Coupled Channel Description of Charmed Exotica

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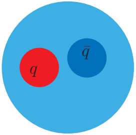
3rd EMMI Workshop: Anti-matter, hyper-matter and exotica production at the LHC 2019
4 December, 2019

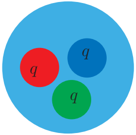
Outline

- Introduction
- $X(3872)$, $X(3940)$ and $X(4160)$
- $Y(4260)$
- $Z_c(3900)$

Hadron Spectroscopy

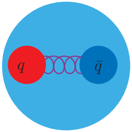
- Ordinary hadrons

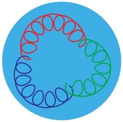




Meson($q\bar{q}$)   Baryon (qqq)

- Gluonic excitations

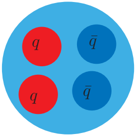


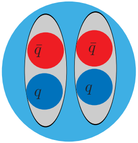


Hybrid meson:
$q\bar{q}$ with gluonic excitations,

Glueball:
only gluons, no valence quarks

- Multiquark states





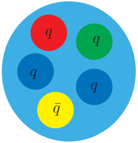
Tetraquark:

Two quarks and two antiquarks,

Hadronic molecule:

composed of two or more color-neutral hadrons

- Pentaquark



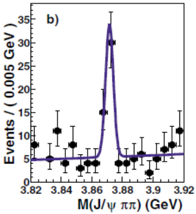
four quarks and one antiquark bound together

State	$I^G(J^{PC})$	M (MeV)	Γ (MeV)	S-wave threshold(s) (MeV)	Observed mode(s) (branching ratios)
$X(3872)$	$0^+(1^{++})$	3871.69 ± 0.17	< 1.2	$D^{*+}D^- + \text{c.c.}(-8.15 \pm 0.20)$ $D^{*0}\bar{D}^0 + \text{c.c.}(0.00 \pm 0.18)$	$B \to K[\bar{D}^{*0}D^0](> 24\%)$ $B \to K[D^0\bar{D}^0\pi^0](> 32\%)$ $B \to K[J/\psi\pi^+\pi^-](> 2.6\%)$ $B \to K[J/\psi\pi^+\pi^-\pi^0]$ $p\bar{p} \to [J/\psi\pi^+\pi^-]\ldots$ $pp \to [J/\psi\pi^+\pi^-]\ldots$ $B \to K[J/\psi\omega](> 1.9\%)$ $B \to [J/\psi\gamma](> 6 \times 10^{-3})$ $B \to [\psi(2S)\gamma](> 3.0\%)$
$X(3940)$	$?^?(?^{??})$	3942.0 ± 9	37^{+27}_{-17}	$D^*\bar{D}^*(-75.1 \pm 9)$	$e^+e^- \to J/\psi[D\bar{D}^*]$
$X(4160)$	$?^?(?^{??})$	4156^{+29}_{-25}	139^{+110}_{-60}	$D^*\bar{D}^*(139^{+29}_{-25})$	$e^+e^- \to J/\psi[D^*\bar{D}^*]$
$Z_c(3900)$	$1^+(1^{+-})$	3886.6 ± 2.4	28.1 ± 2.6	$D^*\bar{D}(10.8 \pm 2.4)$	$e^+e^- \to \pi[D\bar{D}^* + \text{c.c.}]$ $e^+e^- \to \pi[J/\psi\pi]$
$Z_c(4020)$	$1(?^?)$	4024.1 ± 1.9	13 ± 5	$D^*\bar{D}^*(7.0 \pm 2.4)$	$e^+e^- \to \pi[D^*\bar{D}^*]$ $e^+e^- \to \pi[h_c\pi]$ $e^+e^- \to \pi[\psi'\pi]$
$Y(4260)$	$?^?(1^{--})$	4251 ± 9	120 ± 12	$D_1\bar{D} + \text{c.c.}(-38.2 \pm 9.1)$ $\chi_{c0}\omega(53.6 \pm 9.0)$	$e^+e^- \to J/\psi\pi\pi$ $e^+e^- \to \pi D\bar{D}^* + \text{c.c.}$ $e^+e^- \to \chi_{c0}\omega$ $e^+e^- \to X(3872)\gamma$
$Y(4360)$	$?^?(1^{--})$	4346 ± 6	102 ± 10	$D_1\bar{D}^* + \text{c.c.}(-85 \pm 6)$	$e^+e^- \to \psi(2S)\pi^+\pi^-$
$Y(4660)$	$?^?(1^{--})$	4643 ± 9	72 ± 11	$\psi(2S)f_0(980)(-33 \pm 21)$ $\Lambda_c^+\Lambda_c^-(70 \pm 6)$	$e^+e^- \to \psi(2S)\pi^+\pi^-$
$Z_c(4430)^+$	$?(1^+)$	4478^{+15}_{-18}	181 ± 31	$\psi(2S)\rho(17^{+15}_{-18})$	$B \to K[\psi(2S)\pi^+]$ $B \to K[J/\psi\pi^+]$
$Z_c(4200)^+$	$?(1^+)$	4196^{+35}_{-32}	370^{+100}_{-32}		$\bar{B}^0 \to K^-[J/\psi\pi^+]$
$Z_c(4050)^+$	$?(?^?)$	4051^{+24}_{-40}	82^{+50}_{-28}	$D^*\bar{D}^*(34^{+24}_{-40})$	$\bar{B}^0 \to K^-[\chi_{c1}\pi^+]$
$Z_c(4250)^+$	$?(?^?)$	4248^{+190}_{-50}	177^{+320}_{-70}	$\chi_{c1}\rho(-37^{+24}_{-50})$	$\bar{B}^0 \to K^-[\chi_{c1}\pi^+]$
$X(4140)$ (Aaij *et al.*, 2017a, 2017b)	$0^+(1^{++})$	$4146.5 \pm 4.5^{+4.6}_{-2.8}$	$83 \pm 21^{+21}_{-14}$	$D_s\bar{D}_s^*(-66.1^{+4.9}_{-3.2})$	$B^+ \to K^+[J/\psi\phi]$
$X(4274)$ (Aaij *et al.*, 2017a, 2017b)	$0^+(1^{++})$	$4273.3 \pm 8.3^{+17.2}_{-3.6}$	$56 \pm 11^{+8}_{-11}$	$D_s^*\bar{D}_s^*(-49.1^{+19.1}_{-9.1})$	$B^+ \to K^+[J/\psi\phi]$
$X(4500)$ (Aaij *et al.*, 2017a, 2017b)	$0^+(0^{++})$	$4506 \pm 11^{+12}_{-15}$	$92 \pm 21^{+21}_{-20}$	$D_{s0}^*(2317)\bar{D}_{s0}^*(2317)(-129^{+16}_{-19})$	$B^+ \to K^+[J/\psi\phi]$
$X(4700)$ (Aaij *et al.*, 2017a, 2017b)	$0^+(0^{++})$	$4704 \pm 10^{+14}_{-24}$	$120 \pm 31^{+42}_{-33}$	$D_{s0}^*(2317)\bar{D}_{s0}^*(2317)(69^{+17}_{-26})$	$B^+ \to K^+[J/\psi\phi]$

F-K. Guo, C. Hanhart, Ulf-G. Meißner, Q. Wang, Q. Zhao, and B-S. Zou, Rev.Mod.Phys. 90 (2018) no.1, 015004

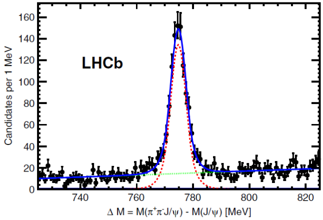
$X(3872)$

$B \to KX(3872); X(3872) \to \pi^+\pi^- J/\psi$



Belle, PRL91,262001(2003)

$B \to KX(3872); X(3872) \to \pi^+\pi^- J/\psi$



LHCb, PRD92,011102 (2015)

In Coupled Channels:

D. Gamermann, E. Oset, Eur. Phys. J A33(2007),
D. Gamermann, E. Oset, Eur. Phys. J A36(2008),
D. Gamermann, E. Oset, PRD80 (2009),
D. Gamermann, J. Nieves, E. Oset, E. Ruiz Arriola, PRD81 (2010),
F. Aceti, R. Molina, E. Oset, PRD86 (2012) ……
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The Lagrangian:

$$\mathcal{L} = \frac{-1}{4f^2} Tr\left(J_\mu \mathcal{J}^\mu\right), \quad J_\mu = (\partial_\mu \Phi)\Phi - \Phi\partial_\mu\Phi, \quad \mathcal{J}_\mu = (\partial_\mu \mathcal{V}_\nu)\mathcal{V}^\nu - \mathcal{V}_\nu \partial_\mu \mathcal{V}^\nu \tag{1}$$

The pseudoscalar and vector mesons fields:

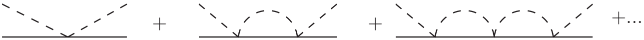
$$\Phi = \begin{pmatrix} \frac{\pi^0}{} + \frac{\eta}{} + \frac{\eta c}{\sqrt{12}} & \pi^+ & K^+ & \bar{D}^0 \\ \pi^- & \frac{-\pi^0}{} + \frac{\eta}{} + \frac{\eta c}{\sqrt{12}} & K^0 & D^- \\ K^- & \bar{K}^0 & \frac{-2\eta}{} + \frac{\eta c}{\sqrt{12}} & D_s^- \\ D^0 & D^+ & D_s^+ & \frac{-3\eta c}{\sqrt{12}} \end{pmatrix} \tag{2}$$

$$\mathcal{V}_\mu = \begin{pmatrix} \frac{\rho^0_\mu}{} + \frac{\omega_\mu}{} + \frac{J/\psi_\mu}{\sqrt{12}} & \rho^+_\mu & K^{*+}_\mu & \bar{D}^{*0}_\mu \\ \rho^{*-}_\mu & \frac{-\rho^0_\mu}{} + \frac{\omega_\mu}{} + \frac{J/\psi_\mu}{\sqrt{12}} & K^{*0}_\mu & D^{*-}_\mu \\ K^{*-}_\mu & \bar{K}^{*0}_\mu & \frac{-2\omega_\mu}{} + \frac{J/\psi_\mu}{\sqrt{12}} & D^{*-}_{s\mu} \\ D^{*0}_\mu & D^{*+}_\mu & D^{*+}_{s\mu} & \frac{-3J/\psi_\mu}{\sqrt{12}} \end{pmatrix}. \tag{3}$$

Unitarized scattering amplitude D. Gamermann, E. Oset, Eur. Phys. J A33(2007)

$I^G(J^{PC})$=$0^+(1^{++})$, $X(3872) \Rightarrow (\bar{K}K^* + c.c.), (\bar{D}D^* + c.c.), (\bar{D}_s D_s^* - c.c.)$

- The Bethe-Salpeter equation in coupled channels: $t = [1 + V\hat{G}]^{-1}(-V)\vec{\epsilon}\cdot\vec{\epsilon}'$



- The two meson loop function:

  $G_l(\sqrt{s}) = i\int \frac{d^4q}{(2\pi)^4}\frac{1}{(P-q)^2 - M_l^2 + i\epsilon}\frac{1}{q^2 - m_l^2 + i\epsilon}$
- In the dimensional regularization scheme the loop function:

$$
\begin{aligned}
G_l(\sqrt{s}) \quad = \quad & \frac{1}{16\pi^2}\Bigg\{a(\mu) + \ln\frac{M_l^2}{\mu^2} + \frac{m_l^2 - M_l^2 + s}{2s}\ln\frac{m_l^2}{M_l^2} \\
& + \frac{q_l}{\sqrt{s}}\Big[\ln(s - (M_l^2 - m_l^2) + 2q_l\sqrt{s}) \\
& + \ln(s + (M_l^2 - m_l^2) + 2q_l\sqrt{s}) \\
& - \ln(-s + (M_l^2 - m_l^2) + 2q_l\sqrt{s}) \\
& - \ln(-s - (M_l^2 - m_l^2) + 2q_l\sqrt{s})\Big]\Bigg\}
\end{aligned}
$$

- q_l determined at the center of mass frame, $q_l = \frac{\sqrt{[s-(M_l-m_l)^2][s-(M_l+m_l)^2)]}}{2\sqrt{s}}$
- $\mu \Rightarrow$ a scale parameter in this scheme, $a(\mu)\Rightarrow$the subtraction constant

Pole position:

C	Mass (MeV)	S	$I^G(J^{PC})$	RE($\sqrt{s}$) (MeV)	IM($\sqrt{s}$) (MeV)	Resonance ID
	3867.5	0	$0^+(1^{++})$	3837.57	-0.00	$X(3872)$

Residues for the C=0,S=0,I^P=0^+ sector:

Channel	(3837.57-i0.00) MeV $\lvert g_i \rvert$ (GeV)
$(D\bar{D}^* + c.c.)$	13.61
$(D_s\bar{D}_s^* - c.c.)$	10.58
$(K\bar{K}^* + c.c.)\downarrow$	0.03

PDG:

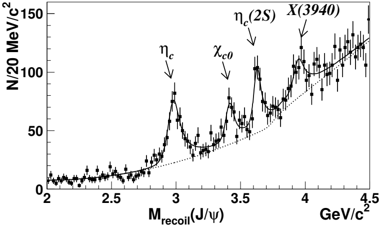
X(3872) $\Rightarrow \chi_{c1}(3872), m = 3871.69 \pm 0.17 MeV$

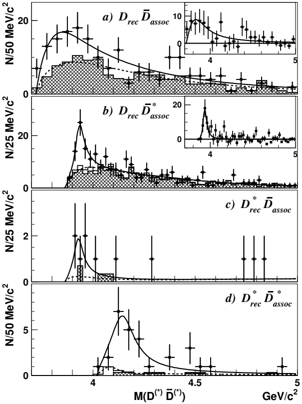
M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018) and 2019 update.

$X(3940)$ and $X(4160)$

Belle, Phys.Rev.Lett. 98 (2007) 082001. $X(3940)$; $e^+e^- \to J/\psi\, X(3940)$: $X(3940) \to D^*\bar{D}$.

Belle, Phys.Rev.Lett. 100 (2008) 202001. $X(4160)$; $e^+e^- \to J/\psi D^*\bar{D}$.





PDG: $X(3940)$, $I^G(J^{PC}) = ?^?(?^{??})$, $m \simeq 3942\ MeV$, $\Gamma \sim 37 \pm 8\ MeV$ the

$X(4160)$, $I^G(J^{PC}) = ?^?(?^{??})$, $m \simeq 4156\ MeV$, $\Gamma \sim 139 \pm 21\ MeV$

The Bethe-Salpeter equation:

$$T = (\hat{1} - VG)^{-1} V \, . \tag{4}$$

The amplitude close to a pole:

$$T_{ij} \approx \frac{g_i g_j}{s - s_p} \tag{5}$$

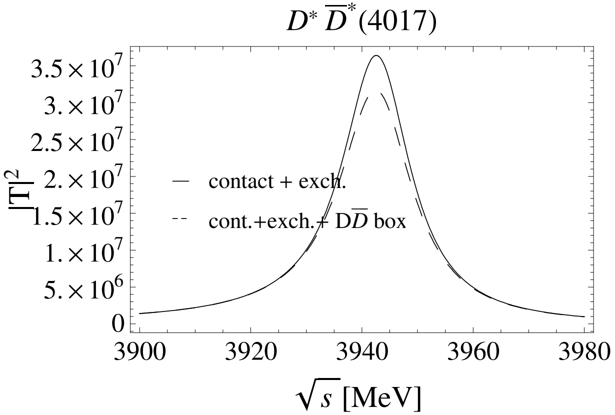
Couplings g_i in units of MeV for $I = 0$, $J = 0$.
$\sqrt{s}_{pole} = 3943 + i7.4$, $I^G[J^{PC}] = 0^+[0^{++}]$

$D^*\bar{D}^*$	$D_s^*\bar{D}_s^*$	$K^*\bar{K}^*$	$\rho\rho$	$\omega\omega$
$18810 - i682$	$8426 + i1933$	$10 - i11$	$-22 + i47$	$1348 + i234$
$\phi\phi$	$J/\psi J/\psi$	$\omega J/\psi$	$\phi J/\psi$	$\omega\phi$
$-1000 - i150$	$417 + i64$	$-1429 - i216$	$889 + i196$	$-215 - i107$

Couplings g_i in units of MeV for $I = 0$, $J = 2$ (second pole).
$\sqrt{s}_{pole} = 4169 + i66$, $I^G[J^{PC}] = 0^+[2^{++}]$

$D^*\bar{D}^*$	$D_s^*\bar{D}_s^*$	$K^*\bar{K}^*$	$\rho\rho$	$\omega\omega$
$1225 - i490$	$18927 - i5524$	$-82 + i30$	$70 + i20$	$3 - i2441$
$\phi\phi$	$J/\psi J/\psi$	$\omega J/\psi$	$\phi J/\psi$	$\omega\phi$
$1257 + i2866$	$2681 + i940$	$-866 + i2752$	$-2617 - i5151$	$1012 + i1522$

$|T|^2$ for $I = 0$ and $J = 0$:

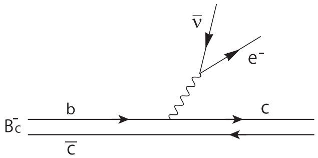


Production of X Resonances in B_c^- Decays

N. Ikeno, M. Bayar, E. Oset, Eur.Phys.J. C78 (2018), 429

- $B_c^- \to \bar{\nu} e^- X(3940) (X(4160))$
- $X(3940)$ (0^{++}), $X(4160)$ (2^{++}) $\Rightarrow$ dynamically generated from vector–vector interaction ($D^* \bar{D}^*$, $D_s^* \bar{D}_s^*$) in the charm sector.
- To produce X states, we consider three steps:

  First step : $B_c^- \to \bar{\nu} e^- (\bar{c}c)$ at quark level

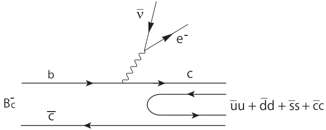


bc weak transition

- If we want to see two mesons, the $\bar{c}c$ quarks must hadronize into two mesons components

Hadronization: second step

- Introduce an extra $q\bar{q}$ pair with vacuum quantum numbers; $\bar{u}u + \bar{d}d + \bar{s}s + \bar{c}c$



- The $q\bar{q}$ matrix M:

$$M \equiv q\bar{q}^{\tau} = \begin{pmatrix} u\bar{u} & u\bar{d} & u\bar{s} & u\bar{c} \\ d\bar{u} & d\bar{d} & d\bar{s} & d\bar{c} \\ s\bar{u} & s\bar{d} & s\bar{s} & s\bar{c} \\ c\bar{u} & c\bar{d} & c\bar{s} & c\bar{c} \end{pmatrix}$$

- In terms of vector mesons:

$$M \to V \equiv \begin{pmatrix} \frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & \rho^+ & K^{*+} & \bar{D}^{*0} \\ \rho^- & -\frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & K^{*0} & \bar{D}^{*-} \\ K^{*-} & \bar{K}^{*0} & \phi & \bar{D}_s^{*-} \\ D^{*0} & D^{*+} & D_s^{*+} & J/\psi \end{pmatrix}.$$

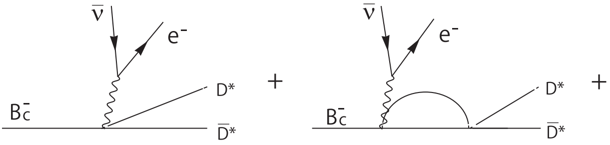
$$c(\bar{u}u + \bar{d}d + \bar{s}s + \bar{c}c)\bar{c} = \sum_{i=1}^{4} M_{4i} M_{i4} = (M^2)_{44}$$

$$\Rightarrow (V \cdot V)_{44} = D^{*0}\bar{D}^{*0} + D^{*+}\bar{D}^{*-} + D_s^{*+}\bar{D}_s^{*-} + J/\psi J/\psi.$$

- The production vertex is written as

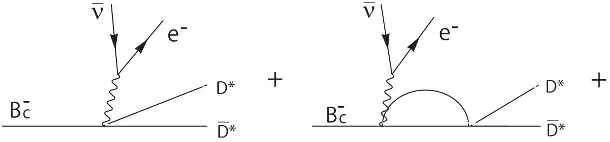
$$(V \cdot V)_{44} \to \sqrt{2}|D^*\bar{D}^*; I = 0\rangle + |D_s^*\bar{D}_s^*; I = 0\rangle. \quad (6)$$

- Next step: These mesons are allowed to undergo final state interaction $\Rightarrow X$ resonances appear.



a) tree level b) rescattering

Rescattering process



a) tree level   b) rescattering

- Hadronization amplitude $V'_{\rm had}$

  $D^* \bar{D}^*$ states for $I = 0,\ J = 0$

$$V'_{\rm had} = C(\sqrt{2} + \sqrt{2}\, G_{D^* \bar{D}^*}\ t_{D^* \bar{D}^*, D^* \bar{D}^*} + \ G_{D_s^* \bar{D}_s^*}\ t_{D_s^* \bar{D}_s^*, D^* \bar{D}^*}). \qquad (7)$$

  $D_s^* \bar{D}_s^*$ state for $I = 0, J = 2$

$$V'_{\rm had} = C'(1 + \sqrt{2}\, G_{D^* \bar{D}^*}\ t_{D^* \bar{D}^*, D_s^* \bar{D}_s^*} + \ G_{D_s^* \bar{D}_s^*}\ t_{D_s^* \bar{D}_s^*, D_s^* \bar{D}_s^*}). \qquad (8)$$

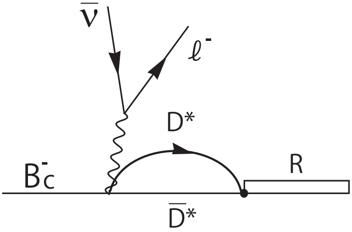
- Scattering amplitudes t :

$$t_{D_s^* \bar{D}_s^*, D^* \bar{D}^*} = \frac{g_{R, D_s^* \bar{D}_s^*}\, g_{R, D^* \bar{D}^*}}{M_{\rm inv}^2 - M_R^2 + i M_R \Gamma_R}, \qquad (9)$$

$\Rightarrow g_{R, D^* \bar{D}^*}, g_{R, D_s^* \bar{D}_s^*} \Rightarrow$ the couplings of the resonance to these channels

Coalescence process

Production of resonances R after rescattering process:



- The hadronization factor V_{had}:

$$V_{\text{had}} = C(\sqrt{2}\, G_{D^*\bar{D}^*}\, g_{R,D^*\bar{D}^*} + G_{D_s^*\bar{D}_s^*}\, g_{R,D_s^*\bar{D}_s^*}), \tag{10}$$

$\Rightarrow g_{R,D^*\bar{D}^*}, g_{R,D_s^*\bar{D}_s^*} \Rightarrow$ the couplings of the resonance to these channels

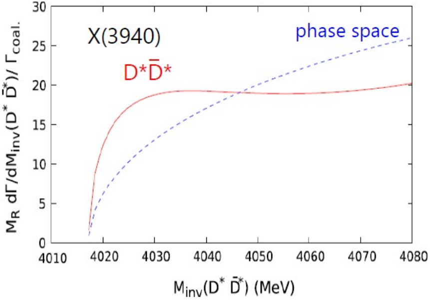
Differential decay width:

$$\frac{d\Gamma_i}{dM_{\rm inv}} = \frac{|G_F V_{bc} V'_{{\rm had},i}|^2}{32\pi^5 m_{B_c}^3 M_{\rm inv}^{(i)}} \int dM_{\rm inv}^{(\nu e)} P^{\rm cm} \tilde{p}_\nu \tilde{p}_i M_{\rm inv}^{(\nu e)^2} \left(\tilde{E}_{B_c} \tilde{E}_i - \frac{\tilde{p}_{B_c}^2}{3} \right)$$

$$\frac{M_R}{\Gamma_{\rm coal}} \frac{d\Gamma_i}{dM_{\rm inv}}$$

Decay widths $\Gamma_{\rm coal}$ for the resonance L = 0 and J = 0 state

$$\Gamma_{\rm coal} = \frac{|G_F V_{bc} V_{\rm had}|^2}{8\pi^3 m_{B_c}^3 m_R} \int dM_{\rm inv}^{(\nu e)} P_R^{\rm cm} \tilde{p}_\nu |M_{\rm inv}^{(\nu e)}|^2 \left(\tilde{E}_{B_c} \tilde{E}_R - \frac{\tilde{p}_{B_c}^2}{3} \right)$$



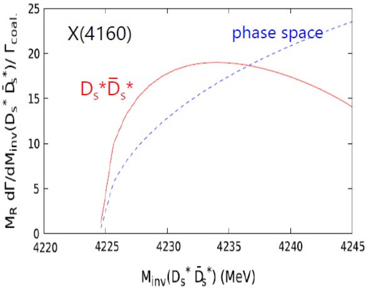
Shape of D*D̄* invariant mass distribution is different from the phase space.

<= due to the presence of a resonance below threshold that couples strongly to the observed channel

Differential decay width for the $L = 2$ state:

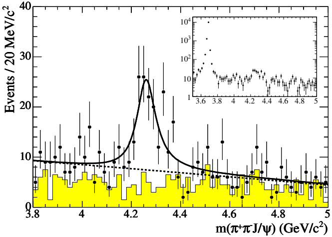
$$\frac{d\Gamma_i}{dM_{\rm inv}} = \frac{|G_{\rm F} V_{bc} V'_{{\rm had},i}|^2}{32\pi^5 m^3_{B_c} M^{(i)}_{\rm inv}} \int dM^{(\nu e)}_{\rm inv} \underline{(P^{\rm cm})^5} \tilde{p}_\nu \tilde{p}_i M^{(\nu e)^2}_{\rm inv} \left(\tilde{E}_{B_c} \tilde{E}_i - \frac{\tilde{p}^2_{B_c}}{3} \right)$$

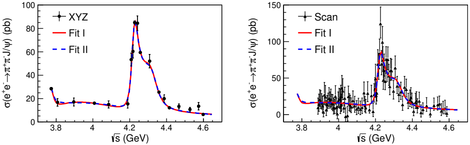
$$\Gamma_{\rm coal} = \frac{|G_{\rm F} V_{bc} V_{\rm had}|^2}{8\pi^3 m^3_{B_c} m_R} \int dM^{(\nu e)}_{\rm inv} \underline{(P^{\rm cm}_R)^5} \tilde{p}_\nu |M^{(\nu e)}_{\rm inv}|^2 \left(\tilde{E}_{B_c} \tilde{E}_R - \frac{\tilde{p}^2_{B_c}}{3} \right)$$



$Y(4260)$

$e^+e^- \to Y(4260) \to \pi^+\pi^- J/\psi$, BaBar, Phys.Rev.Lett. 95 (2005) 142001



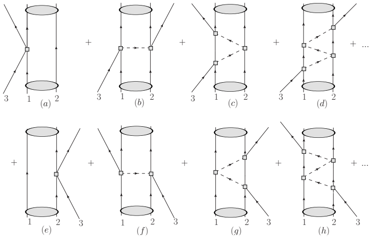


$e^+e^- \to Y(4260) \to \pi^+\pi^- J/\psi$, BESIII, Phys.Rev.Lett. 118 (2017) no.9, 092001

$D_1\bar{D} + c.c.$ hadronic molecule:

G-J Ding, Phys.Rev. D79 (2009) 014001, M. Cleven et al., Phys.Rev. D90 (2014) no.7, 074039, X-G Wu et al., Phys.Rev. D89 (2014) no.5, 054038, ...

- Clusters : $\rho D \Rightarrow D_1(2420) (I = 1/2)$ $\bar{D}(\rho D)_{D_1(2420)}$
- $\rho D(D_1(2420)) \Rightarrow \pi D^*$, $D\rho$, KD_s^*, $D_s K^*$,ηD^*, $D\omega$, $\eta_c D^*$, DJ/ψ, $(I = 1/2)$ and πD^*, $D\rho$, $(I = 3/2)$ (D. Gamermann, E. Oset, D. Strottman, and M. J. Vicente Vacas, PRD76(2007), D. Gamermann and E. Oset,EPJA33(2007))
- The Faddeev equations under the Fixed Center Approximation (FCA):



- T_1: all diagrams beginning with interaction in particle 1.
- T_2: all diagrams beginning with interaction in particle 2.

$$T_1 = t_1 + t_1 G_0 T_2, \qquad T_2 = t_2 + t_2 G_0 T_1 \tag{11}$$

$$T = T_1 + T_2 = \frac{\tilde{t}_1 + \tilde{t}_2 + 2\,\tilde{t}_1\,\tilde{t}_2\,G_0}{1 - \tilde{t}_1\,\tilde{t}_2\,G_0^2}.$$

The function G_0 :

$$G_0(s) = \int \frac{d^3\vec{q}}{(2\pi)^3} F_R(q) \frac{1}{q^{02} - \vec{q}^{\,2} - m_3^2 + i\epsilon}, \qquad q^0(s) = \frac{s + m_3^2 - M_R^2}{2\sqrt{s}}.$$

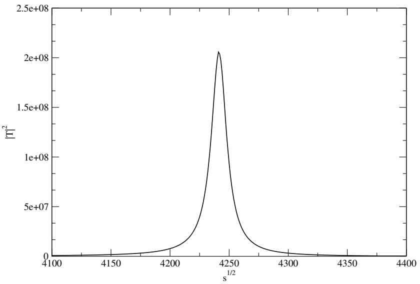
$F_R(q)$ is the cluster form factor

$$F_R(q) = \frac{1}{\mathcal{N}} \int_{|\vec{p}|<\Lambda', |\vec{p}-\vec{q}|<\Lambda'} d^3\vec{p} \frac{1}{2E_1(\vec{p})} \frac{1}{2E_2(\vec{p})} \frac{1}{M_R - E_1(\vec{p}) - E_2(\vec{p})}$$
$$\frac{1}{2E_1(\vec{p}-\vec{q})} \frac{1}{2E_2(\vec{p}-\vec{q})} \frac{1}{M_R - E_1(\vec{p}-\vec{q}) - E_2(\vec{p}-\vec{q})},$$
$$\mathcal{N} = \int_{|\vec{p}|<\Lambda'} d^3\vec{p} \left(\frac{1}{2E_1(\vec{p})} \frac{1}{2E_2(\vec{p})} \frac{1}{M_R - E_1(\vec{p}) - E_2(\vec{p})} \right)^2, \qquad (12)$$

(J.Yamagata-Sekihara, J. Nieves, E. Oset Phys. Rev. D 83,014003 (2011))

$Y(4260)$

- Clusters : $\rho D \Rightarrow D_1(2420) (I = 1/2)$ $\qquad \bar{D}(\rho D)_{D_1(2420)}$
- $\rho D(D_1(2420)) \Rightarrow \pi D^*$, $D\rho$, KD_s^*, $D_s K^*$,ηD^*, $D\omega$, $\eta_c D^*$, DJ/ψ, $(I = 1/2)$ and πD^*, $D\rho$, $(I = 3/2)$ (D. Gamermann, E. Oset, D. Strottman, and M. J. Vicente Vacas, PRD76(2007), D. Gamermann and E. Oset,EPJA33(2007))



$\bar{D}(\rho D)_{D_1(2420)}$, $I = 0$, $m \sim 4241$ MeV, $\Gamma \sim 25 - 30$ MeV
PDG: $Y(4260) \Rightarrow \psi(4260)$, $\qquad I^G(J^{PC}) = 0^-(1^{--})$,

m$\simeq$ 4230 MeV, $\qquad \Gamma \sim 55 \pm 19$ MeV

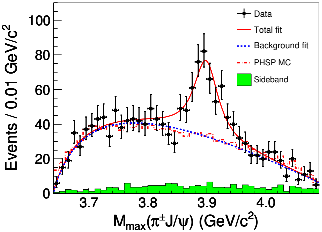
$Z_c(3900)$

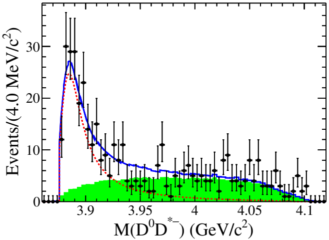
BESIII, Phys. Rev. Lett. 110, 252001 (2013)

$e^+e^- \to \pi^+\pi^- J/\psi$

BESIII, Phys.Rev. D92 (2015) no.9, 092006

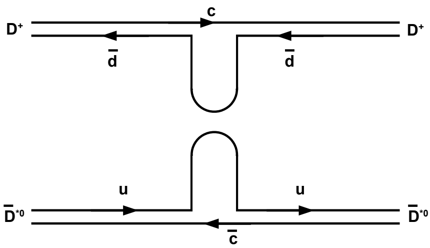
$e^+e^- \to \pi^-(D\bar{D}^*)^+$





PDG: $Z_c(3900)$, ; $I^G(J^{PC}) = 1^+(1^{+-})$, $m \simeq 3887.2 \pm 2.3$ MeV, $\Gamma \sim 28.2 \pm 2.6$ *MeV*

- Possible states $\Rightarrow$ the interaction of $D\bar{D}^* + cc$ in the $I = 1$ channel
- One light meson exchange is OZI forbidden!! This means ρ, ω cancel and π η, η' cancel if equal masses (or for large q)



- Exchange of a heavy vector $c\bar{c}$ or two pions
- The exchange of two pions $\Rightarrow$ small !!

The heavy vector exchange:

- $I^G(J^{PC}) = 1^+(1^{+-})$; six possible channels $\Rightarrow \pi\omega,\ \eta\rho,\ (\bar{K}K^* + c.c.)/\sqrt{2},$ $(\bar{D}D^* + c.c.)/\sqrt{2},\ \ \eta_c\rho,\ \pi J/\Psi$
- The $PV \to PV$ interaction $\Rightarrow$ local hidden gauge approach $\Rightarrow$ generalizes the chiral Lagrangians to include vector mesons
- The Lagrangian describing the VPP and VVV vertex:

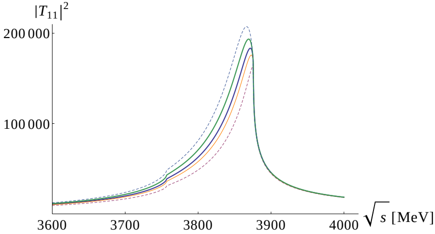
$$\mathcal{L}_{VPP} = -ig\langle V^\mu[P,\partial_\mu P]\rangle\ , \quad \mathcal{L}_{VVV} = ig\langle(V^\mu\partial_\nu V_\mu - \partial_\nu V_\mu V^\mu)V^\nu\rangle\ , \qquad (13)$$

$$P = \begin{pmatrix} \frac{\eta}{\sqrt{3}} + \frac{\eta'}{\sqrt{6}} + \frac{\pi^0}{\sqrt{2}} & \pi^+ & K^+ & \bar{D}^0 \\ \pi^- & \frac{\eta}{\sqrt{3}} + \frac{\eta'}{\sqrt{6}} - \frac{\pi^0}{\sqrt{2}} & K^0 & D^- \\ K^- & \bar{K}^0 & -\frac{\eta}{\sqrt{3}} + \sqrt{\frac{2}{3}}\eta' & D_s^- \\ D^0 & D^+ & D_s^+ & \eta_c \end{pmatrix}, \qquad (14)$$

$$V_\mu = \begin{pmatrix} \frac{\omega}{\sqrt{2}} + \frac{\rho^0}{\sqrt{2}} & \rho^+ & K^{*+} & \bar{D}^{*0} \\ \rho^- & \frac{\omega}{\sqrt{2}} - \frac{\rho^0}{\sqrt{2}} & K^{*0} & D^{*-} \\ K^{*-} & \bar{K}^{*0} & \phi & D_s^{*-} \\ D^{*0} & D^{*+} & D_s^{*+} & J/\psi \end{pmatrix}_\mu . \qquad (15)$$

$$T = (1 - VG)^{-1} V \,,$$

$$V_{ij}(s) = -\frac{\vec{\epsilon}\,\vec{\epsilon}\,'}{8f^2}\,\mathcal{C}_{ij}\left[3s - (M^2 + m^2 + M'^2 + m'^2) - \frac{1}{s}(M^2 - m^2)(M'^2 - m'^2)\right] \quad (16)$$



$q_{max} = 850, 800, 770, 750$ and 700 MeV

The peak moves to the left as the cutoff increases,

$\Gamma \sim 50$ MeV !!! $\Rightarrow$ in coupled channels $\Rightarrow$ open channels; $\eta_c\rho, \pi J/\psi$

- Position of the peak of $|T|^2$ corresponding to different values of q_{max}:

q_{max} [MeV]	$\sqrt{s}$ [MeV]
700	3875
750	3873
770	3872
800	3869
850	3867

Summary

- The chiral unitary approach with coupled channels provides a simple and natural explanation of charmed exotica
- $X(3872) \Rightarrow D\bar{D}^*$; PDG: $X(3872) \Rightarrow \chi_{c1}(3872)$!!!
- $X(3940) \Rightarrow D^*\bar{D}^*$
- $X(4160) \Rightarrow D_s^*\bar{D}_s^*$
- $Y(4260) \Rightarrow \bar{D}(\rho D)_{D_1(2420)}$ PDG: $Y(4260) \Rightarrow \psi(4260)$!!!

  The FCA to the Faddeev equations is an effective tool to deal with multi-hadron interaction
- $Z_c(3900) \Rightarrow \bar{D}D^*$ $(I = 1)$

Thank you for your attention!