Analysis of $\bar{D}^{(*)}\Xi_{cc}^{(*)}$ and $\Xi_{cc}^{(*)}\Xi_{cc}^{(*)}$ molecules as superflavor partners of T_{cc}

M. Sakai, Y. Yamaguchi, PRD 114(2026)014053

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Nagoya University

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Yasuhiro Yamaguchi
Tokyo Metropolitan University

Fundamental Problems in Subatomic Physics, 25th Sep.

Outline

1. Introduction

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

3. Summary

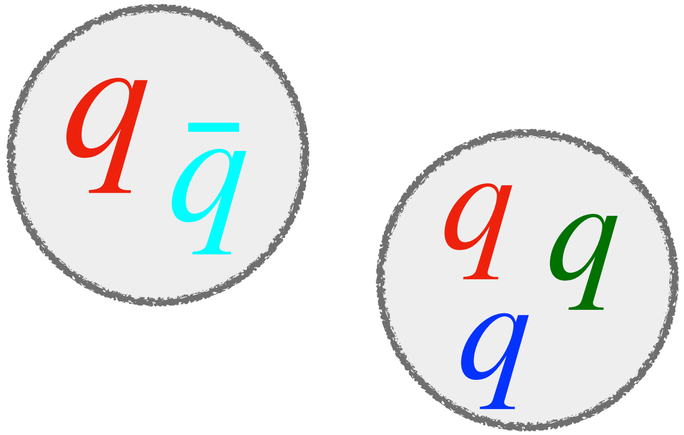
1. Introduction

Hadron and Exotic hadron

- **Hadron**:

  Composite particle of quarks and gluons

  Mesons $\sim q\bar{q}$ (e.g. π, ρ, D), Baryons $\sim qqq$ (e.g. p, n, Ξ_{cc})

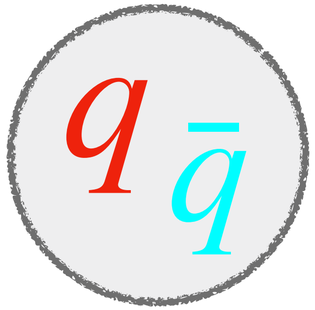


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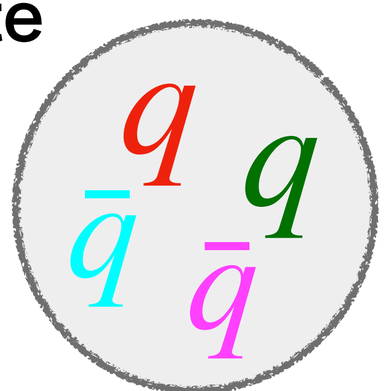


- **Exotic hadron**:

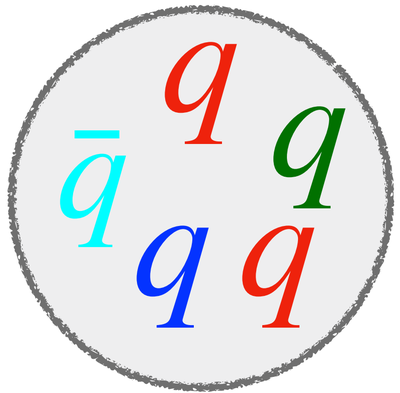
  Hadron which cannot be explained by the ordinary hadron pictures ($q\bar{q}$ and qqq)

  Most of exotic hadrons are multiquark states,

Tetraquark state



Pentaquark state

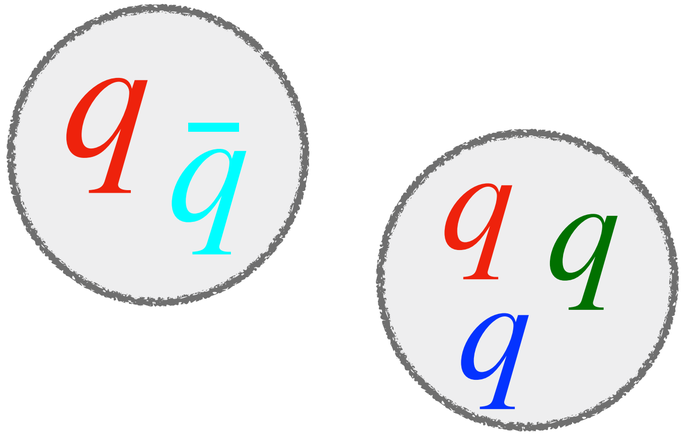


Hadron and Exotic hadron

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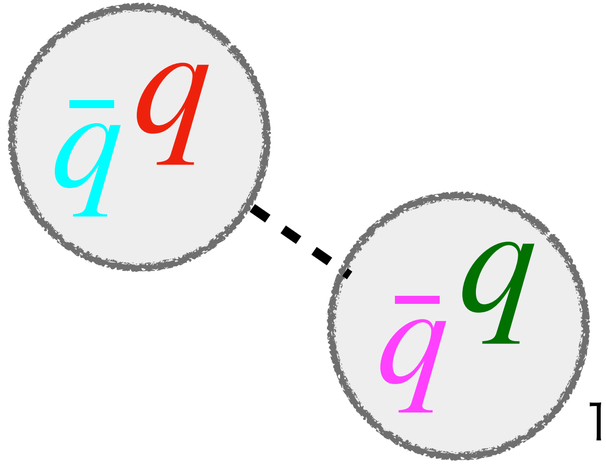
  Most of exotic hadrons are multiquark states,

  but the internal structures are not well-known

Compact state



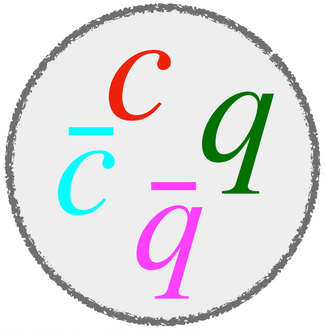
Molecular state



Exotic hadron

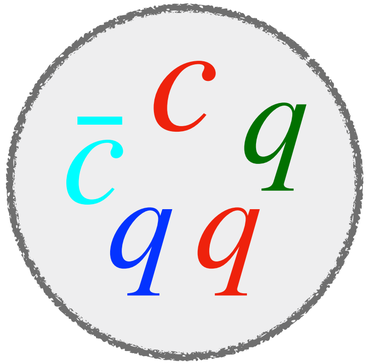
- $X(3872)$:

$\sim c\bar{c}q\bar{q}$



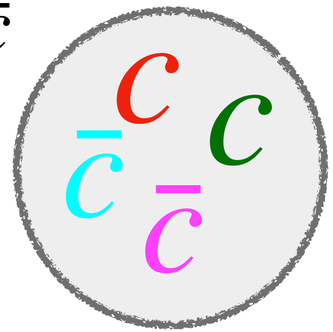
- P_c:

$\sim c\bar{c}qqq$

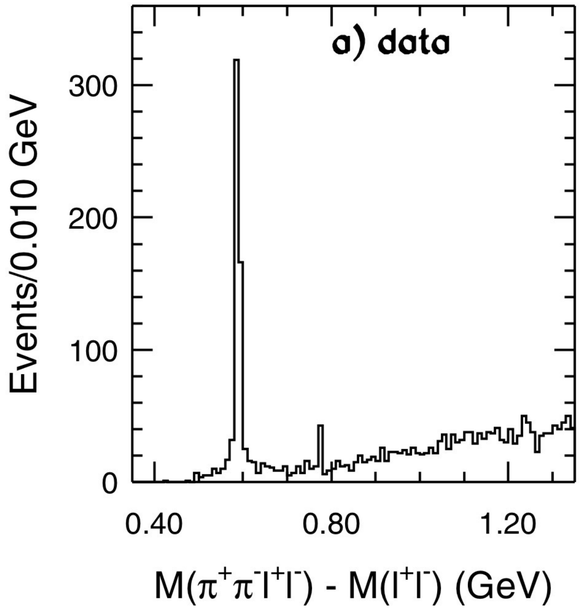


- $X(6900)$:

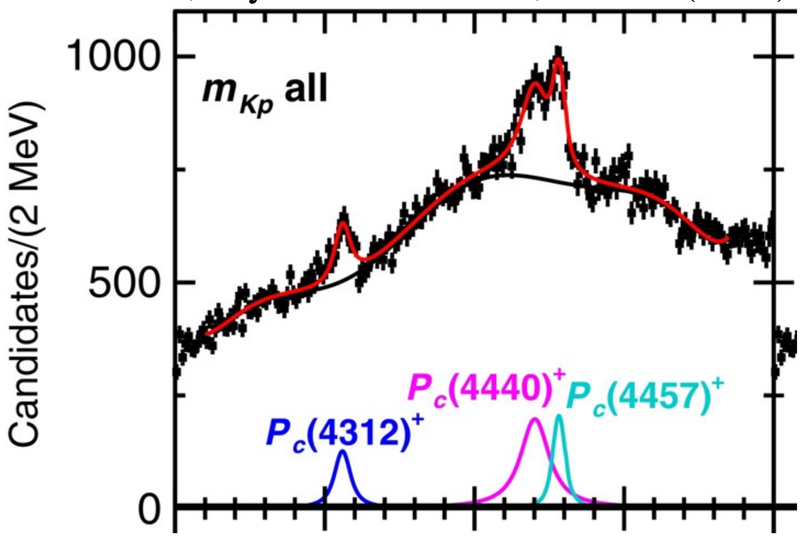
$\sim cc\bar{c}\bar{c}$



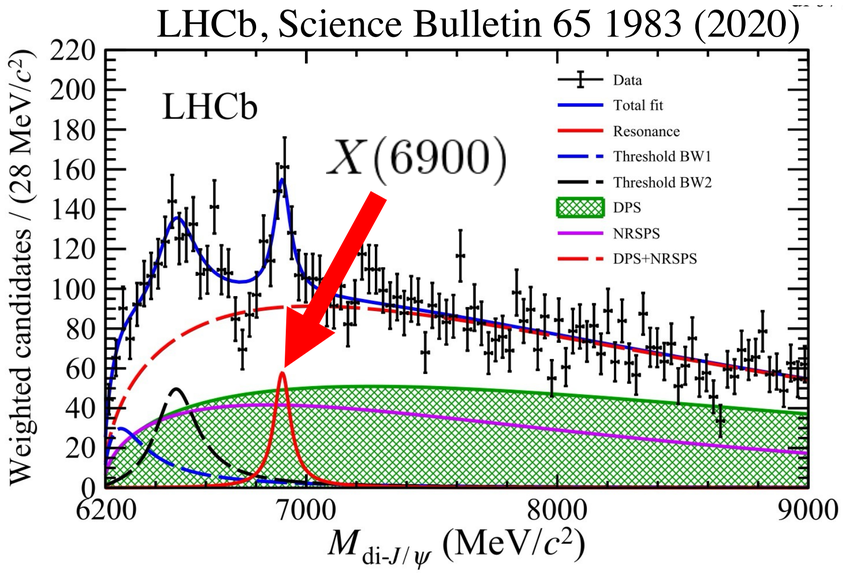
Belle, Phys. Rev. Lett. 91, 262001 (2003)



LHCb, Phys. Rev. Lett. 122, 222001 (2019)



LHCb, Science Bulletin 65 1983 (2020)

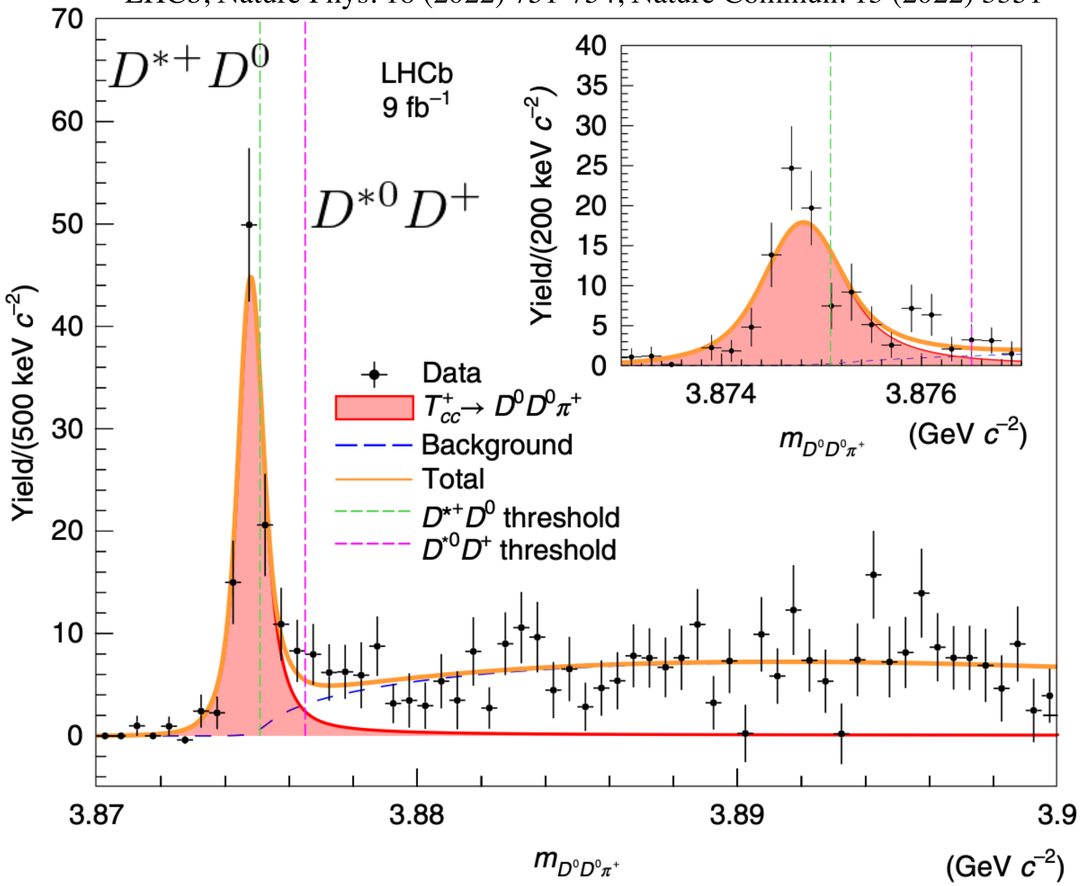


$T_{cc}(cc\bar{u}\bar{d})^+$

- T_{cc} has been reported by LHCb in 2022.

LHCb, Nature Phys. 18 (2022) 751-754, Nature Commun. 13 (2022) 3351

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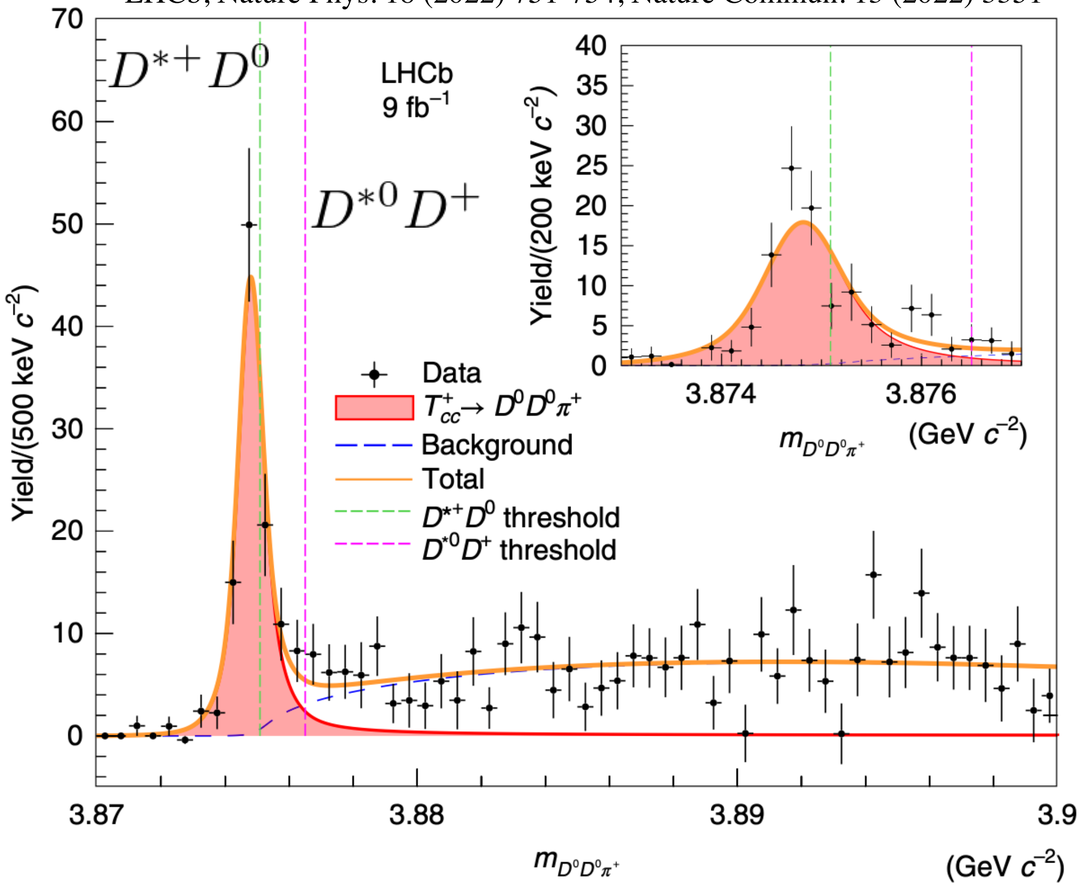
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- $cc\bar{u}\bar{d}$ (Charm number=2, Baryon number=0)

➡ **Genuine exotic!**

- $I = 0,\ J^P = 1^+$ (by LHCb)

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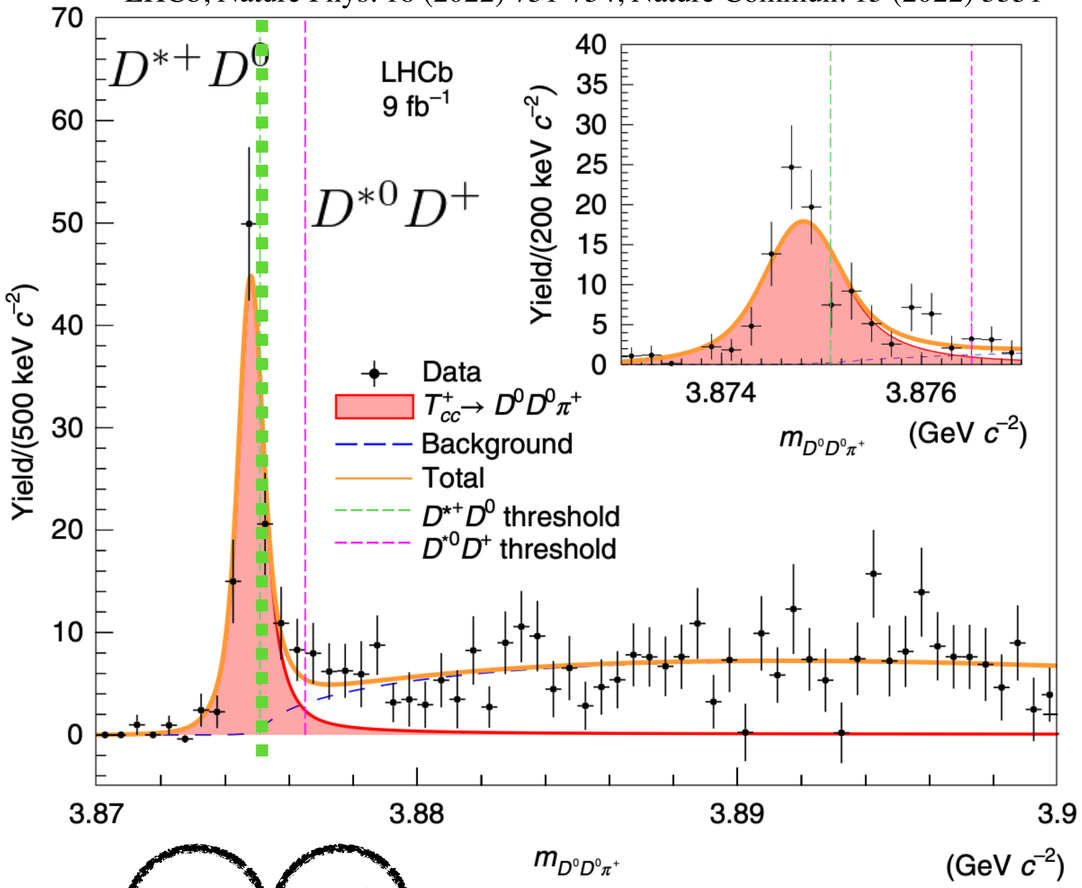
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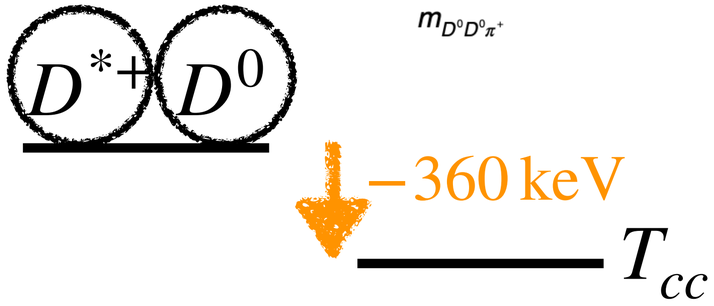
- $I = 0,\ J^P = 1^+$ (by LHCb)
- Mass difference measured from $D^{*+}D^0$ thr.
- ✱ Pole analysis

  $\delta m = -360 \pm 40\,\mathrm{keV}/c^2,\ \Gamma = 48 \pm 2\,\mathrm{keV}$

➡ **T_{cc} lies slightly below the $D^{*+}D^0$ thr.**

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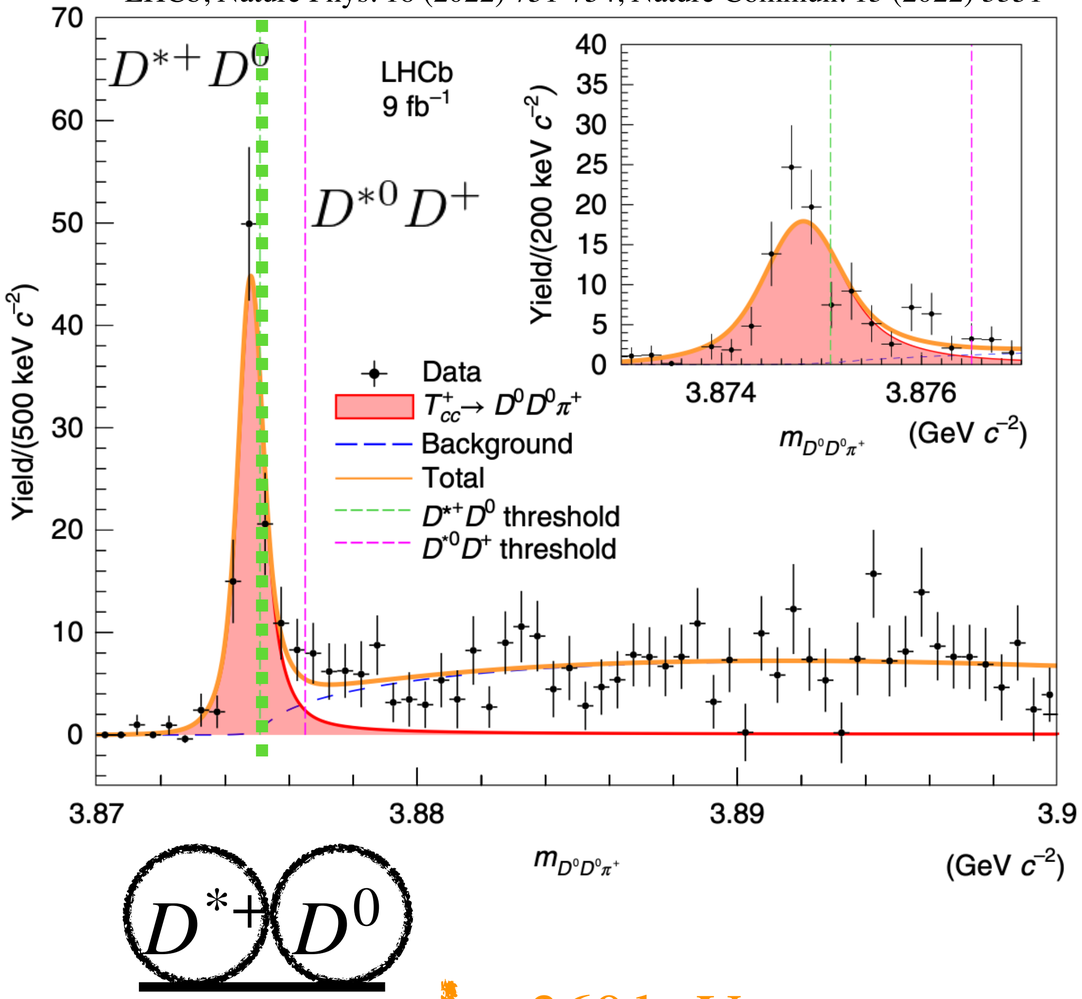
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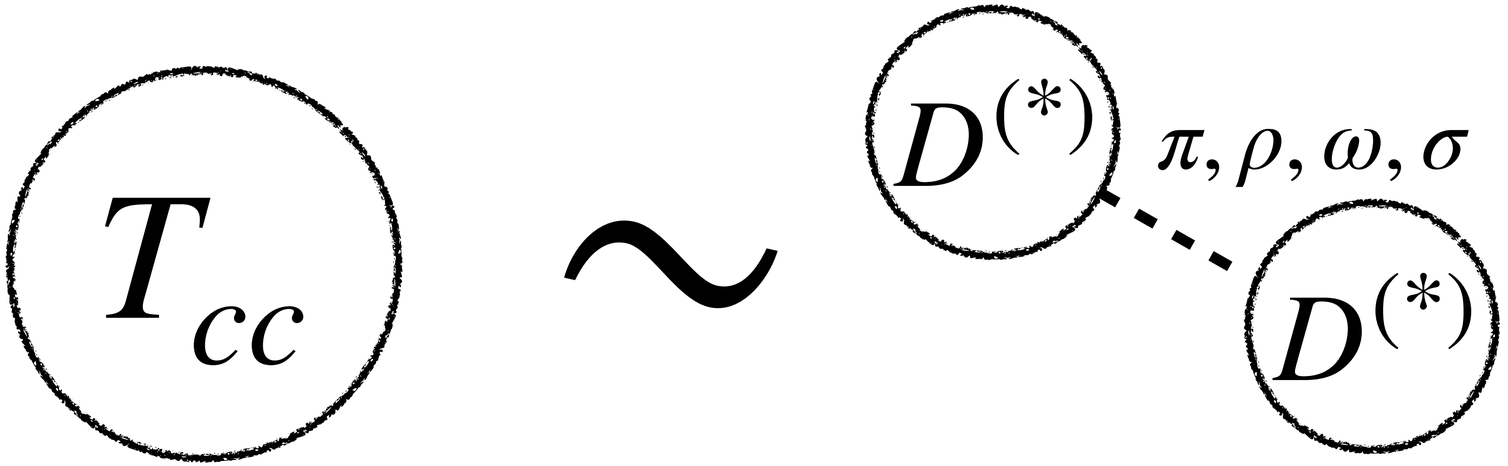
➡ **T_{cc} is expected to be a DD^* molecule!**

LHCb, Nature Phys. 18 (2022) 751-754, Nature Commun. 13 (2022) 3351



Our previous study

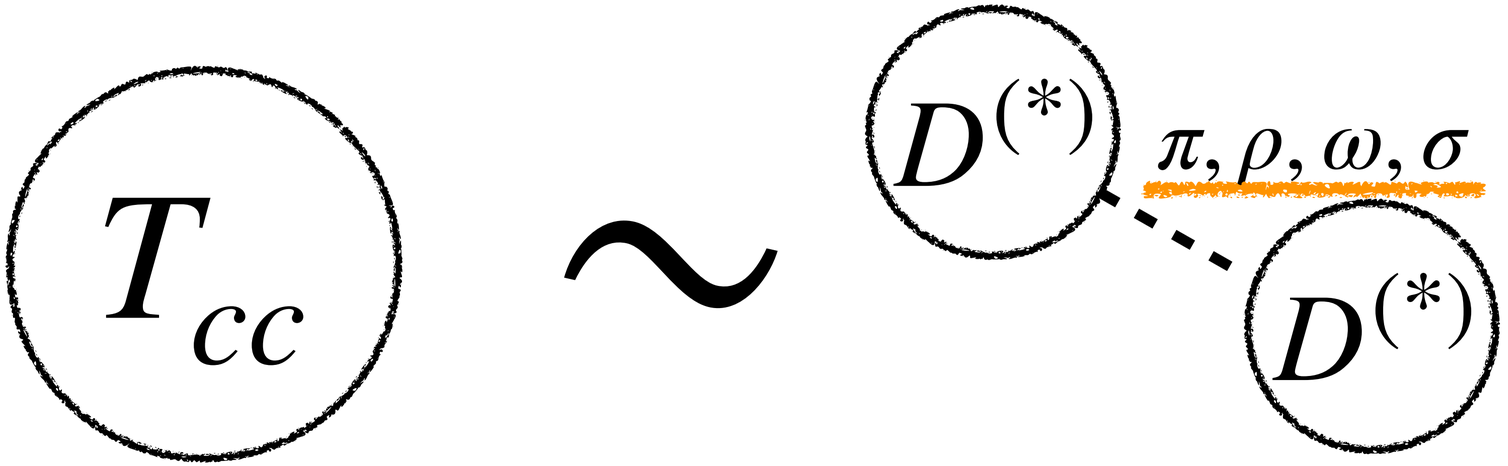
M.S., Y. Yamaguchi, PRD109(2024)054016, PRD112(2025)034038



- T_{cc} is considered as a $D^{(*)}D^{(*)}$ molecule.

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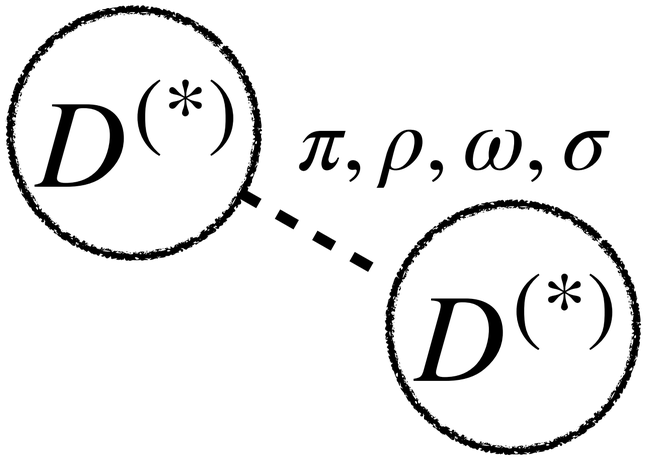
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M.S., Y. Yamaguchi, PRD109(2024)054016, PRD112(2025)034038

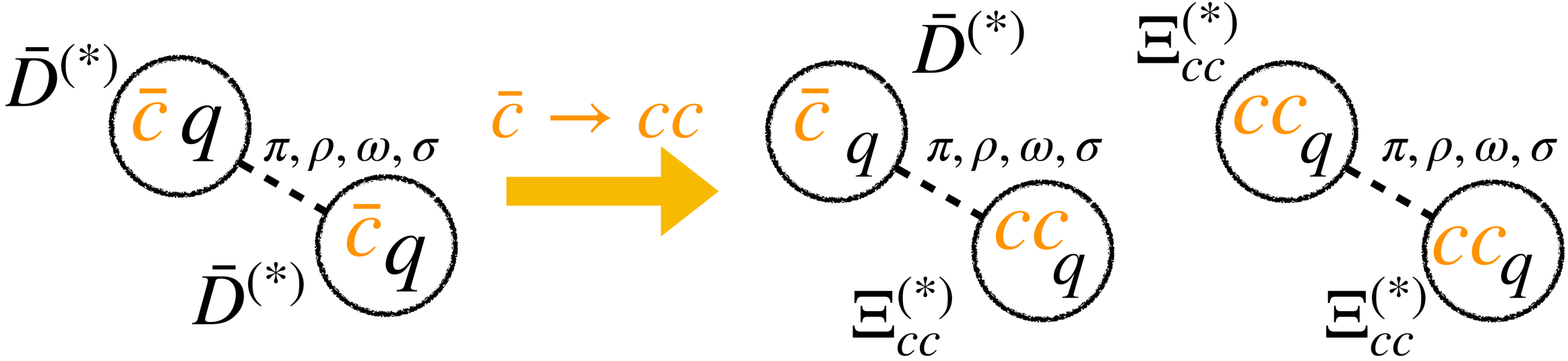




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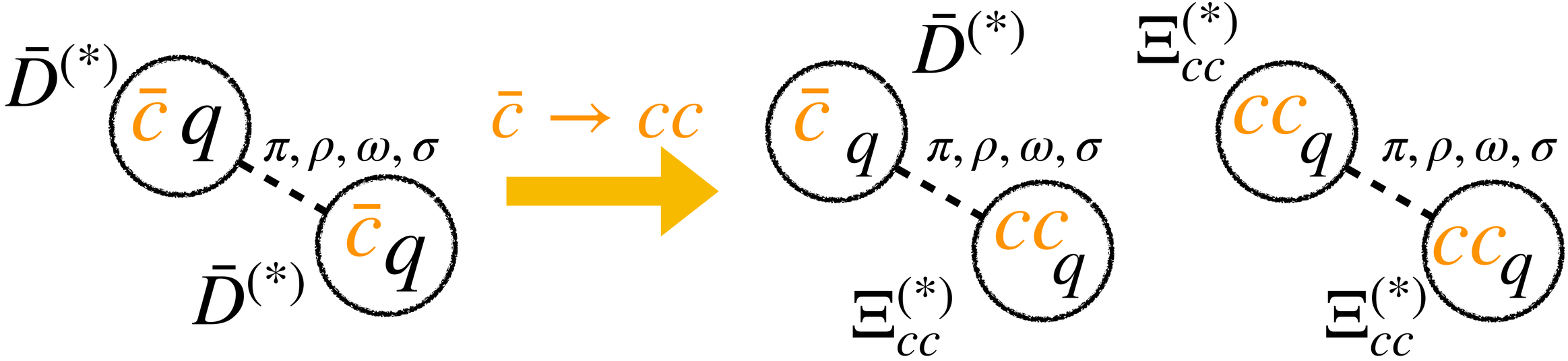
→ **Coupled channel system!**

$\bar{D}^{(*)}\Xi_{cc}^{(*)}$ and $\Xi_{cc}^{(*)}\Xi_{cc}^{(*)}$ as superflavor partner of T_{cc}



- **Superflavor symmetry**: Symmetry between antiheavy quark ($\bar{c}$) and heavy diquark (cc)

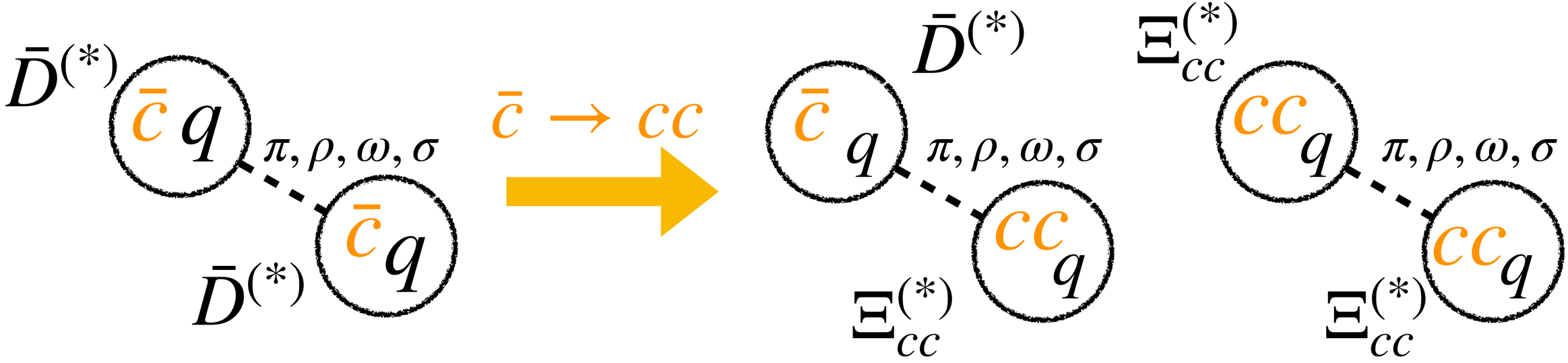
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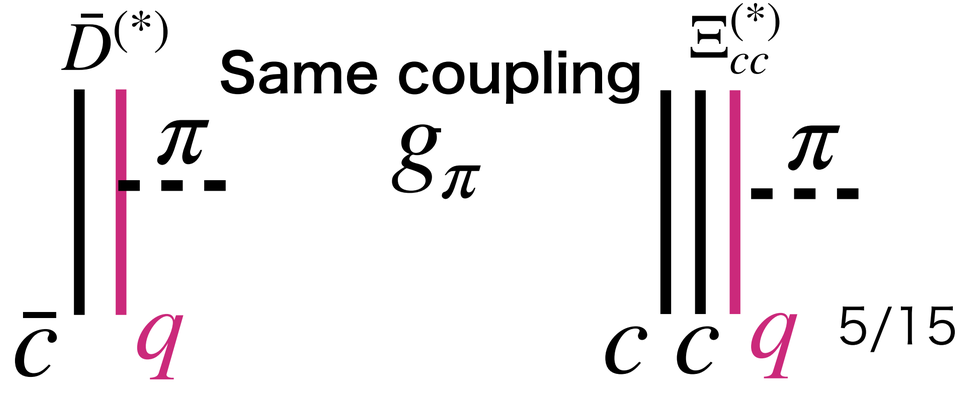
* Interaction: **One boson exchange potential**

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

- $\bar{D}^{(*)}\Xi_{cc}^{(*)}$: T. Asanuma, et al,. PRD110(2024)074030
  - Calculation of bound states of $\bar{D}^{(*)}\Xi_{cc}^{(*)}$

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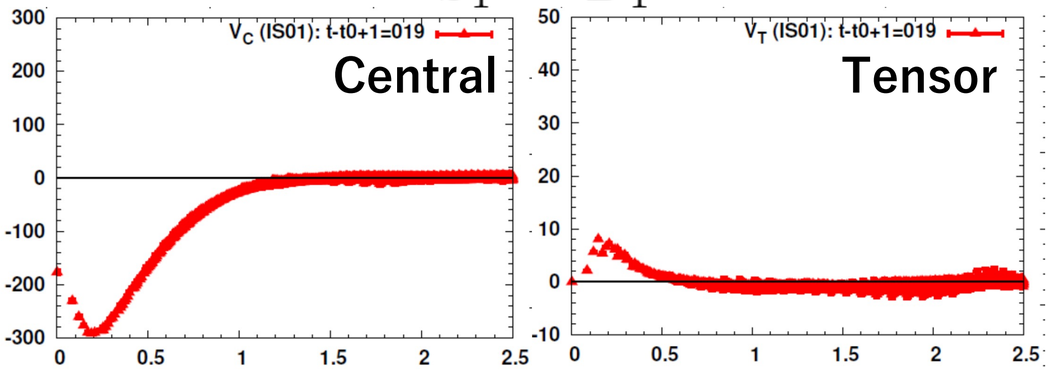
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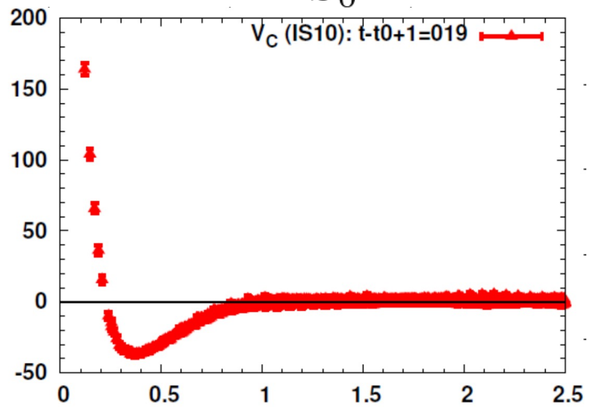
→ **Calculation of bound and resonant states of $\bar{D}^{(*)}\Xi_{cc}^{(*)}$ using the same framework**

- $\Xi_{cc}\Xi_{cc}$ with $I(J^P) = 0(1^+), 1(0^+)$: Slides from HHIQCD 2024 by Doi
  - Calculation of $\Xi_{cc}\Xi_{cc}$ by HAL QCD

$^3S_1 - ^3D_1$



$^1S_0$



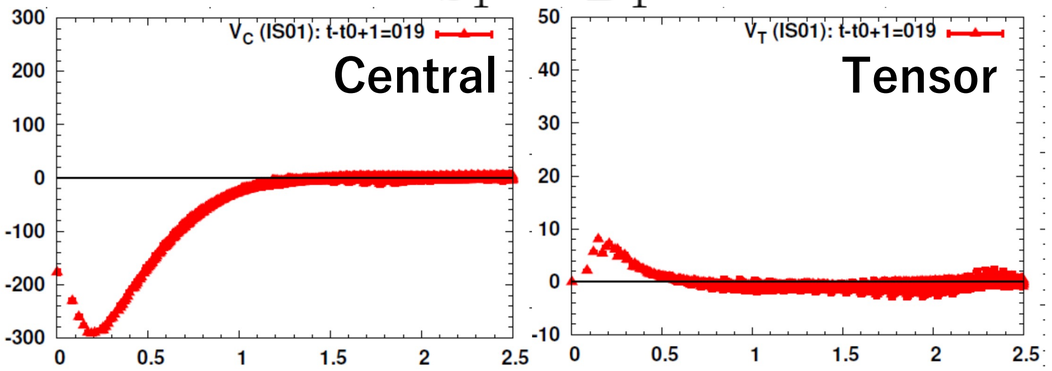
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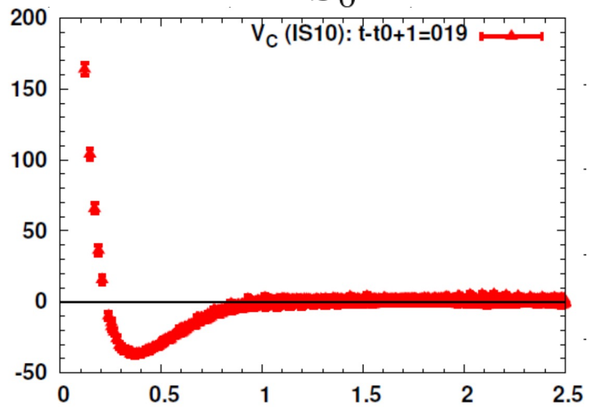
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$^3S_1 - ^3D_1$



$^1S_0$



→ **Calculation of bound and resonant states of $\Xi_{cc}^{(*)}\Xi_{cc}^{(*)}$ using the effective model**

Coupled channel system for $\bar{D}^{(*)}\Xi_{cc}^{(*)}$ and $\Xi_{cc}^{(*)}\Xi_{cc}^{(*)}$

- **Heavy quark spin symmetry** induces:

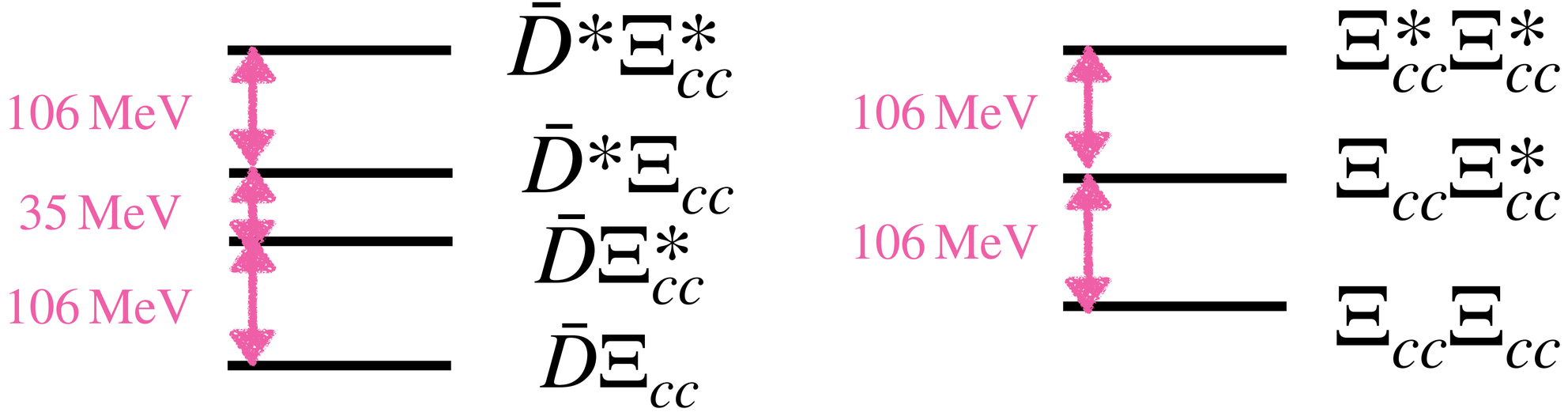
  Small mass differences between $\bar{D}$ and $\bar{D}^*/\Xi_{cc}$ and Ξ_{cc}^*!

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- $\bar{D}^{(*)}\Xi_{cc}^{(*)}$ **and** $\Xi_{cc}^{(*)}\Xi_{cc}^{(*)}$ **threshold** J. Hu and T. Mehen, PRD73(2006)054003



The relevant thresholds are nearly degenerate.

Coupled channel system for $\bar{D}^{(*)}\Xi_{cc}^{(*)}$ and $\Xi_{cc}^{(*)}\Xi_{cc}^{(*)}$

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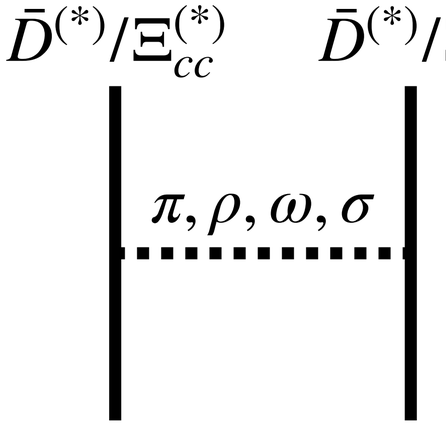
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→ **The relevant thresholds are nearly degenerate.**

→ **Coupled channel system** is considered.

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



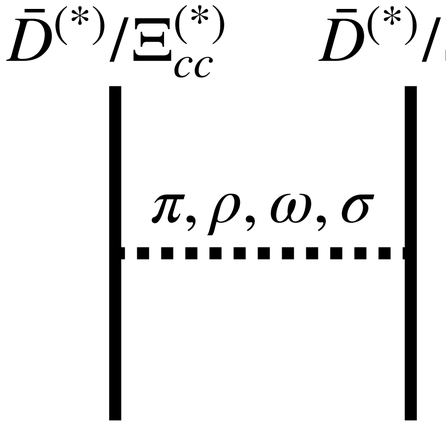
$\boldsymbol{\pi}$ $$V^{\pi}(r) = k_{\pi}\frac{1}{3}\left(\frac{g}{2f_{\pi}}\right)^2[\vec{\mathcal{O}}_1\cdot\vec{\mathcal{O}}_1 C(r;m_{\pi}) + S_{12}(\hat{r})T(r;m_{\pi})]\vec{\tau}_1\cdot\vec{\tau}_2$$

$\boldsymbol{\rho, \omega}$ $$V^{v}(r) = \left(\frac{\beta g_V}{2m_v}\right)^2 C(r;m_v)\vec{\tau}_1\cdot\vec{\tau}_2 + k_{\lambda}\frac{1}{3}(\lambda g_V)^2[2\vec{\mathcal{O}}_1\cdot\vec{\mathcal{O}}_1 C(r;m_v) - S_{12}(\hat{r})T(r;m_v)]\vec{\tau}_1\cdot\vec{\tau}_2$$

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

Form factor: $F(\vec{q};m) = \dfrac{\Lambda^2 - m^2}{\Lambda^2 + \vec{q}^2}$

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



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

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- Coupling constant:

S. Ahmed et al., CLEO Collaboration, PRL.(2001)251801. M.-Z Liu et al., PRD99(2019)094018, C. Isola, PRD 68(2003)114001, R.Chen et al., PRL96(2017)116012, N. Li et al., PRD88(2013)114008

π: $g = 0.59$ ($D^* \to D\pi$ decay),

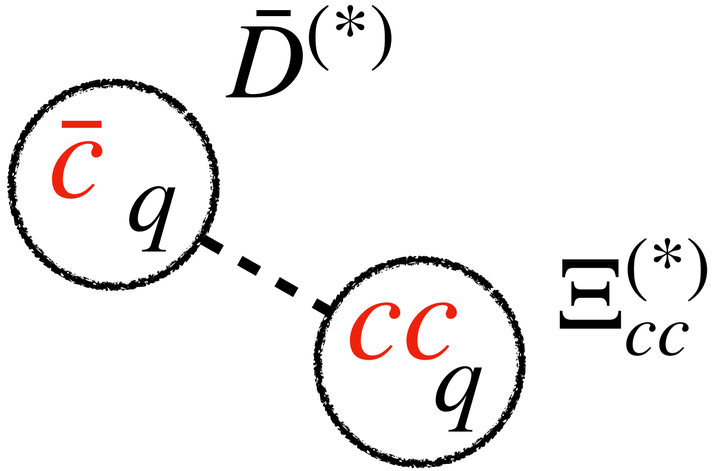
ρ, ω: $\beta = 0.9$ (Lattice QCD), $\lambda = 0.56\,\mathrm{GeV}^{-1}$ (B meson decay)

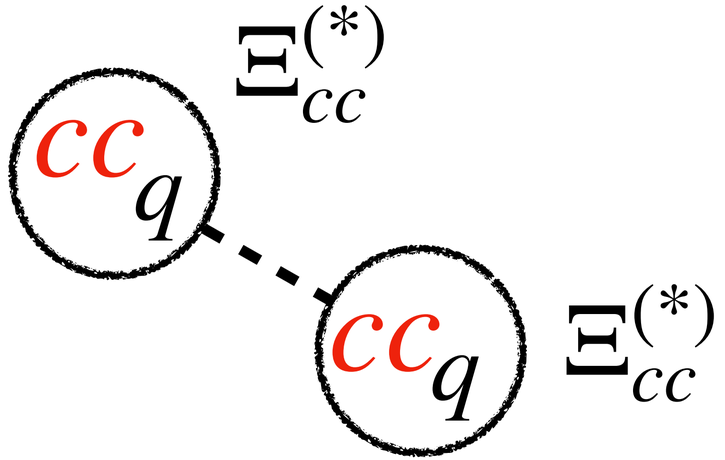
σ (Unknown parameter):

Two typical values: $g_{\sigma}^{L} = g_{\sigma NN}/3 = 3.4$, $g_{\sigma}^{S} = g_{\pi}/2\sqrt{6} = 0.76$

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

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





- Solve the coupled-channel Schrödinger equation.
- Using the Gaussian expansion method and complex scaling method
  E. Hiyama et al., Prog. Part. Nucl. Phys.51(2003)223, E. Hiyama et al., Front.Phys.(Beijing)13(2018)132106
  P. Suzuki et al., AIP Conf. Proc768'2005)445, T. Myo et al., Prog.Part.Nucl.Phys.79(2014)1
- Channels:
  - $\bar{D}^{(*)}\Xi_{cc}^{(*)}(1/2^-)$: $\bar{D}\Xi_{cc}(^2S), \bar{D}\Xi_{cc}^*(^2S,^4D), \bar{D}^*\Xi_{cc}(^2S,^4D), \bar{D}^*\Xi_{cc}(^2S,^4D,^6D)$
  - $\Xi_{cc}^{(*)}\Xi_{cc}^{(*)}(0(1^+))$: $\Xi_{cc}\Xi_{cc}(^3S,^3D), [\Xi_{cc}\Xi_{cc}^*]_-(^3S,^3D), [\Xi_{cc}\Xi_{cc}^*]_+(^5D), \Xi_{cc}^*\Xi_{cc}^*(^3S,^3D,^7D,^7G)$

Determination of cutoff parameter Λ

- Cutoff parameter Λ: (Form factor: $F(\Lambda; m) = (\Lambda^2 - m^2)/(\Lambda^2 + \vec{q}^2)$)

  Determined to reproduce the binding energy of T_{cc} ($\delta m_{T_{cc}} = 360\,\mathrm{keV}$):

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One σ exchange potential does not plays an most important role.

$\Rightarrow$ One π and one ρ exchange potentials need to provide stronger attraction

Bound states of $\bar{D}^{(*)}\Xi_{cc}^{(*)}$ with $J^P = \frac{1}{2}^-$

- Bound states of $\bar{D}^{(*)}\Xi_{cc}^{(*)}$ with $J^P = \frac{1}{2}^-$ are obtained in both cases of g_σ^L, g_σ^S:
- Binding energy: $7.87\,\mathrm{MeV}$ for g_σ^L, $20.5\,\mathrm{MeV}$ for g_σ^S

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Mixing ratio	g_σ^L	g_σ^L
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$\bar{D}\Xi_{cc}^*(^4D)$	0%	0%
$\bar{D}^*\Xi_{cc}(^2S)$	0.104%	1.18%
$\bar{D}^*\Xi_{cc}(^4D)$	0.136%	0.378%
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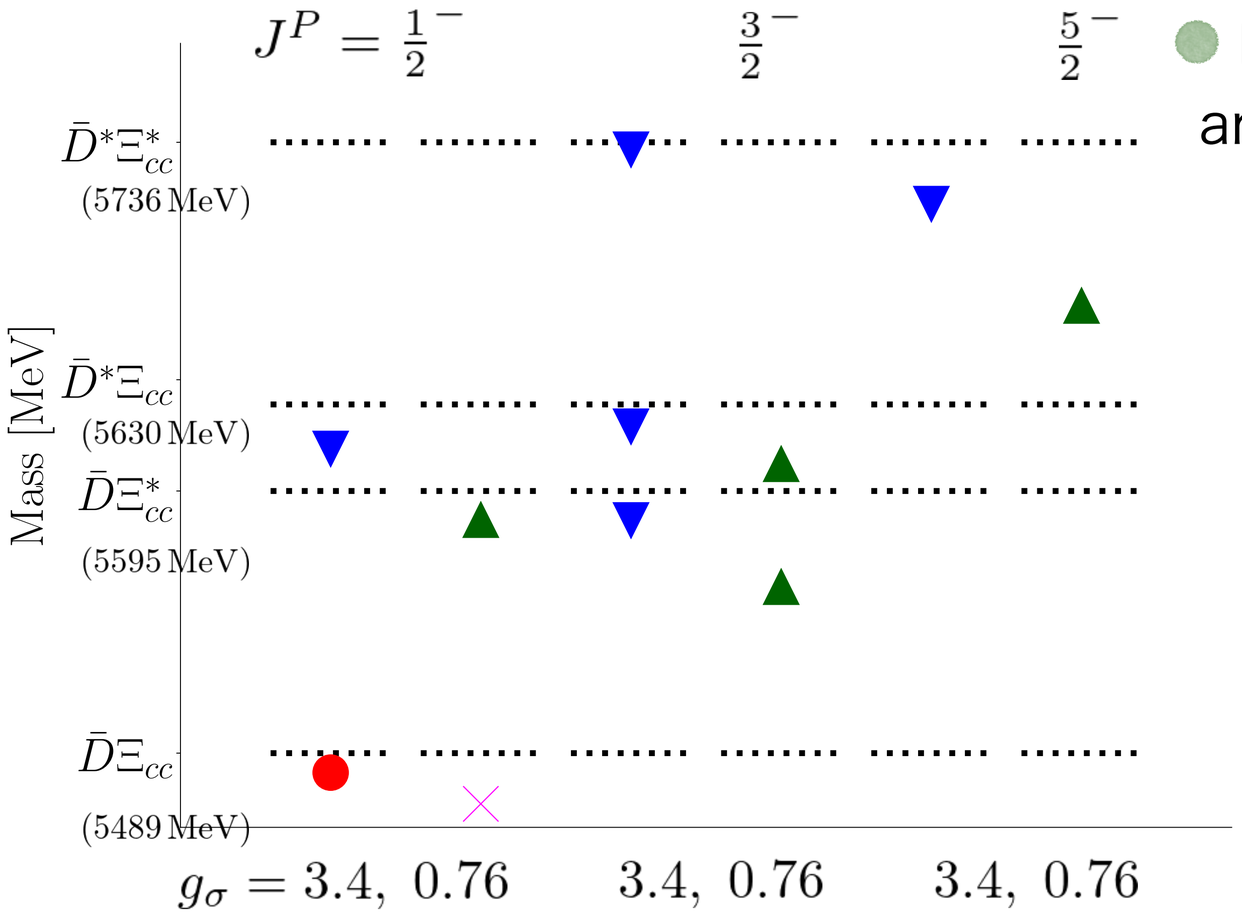
→ **One σ exchange potential is dominant**

- For g_σ^S, other channels $\geq 1\,\%$

→ **One π and One ρ exchange potentials play an important role**

(reflecting $\Lambda^L < \Lambda^S$)

$\bar{D}^{(*)}\Xi_{cc}^{(*)}$ with some quantum numbers J^P

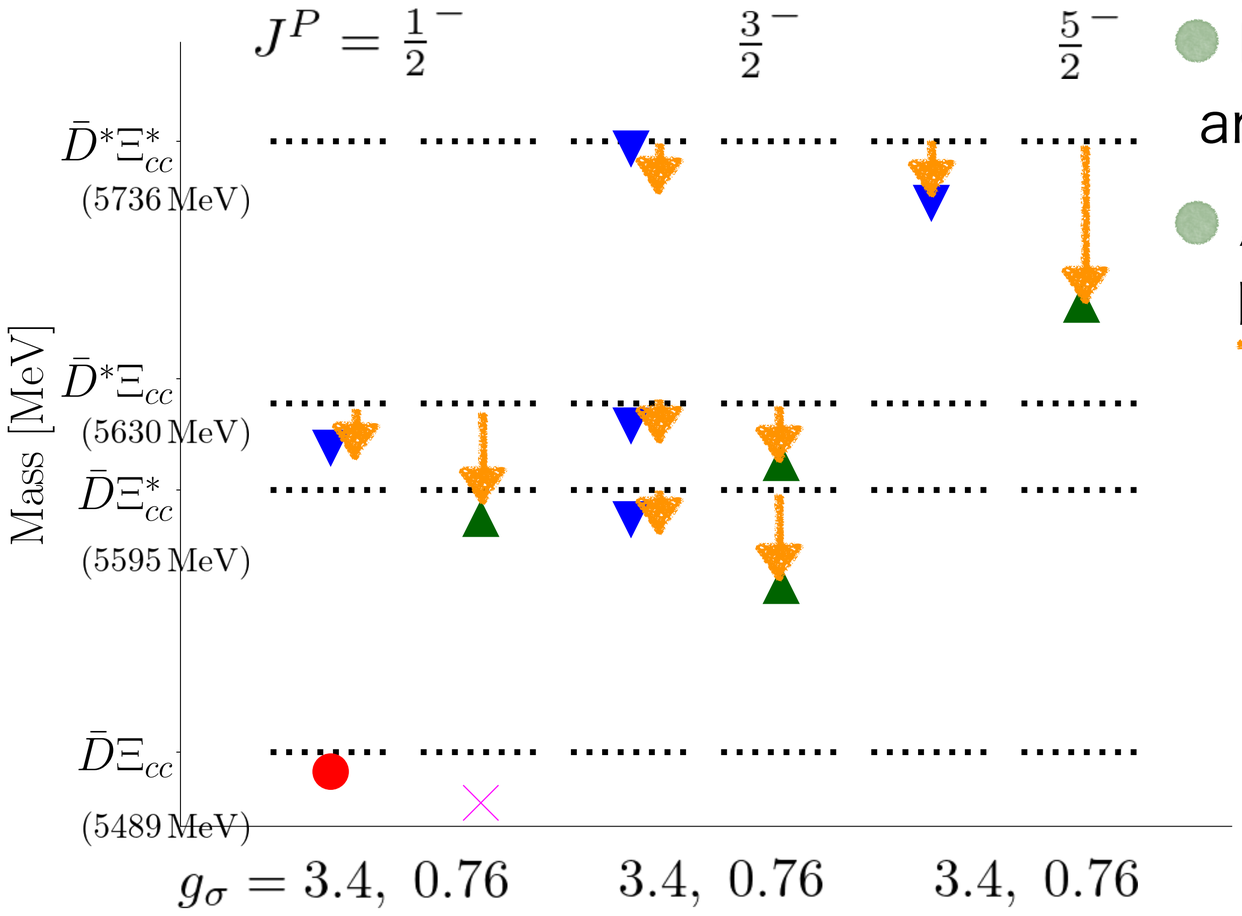


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● Bound state with g_σ^L × Bound state with g_σ^S

▼ Resonance with g_σ^L ▲ Resonance with g_σ^S

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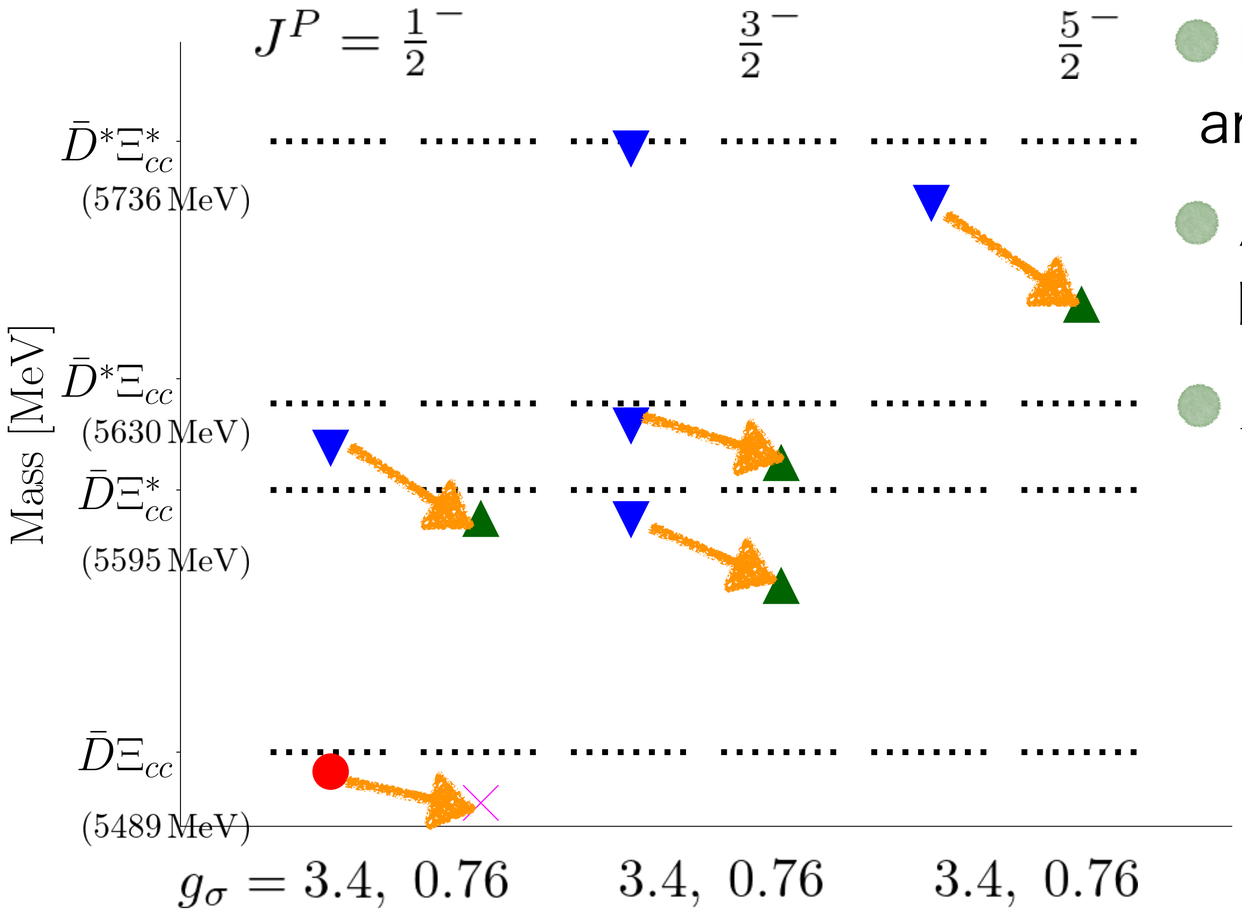


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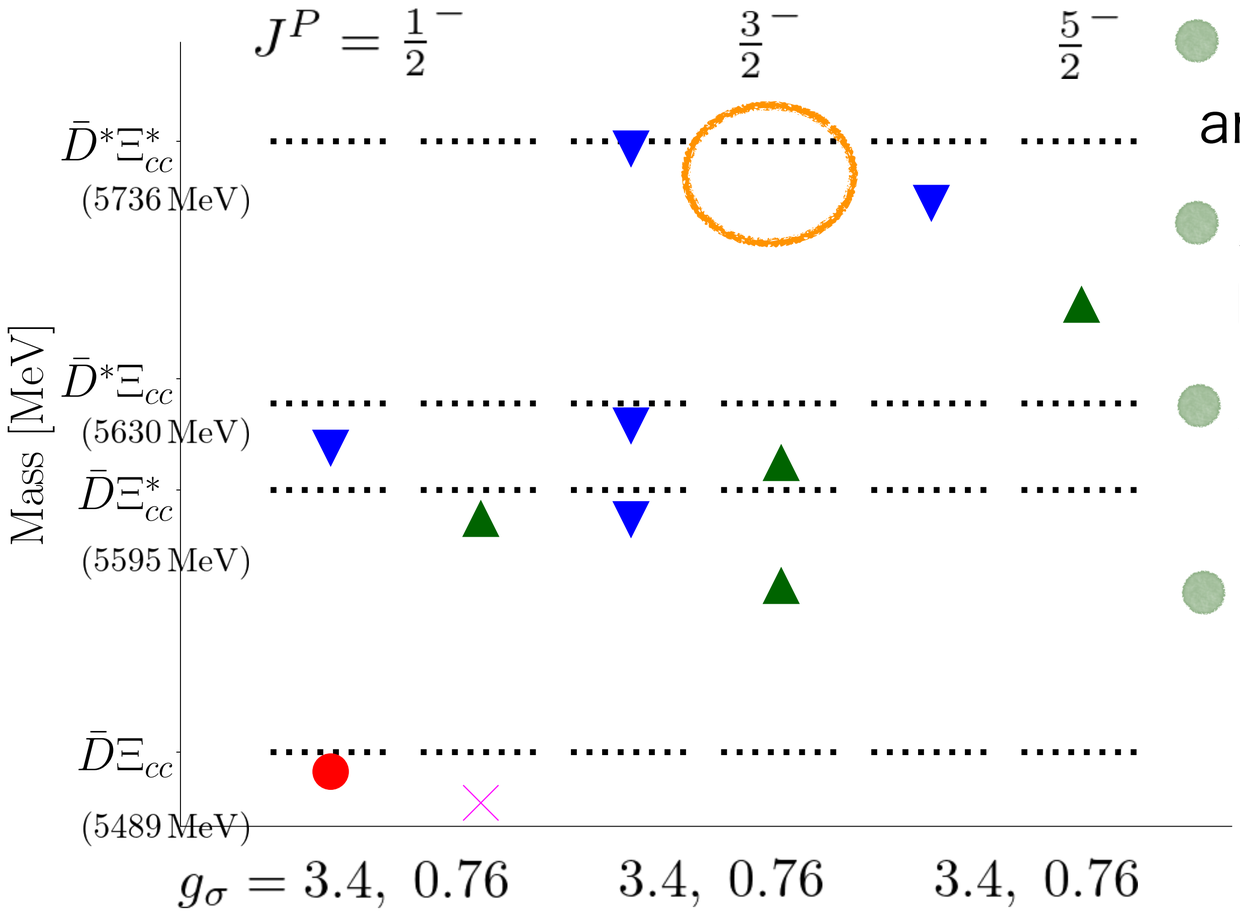


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- $\bar{D}^{(*)}\Xi_{cc}^{(*)}$ with g_σ^S is more deeply bound than $\bar{D}^{(*)}\Xi_{cc}^{(*)}$ with g_σ^L ($\because\ \Lambda^L < \Lambda^S$).

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- For g_σ^S, a quasi bound state of $\bar{D}^*\Xi_{cc}^*$ with $3/2^-$ is not found.

$\because$ One-π and One-ρ exchange potentials cannot generate enough attraction.

Bound states of $\Xi_{cc}^{(*)}\Xi_{cc}^{(*)}$ with $0(1^+)$

- Bound states of $\Xi_{cc}^{(*)}\Xi_{cc}^{(*)}$ with $I(J^P) = 0(1^+)$ are obtained in both cases of g_σ^L, g_σ^S:
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Mixing ratio	g_σ^L	g_σ^L
$\Xi_{cc}\Xi_{cc}(^3S)$	96.6%	85.9%
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➡ **One σ exchange potential is important**

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✱ For g_σ^S, other channels $\geq 1\,\%$

➡ **One π and One ρ exchange potentials play an important role** (reflecting $\Lambda^L < \Lambda^S$)

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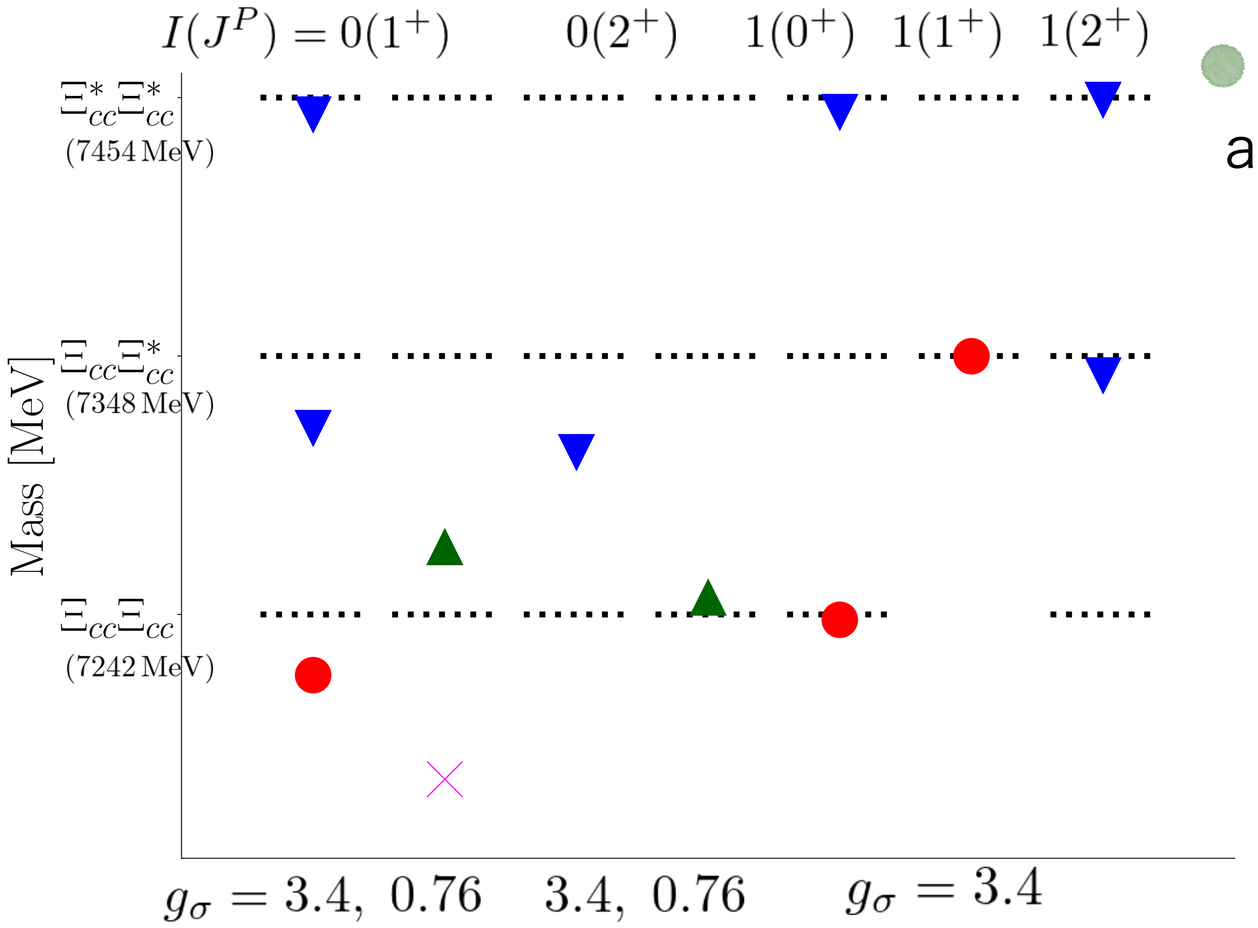
➡ **One π and One ρ exchange potentials play an important role** (reflecting $\Lambda^L < \Lambda^S$)

✱ Non trivial point:

$\Xi_{cc}^*\Xi_{cc}^*(^7D)$ is not negligible.

∵ Large Clebsh-Gordon coefficient

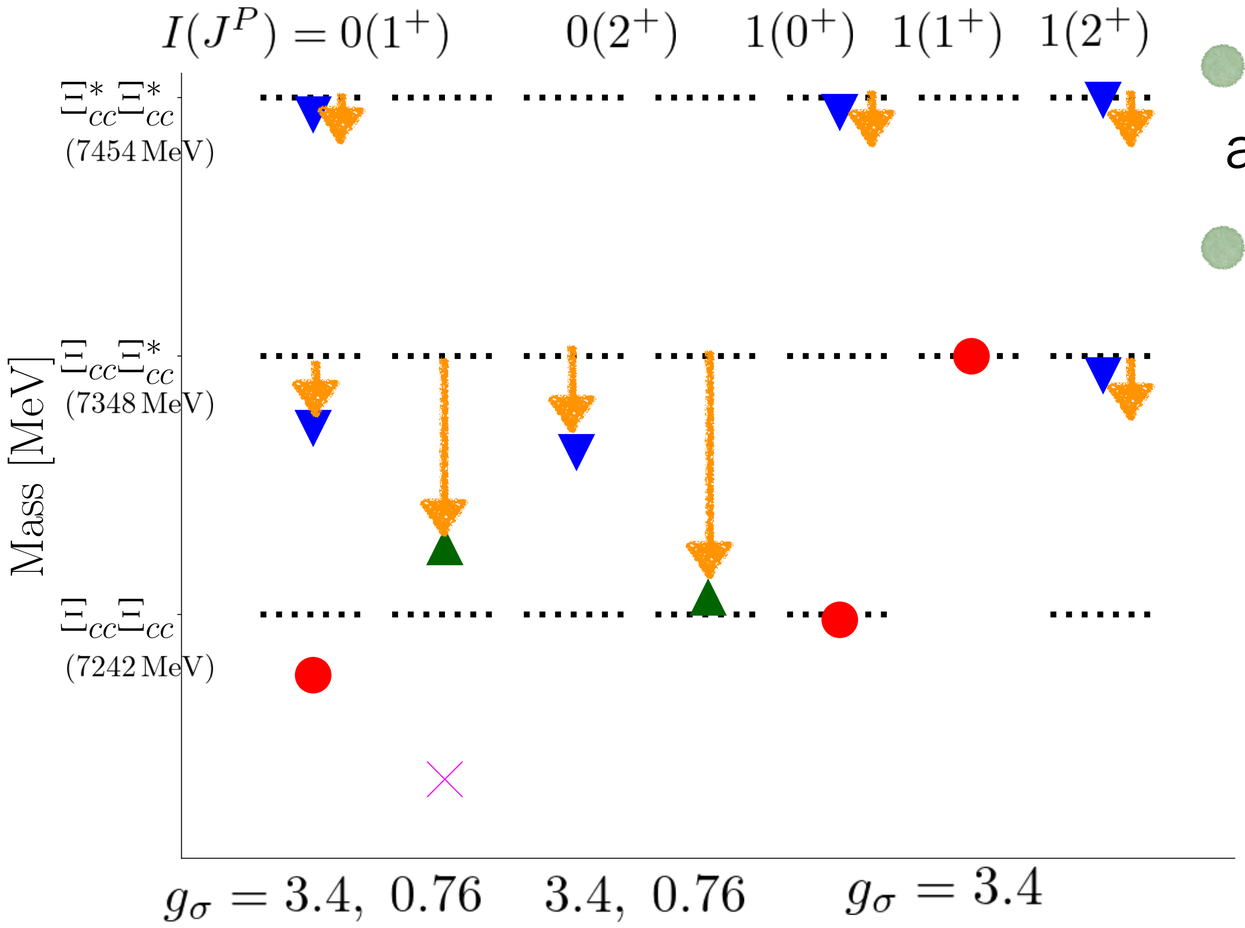
$\Xi_{cc}^{(*)}\Xi_{cc}^{(*)}$ with some quantum numbers $I(J^P)$



- Many bound and resonant states of $\Xi_{cc}^{(*)}\Xi_{cc}^{(*)}$ are found!

- Bound state with g_σ^L
- × Bound state with g_σ^S
- ▼ Resonance with g_σ^L
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$\Xi_{cc}^{(*)}\Xi_{cc}^{(*)}$ with some quantum numbers $I(J^P)$

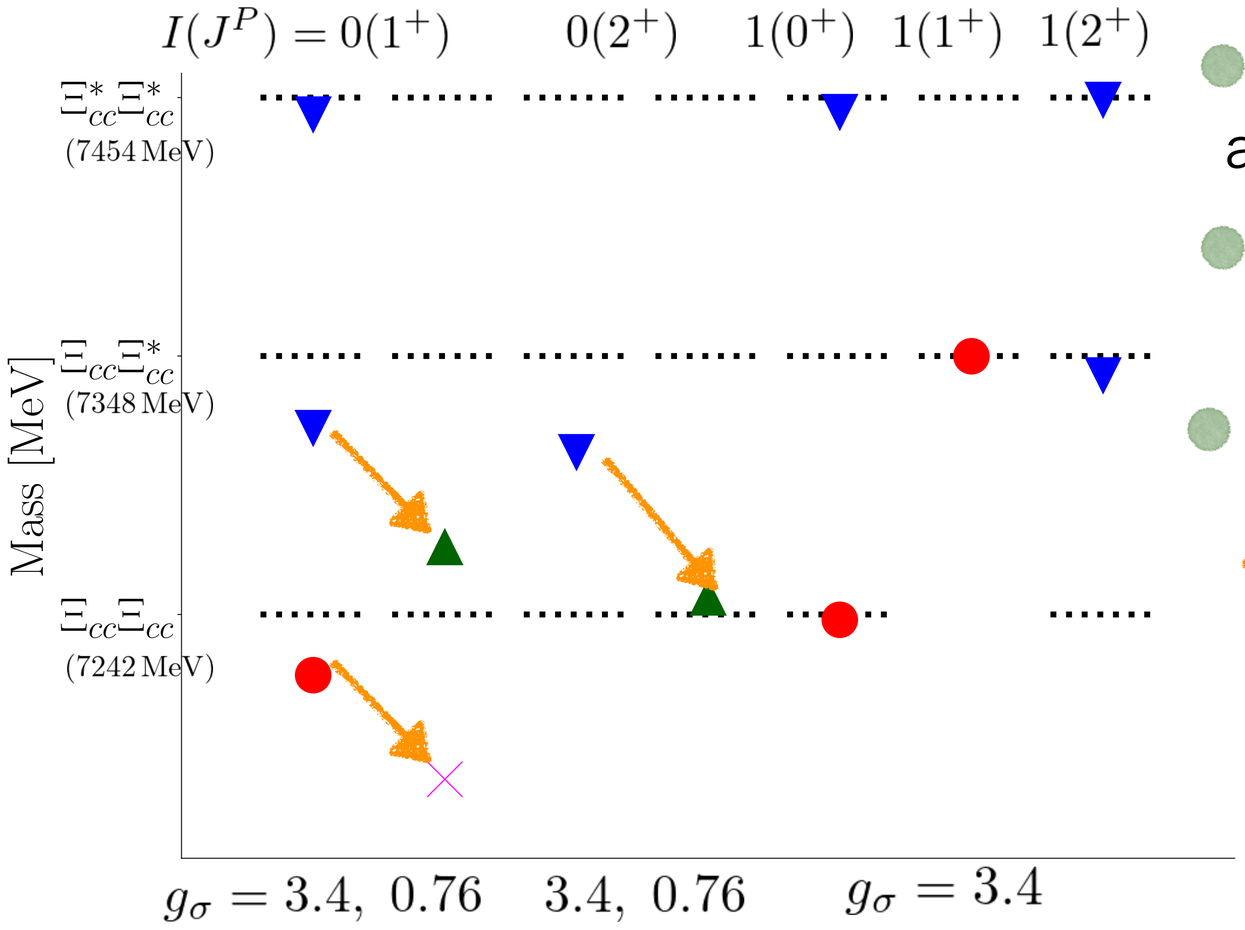


- Many bound and resonant states of $\bar{D}^{(*)}\Xi_{cc}^{(*)}$ are found!
- All resonant states of $\Xi_{cc}^{(*)}\Xi_{cc}^{(*)}$ are Feshbach resonances.

● Bound state with g_σ^L × Bound state with g_σ^S

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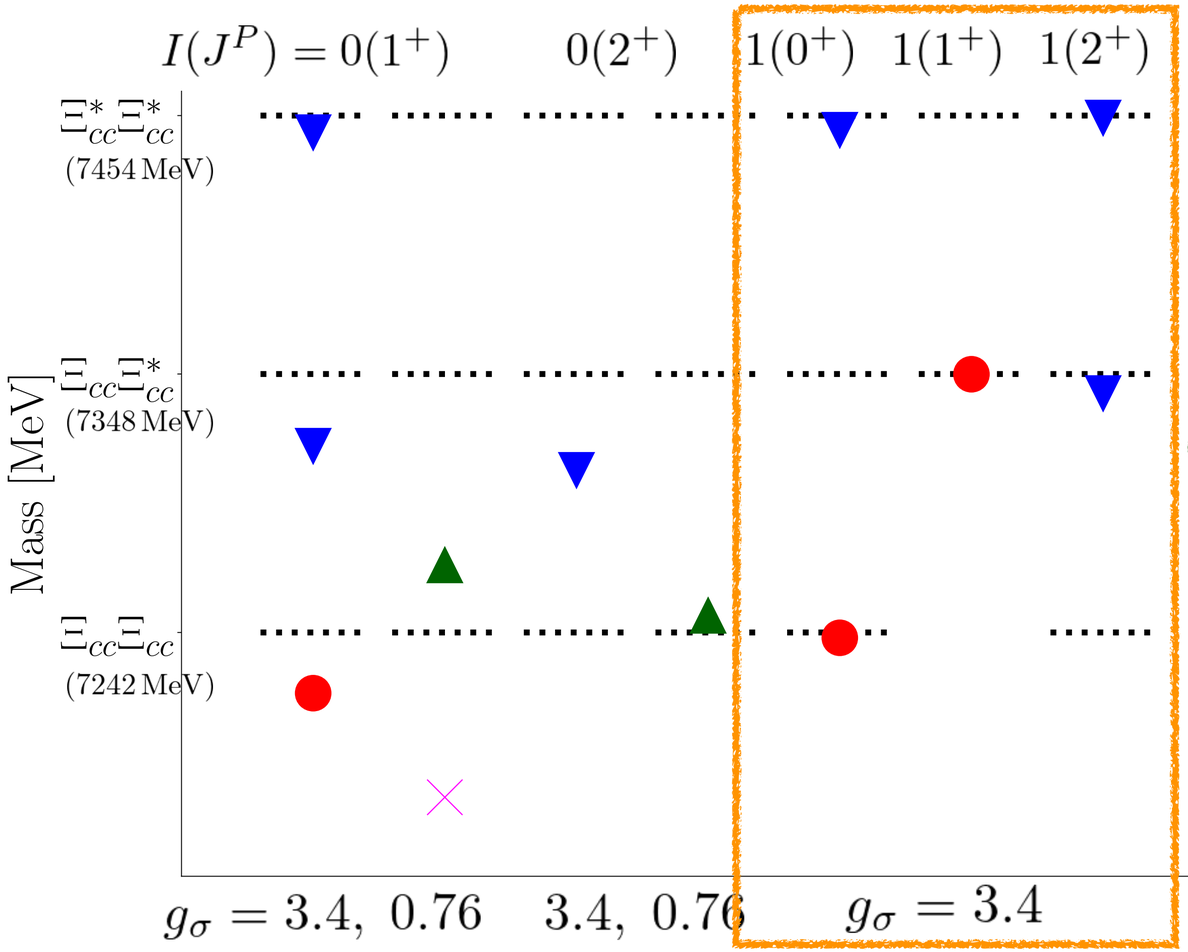


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- For $I = 0$, $\Xi_{cc}^{(*)}\Xi_{cc}^{(*)}$ with g_σ^S are more deeply bound than $\Xi_{cc}^{(*)}\Xi_{cc}^{(*)}$ with g_σ^L.

● Bound state with g_σ^L × Bound state with g_σ^S

▼ Resonance with g_σ^L ▲ Resonance with g_σ^S

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- For $I = 1$, $\Xi_{cc}^{(*)}\Xi_{cc}^{(*)}$ is found only with g_σ^L.

$\because$ One π and One ρ exchange potentials cannot generate enough attraction ($\vec{\tau}\cdot\vec{\tau} = 1$).

● Bound state with g_σ^L × Bound state with g_σ^S

▼ Resonance with g_σ^L ▲ Resonance with g_σ^S

3. Summary

Summary

- Analysis of $\bar{D}^{(*)}\Xi_{cc}^{(*)}$ and $\Xi_{cc}^{(*)}\Xi_{cc}^{(*)}$ as superflavor partners of T_{cc}
  - We constructed of the one boson exchange potential respecting superflaovor symmetry.
  - Many bound and resonant states of $\bar{D}^{(*)}\Xi_{cc}^{(*)}$ and $\Xi_{cc}^{(*)}\Xi_{cc}^{(*)}$ are found.
  - Mass spectra and properties of bound states depends strongly on g_σ.
- Outlook
  - Calculation of observables (e.g., phase shifts).
  - Inclusion of additional meson-exchange effects.

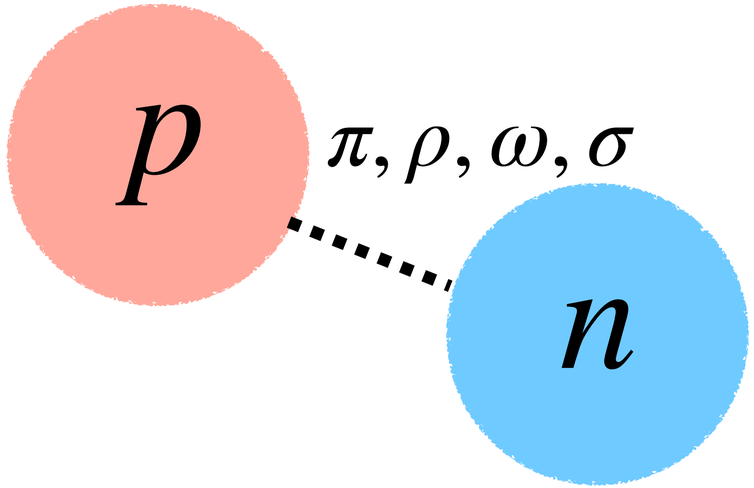
Back up

Deuteron

- **Deuteron**:

  A bound state of a proton and neutron

  Interaction: **One boson exchange potential**



- **One boson exchange potential**:

  Central potential + **Tensor potential**

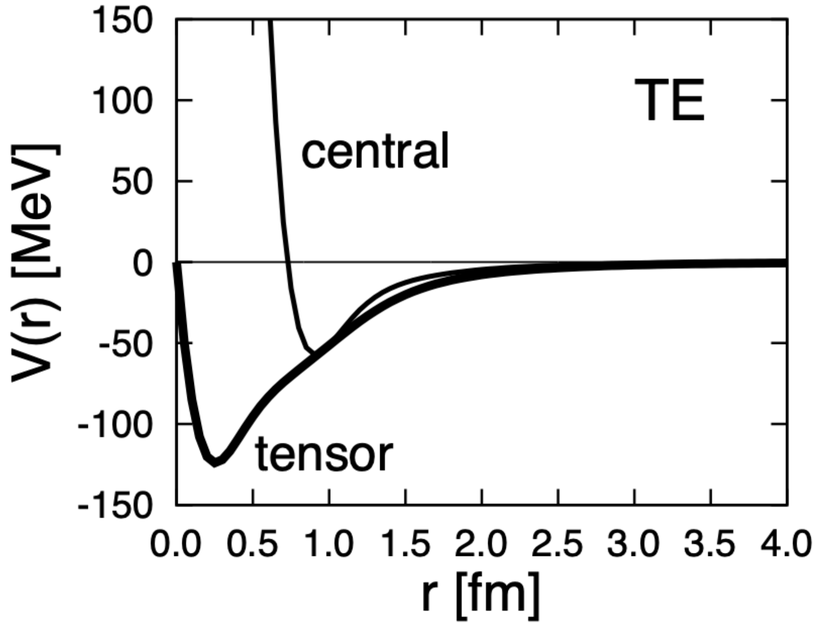
- **Tensor potential**:

  Plays an important role in binding a dueteron

  Induce the $S-D$ **mixing**

$$\langle S|S_{12}(\hat{r})|S\rangle = 0,\ \langle S|S_{12}(\hat{r})|D\rangle \neq 0$$

K. Ikeda, T. Myo, K. Kato and H. Toki, Lect. Notes Phys. 818, 165 (2010).



Lagrangian

$$\mathcal{L}_{\pi PP} = g\,\mathrm{tr}[\bar{H}\gamma^{\mu}\gamma_5 A_{\mu} H]$$

$$\mathcal{L}_{\rho PP} = i\beta\,\mathrm{tr}[\bar{H}v\cdot\rho H] + i\lambda\,\mathrm{tr}[\bar{H}\sigma^{\mu\nu}F_{\mu\nu}(\rho)H]$$

$$\mathcal{L}_{\sigma PP} = g_{\sigma}\,\mathrm{tr}[\bar{H}\sigma H]$$

$$\mathcal{L}_{\pi PP} = ig\bar{\psi}^{\nu}\gamma^{\mu}\gamma_5 A_{\mu}\psi_{\nu}$$

$$\mathcal{L}_{\rho PP} = i\beta\bar{\psi}^{\nu}v\cdot\rho\psi_{\nu} + i\lambda\bar{\psi}^{\nu}\sigma^{\lambda\rho}F_{\lambda\rho}(\rho)\psi_{\nu}$$

$$\mathcal{L}_{\sigma PP} = g_{\sigma}\bar{\psi}^{\nu}\sigma\psi_{\nu}$$

Gaussian expansion method (GEM)

- Solve the Schrödinger equation:

$$H|\psi\rangle = E|\psi\rangle$$

- Expand of ψ by the Gaussian:

$$\psi = \sum_{i=1}^{n_{\max}} c_i e^{-r^2/2b_i^2}, \qquad b_i = b_1 r^{i-1}$$

- Obtain the eigenvalue problem:

$$\mathbf{H}\vec{c} = E\mathbf{N}\vec{c}$$

Complex scaling method

- Rotated $\vec{r}$ by an angle $-\theta$ on the position space:

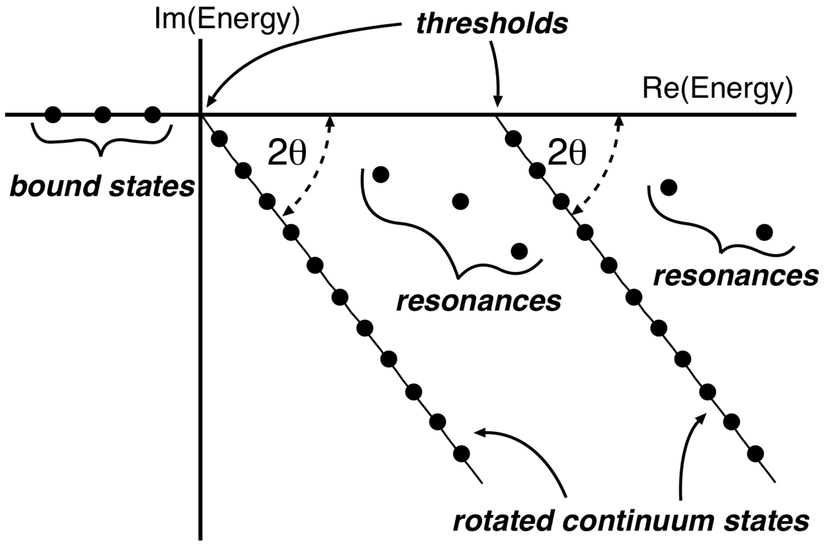
$$\vec{r} \rightarrow \vec{r}e^{-i\theta}$$

- Hamiltonian becomes non-Hermitian ⇒ Complex energy eigenvalue:

- Classification of complex energy eigenvalue

$$E = -B \qquad \text{for a bound state}$$

$$E = E_r - i\frac{\Gamma}{2} \qquad \text{for a resonance}$$



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

$$\frac{1}{2}^{-} \quad \bar{D}\Xi_{cc}(^2S), \bar{D}\Xi_{cc}^{*}(^4D), \bar{D}^{*}\Xi_{cc}(^2S,^4D), \bar{D}^{*}\Xi_{cc}(^2S,^4D,^6D)$$

$$\frac{3}{2}^{-} \quad \bar{D}\Xi_{cc}(^2D), \bar{D}\Xi_{cc}^{*}(^4S,^4D), \bar{D}^{*}\Xi_{cc}(^2D,^4S,^4D), \bar{D}^{*}\Xi_{cc}(^2D,^4S,^4D,^6D,^6G)$$

$$\frac{5}{2}^{-} \quad \bar{D}\Xi_{cc}(^2D), \bar{D}\Xi_{cc}^{*}(^4D,^4G), \bar{D}^{*}\Xi_{cc}(^2D,^4D,^4G), \bar{D}^{*}\Xi_{cc}(^2D,^4D,^4G,^6S,^6D,^6G)$$

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

$0(0^+)$ $[\Xi_{cc}\Xi_{cc}^*]_+(^5D)$

$1(0^+)$ $\Xi_{cc}\Xi_{cc}(^1S), [\Xi_{cc}\Xi_{cc}^*]_-(^5D), \Xi_{cc}^*\Xi_{cc}^*(^1S,^5D)$

$0(1^+)$ $\Xi_{cc}\Xi_{cc}(^3S,^3D), [\Xi_{cc}\Xi_{cc}^*]_-(^3S,^3D), [\Xi_{cc}\Xi_{cc}^*]_+(^5D), \Xi_{cc}^*\Xi_{cc}^*(^3S,^3D,^7D,^7G)$

$1(1^+)$ $[\Xi_{cc}\Xi_{cc}^*]_+(^3S,^3D), [\Xi_{cc}\Xi_{cc}^*]_-(^5D), \Xi_{cc}^*\Xi_{cc}^*(^5D)$

$0(2^+)$ $\Xi_{cc}\Xi_{cc}(^3D), [\Xi_{cc}\Xi_{cc}^*]_-(^3D), [\Xi_{cc}\Xi_{cc}^*]_+(^5S,^5D,^5G), \Xi_{cc}^*\Xi_{cc}^*(^3D,^7D,^7G)$

$1(2^+)$ $\Xi_{cc}\Xi_{cc}(^1D), [\Xi_{cc}\Xi_{cc}^*]_+(^3D), [\Xi_{cc}\Xi_{cc}^*]_-(^5S,^5D,^5G), \Xi_{cc}^*\Xi_{cc}^*(^1D,^5S,^5D,^5G)$

Binding energy and mixing ratio for $\bar{D}^{(*)}\Xi_{cc}^{(*)}$ and $\Xi_{cc}^{(*)}\Xi_{cc}^{(*)}$

TABLE V. The binding energy B, mixing ratios and root mean squared (r.m.s) distances of $\bar{D}^{(*)}\Xi_{cc}^{(*)}$ with $0(\frac{1}{2}^-)$ for each case of $g_\sigma = g_\sigma^L$ and $g_\sigma = g_\sigma^S$. The second and third columns show the properties in the case of $g_\sigma = 3.4$ and $g_\sigma = 0.76$, respectively. The values of the binding energy, mixing ratio, and r.m.s distance are given in units of MeV, %, and fm, respectively.

Properties	g_σ $g_\sigma^L = 3.4$	$g_\sigma^S = 0.76$
B	7.87 MeV	20.5 MeV
$\bar{D}\Xi_{cc}(^2S)$	98.8 %	93.5 %
$\bar{D}\Xi_{cc}^*(^4D)$	0 %	0 %
$\bar{D}^*\Xi_{cc}(^2S)$	0.104 %	1.18 %
$\bar{D}^*\Xi_{cc}(^4D)$	0.136 %	0.378 %
$\bar{D}^*\Xi_{cc}^*(^2S)$	0.287 %	2.78 %
$\bar{D}^*\Xi_{cc}^*(^4D)$	0.0603 %	0.169 %
$\bar{D}^*\Xi_{cc}^*(^6D)$	0.586 %	2.02 %
r.m.s distance	1.39 fm	0.884 fm

TABLE VIII. The binding energy B, mixing ratios and root mean squared (r.m.s) distances of $\Xi_{cc}^{(*)}\Xi_{cc}^{(*)}$ with $0(1^+)$ for each case of $g_\sigma = g_\sigma^L$ and $g_\sigma = g_\sigma^S$. The same conventions as Table V are used.

Properties	g_σ $g_\sigma^L = 3.4$	$g_\sigma^S = 0.76$
B	24.9 MeV	67.6 MeV
$\Xi_{cc}\Xi_{cc}(^3S)$	96.6 %	85.9 %
$\Xi_{cc}\Xi_{cc}(^3D)$	0.133 %	0.143 %
$[\Xi_{cc}\Xi_{cc}^*]_-(^3S)$	0.844 %	5.94 %
$[\Xi_{cc}\Xi_{cc}^*]_-(^3D)$	0.0219 %	0 %
$[\Xi_{cc}\Xi_{cc}^*]_+(^5D)$	0.477 %	1.10 %
$\Xi_{cc}^*\Xi_{cc}^*(^3S)$	0.544 %	3.09 %
$\Xi_{cc}^*\Xi_{cc}^*(^3D)$	0.0314 %	0.0402 %
$\Xi_{cc}^*\Xi_{cc}^*(^7D)$	1.34 %	3.80 %
$\Xi_{cc}^*\Xi_{cc}^*(^7G)$	0 %	0 %
r.m.s distance	0.825 fm	0.530 fm

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

TABLE IV. Eigenvalues of $\bar{D}^{(*)}\Xi_{cc}^{(*)}$. The first column shows $I(J^P)$ with I, J and P with the isospin, spin and parity, respectively. The third and fourth columns show the complex-scaled energy eigenvalues of the bound and resonant states for g_σ^L and g_σ^S, respectively. Here, $-B$ and E_r denote the masses measured from the lowest thresholds for bound states and resonances, respectively, and Γ represents the decay width of the resonances. The values are given in units of MeV.

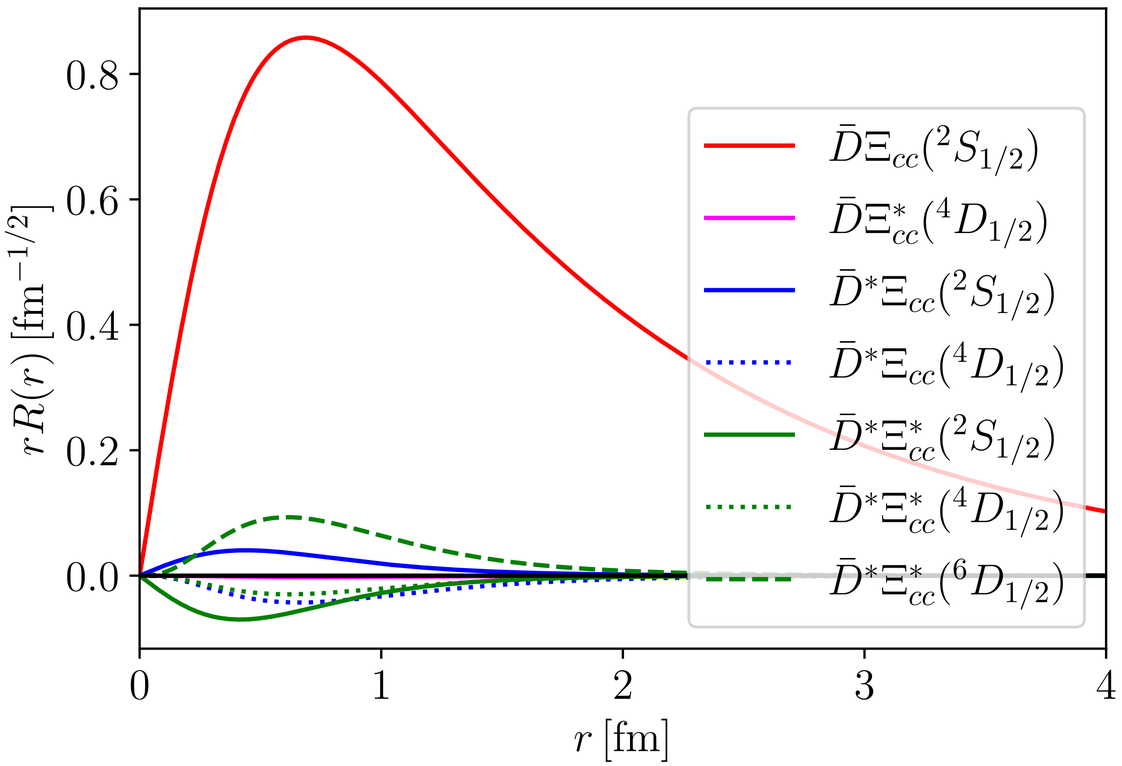
$I(J^P)$	lowest threshold	$g_\sigma^L = 3.4$	$g_\sigma^S = 0.76$
		$-B$, $E_r - i\frac{\Gamma}{2}$	
$0(\frac{1}{2}^-)$	$\bar{D}\Xi_{cc}$	-7.87	-20.5
		$123 - \frac{0.538}{2}$	$94.4 - i\frac{1.04}{2}$
$1(\frac{1}{2}^-)$	$\bar{D}\Xi_{cc}$	$246 - i\frac{0.679}{2}$	-
$0(\frac{3}{2}^-)$	$\bar{D}\Xi_{cc}$	$94.1 - i\frac{0.0387}{2}$	$67.3 - i\frac{0.0828}{2}$
		$132 - i\frac{3.87}{2}$	$117 - i\frac{5.78}{2}$
		$244 - i\frac{8.54}{2}$	-
$0(\frac{5}{2}^-)$	$\bar{D}\Xi_{cc}$	$222 - i\frac{14.5}{2}$	$181 - i\frac{11.6}{2}$

TABLE VII. Eigenvalues of $\Xi_{cc}^{(*)}\Xi_{cc}^{(*)}$. The same conventions as Table IV are used.

$I(J^P)$	lowest threshold	$g_\sigma^L = 3.4$	$g_\sigma^S = 0.76$
		$-B$, $E_r - i\frac{\Gamma}{2}$	
$0(0^+)$	$\Xi_{cc}\Xi_{cc}^*$	-	-
$1(0^+)$	$\Xi_{cc}\Xi_{cc}$	-2.19	
		$206 - i\frac{1.61}{2}$	-
$0(1^+)$	$\Xi_{cc}\Xi_{cc}$	-24.9	-67.6
		$76.4 - i\frac{1.20}{2}$	$27.7 - i\frac{1.83}{2}$
		$205 - i\frac{8.23}{2}$	-
$1(1^+)$	$\Xi_{cc}\Xi_{cc}^*$	-0.0949	-
$0(2^+)$	$\Xi_{cc}\Xi_{cc}$	$66.5 - i\frac{2.43}{2}$	$7.01 - i\frac{0.0113}{2}$
$1(2^+)$	$\Xi_{cc}\Xi_{cc}$	$98.0 - i\frac{0.132}{2}$	
		$211 - i\frac{2.12}{2}$	-

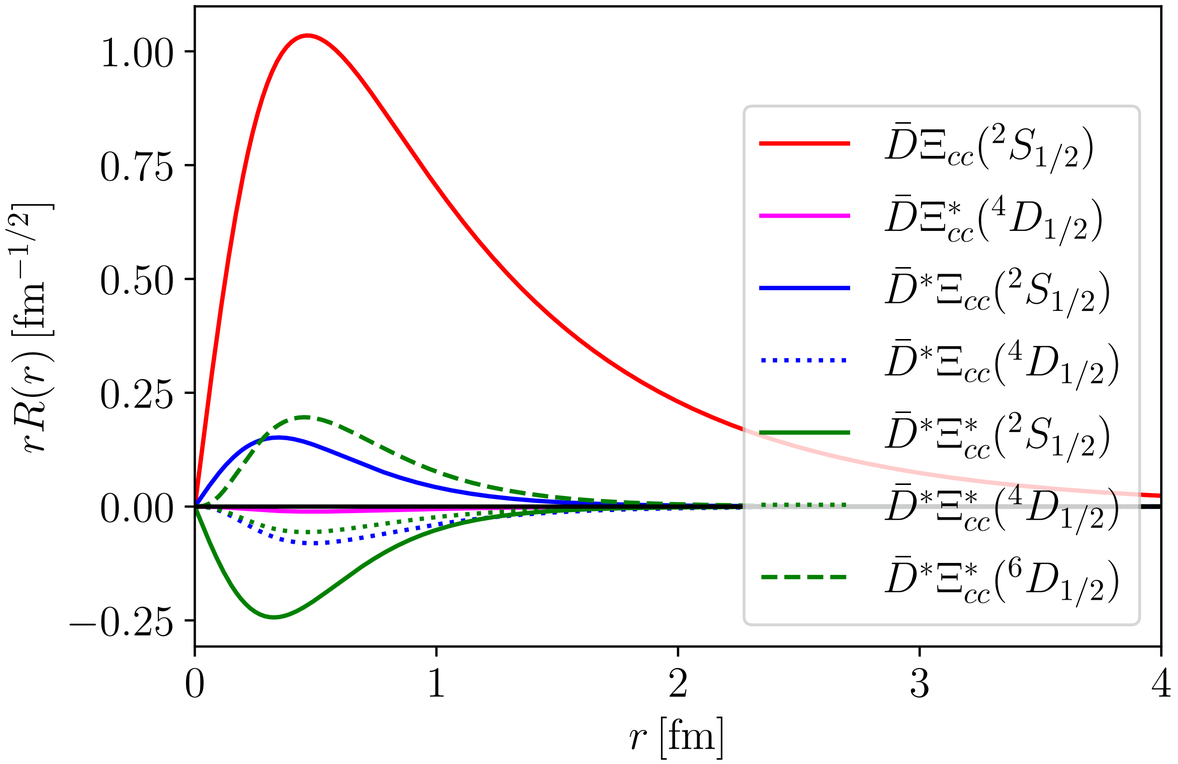
Wavefunction and root squared distance of $\bar{D}^{(*)}\Xi_{cc}^{(*)}$

- For g_σ^L



$$\sqrt{\langle r^2 \rangle} = 1.39\,\mathrm{fm}$$

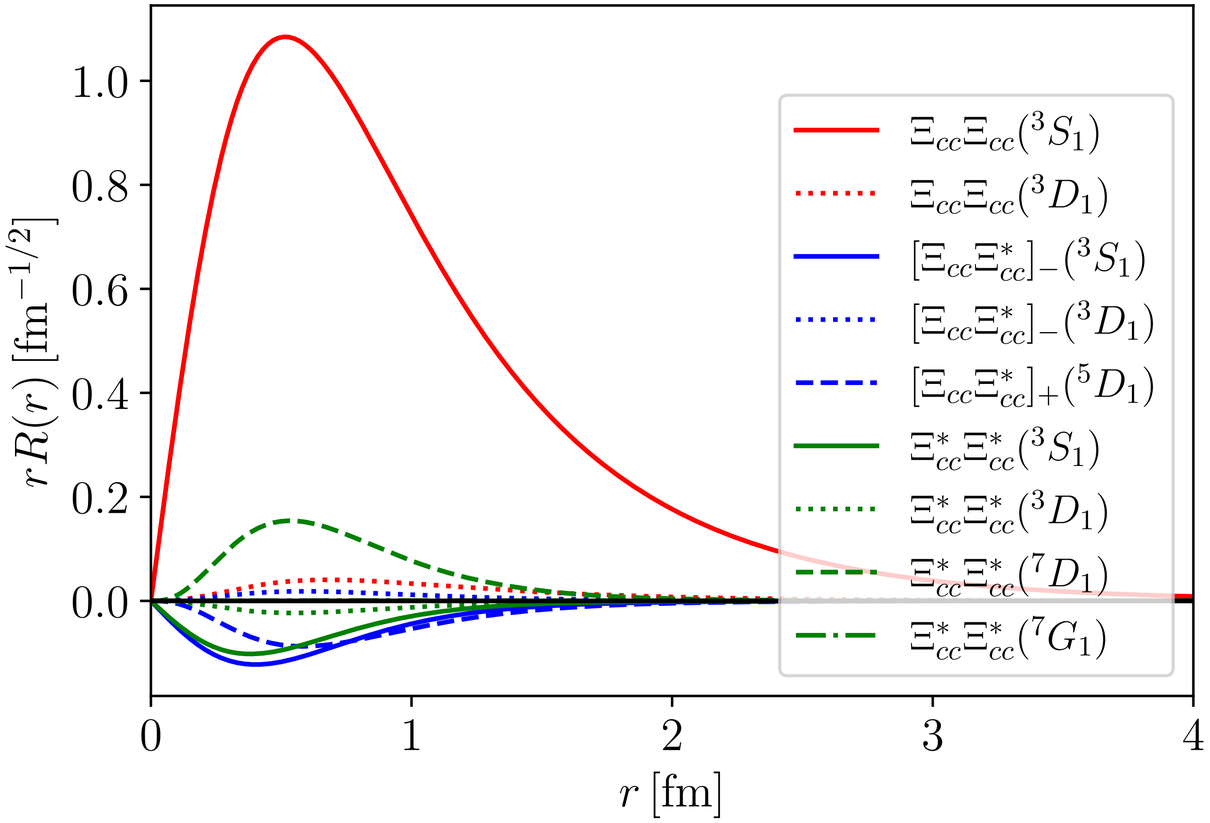
- For g_σ^S



$$\sqrt{\langle r^2 \rangle} = 0.884\,\mathrm{fm}$$

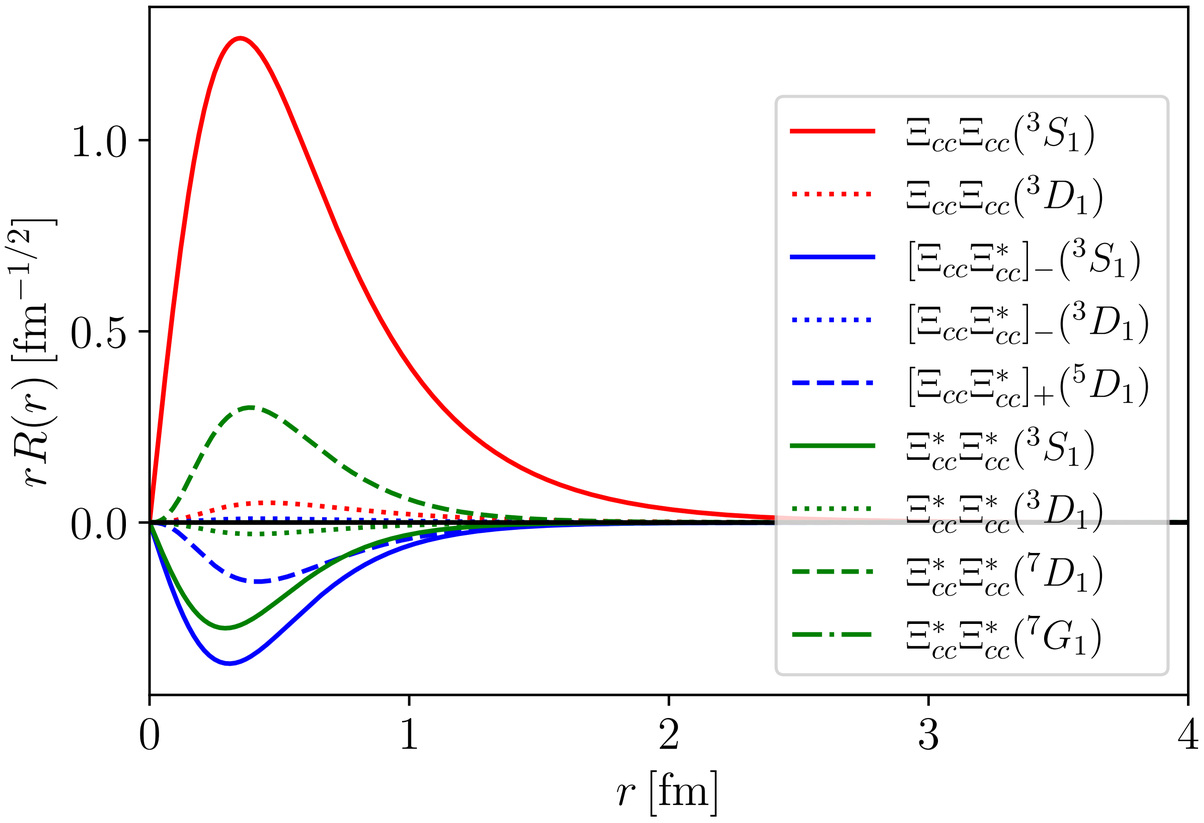
Wavefunction and root squared distance of $\Xi_{cc}^{(*)}\Xi_{cc}^{(*)}$

- For g_σ^L



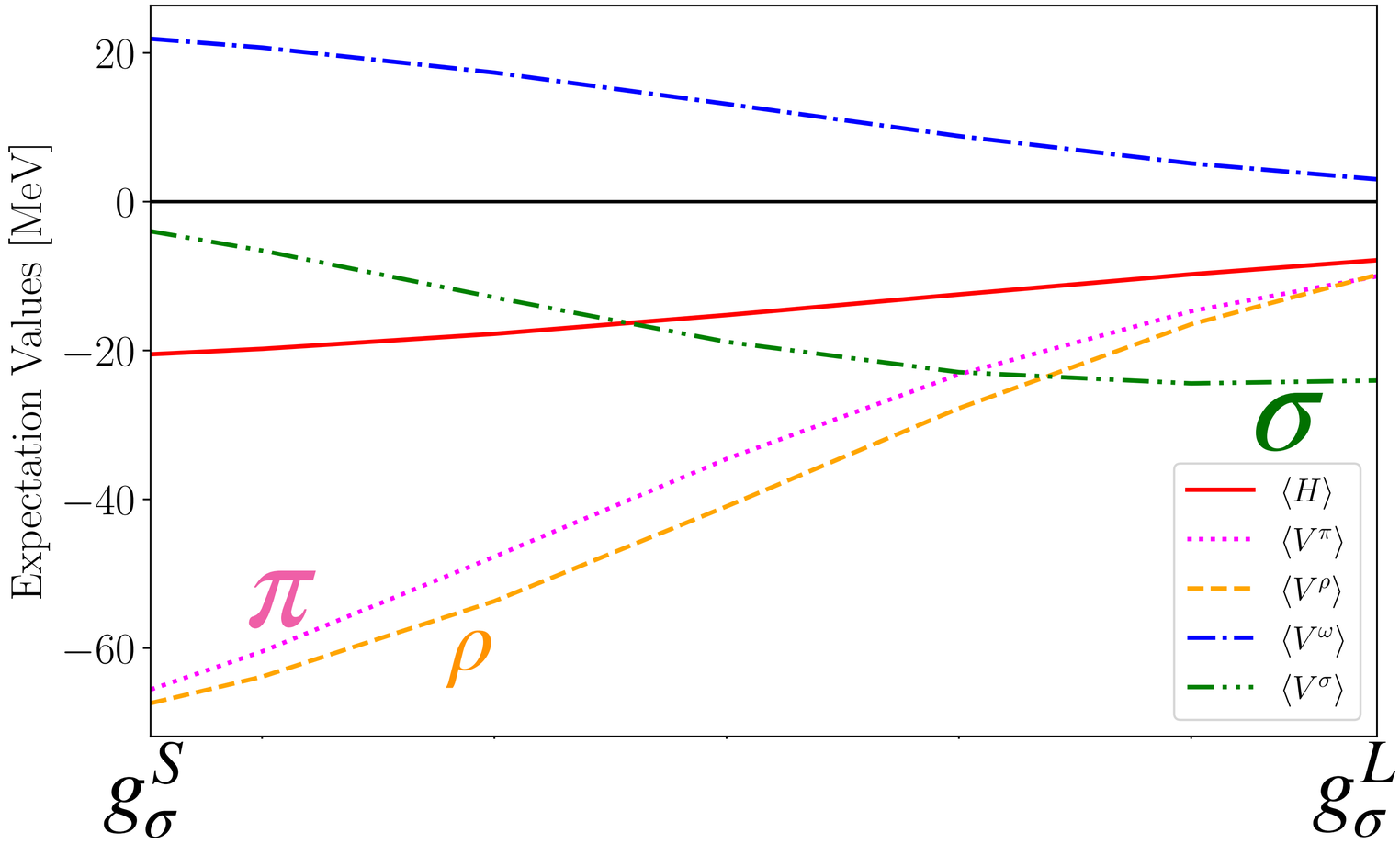
$$\sqrt{\langle r^2 \rangle} = 0.825\,\text{fm}$$

- For g_σ^S



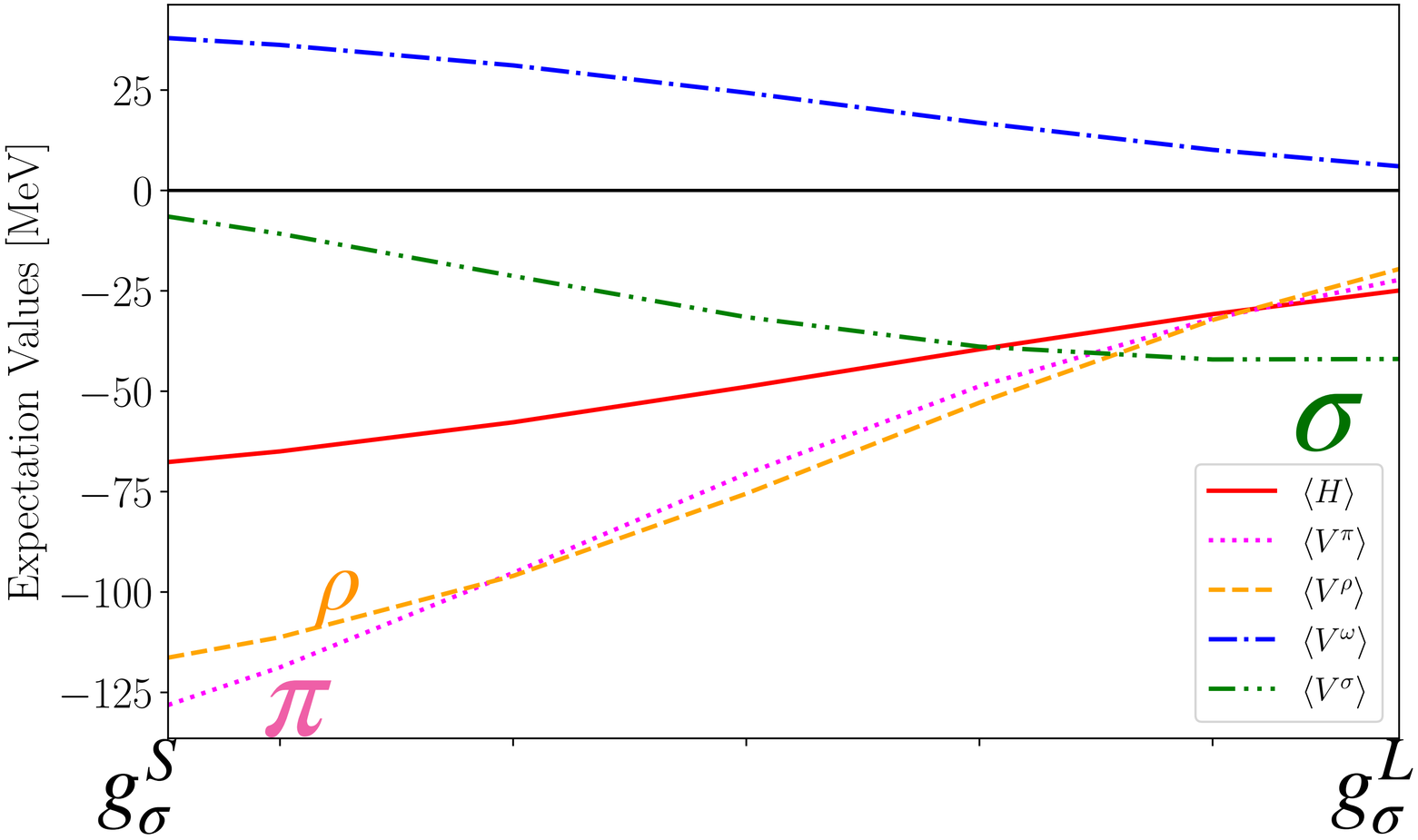
$$\sqrt{\langle r^2 \rangle} = 0.530\,\text{fm}$$

Expectation values of OBEP for $\bar{D}^{(*)}\Xi_{cc}^{(*)}$



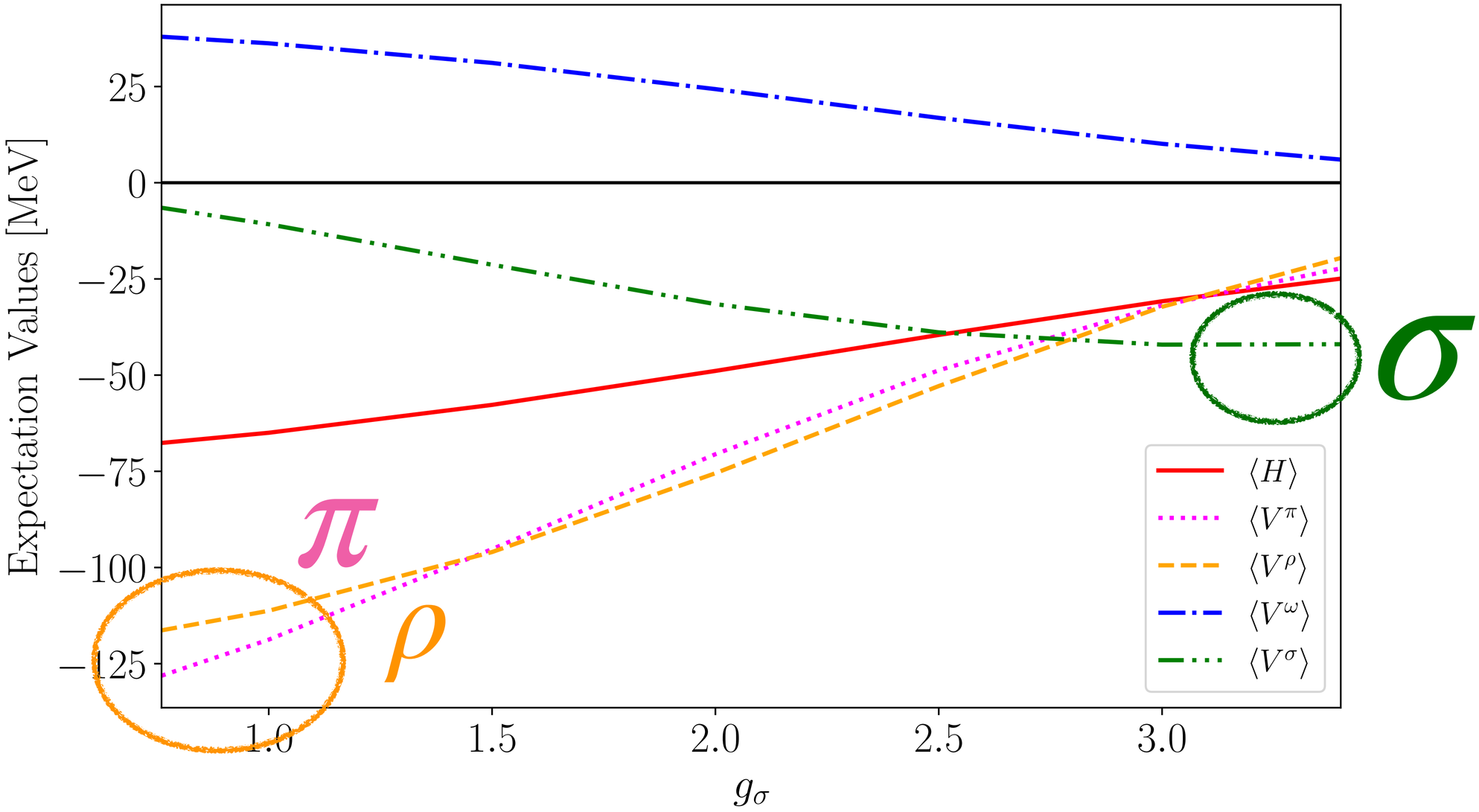
- For g_σ^L, one σ exchange potential provides the strongest attraction.
- For g_σ^S, one-π and one-ρ exchange potentials provide the strongest attractions

Expectation values of OBEP for $\Xi_{cc}^{(*)}\Xi_{cc}^{(*)}$



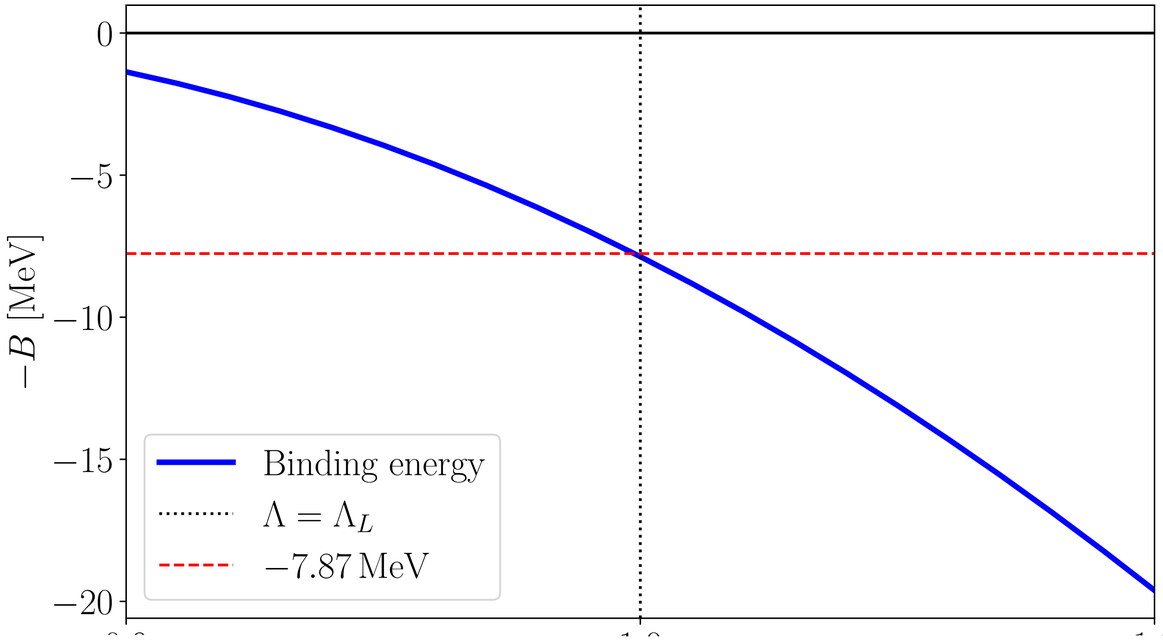
- For g_σ^L, one σ exchange potential provides the strongest attraction.
- For g_σ^S, one-π and one-ρ exchange potentials provide the strongest attractions

Expectation values of OBEP for $\Xi_{cc}^{(*)}\Xi_{cc}^{(*)}$



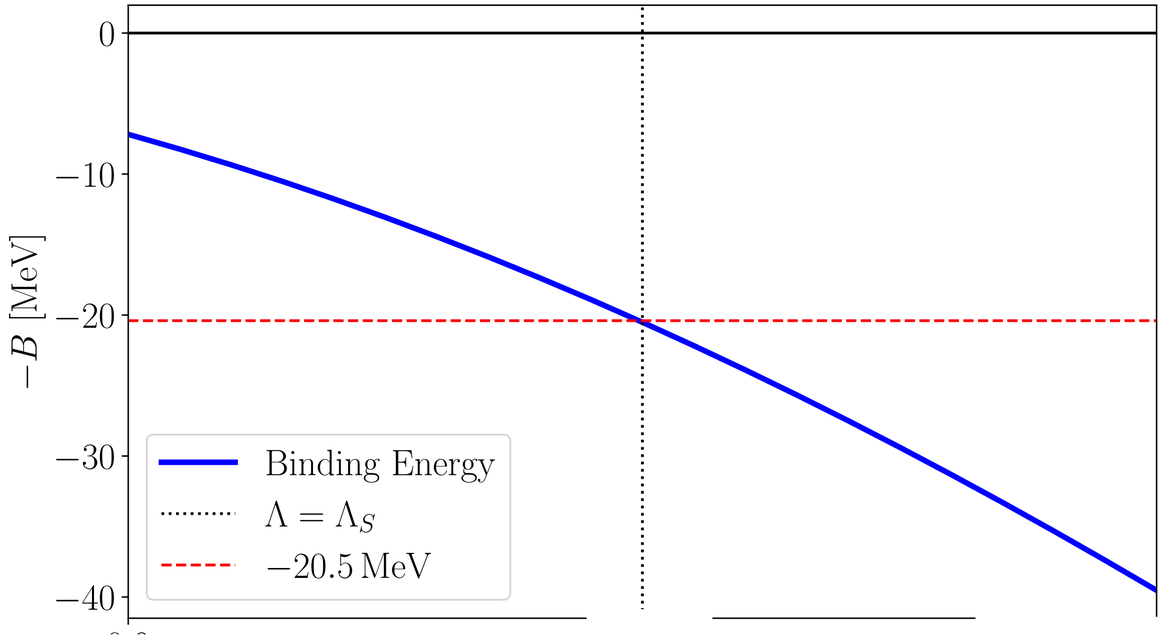
Cutoff dependence of binding energy for $\bar{D}^{(*)}\Xi_{cc}^{(*)}$

- For g_σ^L



$0.9\Lambda^L$ Λ^L $1.1\Lambda^L$

- For g_σ^S

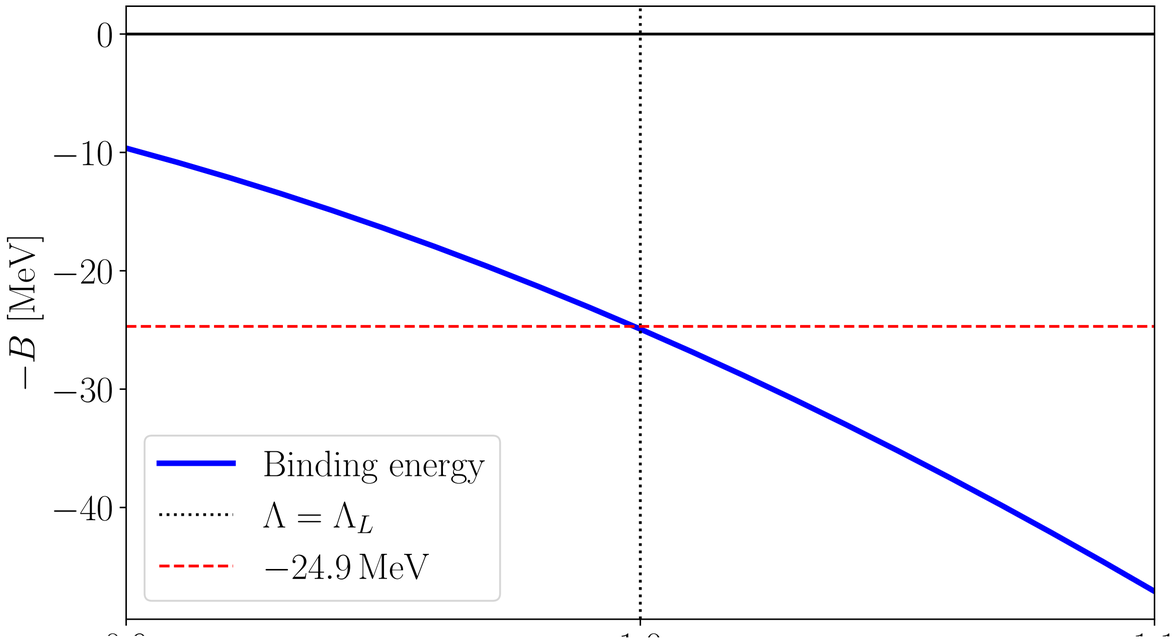


$0.9\Lambda^S$ Λ^S $1.1\Lambda^S$

- The larger the cutoff is, the more deeply the bound state is bound

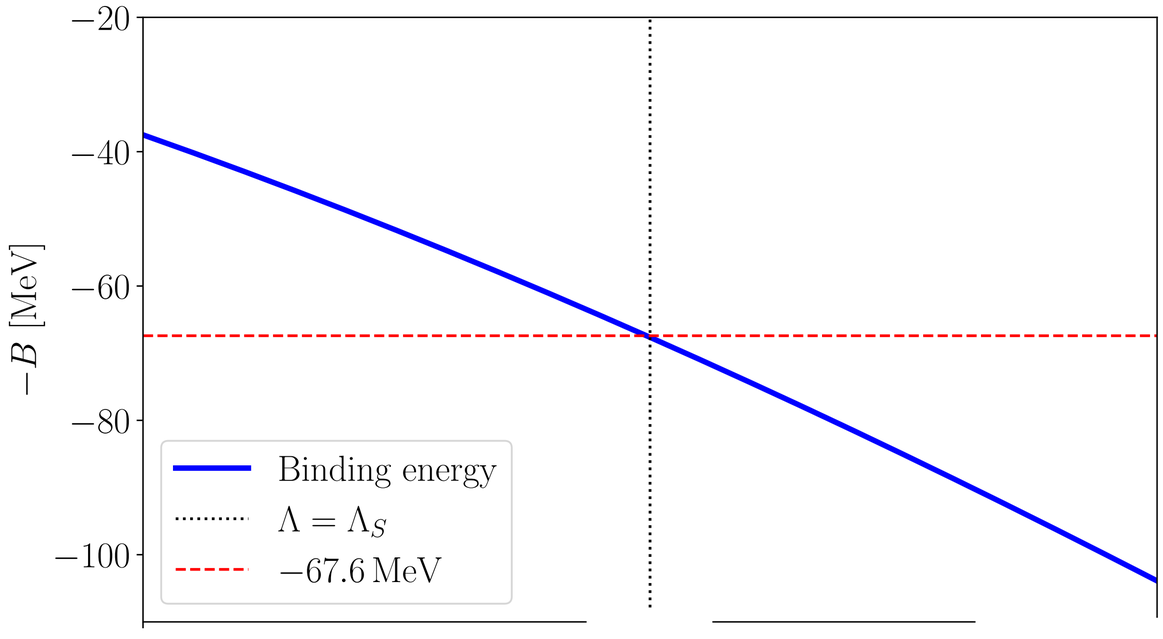
Cutoff dependence of binding energy for $\Xi_{cc}^{(*)}\Xi_{cc}^{(*)}$

- For g_σ^L



$0.9\Lambda^L$ Λ^L $1.1\Lambda^L$

- For g_σ^S



$0.9\Lambda^S$ Λ^S $1.1\Lambda^S$

- The larger the cutoff is, the more deeply the bound state is bound