

BARYONS 2025

INTERNATIONAL
CONFERENCE ON THE
STRUCTURE OF BARYONS

10-14 NOV 2025
ICC JEJU
KOREA



Investigating the Nature of the Exotic State X(3872) within a Coupled-Channel Framework

Guang-Juan Wang (IPNS, KEK)

[Sci. Bull. 69,3036 \(2024\)](#), paper in preparation

In collaboration with Zhi Yang(UESTC), Jia-Jun Wu (UCAS), Shi-Lin Zhu(PKU) and Makoto Oka (RIKEN, JAEA)

Nov. 13, 2025, Jeju Island, Korea

Properties of $X(3872)$

- Proximity to $\bar{D}^{*0}D^0$ thresholds and extremely narrow width

$$\delta m = m_{\bar{D}^{*0}D^0} - m_{X(3872)} = 0.00 \pm 0.18 \text{ MeV} \quad \text{PDG 22}$$

$\Gamma \sim 280 \text{ keV}$ (LHCb), $\Gamma \sim 380 \text{ keV}$ (BESIII)

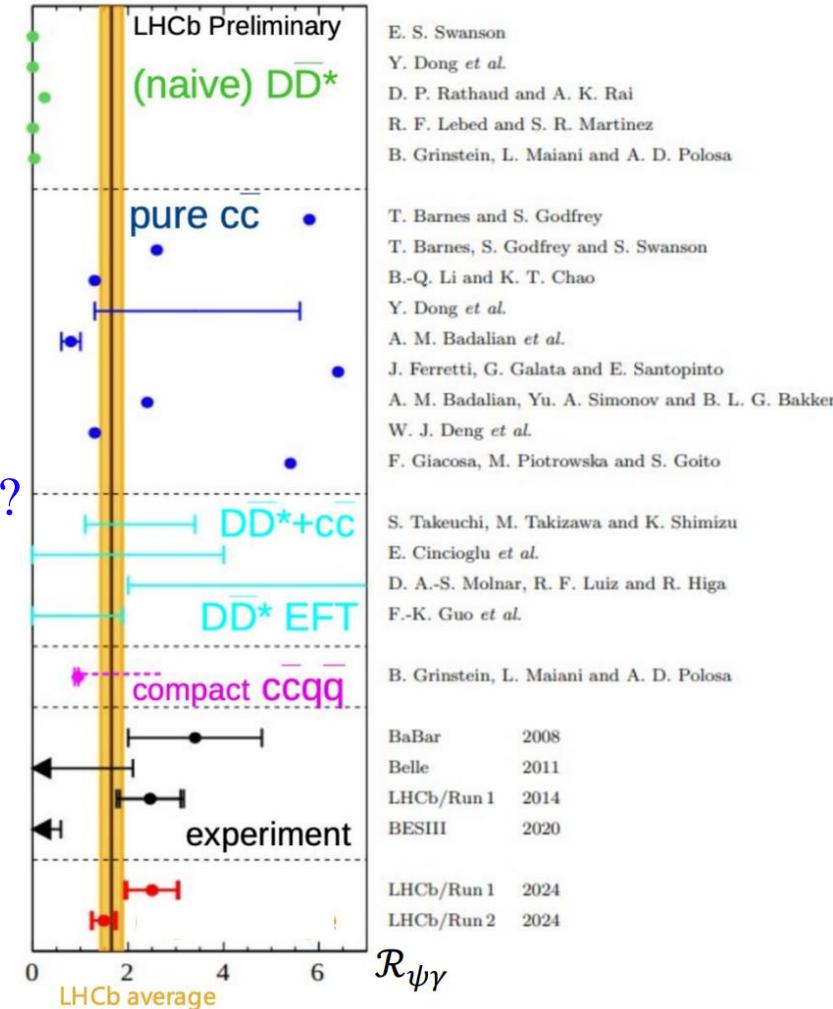
LHCb, *Phys. Rev. D* 102 (2020) 9, 092005.
 BESIII, *Phys. Rev. Lett.* 132, 151903.

- Large isospin violating decay patterns not expected by a pure $\bar{c}c$ -molecule?

$$\frac{\mathcal{B}[X \rightarrow J/\psi\pi^+\pi^-\pi^0]}{\mathcal{B}[X \rightarrow J/\psi\pi^+\pi^-]} = 1.0 \pm 0.4 \pm 0.3 \quad \text{Belle}; \quad \frac{\mathcal{B}[X \rightarrow J/\psi\omega]}{\mathcal{B}[X \rightarrow J/\psi\pi^+\pi^-]} = \begin{cases} 1.6^{+0.4}_{-0.3} \pm 0.2 & \text{BESIII,} \\ 0.7 \pm 0.3 & B^+ \text{ events, BaBar,} \\ 1.7 \pm 1.3 & B^0 \text{ events, BaBar,} \end{cases}$$

- Unexpected large radiative ratio- $\bar{c}c$?

$$\Gamma(X \rightarrow \psi(2S)\gamma)/\Gamma(X \rightarrow J/\psi\gamma) > 1$$



I. Polyakov (LHCb Collab.), CERN Seminar, June 2024.

Theoretical interpretations of $X(3872)$

- Theoretical models

- ✓ Conventional $\bar{c}c$: $\chi_{c1}(2P)$.

Eichten, Lane, Quigg, Suzuki, Barnes, Godfrey,...

- ✓ Compact tetraquark state.

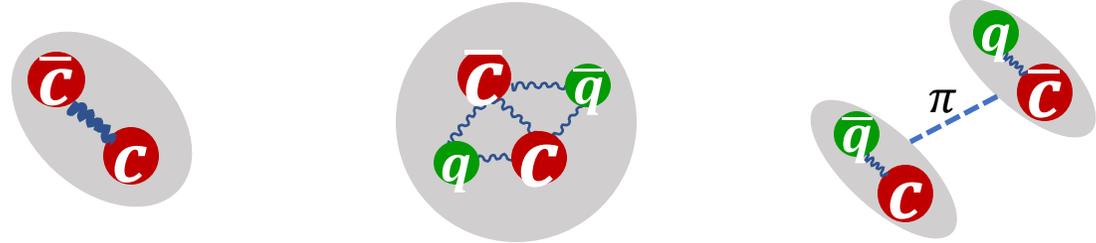
Close, Maiani, Piccinini, Polosa, Riquer,...

- ✓ The $\bar{D}^*D/\bar{D}D^*$ molecular state.

Swanson, Wong, Guo, Liu,....

- ✓ The mixing of the $\bar{c}c$ core with $\bar{D}^*D/\bar{D}D^*$ component.

Chao, H. Q. Zheng, S. Takeuchi, Yu. S. Kalashnikova, P. G. Ortega...



Mass coincidence with the threshold
& large isospin violation

- Goal: Understand structure using a unified coupled-channel framework.
- Mixing between bare $\bar{c}c$ and \bar{D}^*D hadronic channels.
- Coupled-channel dynamics naturally generate near-threshold state.
- Model tested via both mass spectrum and decay observables.

Coupled-channel Framework

- The Hamiltonian reads

$$H = H_0 + H_I,$$

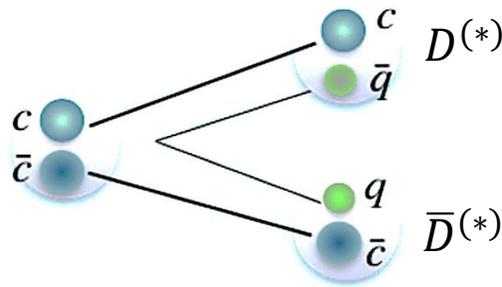
- Non-interacting Hamiltonian

$$H_0 = \sum_B \underbrace{|B\rangle m_B \langle B|}_{\text{Bare } \bar{c}c \text{ meson}} + \sum_\alpha \int d^3 \vec{k} \underbrace{|\alpha(\vec{k})\rangle E_\alpha(\vec{k}) \langle \alpha(\vec{k})|}_{\text{two-meson state } \bar{D}^* D / \bar{D} D^*}.$$

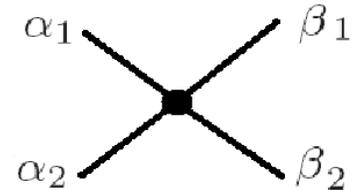
- Interacting Hamiltonian

$$H_I = g + v$$

bare state core \rightarrow channel:



channel \rightarrow channel:



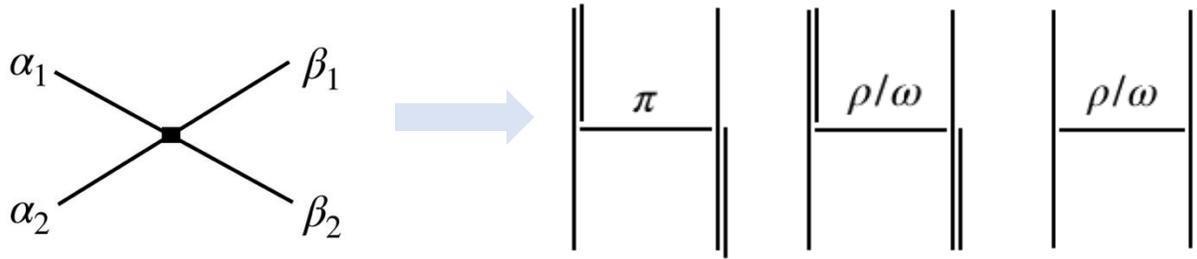
$$g = \sum_{\alpha, B} \int d^3 \vec{k} \left\{ |\alpha(\vec{k})\rangle g_{\alpha B}(|\vec{k}|) \langle B| + h.c. \right\}$$

$$v = \sum_{\alpha, \beta} \int d^3 \vec{k} d^3 \vec{k}' |\alpha(\vec{k})\rangle V_{\alpha, \beta}^L(|\vec{k}|, |\vec{k}'|) \langle \beta(\vec{k}')|$$

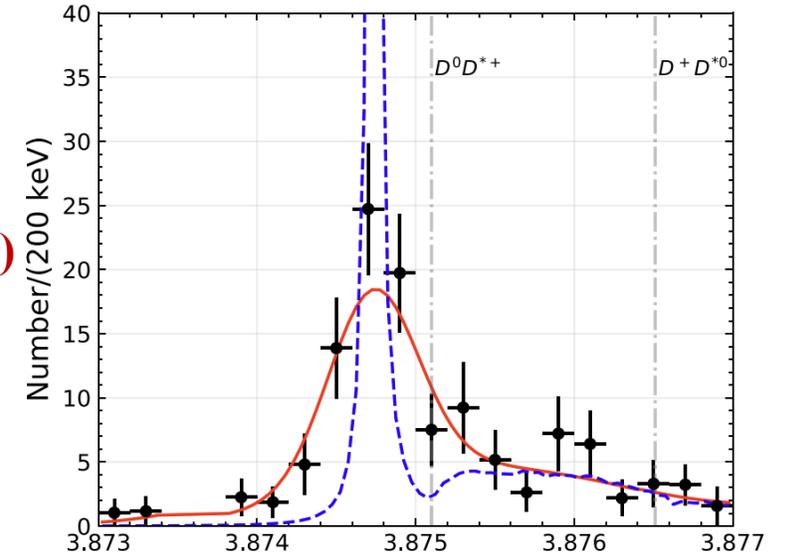
3P0 mechanism: $\gamma - \psi(3770)(\bar{c}c \ ^3D_1)$

Coupled-channel Framework

$$v: D^{(*)}\bar{D} - D^{(*)}\bar{D}$$



One-Boson-exchange model



LHCb, Nature Commun. 13 (2022) 1, 3351

	wave function	$I(J^{PC})$	u - channel : π	u - channel : ρ/ω	t - channel : ρ/ω
DD^*	$\frac{1}{\sqrt{2}}(D^+D^{*0} - D^0D^{*+})$	$0(1^+) [T_{cc}^+]$	$\frac{3}{2}V_\pi$	$\frac{3}{2}V_\rho^u - \frac{1}{2}V_\omega^u$	$-\frac{3}{2}V_\rho^t + \frac{1}{2}V_\omega^t$
	$\frac{1}{\sqrt{2}}(D^+D^{*0} + D^0D^{*+})$	$1(1^+)$	$\frac{1}{2}V_\pi$	$\frac{1}{2}V_\rho^u + \frac{1}{2}V_\omega^u$	$\frac{1}{2}V_\rho^t + \frac{1}{2}V_\omega^t$
$D\bar{D}^*$	$\frac{1}{\sqrt{2}} ([D^+D^{*-}] + [D^0\bar{D}^{*0}])$	$0(1^{++})[X(3872)]$	$\frac{3}{2}V_\pi$	$-\frac{3}{2}V_\rho^u - \frac{1}{2}V_\omega^u$	$-\frac{3}{2}V_\rho^t - \frac{1}{2}V_\omega^t$
	$\frac{1}{\sqrt{2}} ([D^+D^{*-}] - [D^0\bar{D}^{*0}])$	$1(1^{++})$	$-\frac{1}{2}V_\pi$	$\frac{1}{2}V_\rho^u - \frac{1}{2}V_\omega^u$	$\frac{1}{2}V_\rho^t - \frac{1}{2}V_\omega^t$
	$\frac{1}{\sqrt{2}} (\{D^+D^{*-}\} + \{D^0\bar{D}^{*0}\})$	$0(1^{+-})[h_c]$	$-\frac{3}{2}V_\pi$	$\frac{3}{2}V_\rho^u + \frac{1}{2}V_\omega^u$	$-\frac{3}{2}V_\rho^t - \frac{1}{2}V_\omega^t$
	$\frac{1}{\sqrt{2}} (\{D^+D^{*-}\} - \{D^0\bar{D}^{*0}\})$	$1(1^{+-}) [Z_c(3900)]$	$\frac{1}{2}V_\pi$	$-\frac{1}{2}V_\rho^u + \frac{1}{2}V_\omega^u$	$\frac{1}{2}V_\rho^t - \frac{1}{2}V_\omega^t$

$\bar{D}^*D / \bar{D}D^*$ interaction

$$[D\bar{D}^*] = \frac{1}{\sqrt{2}}(D\bar{D}^* - D^*\bar{D})$$

$$\{D\bar{D}^*\} = \frac{1}{\sqrt{2}}(D\bar{D}^* + D^*\bar{D})$$

Structure of X(3872)

- \bar{D}^*D interaction is attractive but insufficient \rightarrow bound only with $c\bar{c}$

✓ Bound state for X(3872), $\Delta E = -80.4$ keV.

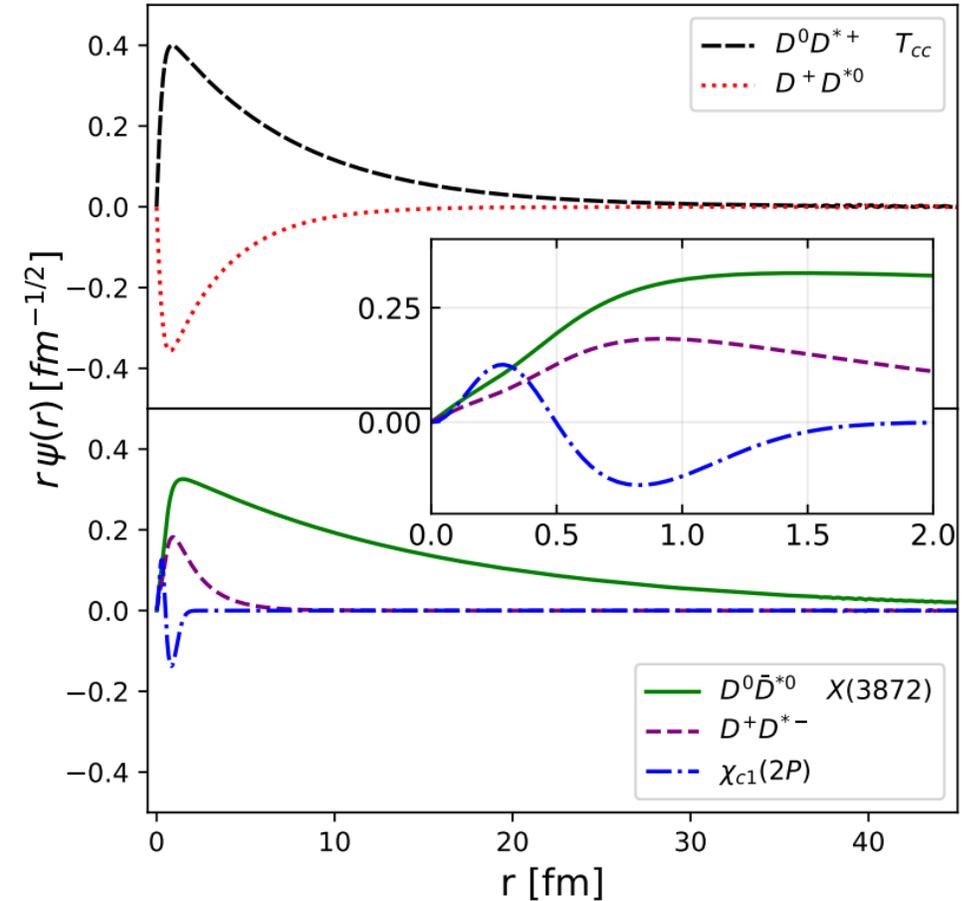
$$\psi_X = \lambda |c\bar{c}(2^3P_1)\rangle + \sum_i \int d^3\vec{q} \chi_i(\vec{q}) |D\bar{D}^*\rangle$$

✓ 94.0 % $D^{*0}\bar{D}^0$, 4.8 % D^+D^{*-} , 1.2% $c\bar{c}$

✓ Important isospin breaking. $I = 0$ (71.9%); $I = 1$ (28.1%)

✓ $\Gamma_{X \rightarrow D^0\bar{D}^0\pi} = 32.5$ keV.

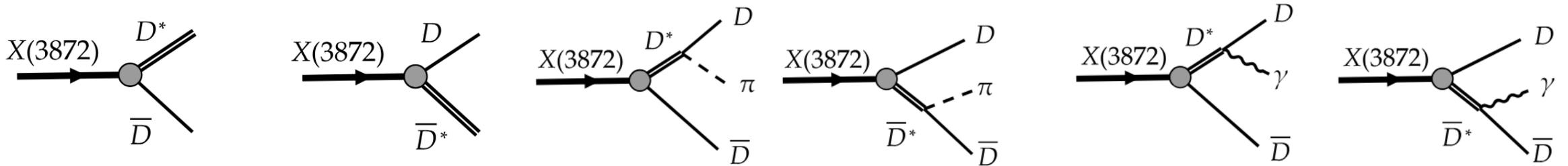
✓ $g_X^n/g_X^c = 1.14$ -dressed coupling.



G.J. Wang, et al., Sci.Bull. 69,3036(2024)

Connecting to Open-charm decay

- For decays: $X(3872) \rightarrow D\bar{D}^* \rightarrow D\bar{D} + \pi/\gamma$



$$\mathcal{L} = \frac{1}{\sqrt{2}} g_X^n X^\mu (\bar{D}_\mu^{*0} D^0 - \bar{D}^0 D_\mu^{*0}) + \frac{1}{\sqrt{2}} g_X^c X^\mu (D_\mu^{*+} D^- - D^- D_\mu^{*0})$$

$$\left. \begin{array}{l} \Gamma_{X(3872) \rightarrow \bar{D}^0 D^0 \pi} = 32.5 \text{ keV} \xrightarrow{g_X^n} \\ g_X^n / g_X^c = 1.14 \xrightarrow{g_X^c} \\ \Gamma_{D^{*0} \rightarrow D^0 + \gamma} \end{array} \right\} \Gamma_{X \rightarrow D^0 \bar{D}^0 \gamma} = 12.2 \text{ keV} \quad \Gamma_{X \rightarrow D^+ D^- \gamma} = 0.04 \text{ keV}$$

- Suppression of the charged channel arise from:

- ✓ Primarily the **near on-shell enhancement** of the intermediate $D^0 \bar{D}^{*0}$.
- ✓ Coupling constant: $g_\gamma(D^{*+,0} \rightarrow D^{+,0} \gamma) \propto e_q$ & $g_X^n / g_X^c = 1.14$.

Connecting to Hidden-charm decay

- For decays: $X(3872) \rightarrow J/\psi \pi\pi (J/\psi\rho), J/\psi\pi\pi\pi(J/\psi\omega), \chi_{cJ}\pi$

✓ $\bar{c}c \rightarrow J/\psi$ +light hadron: OZI suppression

✓ Dominant contributions arise from intermediate $D^{(*)}\bar{D}^{(*)}$ channels.

$$\begin{aligned} \mathcal{M}^{J_z=M_C+M_D, M_C, M_D} &= \langle \psi_X^{JJ_z}(J_A, J_B) | V | C^{J_C M_C} D^{J_D M_D} \rangle \\ &= \int k^2 R(k) dk \int d\Omega_k Y_{00}(\vec{k}) \sum_{J' J'_z} \langle J_C M_C, J_D M_D | J' J'_z \rangle \\ &\times \langle [A(q\bar{Q})^{J_A} B(Q\bar{q})^{J_B}]_{J_z}^J | V | [C^{J_C}(q\bar{q}) D(Q\bar{Q})^{J_D}]_{J'_z}^{J'} \rangle \end{aligned}$$

Quark Interchange Model (QIM) at quark level

$$V = \sum_{i < j} V_{ij}(q)$$

$$V_{ij}(q) = \frac{\lambda_i}{2} \cdot \frac{\lambda_j}{2} (V^{\text{coul}}(q) + V^{\text{lin}}(q) + V^{\text{h}}(q)),$$

$$V_{ij}^{\text{coul}}(q) = \omega_{ij}^{\frac{1}{2}} \frac{4\pi\alpha(q^2)}{q^2} \omega_{ij}^{\frac{1}{2}}$$

$$V_{ij}^{\text{lin}}(q) = \frac{6\pi b}{q^4} e^{-q^2/4\sigma_{ij}^2}$$

$$V_{ij}^{\text{h}}(q) = -\theta_{ij}^{1+\frac{1}{2}\epsilon_{const}} \frac{8\pi\alpha(q^2)}{3m_i m_j} \left(\frac{\tau_{kij}}{\pi}\right)^{3/2} \vec{s}_i \cdot \vec{s}_j \theta_{ij}^{1+\frac{1}{2}\epsilon_{const}}$$

S. Godfrey, N. Isgur, PRD 32,189

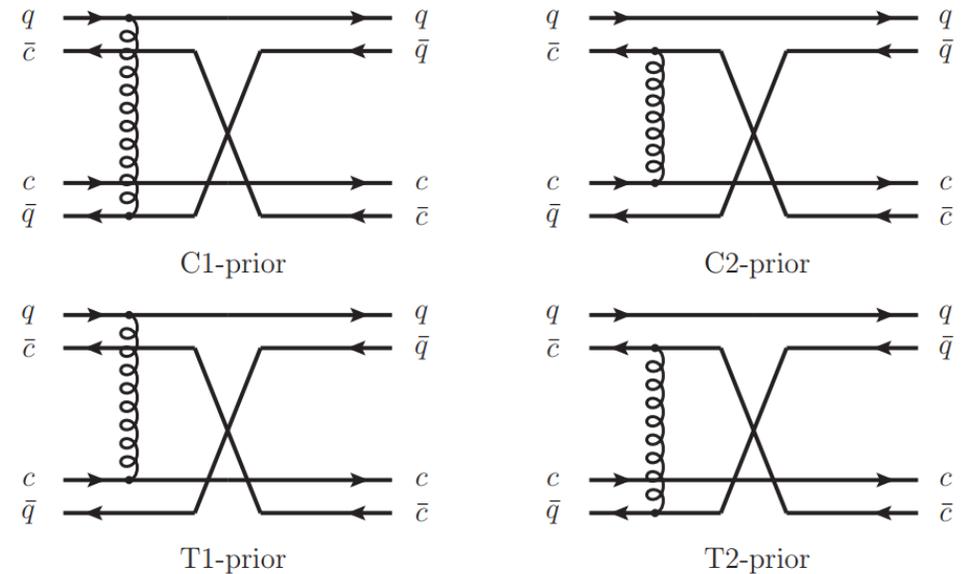
Z.-Yang, et al, JHEP01(2023)058

C. Meng et. al, Phys. Rev. D 75, 114002 (2007).

M. Suzuki, Phys. Rev. D 72, 114013 (2005).

F. K. Guo et al., Phys. Rev. D.83.034013 (2011)

...



C.-Y. Wong, et al, Phys. Rev. C 66.029901.

T. Barnes, et al, Phys. Rev. C.60.045202.

Z.-Y. Zhou, et al, Phys. Rev. D.100.094025.

G.-J. Wang, et al, Eur. Phys. J. C 79, 567.

...

Quark-interchange model

$$\begin{aligned} & \langle [A(q\bar{Q})^{J_A} B(Q\bar{q})^{J_B}]_{J_z}^J | V | [C^{J_C} (q\bar{q}) D(Q\bar{Q})^{J_D}]_{J'_z}^{J'} \rangle \\ &= I_{\text{flavor}} I_{\text{color}} I_{\text{spin-space}} \\ I_{\text{color}} &= \frac{4}{9}(qq), -\frac{4}{9}(q\bar{q}) \end{aligned}$$

TABLE IV. $I_{\text{Spin}} = \langle [\chi_C \chi_D]_M^S | \mathcal{O}_s | [\chi_A \chi_B]_M^S \rangle$.

$\langle [\chi_C \chi_D]_M^1 \mathbf{s}_i \cdot \mathbf{s}_j [\chi_A \chi_B]_M^1 \rangle$				
$(S_A, S_B) \rightarrow (S_C, S_D)$	C1	C2	T1	T2
$(0, 1) \rightarrow (0, 1)$	$-\frac{3}{8}$	$\frac{1}{8}$	$-\frac{1}{8}$	$\frac{3}{8}$
$(1, 1) \rightarrow (0, 1)$	$-\frac{3}{4\sqrt{2}}$	$\frac{1}{4\sqrt{2}}$	$-\frac{1}{4\sqrt{2}}$	$-\frac{1}{4\sqrt{2}}$
$(0, 1) \rightarrow (1, 1)$	$\frac{1}{4\sqrt{2}}$	$\frac{1}{4\sqrt{2}}$	$-\frac{1}{4\sqrt{2}}$	$-\frac{1}{4\sqrt{2}}$
$(1, 1) \rightarrow (1, 1)$	0	0	$-\frac{1}{2}$	$\frac{1}{2}$
$\langle [\chi_C \chi_D]_M^1 \mathbf{1} [\chi_A \chi_B]_M^1 \rangle$				
$(S_A, S_B) \rightarrow (S_C, S_D)$	All diagrams			
$(0, 1) \rightarrow (0, 1)$	$\frac{1}{2}$			
$(1, 1) \rightarrow (0, 1)$	$\frac{1}{\sqrt{2}}$			
$(0, 1) \rightarrow (1, 1)$	$\frac{1}{\sqrt{2}}$			
$(1, 1) \rightarrow (1, 1)$	0			

$$\begin{aligned} I_{\text{space}}^{L,0} &= \langle \phi_A \phi_B | V | [\phi_C \phi_D]_0^L \rangle \\ &= \iint d\boldsymbol{\kappa} d\boldsymbol{\kappa}' \Phi_A [\zeta(2\mathbf{k}_A - \mathbf{K}_A)] \Phi_B [\zeta(2\mathbf{k}_B - \mathbf{K}_B)] \\ &\quad \times \Phi_C [\zeta(2\mathbf{k}_C - \mathbf{K}_C)] \Phi_D^{L,0} [\zeta(2\mathbf{k}_D - \mathbf{K}_D)] V(\boldsymbol{\kappa}' - \boldsymbol{\kappa}) \end{aligned}$$

$$\begin{aligned} I_{C1} &= \int d^3\mathbf{p} \int d^3\mathbf{q} \Phi_A(\mathbf{q} - \mathbf{p}/2 - f_A \mathbf{P}_A) \Phi_B(\mathbf{q} - \mathbf{p}/2 - f_B \mathbf{P}_A - 2\mathbf{P}_C) \\ &\quad \times V(q) \Phi_C^*(\mathbf{q} + \mathbf{p}/2 - 2\mathbf{P}_C) \Phi_D^*(\mathbf{q} - \mathbf{p}/2 - \mathbf{P}_C - 2\mathbf{P}_A), \\ I_{C2} &= \int d^3\mathbf{p} \int d^3\mathbf{q} \Phi_A(\mathbf{q} - \mathbf{p}/2 - f_A \mathbf{P}_A) \Phi_B(\mathbf{q} - \mathbf{p}/2 - f_B \mathbf{P}_A + 2\mathbf{P}_C) \\ &\quad \times V(q) \Phi_C^*(\mathbf{q} + \mathbf{p}/2 + \mathbf{P}_C - 2\mathbf{P}_A) \Phi_D^*(\mathbf{q} - \mathbf{p}/2 + \mathbf{P}_C), \\ I_{T1} &= \int d^3\mathbf{p} \int d^3\mathbf{q} \Phi_A(\mathbf{q} - \mathbf{p}/2 - f_A \mathbf{P}_A) \Phi_B(\mathbf{q} + \mathbf{p}/2 - f_B \mathbf{P}_A - 2\mathbf{P}_C) \\ &\quad \times V(q) \Phi_C^*(\mathbf{q} + \mathbf{p}/2 - \mathbf{P}_C) \Phi_D^*(\mathbf{q} - \mathbf{p}/2 - \mathbf{P}_C - 2\mathbf{P}_A), \\ I_{T2} &= \int d^3\mathbf{p} \int d^3\mathbf{q} \Phi_A(\mathbf{q} - \mathbf{p}/2 - f_A \mathbf{P}_A) \Phi_B(\mathbf{q} + \mathbf{p}/2 - f_B \mathbf{P}_A + 2\mathbf{P}_C) \\ &\quad \times V(q) \Phi_C^*(\mathbf{q} - \mathbf{p}/2 + \mathbf{P}_C - 2\mathbf{P}_A) \Phi_D^*(\mathbf{q} - \mathbf{p}/2 + \mathbf{P}_C + \mathbf{P}_A) \end{aligned}$$

- Quark interchange dynamics \longleftrightarrow spectroscopy:
- ✓ Potential V , all parameters, wave function: quark model
- A unified treatment of various hidden-charm decays

Representative Results: $X(3872) \rightarrow J/\psi + \rho/\omega$

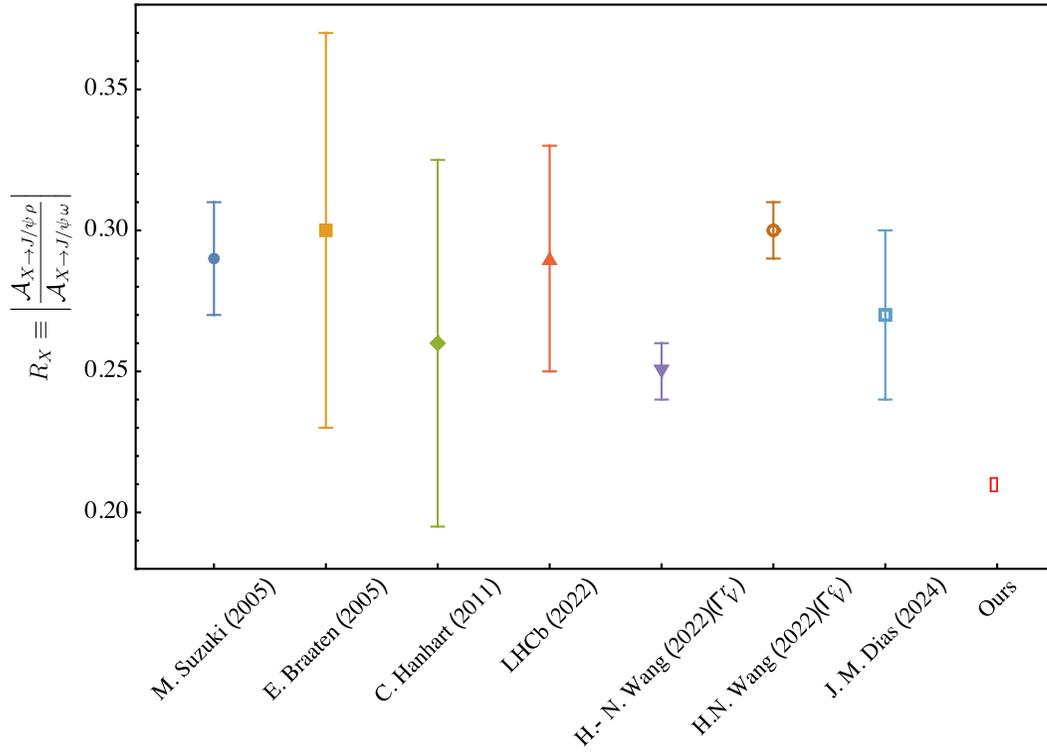
- A direct ratio for the isospin breaking

$$R_X \equiv \left| \frac{\mathcal{A}_{X \rightarrow J/\psi \rho}}{\mathcal{A}_{X \rightarrow J/\psi \omega}} \right| = \left| \frac{\int d^3 \vec{k} \chi_1(\vec{k}) \langle J/\psi + u\bar{u} | [D^0 \bar{D}^{0*}] \rangle - \int d^3 \vec{k} \chi_2(\vec{k}) \langle J/\psi + d\bar{d} | [D^+ D^{*-}] \rangle}{\int d^3 \vec{k} \chi_1(\vec{k}) \langle J/\psi + u\bar{u} | [D^0 \bar{D}^{0*}] \rangle + \int d^3 \vec{k} \chi_2(\vec{k}) \langle J/\psi + d\bar{d} | [D^+ D^{*-}] \rangle} \right|$$

Destructive interference

Constructive interference

- Decay width incorporating running Γ_ρ and Γ_ω



$$\Gamma_{J/\psi \rho} = \int_{2m_\pi}^{M-m_{J/\psi}} \frac{dm'}{2\pi} \frac{|\mathcal{A}_{X \rightarrow J/\psi \rho}|^2 q(m', M) \Gamma_\rho}{(m' - m_\rho)^2 + \Gamma_\rho^2/4},$$

$$\Gamma_{J/\psi \omega} = \Gamma_\omega \int_{3m_\pi}^{M-m_{J/\psi}} \frac{dm'}{2\pi} \frac{|\mathcal{A}_{X \rightarrow J/\psi \omega}|^2 q(m', M) \Gamma_\omega}{(m' - m_\omega)^2 + \Gamma_\omega^2/4},$$

M. Suzuki, Phys. Rev. D 72, 114013.
 E. Braaten, et al. Phys. Rev. D 72.054022.
 C. Hanhart, et al. Phys. Rev. D 85. 011501
 LHCb, Phys. Rev. D 108. L011103.
 H.-N. Wang et al. Phys. Rev. D 106, 056022.
 J. M. Dias, et al. Phys. Rev. D 111, 014031.

$$R_X = 0.21$$

$X(3872) \rightarrow J/\psi + 2(3)\pi$

- $X \rightarrow J/\psi + \rho/\omega \rightarrow J/\psi + 2(3)\pi$: Schematical amplitude

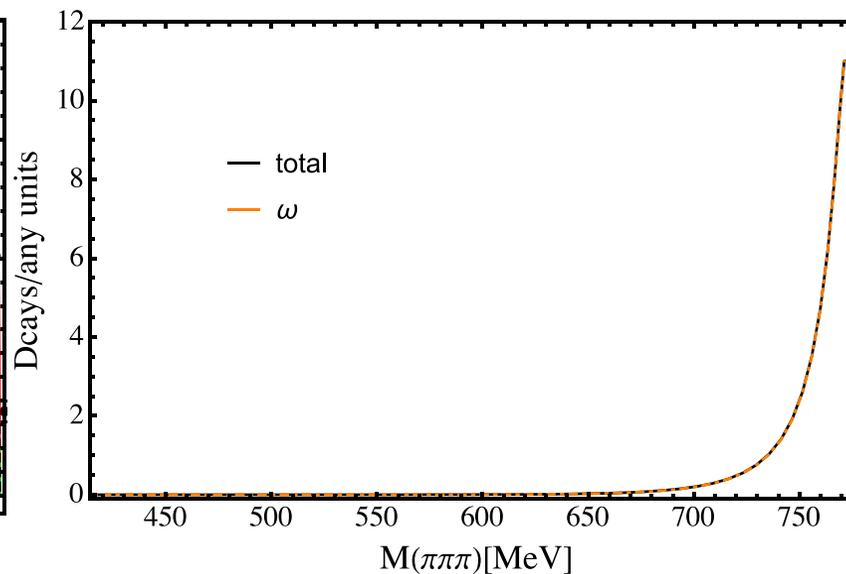
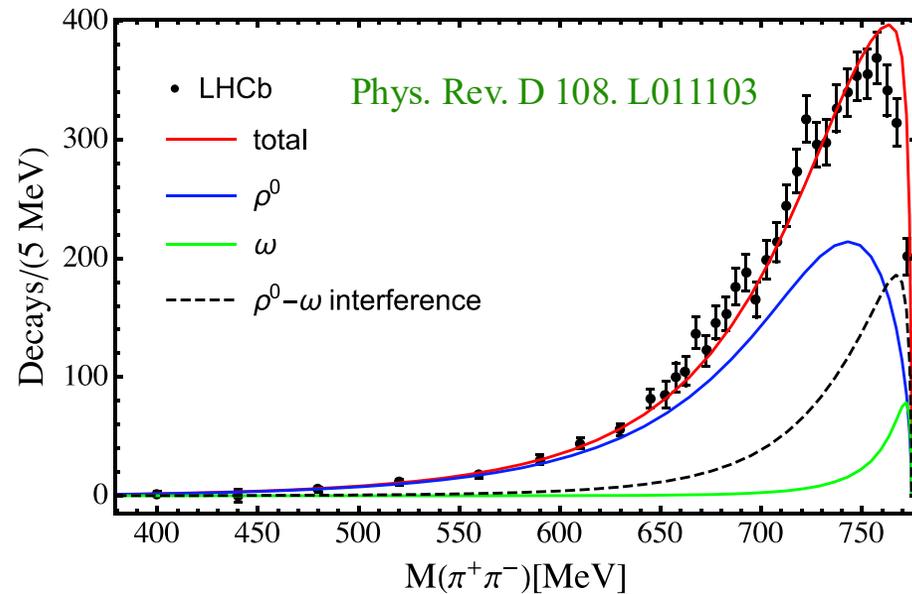
$\sqrt{\mathcal{A}_{X \rightarrow J/\psi V} \& \mathcal{A}_{V \rightarrow 2(3)\pi}}$ include $\rho - \omega$ mixing

$$\mathcal{T}_{X \rightarrow J/\psi 2(3)\pi} = \mathcal{A}_{X \rightarrow J/\psi V}^\mu \frac{-i \left(g^{\mu\nu} - \frac{p^\mu p^\nu}{m_V^2} \right)}{p_V^2 - m_V^2 + im_V \Gamma_V} \mathcal{A}_{V \rightarrow 2(3)\pi}^\nu$$

- $\pi\pi$ distribution: **without any fitting** except a normalization factor

C. Hanhart, et al. Phys. Rev. D 85. 011501
LHCb, Phys. Rev. D 108. L011103.

J. M. Dias, et al. Phys. Rev. D 111, 014031.



Channel	$J/\psi\rho$	$J/\psi\omega$	$J/\psi\pi^+\pi^-$	$J/\psi\pi^+\pi^-\pi^0$
Γ [keV]	11.6	39.1	10.0	17.7

$$\frac{\mathcal{B}[X \rightarrow J/\psi\pi^+\pi^-\pi^0]}{\mathcal{B}[X \rightarrow J/\psi\pi^+\pi^-]} = 1.0 \pm 0.4 \pm 0.3 \quad \text{Belle} \quad \sim 1.8 \text{ (Ours)}$$

Representative Results: $X(3872) \rightarrow \bar{c}c + \gamma$

- Two decay modes

Mode I—Charmonium core: $X \rightarrow \chi_{c1}(2P) \rightarrow J/\psi/\psi(2S) + \gamma$: E1 radiative decay T. Barnes, et al, Phys. Rev. D 72 (2005) 054026

$$\Gamma_{E1}(n^{2S+1}L_J \rightarrow n'^{2S'+1}L'_{J'} + \gamma) = \frac{4}{3} C_{fi} \delta_{SS'} e_c^2 \alpha |\langle \psi_f | r | \psi_i \rangle|^2 E_\gamma^3 \frac{E_f^{(c\bar{c})}}{M_i^{(c\bar{c})}}$$

$$\Gamma_{\chi_{c1}(2P) \rightarrow J/\psi + \gamma}^{E1} = \begin{cases} 7.4 & \text{GI quark model} \\ 71 & \text{NR quark model} \end{cases} \ll \Gamma_{\chi_{c1}(2P) \rightarrow \psi(2S) + \gamma}^{E1} = \begin{cases} 170.7 & \text{GI quark model} \\ 183 & \text{NR quark model} \end{cases}$$

Sensitive to wave function

✓The existence and the position of the radial nodes affect the overlap integrals.

Mode II—Molecular: $X \rightarrow \bar{D}D^* \rightarrow J/\psi/\psi(2S) + \gamma$ $\Gamma_{X \rightarrow \bar{D}D^* \rightarrow J/\psi\gamma} = 0.1 \text{ keV} \gg \Gamma_{X \rightarrow \bar{D}D^* \rightarrow \psi(2S)\gamma} = 0.006 \text{ keV}$

$$T_a = \sum_i \int d^3\vec{q} \chi_i(\vec{q}) \mathcal{A}_{D\bar{D}^* \rightarrow J/\psi V}^\mu \frac{-i \left(g^{\mu\nu} - \frac{p^\mu p^\nu}{m_v^2} \right)}{p_v^2 - m_v^2 + im_v \Gamma_v} \mathcal{A}_{V \rightarrow \gamma}^\nu$$

J.Sakurai, Currents and Mesons, (Chicago: University of Chicago Press).
M. Bando, et al, Phys.Rev. Lett., 54:1215 (1985).

$$\mathcal{L}_{V\gamma} = -M_V^2 \frac{e}{g} A_\mu \left[\frac{\rho^\mu}{\sqrt{2}} + \frac{\omega^\mu}{3\sqrt{2}} - \frac{\phi^\mu}{3} \right] \text{ Vector meson dominance model}$$

$X(3872) \rightarrow \bar{c}c + \gamma$

• Mixing of $X \rightarrow \bar{D}D^* \rightarrow J/\psi/\psi(2S) + \gamma$ and $X \rightarrow \chi_{c1}(2P) \rightarrow J/\psi/\psi(2S) + \gamma$:

✓ The phase between $\chi_{c1}(2P)$ and $\bar{D}D^*$ is determined; However, undetermined phase between two decay modes

$$T_{\text{total}} = T_a + T_b e^{i\phi}$$

$$\Gamma_{X \rightarrow J/\psi\gamma}^{\text{GI}} = 0.2 + 0.2 \text{Cos}\phi$$

$$\Gamma_{X \rightarrow J/\psi\gamma}^{\text{NR}} = 1.0 + 0.6 \text{Cos}\phi$$

$$\Gamma_{X \rightarrow \psi(2S)\gamma}^{\text{GI}} = 2.1 + 0.2 \text{Cos}\phi$$

✓ $J/\psi\gamma$: both decay modes and their interference are important.

✓ $\psi(2S)\gamma$: Dominant contribution stem from E1 decay of $\bar{c}c$ component in $X(3872)$.

• $\Gamma_{X \rightarrow \psi(2S)\gamma} > \Gamma_{X \rightarrow J/\psi\gamma}$

Lineshapes of $X(3872)$ decay

- Using the FLATTÉ parametrization, the line shape as a function of E

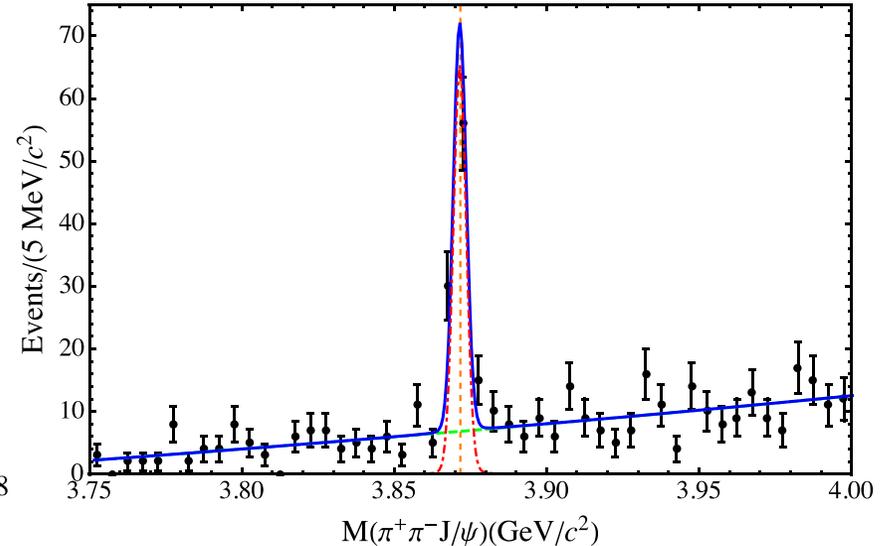
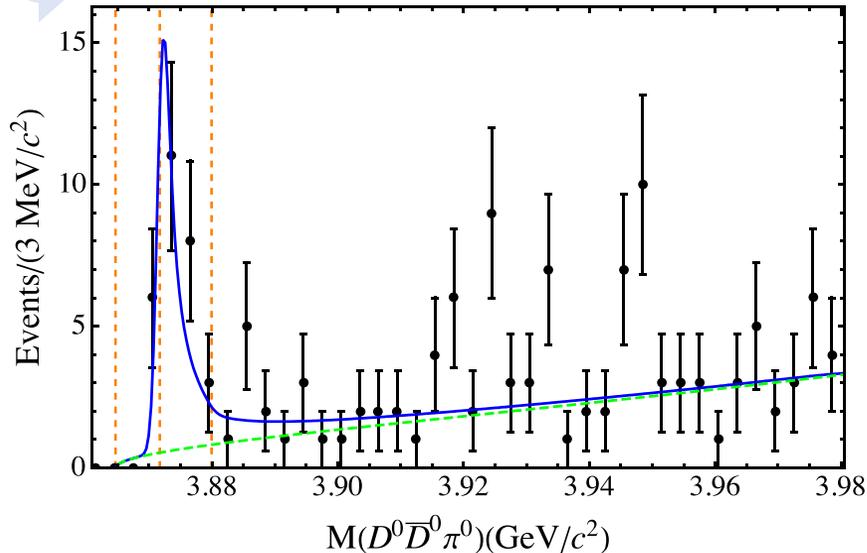
$$\frac{d\text{Br}(B \rightarrow KD^0\bar{D}^{*0})}{dE} = \mathcal{B} \frac{1}{2\pi} \frac{g_1 k_1}{|D(E)|^2}$$

$$\frac{d\text{Br}(B \rightarrow K + \text{charmonium})}{dE} = \mathcal{B} \frac{1}{2\pi} \frac{\Gamma_{\text{charmonium}}(E)}{|D(E)|^2}$$

C. Hanhart, et al. Phys. Rev. D.76.034007
 Y. S. Kalashnikova, et al. Phys. Rev. D 80, 074004.
 M. Ablikim et al. (BESIII), Phys. Rev. Lett. 132, 151903

$\times N_{\text{normalization}}$

$$D(E) = E - E_f + \frac{g_1}{2}(\kappa_1 + ik_1) + \frac{g_2}{2}(\kappa_2 + ik_2) + i\frac{\Gamma(E)}{2} \rightarrow \text{All decay widths except } \bar{D}D^*$$



Summary

- X(3872) is a mixture of $D\bar{D}^*$ molecular component & $c\bar{c}(\chi_{c1}(2P))$
- No new adjustable parameters after fixing to Tcc data.
- Describes spectrum and decays **without free parameters.**
- The isospin breaking ratio $R_X = 0.21$.
- Only 1.2% $c\bar{c}$ -core : important for radiative decay, and govern $X \rightarrow \psi(2S) + \gamma$.
- ✓ Radiative decay ratios sensitive to **interference** and **wavefunction nodes.**
- Framework applicable to future multi-channel exotic states, e.g. X(4010)

Thank you for your attention!

Backup slides

Properties of $X(3872)$

- Aka $\chi_{c1}(2P)$ in PDG. $J^{PC} = 1^{++}$.

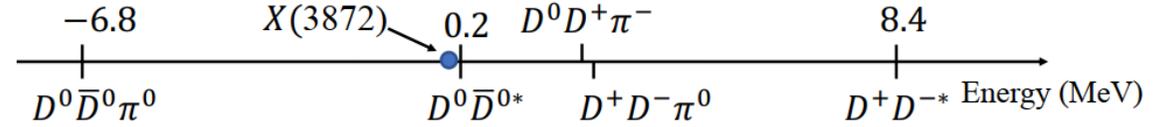
- **Mass and decay width derive from $\chi_{c1}(2P)$ ($\bar{c}c$)**

S. Godfrey, et al. Phys. Rev. D 32, 189 (1985)

T. Barnes, et al, Phys. Rev. D 72 (2005) 054026

$$\delta m = m_{\chi_{c1}(2P)} - m_{X(3872)} = 81.35 \text{ MeV}, \Gamma_{\chi_{c1}(2P)} = 165 \text{ MeV}$$

- Extremely close to $\bar{D}^{*0}D^0 / \bar{D}^0D^{*0}$ thresholds



$$\delta m = m_{\bar{D}^{*0}D^0} - m_{X(3872)} = 0.00 \pm 0.18 \text{ MeV} \quad \text{PDG 22}$$

L. Meng, et al. Phys. Rept. 1019 (2023) 1-149

- Small total width: ~ 280 keV (LHCb), ~ 380 keV (BESIII)

LHCb, Phys. Rev. D 102 (2020) 9, 092005.

BESIII, Phys. Rev. Lett. 132, 151903.

- **Large isospin violating decay patterns not expected by a pure $\bar{c}c$ -molecule?**

$$\frac{\mathcal{B}[X \rightarrow J/\psi \pi^+ \pi^- \pi^0]}{\mathcal{B}[X \rightarrow J/\psi \pi^+ \pi^-]} = 1.0 \pm 0.4 \pm 0.3 \quad \text{Belle}; \quad \frac{\mathcal{B}[X \rightarrow J/\psi \omega]}{\mathcal{B}[X \rightarrow J/\psi \pi^+ \pi^-]} = \begin{cases} 1.6_{-0.3}^{+0.4} \pm 0.2 & \text{BESIII,} \\ 0.7 \pm 0.3 & B^+ \text{ events, BaBar,} \\ 1.7 \pm 1.3 & B^0 \text{ events, BaBar,} \end{cases}$$

- **Unexpected large radiative ratio- $\bar{c}c$?**

$$\Gamma(X \rightarrow \psi(2S)\gamma) / \Gamma(X \rightarrow J/\psi\gamma) > 1$$

Collaboration	$\mathcal{R}(\chi_{c1}(3872))$
BaBar 2008 [29]	3.4 ± 1.4
Belle 2011 [30]	< 2.1 (90%C.L.)
LHCb 2014 [13]	$2.46 \pm 0.64 \pm 0.29$
BESIII 2020 [31]	< 0.59 (90%C.L.)
LHCb 2024 (Run 1)	$2.50 \pm 0.52 \pm_{0.23}^{0.20} \pm 0.06$
LHCb 2024 (Run2)	$1.49 \pm 0.23 \pm_{0.12}^{0.13} \pm 0.03$
LHCb 2024 Average [32]	$1.67 \pm 0.21 \pm 0.12 \pm 0.04$

P. Colangelo et al, arXiv:2501.15888

One-boson-exchange model

$$D^{(*)}D^{(*)}$$

$$H_a^{(Q)} = \frac{1+\not{p}}{2} [P_a^{*\mu} \gamma_\mu - P_a \gamma_5]$$

$$\bar{H}_a^{(Q)} \equiv \gamma_0 H_a^{(Q)\dagger} \gamma_0 = [P_a^{*\dagger\mu} \gamma_\mu + P_a^\dagger \gamma_5] \frac{1+\not{p}}{2}$$

$$P = (D^0, D^+, D_s^+) \ \& \ P^* = (D^{*0}, D^{*+}, D_s^{*+})$$

$$\mathcal{L}_{MH^{(Q)}H^{(Q)}} = ig \text{Tr} \left[H_b^{(Q)} \gamma_\mu \gamma_5 A_{ba}^\mu \bar{H}_a^{(Q)} \right]$$

$$\mathcal{L}_{VH^{(Q)}H^{(Q)}} = i\beta \text{Tr} \left[H_b^{(Q)} v_\mu (V_{ba}^\mu - \rho_{ba}^\mu) \bar{H}_a^{(Q)} \right] \\ + i\lambda \text{Tr} \left[H_b^{(Q)} \sigma_{\mu\nu} F^{\mu\nu}(\rho)_{ba} \bar{H}_a^{(Q)} \right]$$

$$D^{(*)}\bar{D}^{(*)}$$

$$H_a^{(\bar{Q})} \equiv C \left(C H_a^{(Q)} C^{-1} \right)^T C^{-1} = [P_{a\mu}^{(\bar{Q})*} \gamma^\mu - P_a^{(\bar{Q})} \gamma_5] \frac{1-\not{p}}{2}$$

$$\bar{H}_a^{(\bar{Q})} \equiv \gamma_0 H_a^{(\bar{Q})\dagger} \gamma_0 = \frac{1-\not{p}}{2} [P_{a\mu}^{(\bar{Q})* \dagger} \gamma^\mu + P_a^{(\bar{Q})\dagger} \gamma_5]$$

$$\tilde{P} = (\bar{D}^0, D^-, D_s^-) \ \& \ \tilde{P}^* = (\bar{D}^{*0}, D^{*-}, D_s^{*-})$$

$$\mathcal{L}_{MH^{(\bar{Q})}H^{(\bar{Q})}} = ig \text{Tr} \left[\bar{H}_a^{(\bar{Q})} \gamma_\mu \gamma_5 A_{ab}^\mu H_b^{(\bar{Q})} \right]$$

$$\mathcal{L}_{VH^{(\bar{Q})}H^{(\bar{Q})}} = -i\beta \text{Tr} \left[\bar{H}_a^{(\bar{Q})} v_\mu (V_{ab}^\mu - \rho_{ab}^\mu) H_b^{(\bar{Q})} \right] \\ + i\lambda \text{Tr} \left[\bar{H}_a^{(\bar{Q})} \sigma_{\mu\nu} F_{ab}^{\prime\mu\nu}(\rho) H_b^{(\bar{Q})} \right]$$

$$\mathcal{V}(l, l', S, j) = \frac{1}{(2\pi)^3} \sqrt{\frac{1}{2E_D^i 2E_D^f 2E_K^i 2E_K^f}} 2\pi \int d\cos\theta V^v(\vec{p}_f, \vec{p}_i) \left(\frac{\Lambda^2}{\Lambda^2 + p_f^2} \right)^2 \left(\frac{\Lambda^2}{\Lambda^2 + p_i^2} \right)^2$$

- $g = 0.57$ is determined by the strong decays $D^* \rightarrow D\pi$.
- **undetermined λ & β .**

T_{cc} & $X(3872)$ & Z_c & h_c

- In isospin limit:

$$[D\bar{D}^*] = \frac{1}{\sqrt{2}}(D\bar{D}^* - D^*\bar{D}) \quad \{D\bar{D}^*\} = \frac{1}{\sqrt{2}}(D\bar{D}^* + D^*\bar{D})$$

	wave function	$I(J^{PC})$	u - channel : π	u - channel : ρ/ω	t - channel : ρ/ω
DD^*	$\frac{1}{\sqrt{2}}(D^+D^{*0} - D^0D^{*+})$	$0(1^+) [T_{cc}^+]$	$\frac{3}{2}V_\pi$	$\frac{3}{2}V_\rho^u - \frac{1}{2}V_\omega^u$	$-\frac{3}{2}V_\rho^t + \frac{1}{2}V_\omega^t$
	$\frac{1}{\sqrt{2}}(D^+D^{*0} + D^0D^{*+})$	$1(1^+)$	$\frac{1}{2}V_\pi$	$\frac{1}{2}V_\rho^u + \frac{1}{2}V_\omega^u$	$\frac{1}{2}V_\rho^t + \frac{1}{2}V_\omega^t$
$D\bar{D}^*$	$\frac{1}{\sqrt{2}}([D^+D^{*-}] + [D^0\bar{D}^{*0}])$	$0(1^{++})[X(3872)]$	$\frac{3}{2}V_\pi$	$-\frac{3}{2}V_\rho^u - \frac{1}{2}V_\omega^u$	$-\frac{3}{2}V_\rho^t - \frac{1}{2}V_\omega^t$
	$\frac{1}{\sqrt{2}}([D^+D^{*-}] - [D^0\bar{D}^{*0}])$	$1(1^{++})$	$-\frac{1}{2}V_\pi$	$\frac{1}{2}V_\rho^u - \frac{1}{2}V_\omega^u$	$\frac{1}{2}V_\rho^t - \frac{1}{2}V_\omega^t$
	$\frac{1}{\sqrt{2}}(\{D^+D^{*-}\} + \{D^0\bar{D}^{*0}\})$	$0(1^{+-})[h_c]$	$-\frac{3}{2}V_\pi$	$\frac{3}{2}V_\rho^u + \frac{1}{2}V_\omega^u$	$-\frac{3}{2}V_\rho^t - \frac{1}{2}V_\omega^t$
	$\frac{1}{\sqrt{2}}(\{D^+D^{*-}\} - \{D^0\bar{D}^{*0}\})$	$1(1^{+-}) [Z_c(3900)]$	$\frac{1}{2}V_\pi$	$-\frac{1}{2}V_\rho^u + \frac{1}{2}V_\omega^u$	$\frac{1}{2}V_\rho^t - \frac{1}{2}V_\omega^t$

- The π interactions for $D^*D(I = 0, T_{cc})$ are the same with those of $\bar{D}^*D(I = 0, C = +)(X(3872))$

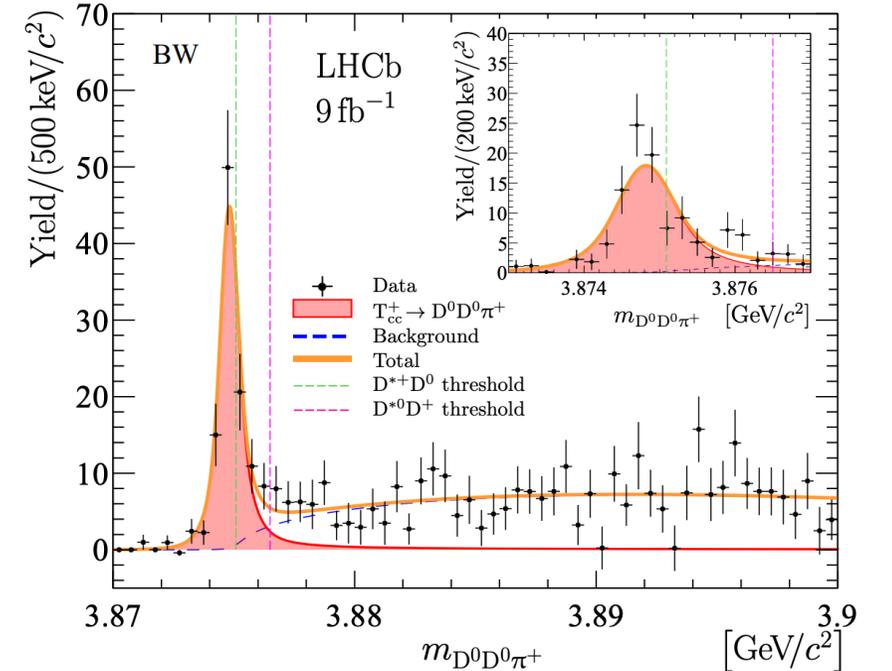
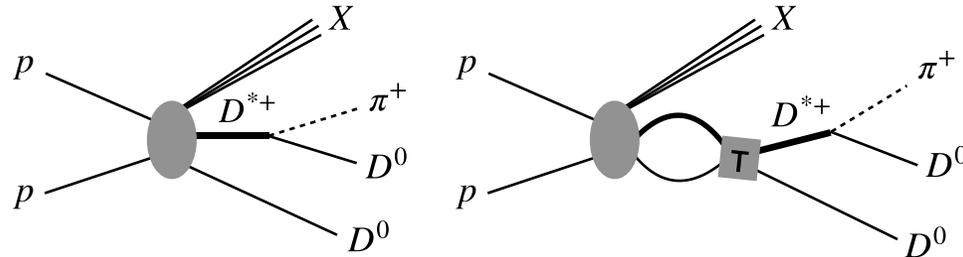
- The long-range light meson exchanging : T_{cc} , $X(3872)$, & Z_c & h_c are related to each other.

Crucial to understanding the inner structures

- Note there is additional short-range interactions for $X(3872)$ (by exchanging $c\bar{c}$)

Fitting

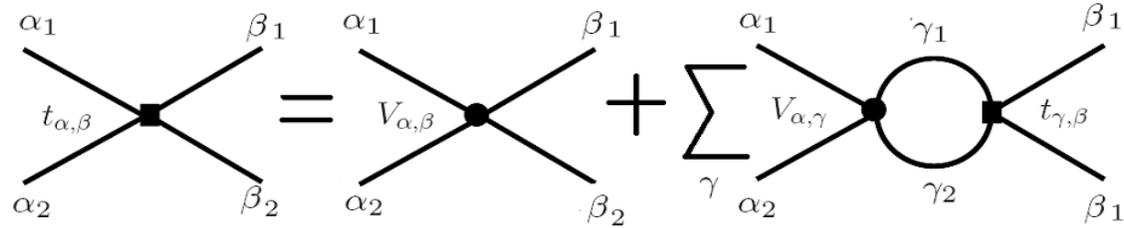
• $pp \rightarrow D(p_{D_1})D(p_{D_2})\pi(p_\pi)$



$$|\mathcal{M}|^2 = |a_{pp \rightarrow DD^*X}|^2 \sum_{\lambda_X} \epsilon_\mu(p_X, \lambda_X) \epsilon_{\mu'}^\dagger(p_X, \lambda_X) \sum_j \mathcal{B}_{j\mu} \mathcal{B}_j^{\dagger\mu'}$$

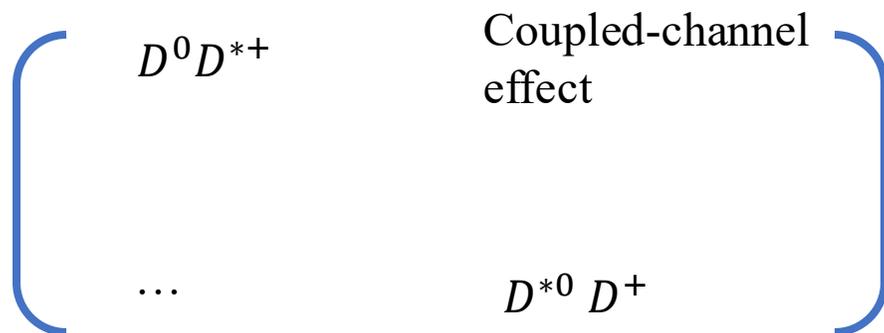
$$\mathcal{B}_j^\mu(p_{12}, p_{23}) = g \left\{ \frac{-i(p_\pi^\mu - \frac{p_{12}^\mu p_{12} \cdot p_\pi}{m_{D^*}^2})}{p_{12}^2 - m_{D^*}^2 + im_{D^*} \Gamma_{D^*}} \right\}_j + \sum_{i=1,2} ig \left\{ \int dq_{D^*} q_{D^*}^2 \frac{d\Omega_{q_{D^*}}}{4\pi} \frac{\sqrt{2w_{D_2}}}{\sqrt{2w_{D^*}}} \frac{\sqrt{2w_{D_{12}}}}{\sqrt{2w_D}} \frac{T_{ij}^{J00}(M, |q_{D^*}|, |p_{12}|)}{(M - w_{D^*}^i) - w_{D^*}^i + i\epsilon} \frac{\epsilon_a^{*\mu}(w_{D^*}, q_{D^*}) \epsilon_a(p_{12}) \cdot p_\pi}{p_{12}^2 - m_{D^*}^2 + im_{D^*} \Gamma_{D^*}} \right\}_j + (p_{D_1} \rightarrow p_{D_2})$$

Fitting

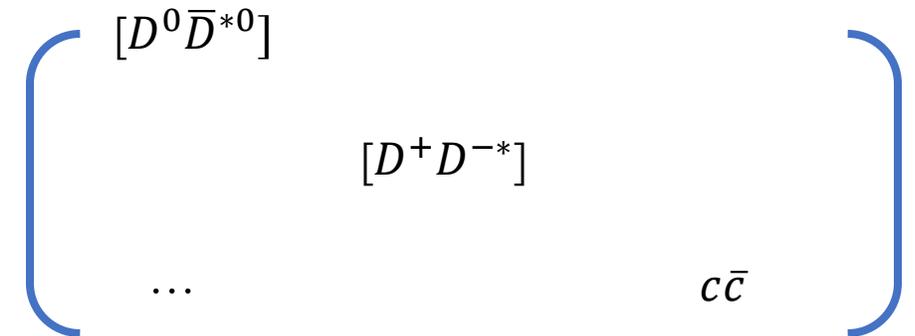


$$T(\vec{k}_{D^*}, \vec{k}'_{D^*}; E) = \mathcal{V}(\vec{k}_{D^*}, \vec{k}'_{D^*}; E) + \int d\vec{q} \frac{\mathcal{V}(\vec{k}_{D^*}, \vec{q}; E) T(\vec{q}, \vec{k}'_{D^*}; E)}{E - \sqrt{m_D^2 + q^2} - \sqrt{m_{D^*}^2 + q^2} + i\epsilon}$$

- T_{cc}^+ : \mathcal{V} and T – 2×2 matrix



- $X(3872)$: \mathcal{V} and T – 3×3 matrix



X(3872)

Inclusion of $c\bar{c}$ core

- A bound state + a resonant state

- Bound state -- X(3872)

$$\Delta E = -80.4 \text{ keV}$$

$$\Gamma_X = 32.5 \text{ keV}$$

- $\sqrt{\langle r^2 \rangle} = 11.2 \text{ fm}$

- 94.0 % $D^{*0}\bar{D}^0$, 4.8 % D^+D^{*-} , 1.2% $c\bar{c}$ \longleftrightarrow 71.9%, $I = 0$

$$28.1\%, I = 1$$

- Important isospin breaking.

