchange potential by respecting the superflavor symmetry and solved the coupled-channel Schrodinger equation.

$\Rightarrow$ The bound and resonant states of $\bar{D}^{(*)}\Xi_{cc}^{(*)}$ and $\Xi_{cc}^{(*)}\Xi_{cc}^{(*)}$ were obtained.

$\Rightarrow$ Binding energy and mixing ratios differ depending on g_σ.

- Outlook
  - ▷ We will calculate the observable quantities such as the phase shift, scattering length in order to compare our result with HAL QCD result.
  - ▷ We try to consider the $\Lambda_c\Omega_{ccc} - \Xi_{cc}\Xi_{cc}$.

Back Up

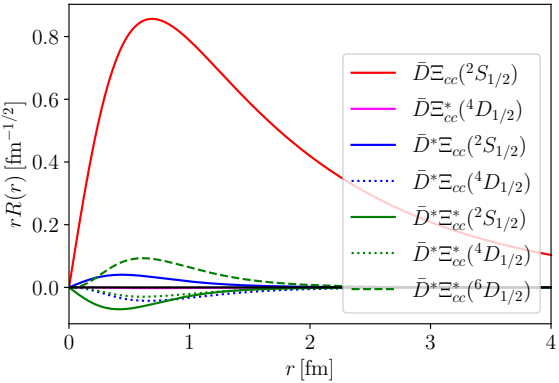
Channels for $\bar{D}^{(*)}\Xi_{cc}^{(*)}$

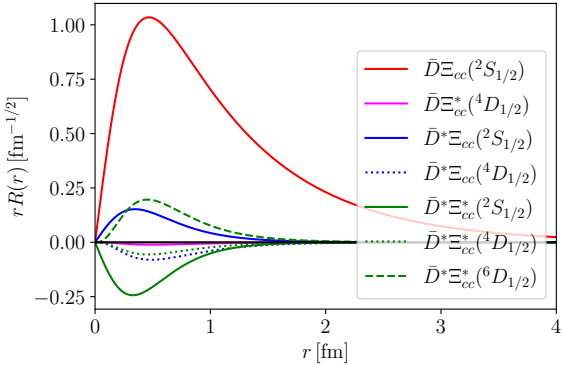
J^P	Channels
$\frac{1}{2}^-$	$\bar{D}\Xi_{cc}(^2S_{1/2})$, $\bar{D}\Xi_{cc}^*(^4D_{1/2})$, $\bar{D}^*\Xi_{cc}(^2S_{1/2},^4D_{1/2})$, $\bar{D}^*\Xi_{cc}^*(^2S_{1/2},^4D_{1/2},^6D_{1/2})$
$\frac{3}{2}^-$	$\bar{D}\Xi_{cc}(^2D_{3/2})$, $\bar{D}\Xi_{cc}^*(^4S_{3/2},^4D_{3/2})$, $\bar{D}^*\Xi_{cc}(^2D_{3/2},^4S_{3/2},^4D_{3/2})$, $\bar{D}^*\Xi_{cc}^*(^2D_{3/2},^4S_{3/2},^4D_{3/2}.^6D_{3/2},^6G_{3/2})$
$\frac{5}{2}^-$	$\bar{D}\Xi_{cc}(^2D_{5/2})$, $\bar{D}\Xi_{cc}^*(^4D_{5/2},^4G_{5/2})$, $\bar{D}^*\Xi_{cc}(^2D_{5/2},^4D_{5/2},^4G_{5/2})$, $\bar{D}^*\Xi_{cc}^*(^2D_{5/2},^4D_{5/2},^4G_{5/2}.^6S_{5/2},^6D_{5/2},^6G_{5/2})$

Channels for $\Xi_{cc}^{(*)}\Xi_{cc}^{(*)}$

$I(J^P)$	Channels
$0(0^+)$	$[\Xi_{cc}\Xi_{cc}^*]_+({}^5D_0)$
$1(0^+)$	$\Xi_{cc}\Xi_{cc}({}^1S_0)$, $[\Xi_{cc}\Xi_{cc}^*]_-({}^5D_0)$, $\Xi_{cc}^*\Xi_{cc}^*({}^1S_0, {}^5D_0)$
$0(1^+)$	$\Xi_{cc}\Xi_{cc}({}^3S_1, {}^3D_1)$, $[\Xi_{cc}\Xi_{cc}^*]_-({}^3S_1, {}^3D_1)$, $[\Xi_{cc}\Xi_{cc}^*]_+({}^5D_1)$, $\Xi_{cc}^*\Xi_{cc}^*({}^3S_1, {}^3D_1, {}^7D_1, {}^7G_1)$
$1(1^+)$	$[\Xi_{cc}\Xi_{cc}^*]_+({}^3S_1, {}^3D_1)$, $[\Xi_{cc}\Xi_{cc}^*]_-({}^5D_1)$, $\Xi_{cc}^*\Xi_{cc}^*({}^5D_1)$
$0(2^+)$	$\Xi_{cc}\Xi_{cc}({}^3D_2)$, $[\Xi_{cc}\Xi_{cc}^*]_-({}^3D_2)$, $[\Xi_{cc}\Xi_{cc}^*]_+({}^5S_2, {}^5D_2, {}^5G_2)$, $\Xi_{cc}^*\Xi_{cc}^*({}^3D_2, {}^7D_2, {}^7G_2)$
$1(2^+)$	$\Xi_{cc}\Xi_{cc}({}^1D_2)$, $[\Xi_{cc}\Xi_{cc}^*]_+({}^3D_2)$, $[\Xi_{cc}\Xi_{cc}^*]_-({}^5S_2, {}^5D_2, {}^5G_2)$, $\Xi_{cc}^*\Xi_{cc}^*({}^1D_2, {}^5S_2, {}^5D_2, {}^5G_2)$

Wavefunction for $\bar{D}^{(*)}\Xi_{cc}^{(*)}$





Wavefunction for $\Xi_{cc}^{(*)}\Xi_{cc}^{(*)}$