Production of X Resonances in B_c^- Decays

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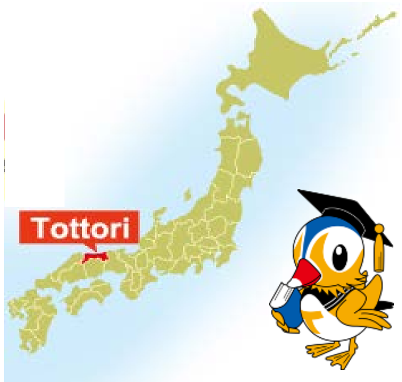

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Introduction: Studies of X, Y, Z states are important subject

- X, Y, Z states challenge the constituent quark model picture of meson, and have been one of the most spectacular findings in hadron spectroscopy recently.
- Tetraquark pictures have been proposed as well as molecular pictures stemming from the interaction of more elementary mesons.
- One of these pictures deals with the interaction of vector mesons with charm: R. Molina, E. Oset, PRD80, 114013 (2009)

Some quasibound states were found which could be associated to known resonances. These states were:

  - 3943 MeV with $I^G[J^{PC}] = 0^+[0^{++}]$, which was associated to the X(3940)
  - 3922 MeV with $0^+[2^{++}]$, X(3930)
  - 4169 MeV with $0^+[2^{++}]$, X(4160)

=> X(3940) and X(3930) were found to mostly couple to $D^*\bar{D}^*$, and X(4160) had its strongest coupling to $D_s^*\bar{D}_s^*$.

Our study and semileptonic weak decays

To see the nature of X resonances, we study the production of X in

$B_c^- \to \bar{\nu} e^- X$ process

$X(3930)(2^{++})$, $X(3940)(0^{++})$, $X(4160)(2^{++})$

In our approach, these resonances are dynamically generated from vector–vector interaction ($D^*\bar{D}^*$, $D_s^*\bar{D}_s^*$) in the charm sector.

We calculate decay rates and compare them with $B_c^- \to \nu e^- (D^*\bar{D}^*)$, $\nu e^- D_s^*\bar{D}_s^*$ decays

Studies of semileptonic weak decay are useful to determine the structure of resonances.

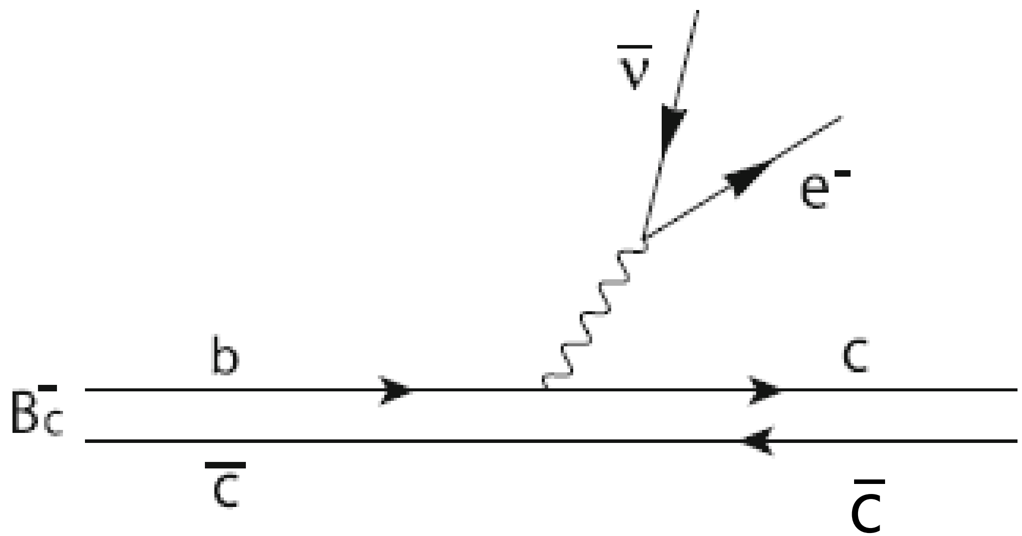
- B_s and B semileptonic decays: F.S. Navarra, M. Nielsen, E. Oset, T. Sekihara, PRD92,014031 (2015)
  $\bar{B}_s^0 \to D_{s0}^*(2317)\bar{\nu}_l l^-$ $\bar{B}^0 \to D_0^*(2400)^+\bar{\nu}_l l^-$
  were studied and compared to related reactions like $\bar{B}_s^0 \to (DK)^+\bar{\nu}_l l^-$
- D and D_s semileptonic decays: T. Sekihara, E. Oset, PRD 92, 054038 (2015)
- Λ_c semileptonic decay: N. Ikeno, E. Oset, PRD93, 014021 (2016)

Formalism: $B^-{}_c \to \bar{\nu} e^- X$ process

To produce X states, we consider three steps

First step :

$B^-{}_c \to \nu_e e^-(\bar{c}c)$ at quark level for



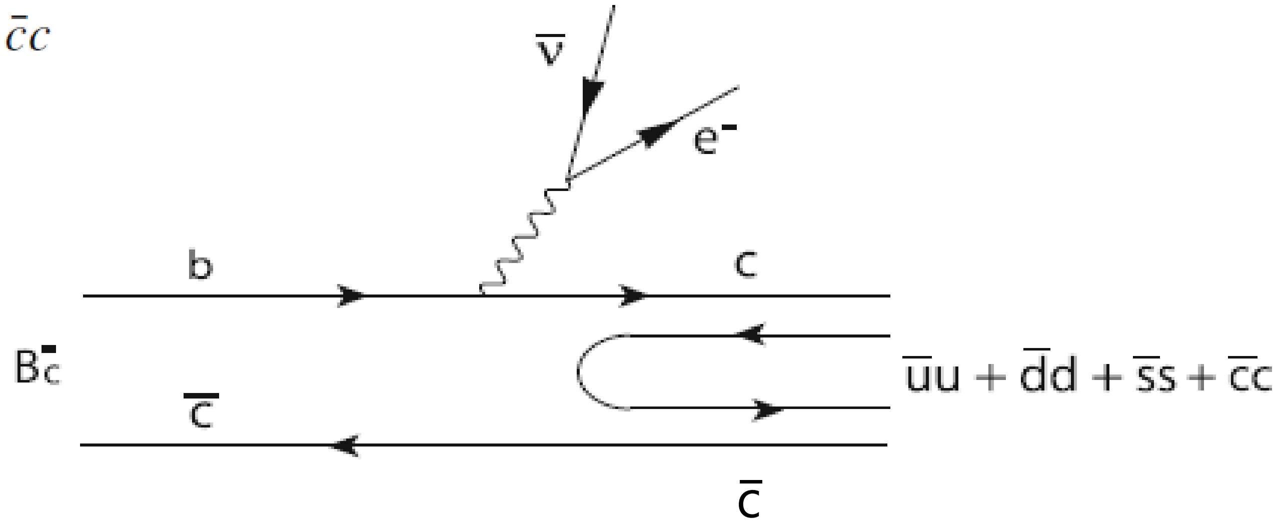
bc weak transition

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

Hadronization: second step

* The $c\bar{c}$ pair must hadronize into two mesons
* Introduce an extra $\bar{q}q$ pair with vacuum quantum numbers

$$\bar{u}u + \bar{d}d + \bar{s}s + \bar{c}c$$



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

Hence, we can write

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

Hadronization

We write the matrix M in terms of vector mesons, and we have vector matrix:

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

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

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

Only an I = 0 state is produced from the $c\bar{c}$ component
because the hadronization is a strong interaction and does not change isospin.

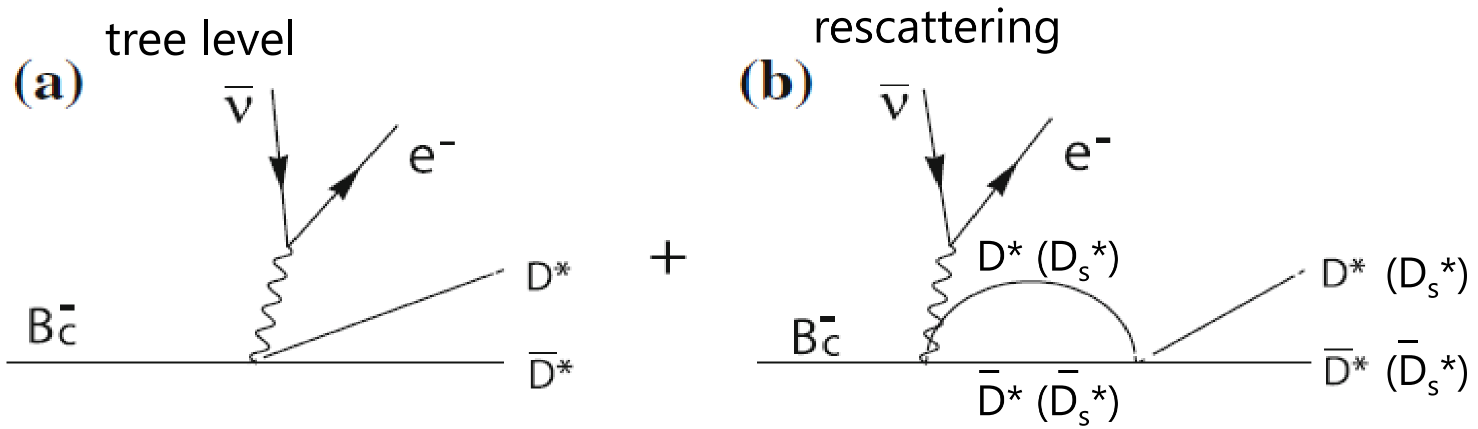
The production vertex is written as

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

=> Next step: These mesons are allowed to undergo final state interaction from where three resonances appear.

Final state interaction : last step

We use interaction of $D^*\bar{D}^*$ and $D_s^*\bar{D}_s^*$: R. Molina, E. Oset, PRD80, 114013 (2009)
Based an extension of the local hidden gauge approach



This interaction generates several resonances,
and some XYZ states were dynamically generated.

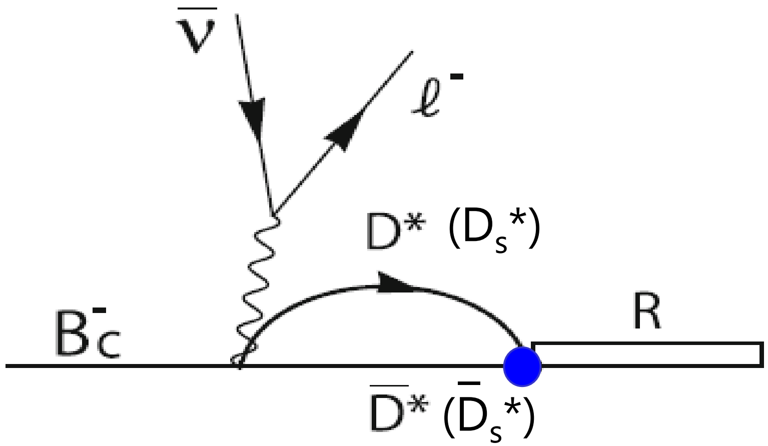
W.H. Liang, J.J. Xie, E. Oset, R. Molina, M. Doring, EPJA 51, 58 (2015)

Energy [MeV]	$I^G[J^{PC}]$	Strongest channel	Experimental state
$3943 - i7.4$	$0^+[0^{++}]$	$D^*\bar{D}^*$	$Y(3940)$ [76]
$3945 - i0$	$0^-[1^{+-}]$	$D^*\bar{D}^*$	? Y_P
$3922 - i26$	$0^+[2^{++}]$	$D^*\bar{D}^*$	$Z(3930)$ [77]
$4169 - i66$	$0^+[2^{++}]$	$D_s^*\bar{D}_s^*$	$X(4160)$ [78]

Resonances most strongly coupled to $D^*\bar{D}^*$ channel correspond to experimental states Y (3940), Z(3930) and $D_s^*\bar{D}_s^*$ channel corresponds to X(4160).

Coalescence process

Production of resonances R after rescattering process



Resonance state:

$X(3940)(0^{++})$,
$X(3930)(2^{++})$,
$X(4160)(2^{++})$

Hadronization factor V_{had} :

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

g_{RD*D*} and g_{RD*D*} are the couplings of the resonance to these channels
G_{D*D*} and G_{D*sD*s} are two meson loop functions

$$G_i(s) = i\int \frac{d^4q}{(2\pi)^4}\frac{1}{q^2 - m_1^2 + i\epsilon}\frac{1}{(P-q)^2 - m_2^2 + i\epsilon}$$

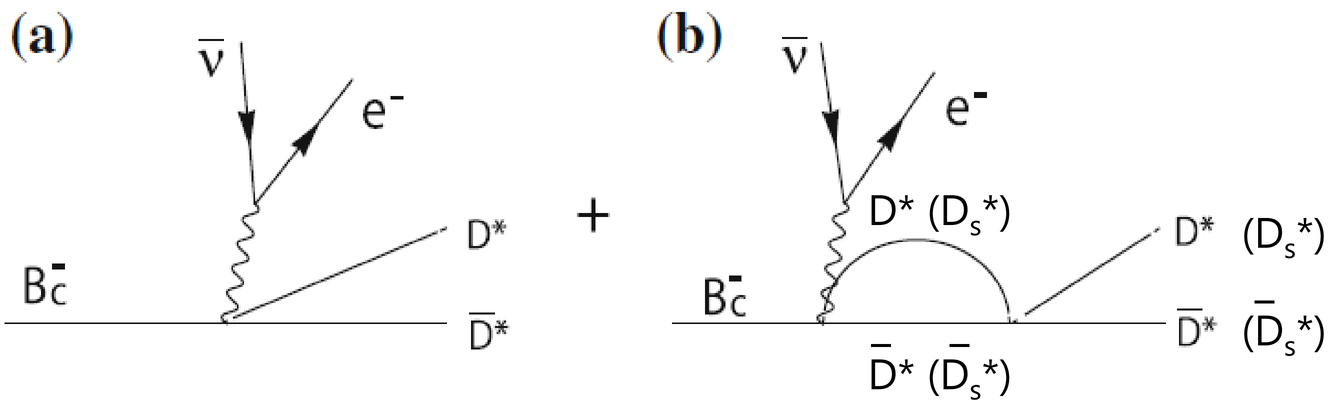
We use the values reported in

R. Molina, E. Oset, Phys. Rev. D 80, 114013 (2009)
F.S. Navarra, M. Nielsen, E. Oset, T. Sekihara, Phys. Rev. D 92(1),014031 (2015)

Rescattering process

We study the rescattering in the final states $D^*\bar{D}^*$ and $D_s^*\bar{D}_s^*$.

Different final states of the $D^*\bar{D}^*$ and $D_s^*\bar{D}_s^*$ are treated separately.



* Hadronization amplitude V'_{had}

- $D^*\bar{D}^*$ states for I=0, J=0 and I=0, J=2, where resonances couple strongly to D^*D^*

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

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

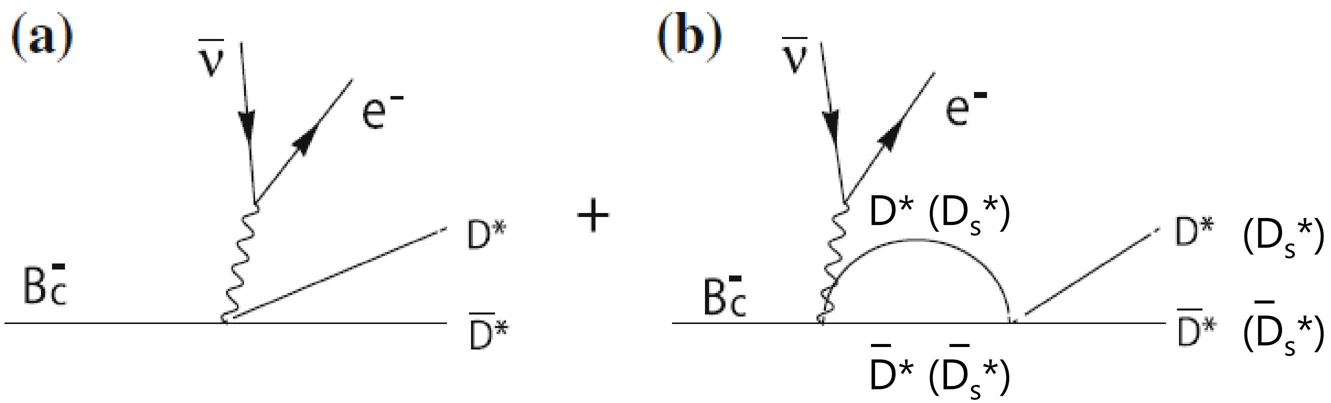
$$V'_{\rm had} = C'(1 + \sqrt{2}\, G_{D^*\bar{D}^*}\, t_{D^*\bar{D}^*,D_s^*\bar{D}_s^*} + G_{D_s^*\bar{D}_s^*}\, t_{D_s^*\bar{D}_s^*,D_s^*\bar{D}_s^*})$$

Scattering amplitudes t : $D^*\bar{D}^* \rightarrow D^*\bar{D}^*$, $D_s^*\bar{D}_s^* \rightarrow D^*\bar{D}^*$ transition

t : $D^*\bar{D}^* \rightarrow D_s^*\bar{D}_s^*$, $D_s^*\bar{D}_s^* \rightarrow D_s^*\bar{D}_s^*$ transition

Rescattering process

We study the rescattering in the final states $D^*\bar{D}^*$ and $D_s^*\bar{D}_s^*$.
Different final states of the $D^*\bar{D}^*$ and $D_s^*\bar{D}_s^*$ are treated separately.



Scattering amplitudes t :

$D^*\bar{D}^* \to D^*\bar{D}^*$ transition

$$t_{D^*\bar{D}^*,D^*\bar{D}^*} = \frac{g_{R,D^*\bar{D}^*}\, g_{R,D^*\bar{D}^*}}{M_{\rm inv}^2 - M_R^2 + i M_R \Gamma_R},$$

$D_s^*\bar{D}_s^* \to D^*\bar{D}^*$ transition

$D^*\bar{D}^* \to D_s^*\bar{D}_s^*$

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

$D_s^*\bar{D}_s^* \to D_s^*\bar{D}_s^*$ transition

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

The coupling constants g_i are the same as the coalescence.

M_{inv} refers to the final $D^*\bar{D}^*$ or $D_s^*\bar{D}_s^*$ states.

Result of coalescence process: X(3940)(0^{++})

We consider X(3940) as the resonance R, namely the $B_c^- \to X(3940)\nu l^-$ process.

Decay widths Γ_{coal} for the resonance L = 0 and J = 0 state using the mass m_R = 3943 MeV.

F.S. Navarra *et al.*, PRD92,014031 (2015)

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

Numerical result:

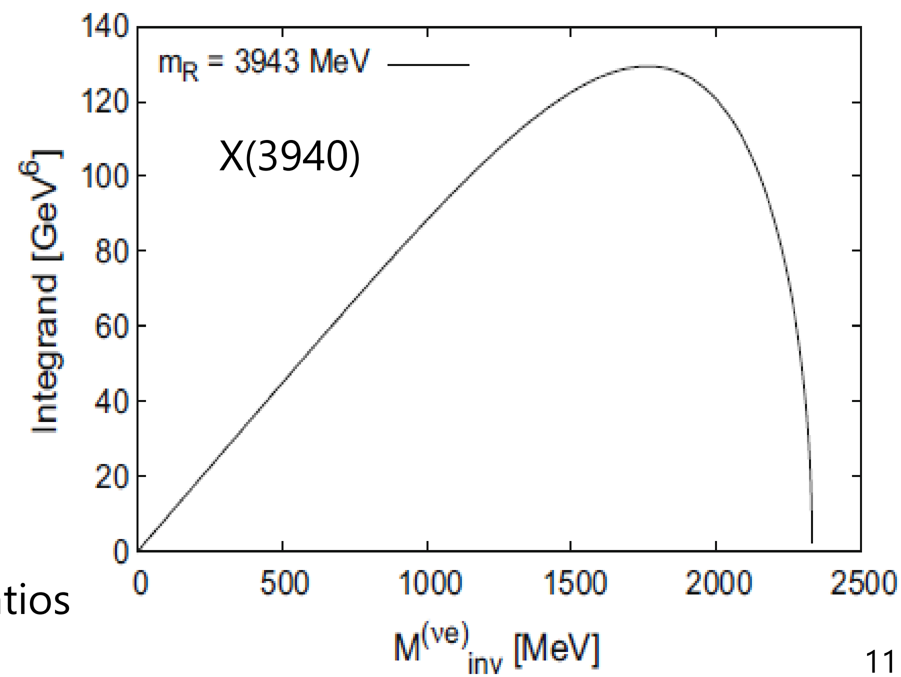
$$\Gamma_{\rm coal} = 2.6 \times 10^{-14}\ \mathrm{MeV}.$$

Mean life of the Bc is 0.507×10^{-12} s

=> Branching ratio:

$$\frac{\Gamma_{\rm coal}}{\Gamma_{\rm tot}(B_c)} = 2.0 \times 10^{-5}$$

Small number, but it is within measuring range, since boundaries of 10^{-6} for certain branching ratios have been established.



Other resonances of 2^{++} : X(3930), X(4160)

For the other resonance of 2^{++}, we can not use the formula because we need L=2 state and hence the matrix element would be different.

Thus, we replace the P_R^{cm} with $(P_R^{cm})^5$

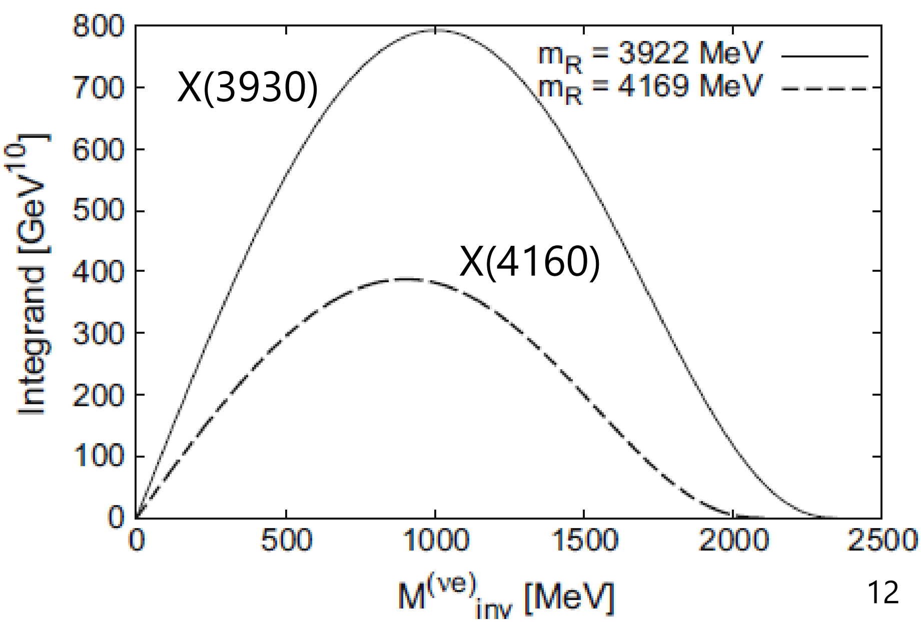
$$\Gamma_{\rm coal} = \frac{|G_{\rm F} V_{bc} V_{\rm had}|^2}{8\pi^3 m_{B_c}^3 m_R} \int dM_{\rm inv}^{(\nu e)} \underline{(P_R^{\rm cm})^5} \tilde{p}_\nu |M_{\rm inv}^{(\nu e)}|^2 \left(\tilde{E}_{B_c} \tilde{E}_R - \frac{\tilde{p}_{B_c}^2}{3} \right)$$

But we do not obtain an absolute value for the width.
We can obtain the ratio of rates for the two 2^{++} resonances.

X(3930) ->
X(4160) ->

$$\frac{\Gamma_{\rm coal}(2)}{\Gamma_{\rm coal}(2')} = 3.6$$

X(3930) has bigger production rate.
The probability to produce the X(3930) is about 3 times larger than for the X(4160).

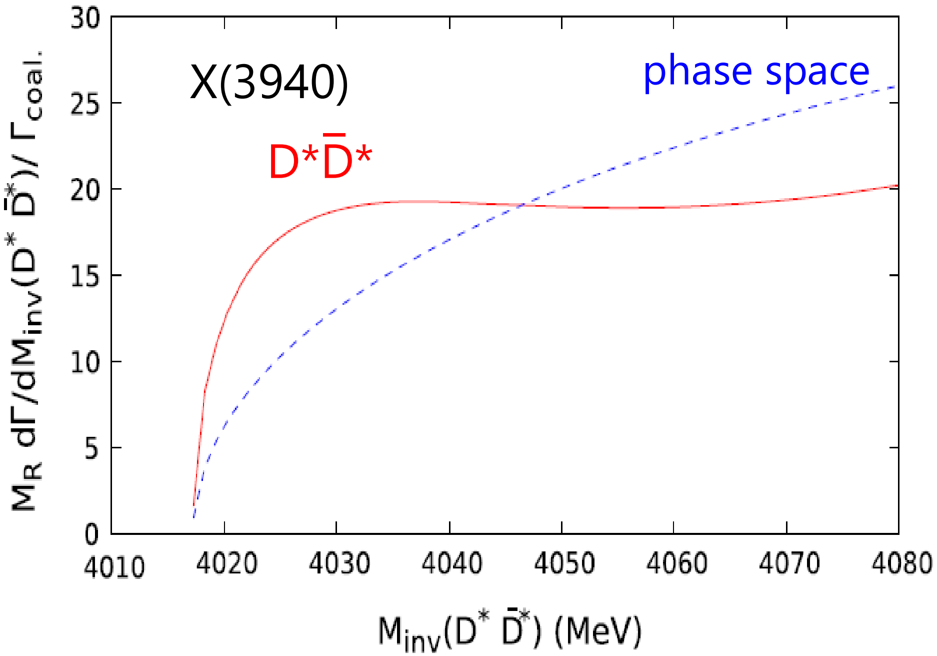


Results of rescattering process

Differential decay width:

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

We show the result for $\frac{M_R}{\Gamma_{\rm coal}} \frac{d\Gamma_i}{dM_{\rm inv}}$ as a function of $M_{inv}(D^*\bar{D}^*)$ for $B_c^- \to X(3940)\nu l^-$



Shape of $D^*\bar{D}^*$ invariant mass distribution is different from the phase space.

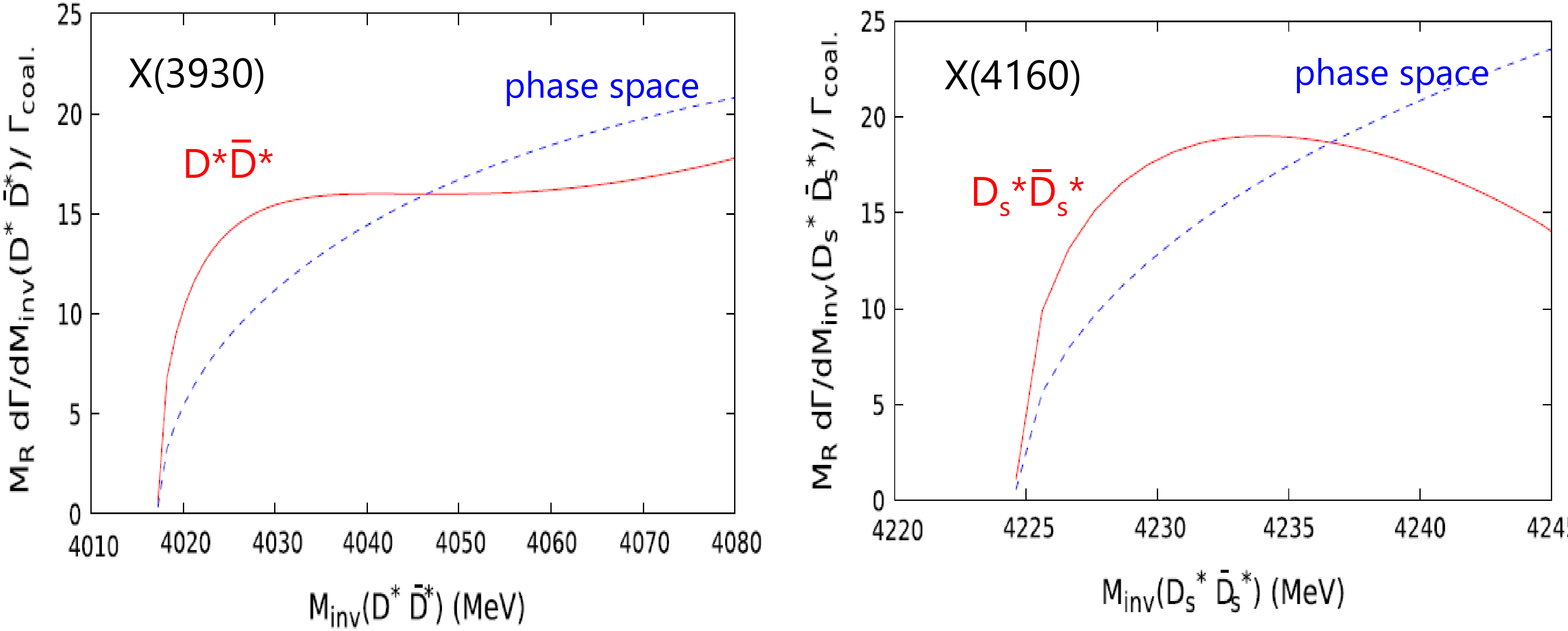
<= due to the presence of a resonance below threshold that couples strongly to the observed channel

Dashed line corresponds to a phase space distribution which we normalize to the same area in the range of the figure.

Other resonances of 2^{++} : X(3930), X(4160)

Differential decay width for the L = 2 state:

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



If the experiment sees an enhancement with respect to phase space close to threshold, it is an indication that there is a resonance below threshold.

Summary

- We studied the X production in $B^{-}_{c} \to \nu e^{-} X$ semileptonic decay process, $X(3930)(2^{++})$, $X(3940)(0^{++})$, $X(4160)(2^{++})$
- In our approach, these resonances are dynamically generated from the vector–vector interaction ($D^{*}\bar{D}^{*}$, $D_s^{*}\bar{D}_s^{*}$) in the charm sector.

- We estimated the rate of $B^{-}_{c} \to \nu e^{-}$ X(3940). Branching ratio is 2×10^{-5} .

  We also obtained the ratio of X(3930) and X(4160).

- We also looked at the production of $D^{*}\bar{D}^{*}$, $D_s^{*}\bar{D}_s^{*}$ close to threshold.

  => related to the nature of these resonances as dynamically generated from $D^{*}\bar{D}^{*}$, $D_s^{*}\bar{D}_s^{*}$ channels

- As more decay modes of B^{-}_{c} become available, it would be interesting to look into these modes which will provide good information on the nature of these resonances.