X atom

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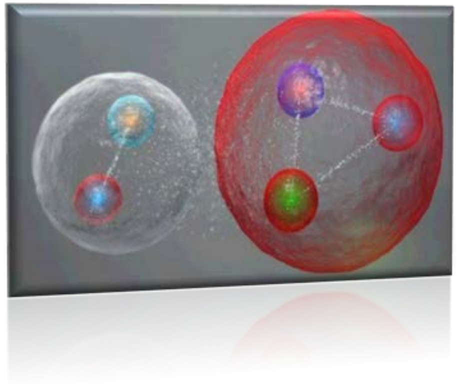
中国物理学会高能物理分会第十三届全国粒子物理学术会议(2021)
2021.08.16-20 青岛

Based on Z.-H. Zhang, F.-K. Guo. Phys. Rev. Lett. 127, 012002 (2021)

X atom: Background



Exotic hadrons are the hadrons beyond the quark model.

XYZ states, Glueballs, Pentaquarks…

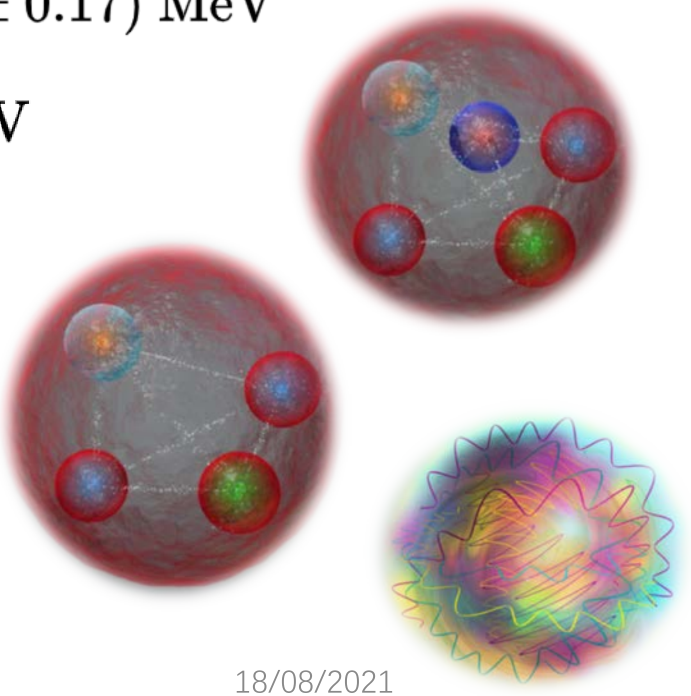
$X(3872)$ **is one of the most important XYZ states**

$X(3872)$ **is first discovered in the** $J/\psi\pi^+\pi^-$ **invariant mass distribution by Belle Collaboration in 2003, with** $I^G J^{PC} = 0^+(1^{++})$ **,** $m_X = (3871.69 \pm 0.17)$ MeV

Salient features: (a) $\delta = m_{D^0} + m_{D^{*0}} - m_X = (0.00 \pm 0.18)$ MeV

(b) $\mathcal{B}\left(X(3872) \to D^0 \bar{D}^0 \pi^0\right) > 40\%$

$\mathcal{B}\left(X(3872) \to D^0 \bar{D}^{*0}\right) > 30\%$



At long distance, $D^0 \bar{D}^{*0}$ **is dominant in** $X(3872)$

$$|X(3872)\rangle = \frac{1}{\sqrt{2}}\left(|D^0\bar{D}^{*0}\rangle - |\bar{D}^0 D^{*0}\rangle\right)$$

$$\begin{pmatrix} \mathcal{C}|D\rangle = |\bar{D}\rangle \\ \mathcal{C}|D^*\rangle = -|\bar{D}^*\rangle \end{pmatrix}$$

X atom: Introduction

Typical size for the $X(3872)$ at long distance: $r_X \simeq \frac{1}{\sqrt{2\mu_c^0\delta}} \gtrsim 10$ fm

Typical size (Bohr radius) for the D^+D^{*-} bound state: $r_B = \frac{1}{\alpha\mu_c} = 27.86$ fm

$$\mu_0 = \frac{m_{D^0} m_{D^{*0}}}{\Sigma_0} \quad \mu_c = \frac{m_D m_{D^*}}{\Sigma_c} \quad \Sigma_0 = m_{D^0} + m_{D^{*0}} \quad \Sigma_c = m_D + m_{D^*} = (3879.91 \pm 0.07)\ \text{MeV}$$

Coulomb binding energies: $-E_n = -\frac{\alpha^2\mu_c}{2n^2} = \frac{-E_1}{n^2} = -\frac{25.81\ \text{keV}}{n^2}$

X atom: The ground state $\frac{1}{\sqrt{2}}\left(|D^+D^{*-}\rangle - |D^-D^{*+}\rangle\right)$ **atom with** $C = +$

Scale separation: $r_B\Lambda_{\text{QCD}} \gg 1$ **, strong interaction between** D^+D^{*-} **is a correction**

Effects of strong interaction at LO:

(a) Energy level shift: $\Delta E_n^{\text{str}} \sim \mathcal{O}(\alpha^3)$ **(b) Decay modes:** $D^0\bar{D}^{*0}, D^0\bar{D}^0\pi^0, J/\psi\pi\pi, \cdots$

The strong interaction is non-perturbative due to the existence of the $X(3872)$

Only hadronic atoms with light quarks have been studied

Gasser, Lyubovitskij, Rusetsky, *Phys. Rept.* 456 (2008)

X atom: Introduction

The X atom is related to the $X(3872)$ (as a hadronic molecule) by isospin symmetry

D^+D^{*-} threshold: $\Sigma_c = m_D + m_{D^*} = (3879.91 \pm 0.07)$ MeV , no signal near the threshold

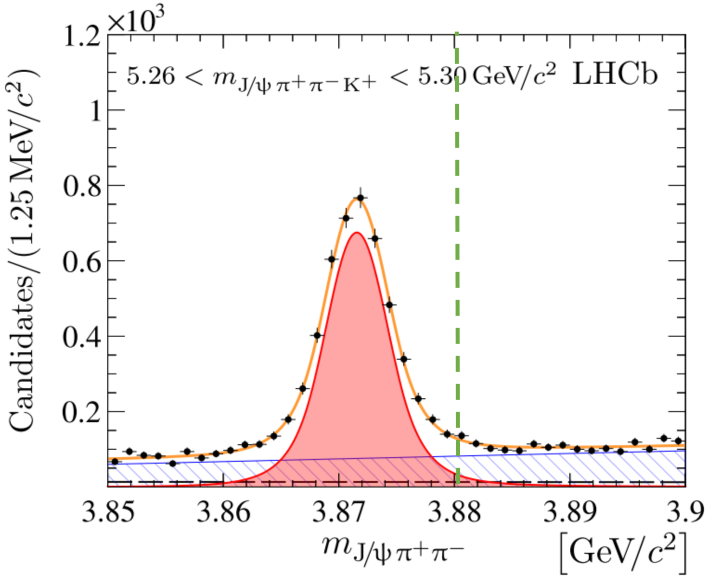
Make use of the zero signal to:

- Put a lower bound on the $X(3872)$ binding energy
- Give a criterion on the $X(3872)$ nature

Scale separation: $r_B \Lambda_{\rm QCD} \gg 1$; Nonrelativistic effective field theory (NREFT) applicable

Approximation: Isospin-1 strong interaction neglected

- No isovector state was found
- Isospin breaking in the couplings is small $\dfrac{g_{X\rho}}{g_{X\omega}} = 0.26^{+0.08}_{-0.05}$



LHCb, *J. High Energy Phys.* 08 (2020) 123

Hanhart et al. , *Phys. Rev. D* 85 (2012) 011501

X atom: NREFT

Coupled channel: $\textbf{CH 1}: D^+D^{*-} \to D^+D^{*-}$ $\textbf{CH 2}: D^0\bar{D}^{*0} \to D^0\bar{D}^{*0}$

Non-relativistic effective Lagrangian: Galilean, Gauge invariant; C, P, T

Around threshold, LO Lagrangian: constant contact terms for strong interactions

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \sum_{\phi=D^\pm,D^0,\bar{D}^0} \phi^\dagger\left(iD_t - m_\phi + \frac{\nabla^2}{2m_\phi}\right)\phi + \sum_{\phi=D^{*\pm},D^{*0},\bar{D}^{*0}} \phi^\dagger\left(iD_t - m_\phi + i\frac{\Gamma_\phi}{2} + \frac{\nabla^2}{2m_\phi}\right)\phi$$
$$-\frac{C_0}{2}\left(D^+D^{*-} - D^-D^{*+}\right)^\dagger\left(D^+D^{*-} - D^-D^{*+}\right) - \frac{C_0}{2}\left[\left(D^+D^{*-} - D^-D^{*+}\right)^\dagger\left(D^0\bar{D}^{*0} - \bar{D}^0D^{*0}\right) + \text{h. c.}\right]$$
$$-\frac{C_0}{2}\left(D^0\bar{D}^{*0} - \bar{D}^0D^{*0}\right)^\dagger\left(D^0\bar{D}^{*0} - \bar{D}^0D^{*0}\right) + \cdots$$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \qquad D_t\phi = \partial_t\phi \mp iQA_0\phi$$

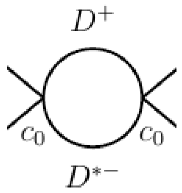
Constant width approximation for D^*

Hanhart, Kalashnikova, Nefediev, *Phys. Rev. D* 81 (2010) 094028

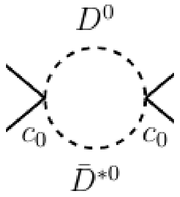
X atom: NREFT

S-wave T-matrix for $I^G J^{PC} = 0^+(1^{++})$ **coupled channel:** $T(E) = V[1 - G(E)V]^{-1}$

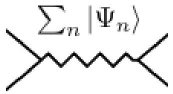
Strong contact term: $V = C_0 \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix}$ **Green's function:** $G(E) = \begin{pmatrix} J_c(E) + J_{|\Psi\rangle}(E) & 0 \\ 0 & J_0(E) \end{pmatrix}$



$$J_c(E) = \frac{\mu_c}{2\pi}\left(-\frac{2\Lambda}{\pi} + \sqrt{-2\mu_c(E + i\Gamma_c/2)}\right) \qquad E = \sqrt{s} - \Sigma_c$$



$$J_0(E) = \frac{\mu_0}{2\pi}\left(-\frac{2\Lambda}{\pi} + \sqrt{-2\mu_0(E + \Delta + i\Gamma_0/2)}\right) \qquad \Delta = \Sigma_c - \Sigma_0$$

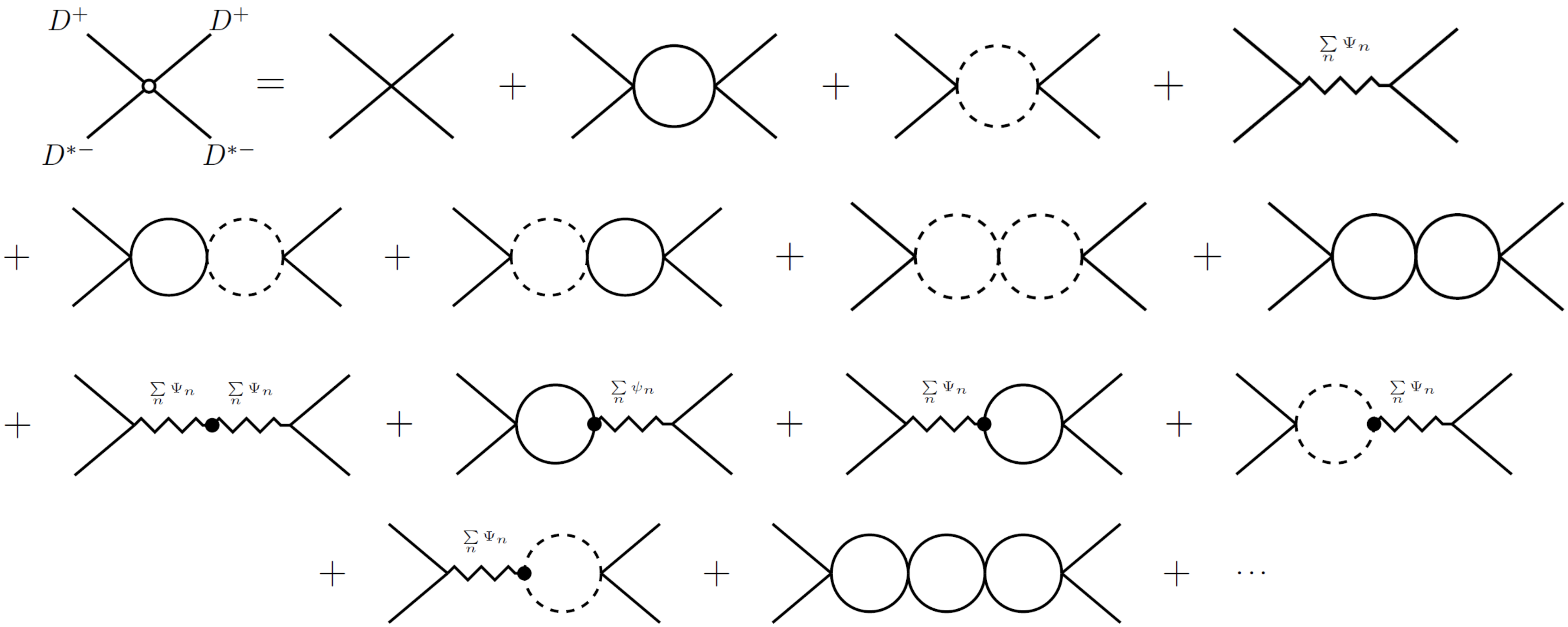


$$J_{|\Psi\rangle}(E) = \sum_{n=1}^{\infty} \frac{\alpha^3 \mu_c^3}{\pi n^3} \frac{1}{E + E_n + i\Gamma_c/2} \qquad \Gamma_c \equiv \Gamma_{D^*}, \quad \Gamma_0 \equiv \Gamma_{D^{*0}}$$

X atom: NREFT

S-wave T-matrix for $I^G J^{PC} = 0^+(1^{++})$ coupled channel:

$$T(E) = \frac{1}{C_0^{-1} - \left[J_0(E) + J_c(E) + J_{|\Psi\rangle}(E)\right]} \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix}$$



X atom: Strong Energy Level Shift

***S*-wave *T*-matrix for $I^G J^{PC} = 0^+(1^{++})$ coupled channel:**

$$T(E) = \frac{1}{C_0^{-1} - \left[J_0(E) + J_c(E) + J_{|\Psi\rangle}(E)\right]} \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix}$$

Renormalization: $C_{0R}^{-1} = C_0^{-1} + \Lambda(\mu_0 + \mu_c)/\pi^2$

The $X(3872)$ and hadronic atoms appear as poles of the *T*-matrix

$X(3872)$ pole: $E = -\Delta - \delta - i\frac{\Gamma_0}{2}$ $\quad\quad \delta\Gamma = \Gamma_c - \Gamma_0$

$$C_{0R}^{-1} = \frac{\mu_0}{2\pi}\sqrt{2\mu_0\delta} + \frac{\mu_c}{2\pi}\sqrt{2\mu_c\left(\Delta + \delta - i\frac{\delta\Gamma}{2}\right)} - \sum_{n=1}^{\infty}\frac{\alpha^3\mu_c^3}{\pi n^3}\frac{1}{\Delta + \delta - E_n - i\delta\Gamma/2} = \frac{\mu_c}{2\pi}\sqrt{2\mu_c\Delta}\left[1 + \mathcal{O}\left(\frac{\delta}{\Delta}, \frac{\delta\Gamma}{\Delta}, \frac{\alpha^3\mu_c^{3/2}}{\Delta^{3/2}}\right)\right]$$

***S*-wave hadronic atom poles:** $E = -E_{An} - i\frac{\Gamma_c}{2}$

$$0 = C_{0R}^{-1} + i\frac{\mu_0}{2\pi}\sqrt{2\mu_0\left(\Delta - E_{An} - i\frac{\delta\Gamma}{2}\right)} - \frac{\mu_c}{2\pi}\sqrt{2\mu_c E_{An}} - \sum_{n=1}^{\infty}\frac{\alpha^3\mu_c^3}{\pi n^3}\frac{1}{-E_{An} + E_n}$$

X atom: Strong Energy Level Shift

Strong energy level shift: $\Delta E_n = E_{An} - E_n$

$$\Delta E_n = \frac{2\alpha^3\mu_c^2}{n^3\sqrt{2\mu_c\Delta}}\left[-1 - i + \mathcal{O}\left(\alpha\sqrt{\frac{\mu_c}{\Delta}}\right)\right]^{-1}$$

***S*-wave hadronic atom poles:** $E = -E_{An} - i\frac{\Gamma_c}{2} = -E_n - \Delta E_n - i\frac{\Gamma_c}{2}$

Ground state: $n = 1$

Binding energy: $\mathrm{Re}\,E_{A1} = E_1 - \frac{\alpha^3\mu_c^2}{\sqrt{2\mu_c\Delta}} \simeq 22.92\ \mathrm{keV}$ $\quad M_{A1} = (3879.89 \pm 0.07)\ \mathrm{MeV}$

Decay width: $\Gamma_c + 2\,\mathrm{Im}\,E_{A1} = \Gamma_c + \frac{2\alpha^3\mu_c^2}{\sqrt{2\mu_c\Delta}} = (89.2 \pm 1.8)\ \mathrm{keV}$

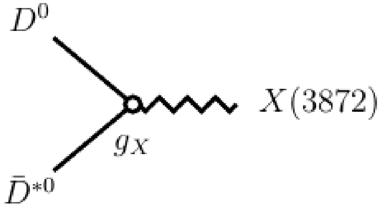
$D^* \to D\pi, D\gamma, \cdots$ $\quad \Gamma_c = (83.4 \pm 1.8)\ \mathrm{keV}$

$A\ (\mathrm{X\ atom}) \to D^0\bar{D}^{*0}(\bar{D}^0 D^{*0})$ $\quad \Gamma_s = 2\mathrm{Im}E_{A1} = 5.8\ \mathrm{keV}$

X atom: Effective Coupling

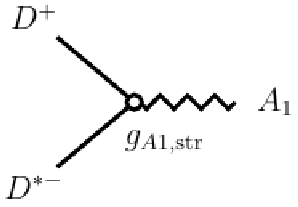
The effective coupling squared is the residue of the *T*-matrix at the pole

$D^0\bar{D}^{*0} \to X(3872)$ $X(3872)$ **pole:** $E = -\Delta - \delta - i\frac{\Gamma_0}{2}$



$$g_X^2 = \lim_{E\to -\Delta-\delta-i\frac{\Gamma_0}{2}} \left(E + \Delta + \delta + i\frac{\Gamma_0}{2}\right) T_{22}(E) = \frac{2\pi}{\mu_0^2}\sqrt{2\mu_0\delta}\left[1+\mathcal{O}\left(\frac{\delta^{1/2}}{\Delta^{1/2}}\right)\right]^{-1}$$

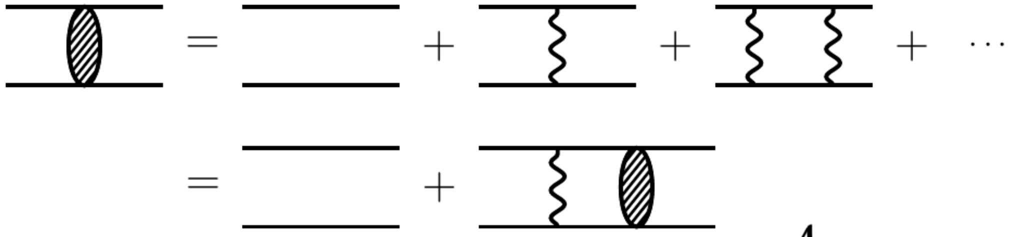
$D^+D^{*-} \to A_1$ **Hadronic atom poles:** $E = -E_{An} - i\frac{\Gamma_c}{2}$

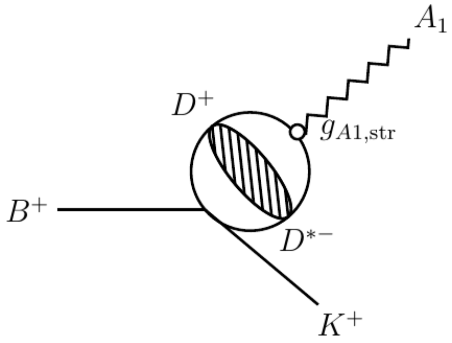


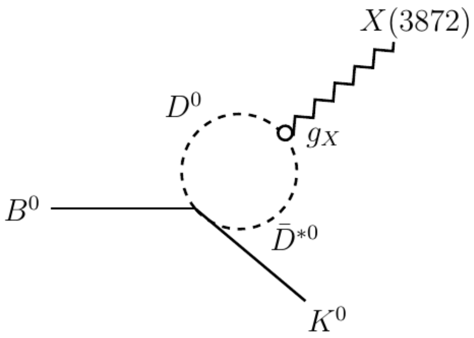
$$g_{A1,\mathrm{str}}^2 = \lim_{E\to -E_{A1}-i\frac{\Gamma_c}{2}} \left(E + E_{A1} + i\frac{\Gamma_c}{2}\right) T_{11}(E) = -i\frac{\pi\alpha^3}{\Delta}\left[1+\mathcal{O}\left(\frac{\alpha^2\mu_c}{\Delta}\right)\right]^{-1}$$

X atom: Production

Production in exclusive B decays:







$$B^+ \to (DD^*)_+ K^+ \to A_1 K^+ \qquad B^0 \to (DD^*)_+^0 K^0 \to X K^0$$

$$\mathcal{A}_{B^+\to A_1 K^+} = \mathcal{A}^{(\Lambda)}_{B^+\to (DD^*)_+ K^+} G_C(\Lambda, E) g_{A_1,\mathrm{str}} \qquad \mathcal{A}_{B^0\to X K^0} = \mathcal{A}^{(\Lambda)}_{B^0\to (DD^*)_+^0 K^0} G_0(\Lambda, E) g_X$$

$$G_C(\Lambda, E) = -\frac{\mu_c \Lambda}{\pi^2} - \frac{\alpha \mu_c^2}{\pi}\left[\ln\frac{\Lambda}{\alpha\mu_c} + \ln(x) + \frac{1}{2x} - \psi(-x) - \gamma_E\right] \qquad G_0(\Lambda, E) = -\frac{\mu_c^0 \Lambda}{\pi^2} + \frac{\mu_c^0}{2\pi}\left(\sqrt{-2\mu_c^0 E - i\epsilon}\right)$$

$$\left|(DD^*)_+^0\right\rangle = \frac{1}{\sqrt{2}}\left(\left|D^0 \bar{D}^{*0}\right\rangle - \left|\bar{D}^0 D^{*0}\right\rangle\right) \qquad x = \frac{\alpha\mu_c}{\sqrt{-2\mu_c(E + i\frac{\Gamma_c}{2})}} \qquad \psi(x) = \frac{\Gamma'(x)}{\Gamma(x)}$$

$$\left|(DD^*)_+\right\rangle = \frac{1}{\sqrt{2}}\left(\left|D^+ D^{*-}\right\rangle - \left|D^- D^{*+}\right\rangle\right)$$

Kong, Ravndal, *Nucl. Phys. A* 665 (2000)

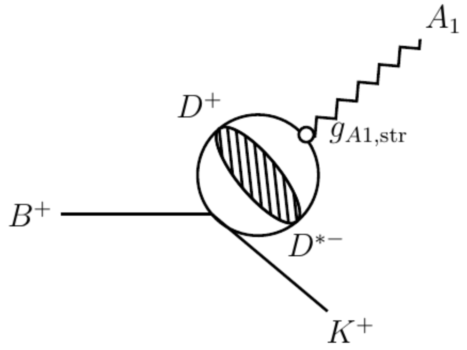
Factorized amplitudes: $\mathcal{A}_{B^+\to A_1 K^+} = \mathcal{A}^{\mathrm{s.d}}_{B^+\to (DD^*)_+ K^+} g_{A1,\mathrm{str}} \qquad \mathcal{A}_{B^0\to X K^0} = \mathcal{A}^{\mathrm{s.d.}}_{B^0\to (DD^*)_+^0 K^0} g_X$

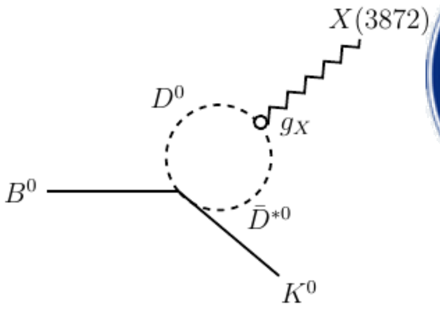
Braaten, Kusunoki, *Phys. Rev. D* 72 (2005) 014012

Isospin symmetry: $\left|\mathcal{A}^{\mathrm{s.d}}_{B^+\to (DD^*)_+ K^+}\right| = \left|\mathcal{A}^{\mathrm{s.d}}_{B^0\to (DD^*)_+^0 K^0}\right|$

X atom: Production

Production in exclusive *B* decays:





$$\left|(DD^*)_+^0\right\rangle = \frac{1}{\sqrt{2}}\left(\left|D^0\bar{D}^{*0}\right\rangle - \left|\bar{D}^0 D^{*0}\right\rangle\right)$$

$$\left|(DD^*)_+\right\rangle = \frac{1}{\sqrt{2}}\left(\left|D^+D^{*-}\right\rangle - \left|D^-D^{*+}\right\rangle\right)$$

$$B^+ \to (DD^*)_+ K^+ \to A_1 K^+ \qquad B^0 \to (DD^*)_+^0 K^0 \to X K^0$$

Factorized amplitudes:

$$\mathcal{A}_{B^+\to A_1K^+} = \mathcal{A}^{\mathrm{s.d}}_{B^+\to(DD^*)_+K^+}\, g_{A1,\mathrm{str}} \qquad \mathcal{A}_{B^0\to XK^0} = \mathcal{A}^{\mathrm{s.d.}}_{B^0\to(DD^*)_+^0K^0}\, g_X$$

Isospin symmetry:

$$\left|\mathcal{A}^{\mathrm{s.d}}_{B^+\to(DD^*)_+K^+}\right| = \left|\mathcal{A}^{\mathrm{s.d}}_{B^0\to(DD^*)_+^0K^0}\right|$$

Lower bound on the $X(3872)$ binding energy:

$$R_\Gamma \equiv \frac{\Gamma_{B^+\to A_1K^+}}{\Gamma_{B^0\to XK^0}} = \frac{\left|g_{A1,\mathrm{str}}\right|^2}{\left|g_X\right|^2} \qquad \delta \simeq \frac{0.25\ \mathrm{eV}}{R_\Gamma^2}$$

Production in inclusive *pp* collisions:

$$R_\sigma \equiv \frac{d\sigma_{pp\to A_1+y}}{d\sigma_{pp\to X+y}} = \frac{\left|g_{A1,\mathrm{str}}\right|^2}{\left|g_X\right|^2} \qquad \delta \simeq \frac{0.25\ \mathrm{eV}}{R_\sigma^2} \qquad R_\Gamma \simeq R_\sigma \gtrsim 1\times 10^{-3}$$

X atom: Decay

Constituent D^* decay: $D^* \to D\pi, D\gamma, \cdots$ $\Gamma_c = (83.4 \pm 1.8)$ keV

Decay into neutral pair: $A\ (\text{X atom}) \to D^0\bar{D}^{*0}(\bar{D}^0 D^{*0})$ $\Gamma_s = 2\text{Im}E_{A1} = 5.8$ keV

Decay into $J/\psi\pi\pi$ & $J/\psi\pi^+\pi^-\pi^0$ (like the $X(3872)$) $A \to J/\psi\pi\pi, J/\psi\pi^+\pi^-\pi^0$

Ratio of branchings for the $X(3872)$: $\frac{\text{Br}^{\text{exp}}_{[X(3872)\to J/\psi\pi^+\pi^-\pi^0]}}{\text{Br}^{\text{exp}}_{[X(3872)\to J/\psi\pi^+\pi^-]}} = 1.1 \pm 0.4$

Isospin breaking: $R_X = \frac{g_{[X(3872)\to J/\psi\rho]}}{g_{[X(3872)\to J/\psi\omega]}} = 0.26$

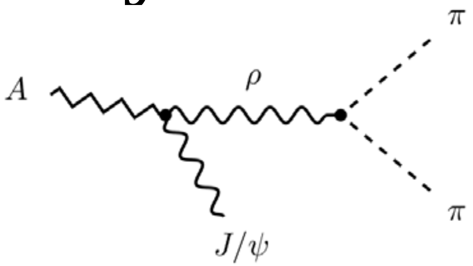
C. Hanhart et al. , *Phys. Rev. D* 85 (2012) 011501

D^+D^{*-} **atom (A):** $m_A = 3879.89 \pm 0.07$ MeV

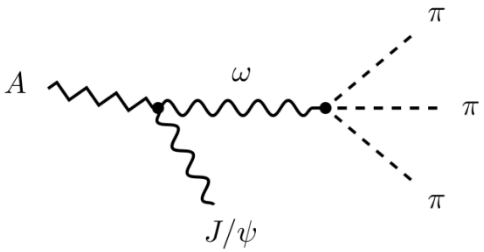
Isospin breaking negligible: $|D^+D^{*-}\rangle = \frac{1}{\sqrt{2}}(|I=1\rangle + |I=0\rangle)$ $R_A = \frac{g_{[A\to J/\psi\rho]}}{g_{[A\to J/\psi\omega]}} = 1$

The phase space of the D^+D^{*-} atom is larger than the phase space of the $X(3872)$

X atom: Decay



$$A \to J/\psi\pi\pi$$



$$A \to J/\psi\pi^+\pi^-\pi^0$$

$$\frac{\mathrm{Br}_{[X(3872)\to J/\psi\pi^+\pi^-\pi^0]}}{\mathrm{Br}_{[X(3872)\to J/\psi\pi^+\pi^-]}} = 1.09$$

$$\frac{\mathrm{Br}^{\mathrm{exp}}_{[X(3872)\to J/\psi\pi^+\pi^-\pi^0]}}{\mathrm{Br}^{\mathrm{exp}}_{[X(3872)\to J/\psi\pi^+\pi^-]}} = 1.1 \pm 0.4$$

C. Hanhart et al. , *Phys. Rev. D* 85 (2012) 011501

O. Kaymakcalan, S. Rajeev, and J. Schechter, *Phys. Rev. D* 30, 594 (1984)

E. A. Kuraev and Z. K. Silagadze, *Phys. At. Nucl.* 58, 1589 (1995)

Effective couplings:

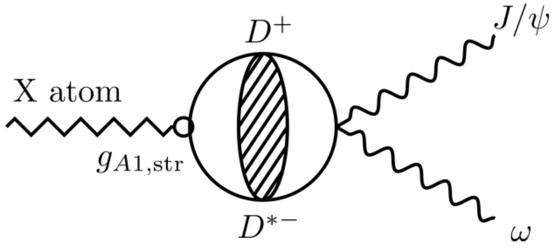
$$R_A = \frac{g_{[A\to J/\psi\rho]}}{g_{[A\to J/\psi\omega]}} = 1 \qquad R_X = \frac{g_{[X(3872)\to J/\psi\rho]}}{g_{[X(3872)\to J/\psi\omega]}} = 0.26$$

Ratio of branchings:

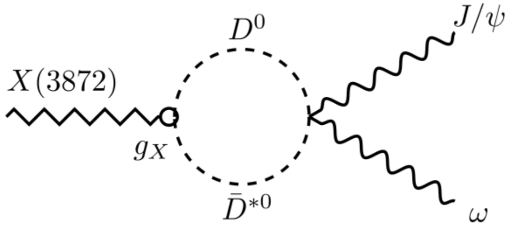
$$\frac{\mathrm{Br}_{[A\to J/\psi\pi\pi]}}{\mathrm{Br}_{[A\to J/\psi\pi^+\pi^0\pi^-]}} = 3.34 \qquad \frac{\mathrm{Br}_{[X(3872)\to J/\psi\pi\pi]}}{\mathrm{Br}_{[X(3872)\to J/\psi\pi^+\pi^0\pi^-]}} = 0.91$$

$$\frac{\mathrm{Br}_{[A\to J/\psi\pi\pi]}}{\mathrm{Br}_{[A\to J/\psi\pi^+\pi^0\pi^-]}} \simeq 3.65 \, \frac{\mathrm{Br}_{[X(3872)\to J/\psi\pi\pi]}}{\mathrm{Br}_{[X(3872)\to J/\psi\pi^+\pi^0\pi^-]}}$$

X atom: Decay



$A \to J/\psi\omega$



$X(3872) \to J/\psi\omega$

Factorized amplitudes : $\mathcal{A}_{[A\to J/\psi\omega]} = g_{A1,\text{str}}\mathcal{A}^{\text{s.d.}}_{[(DD^*)_+\to J/\psi\omega]}$ $\quad \mathcal{A}_{[X(3872)\to J/\psi\omega]} = g_X\mathcal{A}^{\text{s.d.}}_{[(DD^*)^0_+\to J/\psi\omega]}$

Ratio of phase spaces : $\dfrac{\Phi_{[A\to J/\psi\pi^+\pi^-\pi^0]}}{\Phi_{[X(3872)\to J/\psi\pi^+\pi^-\pi^0]}} = 3.76$

Ratio of decay widths : $\dfrac{\Gamma_{[A\to J/\psi\pi^+\pi^-\pi^0]}}{\Gamma_{[X(3872)\to J/\psi\pi^+\pi^-\pi^0]}} = \dfrac{|g_{A1,\text{str}}|^2}{|g_X|^2}\dfrac{\Phi_{[A\to J/\psi\pi^+\pi^-\pi^0]}}{\Phi_{[X(3872)\to J/\psi\pi^+\pi^-\pi^0]}} \gtrsim 3.76\times 10^{-3}$

$$\frac{\text{Br}_{[A\to J/\psi\pi\pi]}}{\text{Br}_{[A\to J/\psi\pi^+\pi^0\pi^-]}} \simeq 3.65\,\frac{\text{Br}_{[X(3872)\to J/\psi\pi\pi]}}{\text{Br}_{[X(3872)\to J/\psi\pi^+\pi^0\pi^-]}} \qquad \frac{\Gamma_{[A\to J/\psi\pi\pi]}}{\Gamma_{[X(3872)\to J/\psi\pi\pi]}} \gtrsim 1.37\times 10^{-2}$$

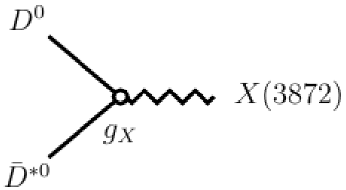
X atom: Results

(a) Binding Energy and Decay Width for the X Atom

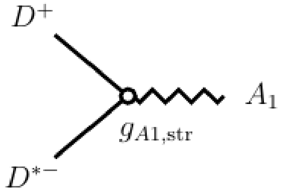
$$\mathrm{Re}\,E_{A1} = E_1 - \frac{\alpha^3\mu_c^2}{\sqrt{2\mu_c\Delta}} \simeq 22.92\ \mathrm{keV} \qquad \Gamma_c + 2\,\mathrm{Im}\,E_{A1} = \Gamma_c + \frac{2\alpha^3\mu_c^2}{\sqrt{2\mu_c\Delta}} = (89.2 \pm 1.8)\ \mathrm{keV}$$

$$M_{A1} = (3879.89 \pm 0.07)\ \mathrm{MeV} \qquad \Gamma_c = (83.4 \pm 1.8)\ \mathrm{keV}$$

(b) LO Effective Couplings



$$g_X^2 = \frac{2\pi}{\mu_0^2}\sqrt{2\mu_0\delta}$$



$$|g_{A1,\mathrm{str}}|^2 = \frac{\pi\alpha^3}{\Delta}$$

(c) Lower bound on the $X(3872)$ binding energy

$$\delta \simeq \frac{0.25\ \mathrm{eV}}{R^2_{\Gamma(\sigma)}} \qquad R_\Gamma \equiv \frac{\Gamma_{B^+\to A_1K^+}}{\Gamma_{B^0\to XK^0}} \qquad R_\sigma \equiv \frac{d\sigma_{pp\to A_1+y}}{d\sigma_{pp\to X+y}} \qquad \delta = m_{D^0} + m_{D^{*0}} - m_X \qquad R_\Gamma \simeq R_\sigma \gtrsim 1\times 10^{-3}$$

(d) Ratio of decay widths

$$\frac{\mathrm{Br}_{[A\to J/\psi\pi\pi]}}{\mathrm{Br}_{[A\to J/\psi\pi^+\pi^0\pi^-]}} \simeq 3.65\,\frac{\mathrm{Br}_{[X(3872)\to J/\psi\pi\pi]}}{\mathrm{Br}_{[X(3872)\to J/\psi\pi^+\pi^0\pi^-]}}$$

$$\frac{\Gamma_{[A\to J/\psi\pi^+\pi^-\pi^0]}}{\Gamma_{[X(3872)\to J/\psi\pi^+\pi^-\pi^0]}} \gtrsim 3.76\times 10^{-3} \qquad \frac{\Gamma_{[A\to J/\psi\pi\pi]}}{\Gamma_{[X(3872)\to J/\psi\pi\pi]}} \gtrsim 1.37\times 10^{-2}$$

X atom: Summary

- We show that a null signal of the X atom can be used to put a lower limit on the binding energy of the $X(3872)$.
- If the binding energy of the $X(3872)$ is measured, the lower limit could give a criterion on the $X(3872)$ nature.
- From more and more events collected at the PANDA and LHCb experiments for the $X(3872)$, we can except the signal from the X atom.

Thank you for your attention!

Back Up

Line Shape of the X atom

Binding energy of the X atom: $E_{XA} \sim \mathrm{Re}\, E_{A1} = E_1 - \frac{\alpha^3 \mu_c^2}{\sqrt{2\mu_c \Delta}} \simeq 22.92\mathrm{keV}$

Decay width of the X atom: $\Gamma_{XA} \sim \Gamma_c + 2\, \mathrm{Im}\, E_{A1} = \Gamma_c + \frac{2\alpha^3 \mu_c^2}{\sqrt{2\mu_c \Delta}} = (89.2 \pm 1.8)\mathrm{keV} \gg E_{XA}$

The line shape of the X atom is more like the line shape of the Toponium.

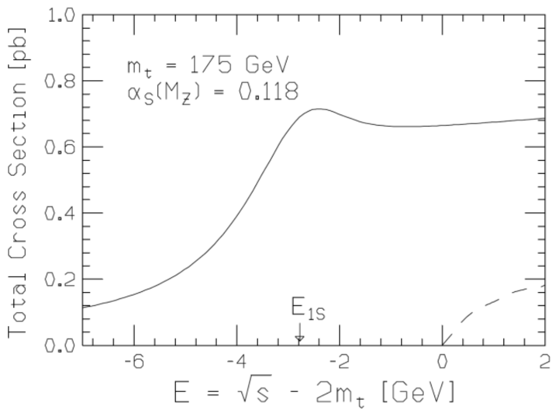


Fig. 4. The total cross section vs. energy, $E = \sqrt{s} - 2m_t$. The solid curve is calculated from the Green function. The dashed curve shows the tree-level total cross section for a stable top quark.

Total cross section of the Toponium.

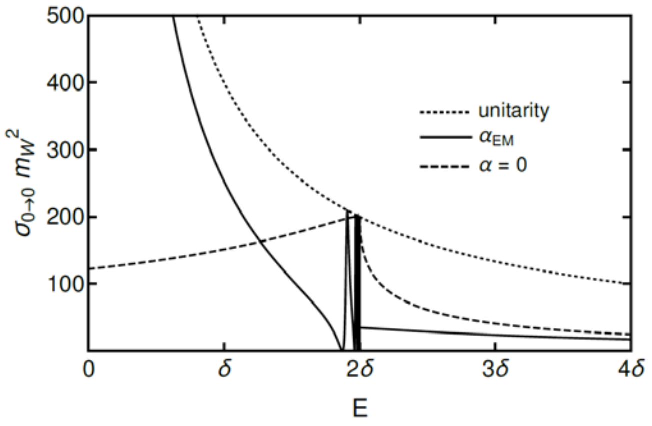


Figure 4. Neutral-wino elastic cross section $\sigma_{0\to0}$ as a function of the energy E. The cross section for $M_* = 2.39\,\mathrm{TeV}$ is shown for $\alpha = 1/137$ (solid curve) and for $\alpha = 0$ (dashed curve). The S-wave unitarity bound is shown as a dotted curve.

Total cross section of the Neutral-wino.

Y. Sumino, *Adv. Ser. Direct. High Energy Phys*. 19, 135(2005) **E. Braaten, E. Johnson and H. Zhang, *J. High Energy Phys*. 02(2018) 150**

3-body treatment for the $X(3872)$

V. Baru et al. , *Phys. Rev. D* 84 (2011) 074029

V. BARU *et al.*

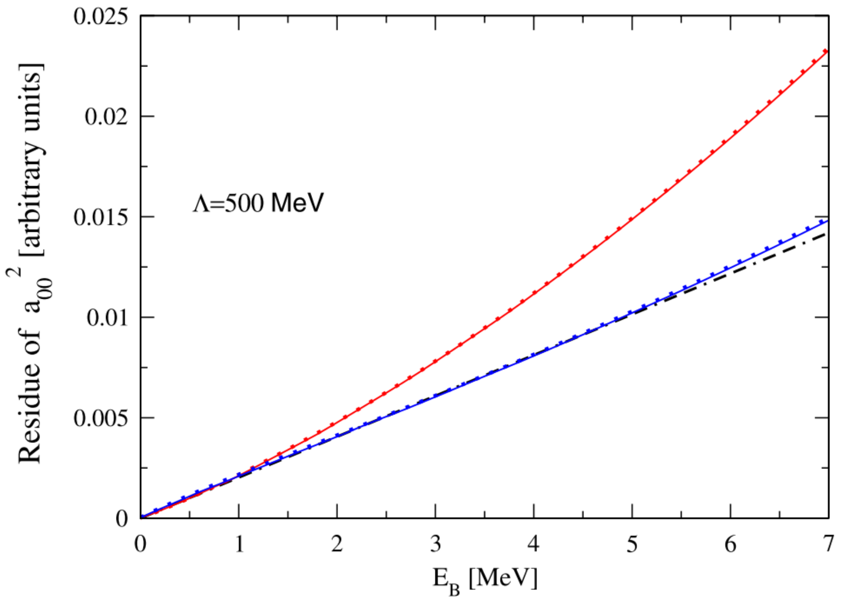


FIG. 3 (color online). Residue of the $D^0\bar{D}^{*0}$ scattering amplitude squared versus the binding energy in the $D^0\bar{D}^{*0}$ system. The upper, red (lower, blue) dotted curve corresponds to the solution of the single(two)-channel $D^0\bar{D}^{*0}$ problem with the contact $D\bar{D}^*$ interaction. Solutions of the full three-body equation with dynamical pions are given by the solid lines: upper, red line—for the single-channel case and lower, blue line—for the two-channel case. The straight dot-dashed line (black) is shown to guide the eye.

PHYSICAL REVIEW D **84,** 074029 (2011)

Three-body $D\bar{D}\pi$ dynamics for the $X(3872)$

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(Received 2 September 2011; published 20 October 2011)

Single Channel $D^0\bar{D}^{*0}$

Coupled Channel $D^0\bar{D}^{*0}$ D^+D^{*-}

In addition, we found that the residue for $X \to D\bar{D}^*$ is weakly dependent on the kind of pion dynamics included. Especially, the dependence of the residue on the X binding energy is very close for a fully dynamical calculation and for a calculation with a contact-type interaction only. A deviation between the coupled-channel and the single-channel treatment is clearly observed but with the larger effect for binding energies beyond 1 MeV.

3-body treatment for the $X(3872)$

V. Baru et al. , *Phys. Rev. D* 84 (2011) 074029

THREE-BODY $D\bar{D}\pi$ DYNAMICS FOR THE $X(3872)$

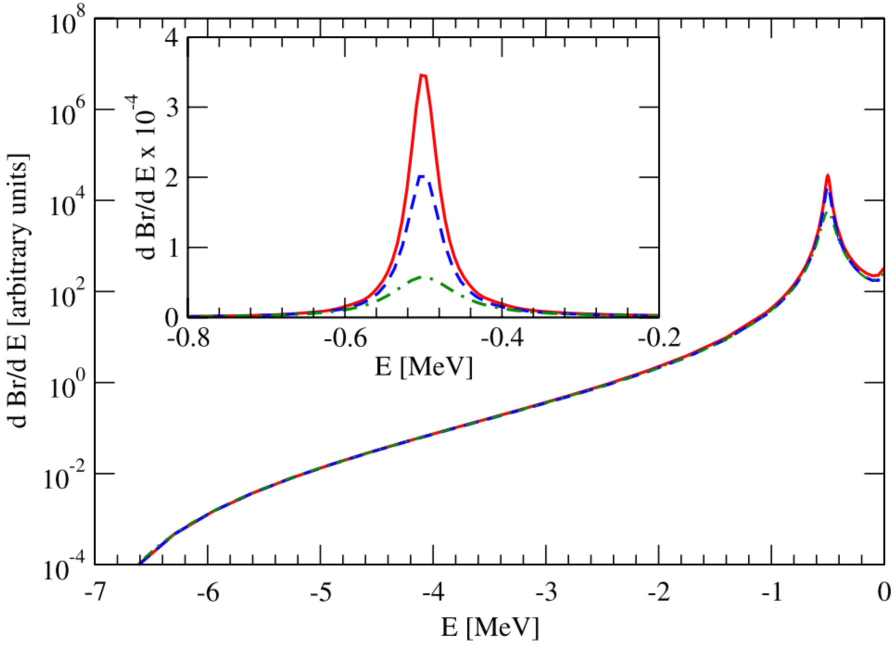

FIG. 5 (color online). Production rate (in logarithmic scale) for the three calculations as described in the text: (i) solution of the single-channel problem in the static limit—(green) dot-dashed line; (ii) solution of the single-channel dynamical calculation—(blue) dashed line; (iii) solution of the full two-channel dynamical problem—(red) solid line. All curves are normalized near the $D^0\bar{D}^0\pi^0$ threshold, located at $E = -7$ MeV. The inlay shows a zoom into the peak region in linear scale.

The most striking effect of dynamical pions is observed in their impact on the X line shapes: in the fully dynamical calculation the width from the $D\bar{D}\pi$ intermediate states appears to be reduced by about a factor of 2, from 102 keV down to 44 keV, assuming that the $X(3872)$ corresponds to a resonance state with a peak at 0.5 MeV below the $D\bar{D}^*$ threshold. Stated differently, by using the naive static approximation for the $D\bar{D}\pi$ intermediate states one overestimates substantially their effect on the X width.

On the contrary, the effect of the coupled-channel dynamics on the X width turned out to be rather moderate, which can be attributed to the fact that both the real part of the resonance pole E_B and the X width Γ_X are small as compared to the separation ΔM between the neutral and the charged thresholds.