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Study of the $B^- \to K^- \eta\eta_c$ decay due to the $D\bar{D}$ bound state

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Xin-Qiang Li, Li-Juan Liu, En Wang, and Le-Le Wei. Phys. Rev. D 109, 094014 (2024)

2024-11-30

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Exotic state

- Hadron: strong interaction, composites of quarks and gluons

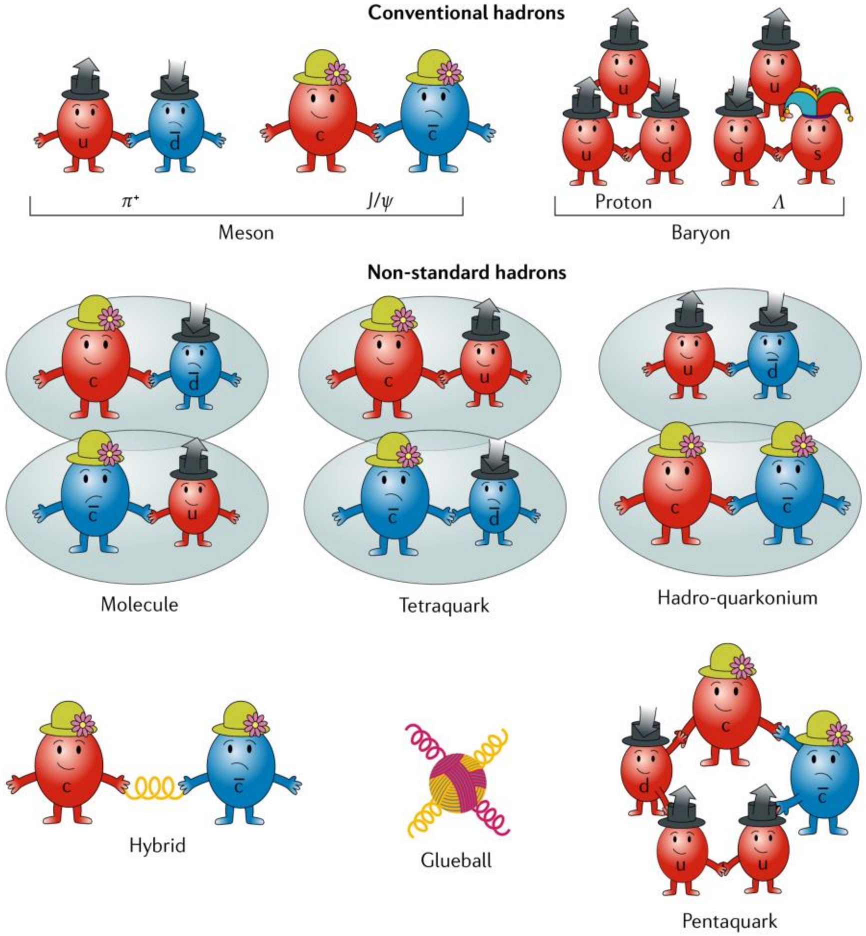
- Traditional quark model:

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

Phys. Lett. 8, 214 (1964)
CERN-TH-401, CERN-TH-412

- Quantum Chromodynamics:

Exotic state {
Molecular ($M\bar{M}$, $B\bar{B}\ldots$)
Tetraquark ($qq\bar{q}\bar{q}\ldots$)
Pentaquark ($qqqq\bar{q}\ldots$)
Hybrid ($q\bar{q}g$, $qqqg\ldots$)
Glueball (gg, $ggg\ldots$)
…



Exotic state

- 2003, Belle Collaboration, $X(3872)$ in the $J/\psi\pi^+\pi^-$ invariant mass distribution
  [Belle] Phys. Rev. Lett. 91, 262001 (2003)
  LHCb, Belle, BABAR, BESIII… many exotic states have been observed experimentally

- Exotic states near the thresholds of a pair of hadrons:
  $X(3872) \leftrightarrow D\bar{D}^*$ [Belle] Phys. Rev. Lett. 91, 262001 (2003)
  $Z_c(3900) \leftrightarrow D\bar{D}^*$ [BESIII] Phys. Rev. Lett. 110, 252001 (2013)
  $Z_{cs}(3985) \leftrightarrow D\bar{D}_s^*$ [BESIII] Phys. Rev. Lett. 126, 102001 (2021)
  $P_{cs}(4459) \leftrightarrow \Xi_c\bar{D}^*$ [LHCb] Sci. Bull. 66, 1278 (2021)
  $T_{cc}^+ \leftrightarrow DD^*$ [LHCb] Nature Phys. 18, 751 (2022) …
  Explanations: compact tetraquark, pentaquark, or hexaquark, hadronic molecule,
  kinematic effect (threshold cusp, triangle singularity) …

- Hadronic molecule:
  Two or more hadrons bounded through the strong interactions
  Mass around the threshold of a pair of hadrons
  Quantum number $J^{PC} \leftrightarrow S$-wave of the composites Rev. Mod. Phys. 90, 015003 (2018)

$D\bar{D}$ bound state

- 2007, $\pi^+\pi^-$, $\pi^0\pi^0$, K^+K^-, $K^0\bar{K}^0$, D^+D^-, $D^0\bar{D}^0$, $D_s^+D_s^-$, $\eta\eta$, $\eta\eta_c$ coupled channels, unitary coupled-channel approach, Phys. Rev. D 76, 074016 (2007)
  $D\bar{D}$ bound state with $I(J^{PC}) = 0(0^{++})$, $M \approx 3720$ MeV, denote as $X(3700)$

- Unitary coupled-channel approach: $\sqrt{s} = (3722 - i18)$ MeV Eur. Phys. J. A 41, 85 (2009)
  Lattice QCD: binding nergy $B = \left(4.0^{+5.0}_{-3.7}\right)$ MeV J. High Energy Phys. 06, 035 (2021)
  QCD sum rule: $M_{D\bar{D}} = (3.73 \pm 0.08)$ GeV Phys. Rev. D 105, 094003 (2022)
  Nonrelativistic EFT: $M = (3739.3 \pm 0.1)$ MeV Phys. Rev. D 105, 034024 (2022)

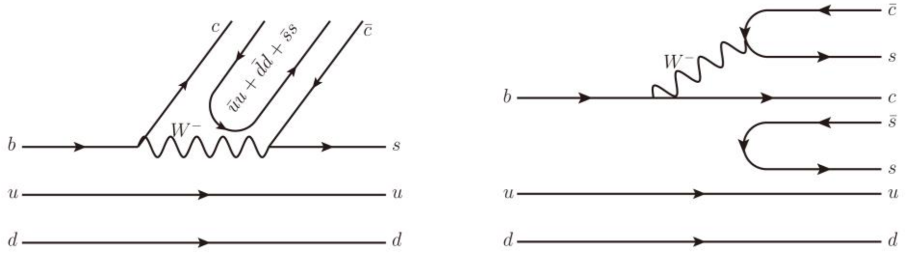
- Some theoretical studies of the experimental measured process support the existence of such a $D\bar{D}$ bound state, e.g., $e^+e^- \to J/\psi D\bar{D}^{(*)}$, $B \to D\bar{D}K$, $\gamma\gamma \to D\bar{D}$.
  Eur. Phys. J. A 36, 189 (2008), Eur. Phys. J. C 76, 121 (2016), Phys. Lett. B 827, 136982 (2022),
  Eur. Phys. J. A 57, 38 (2021), Phys. Rev. D 103, 054008 (2021)

- Some process suggested to search for the $D\bar{D}$ bound state:
  $\psi(3770)/\psi(4040) \to \gamma X(3700) \to \gamma\eta\eta'$, $e^+e^- \to J/\psi X(3700) \to J/\psi\eta\eta'$,
  $\psi(3770) \to \gamma D\bar{D}$, $\Lambda_b \to \Lambda D\bar{D}$, $B^+ \to K^+\eta\eta$
  Eur. Phys. J. A 41, 85 (2009), Eur. Phys. J. A 49, 52 (2013), Eur. Phys. J. C 80, 510 (2020),
  Phys. Rev. D 103, 114013 (2021), Phys. Rev. D 108, 054004 (2023)

$\Lambda_b \to \Lambda D\bar{D}$

The internal (left) and external (right) W^- emission:

Phys. Rev. D 103, 114013 (2021)



$$t^{S-\text{wave}}_{\Lambda_b\to\Lambda D^0\bar{D}^0} = V_p(1 + G_{D^+D^-}t_{D^+D^-\to D^0\bar{D}^0} + G_{D^0\bar{D}^0}t_{D^+D^-\to D^0\bar{D}^0} + (1+C)G_{D_s^+D_s^-}t_{D_s^+D_s^-\to D^0\bar{D}^0})$$

$$t^{S-\text{wave}}_{\Lambda_b\to\Lambda D^+D^-} = V_p(1 + G_{D^+D^-}t_{D^+D^-\to D^+D^-} + G_{D^0\bar{D}^0}t_{D^0\bar{D}^0\to D^+D^-} + (1+C)G_{D_s^+D_s^-}t_{D_s^+D_s^-\to D^+D^-})$$

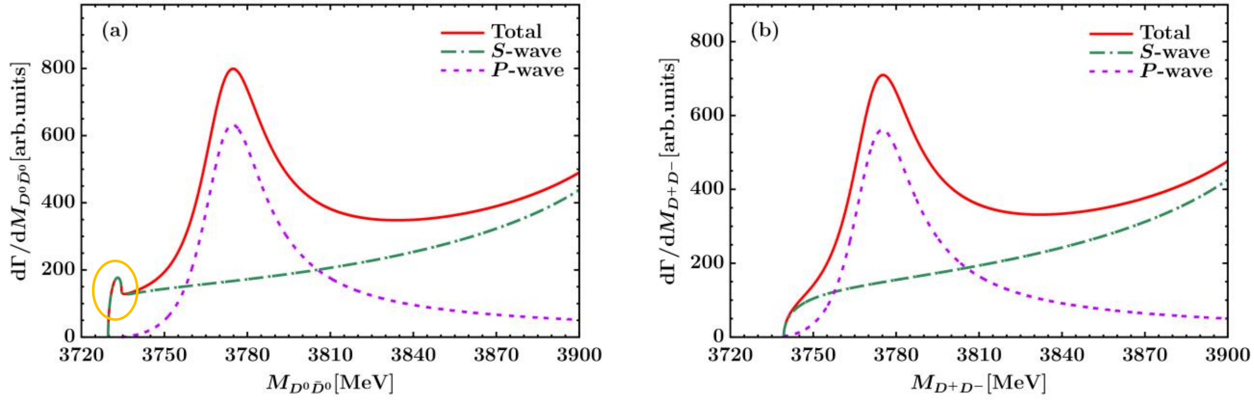
The intermediate state $\psi(3770)$:

$$t^{P-\text{wave}} = \frac{\beta \times V_p \times M_{\psi(3770)}\tilde{p}_D}{M^2_{D\bar{D}} - M^2_{\psi(3770)} + iM_{\psi(3770)}\tilde{\Gamma}_{\psi(3770)}}$$

BS equation: $t_{i\to j} = [1 - VG]^{-1}V$

The $D^0\bar{D}^0$ (left) and D^+D^- (right) invariant mass distributions:

J. High Energy Phys. 07,140 (2024)



- An enhancement near $D\bar{D}$ threshold
- Partial wave analysis

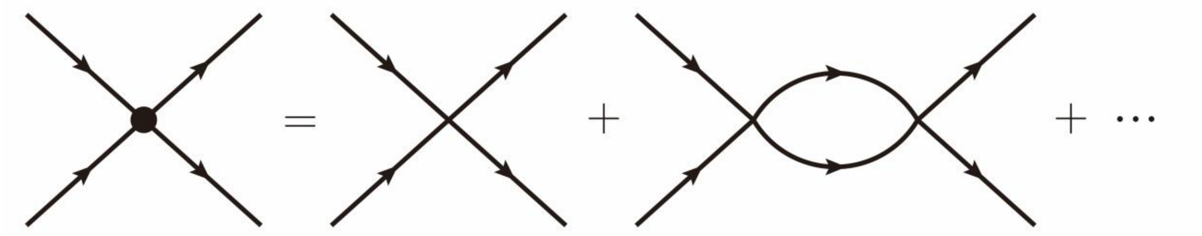
- Sizeable coupling between $X(3700)$ and $\eta\eta_c$, $M_{X(3700)} - (M_\eta + M_{\eta_c}) \approx 200$ MeV

$\to$ A clear peak in the $\eta\eta_c$ invariant mass distribution $\to B^- \to K^-\eta\eta_c$ decay

Contents

Unitary coupled-channel approach

- Bethe-Salpeter equation:



Scattering amplitude: $T = V + VGT \longrightarrow T = [1 - VG]^{-1}V$

V: transition potential between the coupled channels

G: loop function for the two-meson propagation in the lth coupled channel

Prog. Part. Nucl. Phys. 45, 157 (2000)

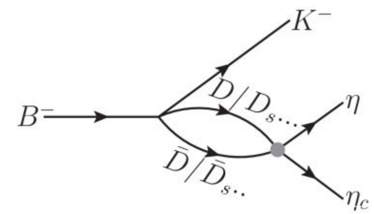
$$G_l(s) = \frac{1}{16\pi^2}\left[\alpha_l + \ln\frac{m_1^2}{\mu^2} + \frac{m_2^2 - m_1^2 + s}{2s}\ln\frac{m_2^2}{m_1^2} + \frac{\boldsymbol{p}}{\sqrt{s}} \times \left(\ln\frac{s - m_2^2 + m_1^2 + 2\boldsymbol{p}\sqrt{s}}{-s + m_2^2 - m_1^2 + 2\boldsymbol{p}\sqrt{s}} + \ln\frac{s + m_2^2 - m_1^2 + 2\boldsymbol{p}\sqrt{s}}{-s - m_2^2 + m_1^2 + 2\boldsymbol{p}\sqrt{s}}\right)\right]$$

- Pole in the complex energy plane (T) $\leftrightarrow$ bound state of a pair of hadrons

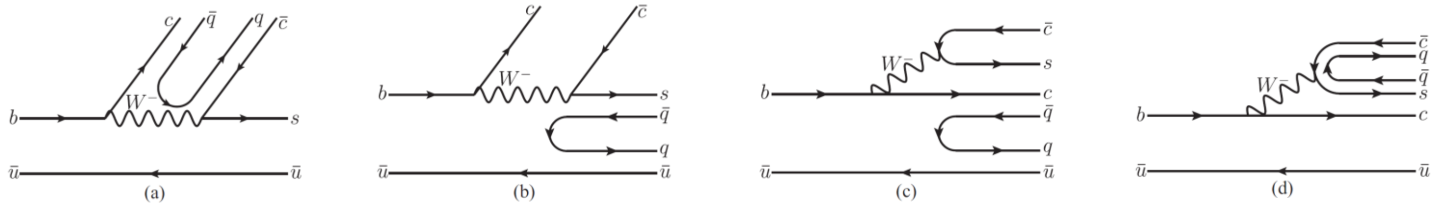
$\sqrt{s}_{\mathrm{p}} = (M_{\mathrm{R}} - i\Gamma_{\mathrm{R}}/2)$ MeV $\quad$ $M_{\mathrm{R}} \leftrightarrow$ mass; $\Gamma_{\mathrm{R}} \leftrightarrow$ width

$B^- \to K^- \eta \eta_c$

Three steps: weak decay → hadronization → final-state interactions



The internal (a-b) and external (c-d) W^- emission:

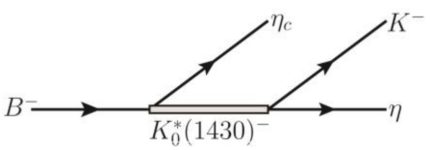


Rescattering amplitude: $T_{X(3700)} = V_p V_{cb} V_{cs} \Big((1+C) G_{D^0\bar{D}^0} t_{D^0\bar{D}^0 \to \eta\eta_c} + G_{D^+D^-} t_{D^+D^- \to \eta\eta_c}$

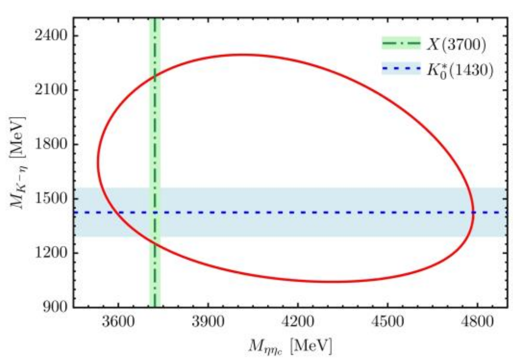
$+ (1+C) G_{D_s^+D_s^-} t_{D_s^+D_s^- \to \eta\eta_c} + 3/\sqrt{6}\, G_{\eta'\eta_c} t_{\eta'\eta_c \to \eta\eta_c} \Big)$

Eur. Phys. J. A 41, 85 (2009)

The intermediate state $K^*(1430)$:



$$T_{K^*} = \frac{V_p \times \beta \times M^2_{K_0^*(1430)}}{M^2_{K^-\eta} - M^2_{K_0^*(1430)} + i M_{K_0^*(1430)} \Gamma_{K_0^*(1430)}}$$



Doubly differential decay width:

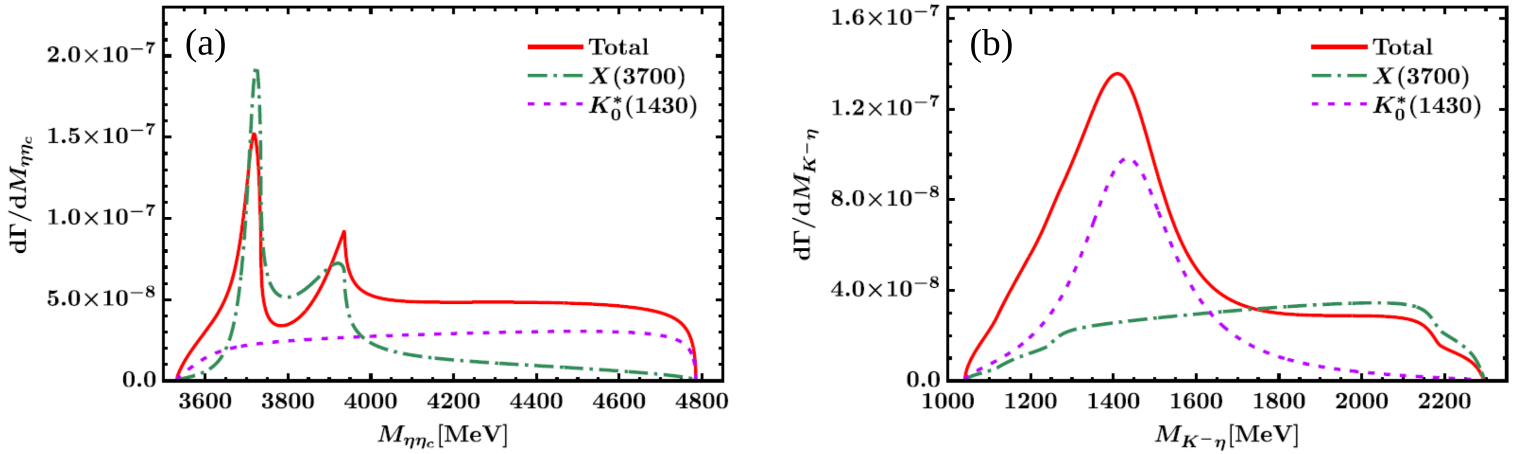
$$\frac{d^2\Gamma}{dM_{\eta\eta_c} dM_{K^-\eta}} = \frac{1}{(2\pi)^3} \frac{M_{K^-\eta} M_{\eta\eta_c}}{8 M^3_{B^-}} \left| T_{X(3700)} + e^{i\varphi} T_{K^*} \right|^2$$

Differential decay width: $$\frac{d\Gamma}{dM_{12}} = \int \frac{d^2\Gamma}{dM_{12} dM_{23}} dM_{23}$$

Contents

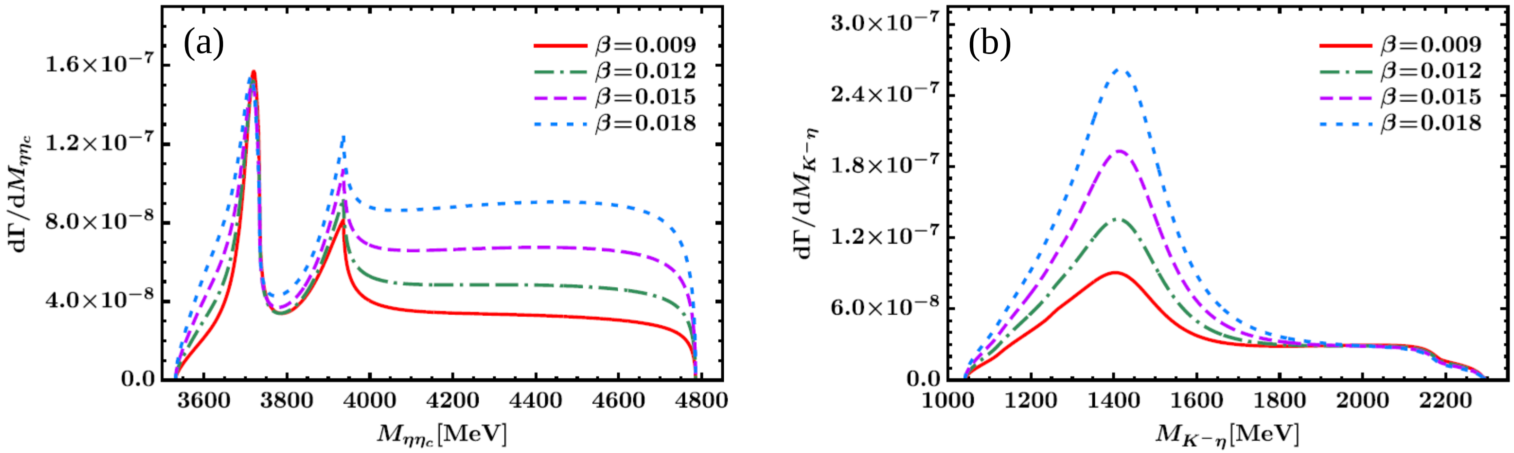
Results and discussion

The $\eta\eta_c$ (a) and $K^-\eta$ (b) invariant mass distributions (fixed parameter):



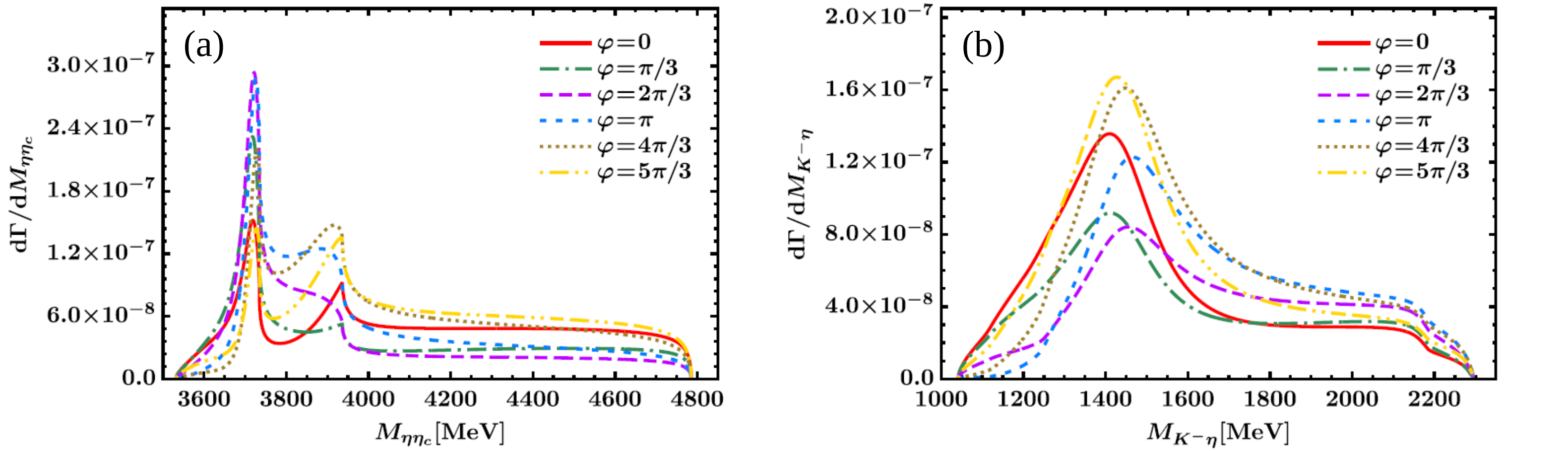
➢ a clear peak around 3720 MeV in the $\eta\eta_c$ IMD associated with the $D\bar{D}$ bound state

The $\eta\eta_c$ (a) and $K^-\eta$ (b) invariant mass distributions with $\beta = 0.009, 0.012, 0.015, 0.018$:

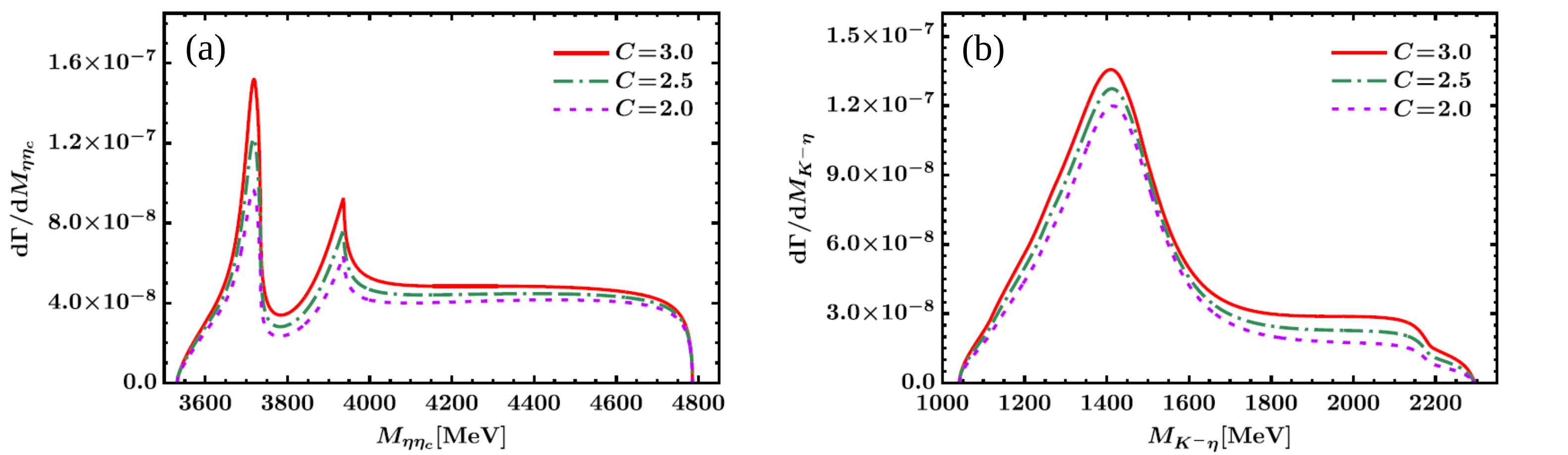


Results and discussion

The $\eta\eta_c$ (a) and $K^-\eta$ (b) invariant mass distributions with $\varphi = 0, \frac{\pi}{3}, \frac{2\pi}{3}, \pi, \frac{4\pi}{3}, \frac{5\pi}{3}$:



The $\eta\eta_c$ (a) and $K^-\eta$ (b) invariant mass distributions with $C = 3.0, 2.5, 2.0$:



- Within the variation ranges of parameters, always a clear peak in the $\eta\eta_c$ IMD

Contents

Summary

- Sizeable coupling between $X(3700)$ and $\eta\eta_c$, $M_{X(3700)} - (M_\eta + M_{\eta_c}) \approx 200$ MeV
  Many exotic states discovered in the B-meson three-body decay
  $\rightarrow$ Search for the $D\bar{D}$ bound state in the $B^- \rightarrow K^-\eta\eta_c$ process

- Unitary coupled-channel approach, calculate the $\eta\eta_c$ invariant mass distributions
  $X(3700)$: S-wave pseudoscalar meson-pseudoscalar meson interactions
  Intermediate resonance $K_0^*(1430)$

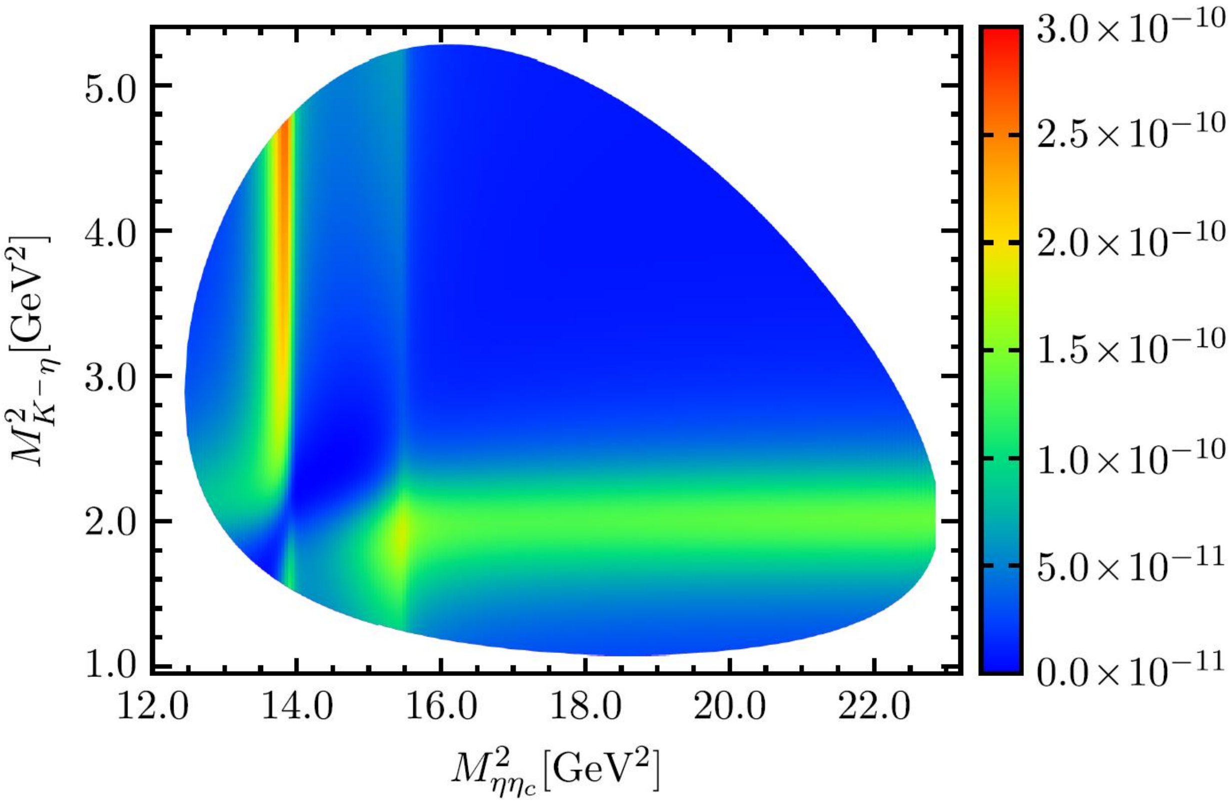
- $\eta\eta_c$ invariant mass distribution:
  A clear peak appears around 3720 MeV associated with the $D\bar{D}$ bound state $X(3700)$
  Intermediate resonance $K_0^*(1430)$ gives a smooth contribution

- A more precise measurement of the $B^- \rightarrow K^-\eta\eta_c$ decay at the Belle II and LHCb experiments in the future, to confirm the existence of such a predicted $D\bar{D}$ bound state and measure its mass and width

Thank you for your attention!

Backup

Doubly differential decay width of the $B^- \to K^-\eta\eta_c$ decay in the $\left(M^2_{\eta\eta_c}, M^2_{K^-\eta}\right)$ plane



- The $X(3700)$ and $K_0^*(1430)$ resonances can be clearly seen

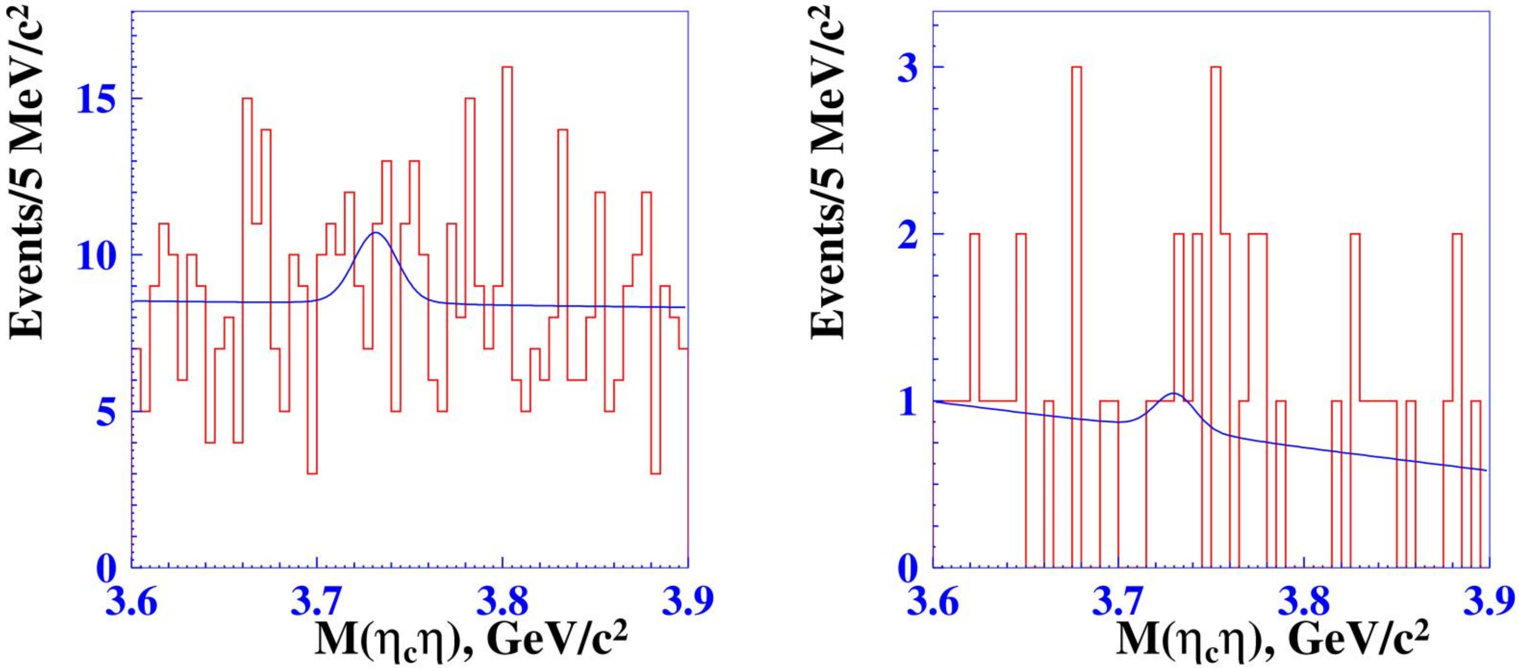
Backup

$B^{\pm} \to K^{\pm}\eta_c\eta$ Belle Collaboration: 772×10^6 $B\bar{B}$ pairs collected at $\Upsilon(4S)$

No obvious $X(3730)$ signal, the upper limits of the branching ratios:

$\mathcal{B}(B^{\pm} \to K^{\pm}\eta_c\eta) < 2.2 \times 10^{-4}$ [Belle] J. High Energy Phys. 06, 132 (2015)

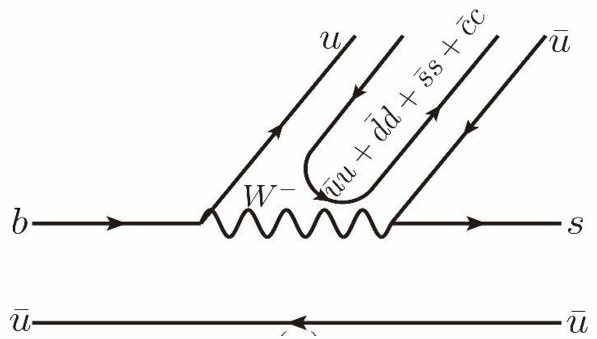
$\mathcal{B}(B^{\pm} \to K^{\pm}X(3730)) \times \mathcal{B}(X(3730) \to \eta_c\eta) < 4.6 \times 10^{-5}$



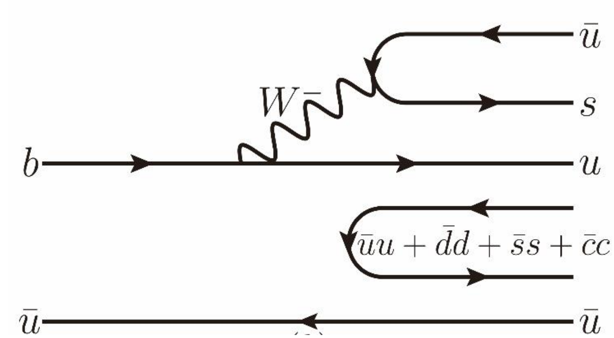
$\eta \to \gamma\gamma$ $\eta \to \pi^+\pi^-\pi^0$

Backup

Other quark level diagrams:



(a) Internal W^- emission



(b) External W^- emission

Components of the meson systems after hadronization:

$$|H\rangle^{3a} = V_p V_{ub} V_{us} \left(\frac{1}{3}\eta\eta + \frac{1}{2}\pi^0\pi^0 + \frac{1}{6}\eta'\eta' + \frac{1}{\sqrt{18}}\eta\eta' + \pi^+\pi^- + K^+K^- + D^0\bar{D}^0 \right) K^-$$

$$|H\rangle^{3b} = C \times V_p V_{ub} V_{us} \left(\frac{1}{3}\eta\eta + \frac{1}{2}\pi^0\pi^0 + \frac{1}{6}\eta'\eta' + \frac{1}{\sqrt{18}}\eta\eta' + \pi^+\pi^- + K^+K^- + D^0\bar{D}^0 \right) K^-$$

$$|V_{ub}| = 0.00369 \pm 0.00011 \qquad |V_{us}| = 0.22500 \pm 0.00067$$

$$|V_{cb}| = 0.04182^{+0.00085}_{-0.00074} \qquad |V_{cs}| = 0.97349 \pm 0.00016$$

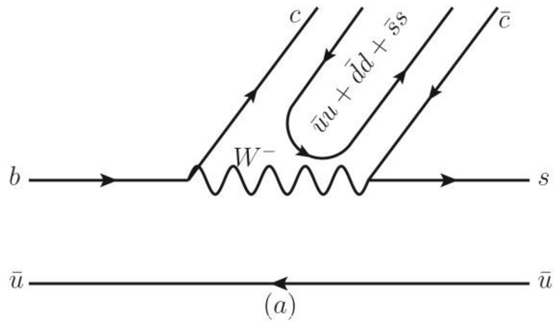
Prog. Theor. Exp. Phys. 2022, 083C01 (2022)

Backup

Hadronization:

L. R Dai, et al. Eur. Phys. J. C 76, 121 (2016)

e.g.



$$\sum_k q_i(\bar{q}_k q_k)\bar{q}_j = \sum_k M_{ik}M_{kj} = (M^2)_{ij}$$

$$|H\rangle^a = V_p V_{cb} V_{cs}^* (D^0\bar{D}^0 + D^+D^- + D_s^+D_s^-)K^-$$

$q\bar{q}$ matrix expressed in terms of the physical pseudoscalar mesons:

$$M \Rightarrow \begin{pmatrix} \frac{\eta}{\sqrt{3}} + \frac{\pi^0}{\sqrt{2}} + \frac{\eta'}{\sqrt{6}} & \pi^+ & K^+ & \bar{D}^0 \\ \pi^- & \frac{\eta}{\sqrt{3}} - \frac{\pi^0}{\sqrt{2}} + \frac{\eta'}{\sqrt{6}} & K^0 & D^- \\ K^- & \bar{K}^0 & \frac{\sqrt{2}}{\sqrt{3}}\eta' - \frac{\eta}{\sqrt{3}} & D_s^- \\ D^0 & D^+ & D_s^+ & \eta_c \end{pmatrix}$$