第十届XYZ研讨会·长沙

$\psi_3(3842)$ 的轻介子对衰变性质研究

报告人：赖宝君

合作者：白紫跃博士，刘翔教授

arXiv:2412.09408v2

2025年4月13日

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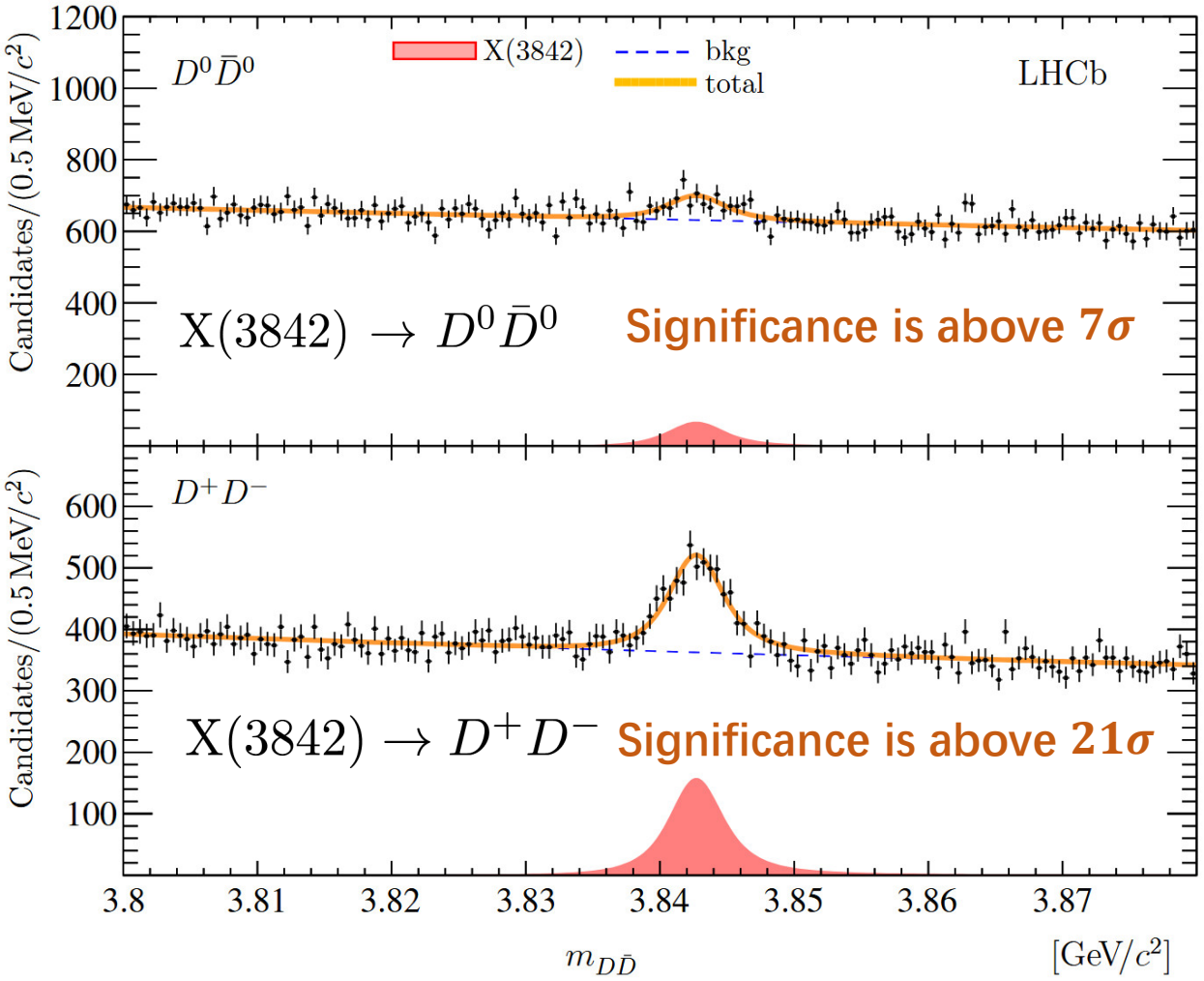
► Background and Motivation

In 2019, the LHCb Collaboration observed a new narrow charmonium state, the X(3842).

LHCb Collaboration, JHEP 07, 035 (2019).



$$m_{X(3842)} = 3842.71 \pm 0.16 \pm 0.12\ \text{MeV}/c^2$$
$$\Gamma_{X(3842)} = 2.79 \pm 0.51 \pm 0.35\ \text{MeV}$$

Consistent with theoretical prediction of $\psi_3(1^3D_3)$

$$m_{\psi_3} \sim 3815 - 3863\ \text{MeV}/c^2$$
$$\Gamma_{\psi_3} \sim 1 - 2\ \text{MeV}$$

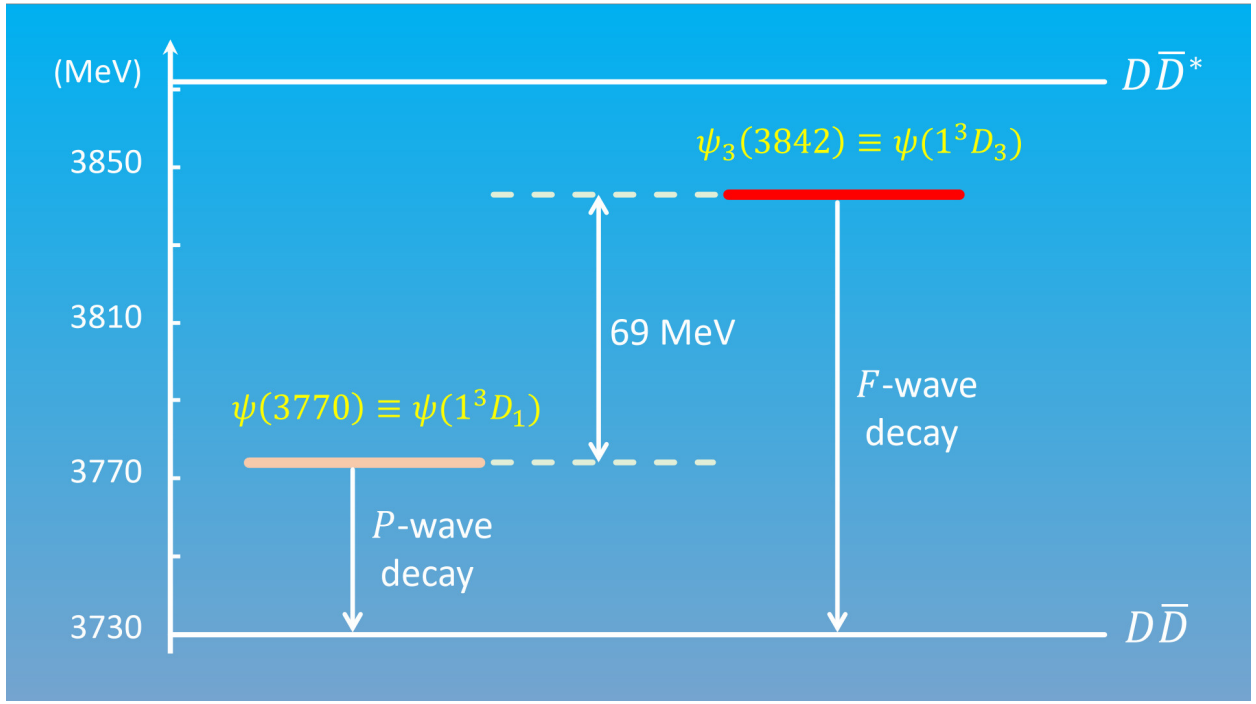
S.F. Radford and W.W. Repko, Phys. Rev. D 75 (2007) 074031.
E. Eichten and F. Feinberg, Phys. Rev. D 23 (1981) 2724.
S. Godfrey and N. Isgur, Phys. Rev. D 32 (1985) 189.
S.N. Gupta, S.F. Radford and W.W. Repko, Phys. Rev. D 34 (1986) 201.
L.P. Fulcher, Perturbative QCD, Phys. Rev. D 44 (1991) 2079.
J. Zeng, J.W. Van Orden and W. Roberts, Phys. Rev. D 52 (1995) 5229.
D. Ebert, R.N. Faustov and V.O. Galkin, Phys. Rev. D 67 (2003) 014027.
T. Barnes and S. Godfrey, Phys. Rev. D 69 (2004) 054008.
T. Barnes, S. Godfrey and E.S. Swanson, Phys. Rev. D 72 (2005) 054026.
E.J. Eichten, K. Lane and C. Quigg, Phys. Rev. D 73 (2006) 014014 [Erratum ibid. D 73 (2006) 079903].

Confirmed by BESIII Collaboration in 2022 with a significance of 4.2σ.

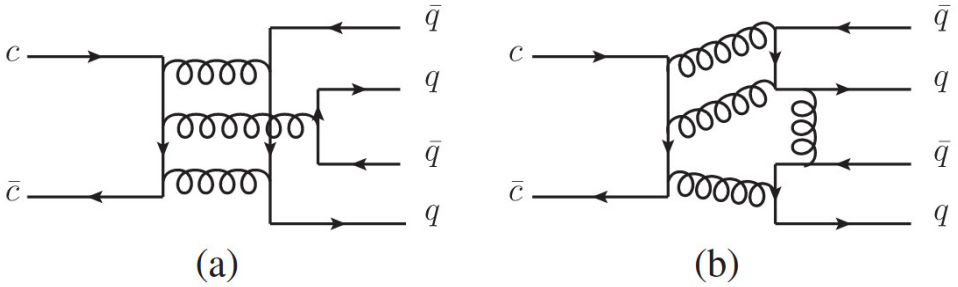
BESIII Collaboration, Phys. Rev. D 106, 052012 (2022).

► Background and Motivation

There is a longstanding puzzle concerns the non-$D\bar{D}$ decay of $\psi(3770)$, which is the *D*-wave partner of $\psi_3(3842)$, with $J^P = 1^-$



Traditional theories predict it mainly decays into pure $D\bar{D}$, with non-$D\bar{D}$ suppressed by the OZI rule.



G. Li, X. H. Liu, Q. Wang, and Q. Zhao, Phys. Rev. D 88, 014010 (2013).

However, experimental data show that

$$\Gamma_{non-D\bar{D}}/\Gamma_{\psi(3770)} = (10.9 \pm 6.9 \pm 9.2)\%$$

G. Rong, D. H. Zhang, and J. C. Chen, arXiv: hep-ex/0506051.

$$\Gamma_{non-D\bar{D}}/\Gamma_{\psi(3770)} = (16.4 \pm 7.3 \pm 4.2)\%$$

BES Collaboration, Phys. Rev. Lett. 97, 121801 (2006).

$$\Gamma_{non-D\bar{D}}/\Gamma_{\psi(3770)} = (14.5 \pm 1.7 \pm 5.8)\%$$

BES Collaboration, Phys. Lett. B 641, 145 (2006).

$$\Gamma_{non-D\bar{D}}/\Gamma_{\psi(3770)} = (13.4 \pm 5.0 \pm 3.6)\%$$

BES Collaboration, Phys. Rev. D 76, 122002 (2007).

$$\Gamma_{non-D\bar{D}}/\Gamma_{\psi(3770)} = (15.1 \pm 5.6 \pm 1.8)\%$$

BES Collaboration, Phys. Lett. B 659, 74 (2008).

$$\Gamma_{D\bar{D}} = (100.3 \pm 1.4^{+4.8}_{-6.6})\%$$

CLEO Collaboration, Phys. Rev. Lett. 96, 092002 (2006); 104, 159901 (E) (2010).

The non-$D\bar{D}$ decay channels such as $J/\psi\pi\pi$, $\phi\eta$ and $\gamma\chi_{cJ}$, $(J = 0, 1)$, their combined branching ratios total less than 2%

Γ_5	$J/\psi\pi^+\pi^-$	$(1.93 \pm 0.28) \times 10^{-3}$
Γ_6	$J/\psi\pi^0\pi^0$	$(8.0 \pm 3.0) \times 10^{-4}$
Γ_7	$J/\psi\eta$	$(8.7 \pm 1.2) \times 10^{-4}$
Γ_{14}	$\phi\eta$	$(3.1 \pm 0.7) \times 10^{-4}$
Γ_{101}	$\gamma\chi_{c1}$	$(2.49 \pm 0.23) \times 10^{-3}$
Γ_{102}	$\gamma\chi_{c0}$	$(6.9 \pm 0.6) \times 10^{-3}$

Theo. studies indicate that light hadron decays (esp. PV) contributed significantly.

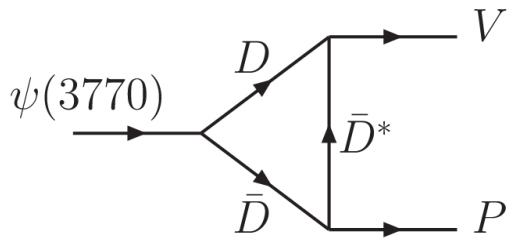
- **NRQCD, color-octet contributions, $\psi(3770) \rightarrow$ LH**

$$\Gamma_{LH}\ /\Gamma_{\psi(3770)} \sim 2\%$$

Z. G. He, Y. Fan, and K. T. Chao, Phys. Rev. Lett. 101, 112001 (2008).

- **Hadronic loop mechanism**

$$\Gamma_{PV}\ /\Gamma_{\psi(3770)} \sim 5\%$$

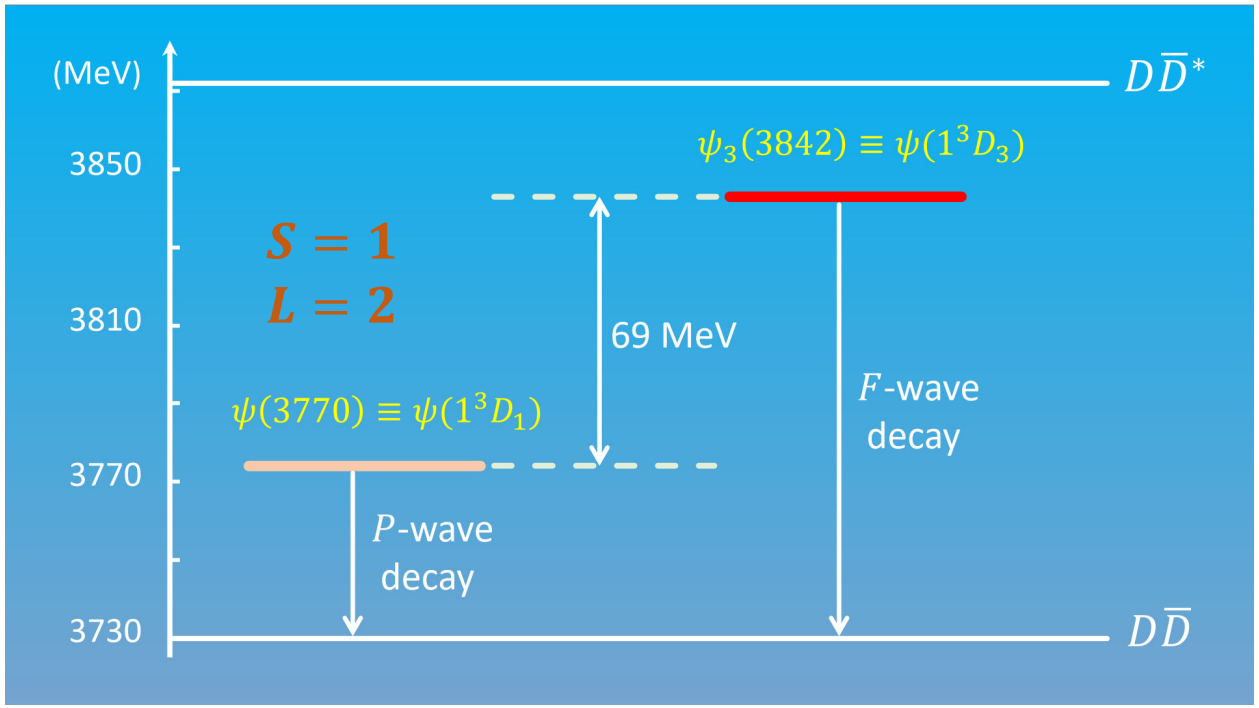


Y. J. Zhang, G. Li, and Q. Zhao, Phys. Rev. Lett. 102, 172001 (2009).
X. Liu, B. Zhang, and X. Q. Li, Phys. Lett. B 675, 441 (2009).
G. Li, X. h. Liu, Q. Wang, and Q. Zhao, Phys. Rev. D 88, 014010 (2013).

Hadronic loop mechanism can provide a sizable contribution.

► Background and Motivation

Several similarities between $\psi_3(3842)$ and $\psi(3770)$

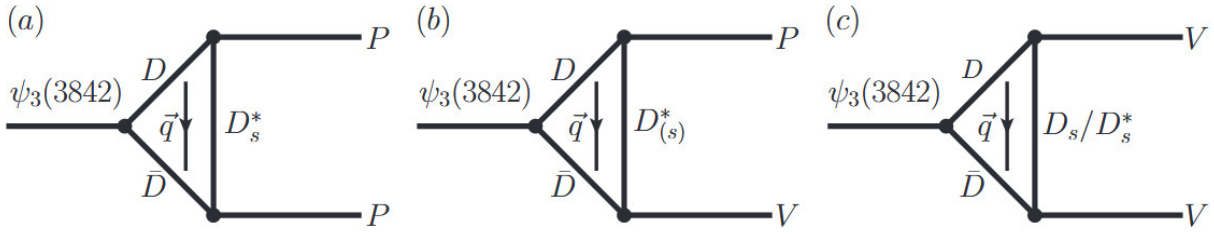


- **$\psi_3(3842)$ and $\psi(3770)$ are D-wave partner states.**
- **$\psi_3(3842)$ and $\psi(3770)$ have small mass gap.**
- **$\psi_3(3842)$ and $\psi(3770)$ share the same dominant decay modes.**

It is reasonable to infer that $\psi_3(3842)$ would also have a large non-$D\bar{D}$ branching ratio.

► Framework

In general, the processes we study can be divided into three categories



The decay amplitudes can be expressed as follows

$$\mathcal{M} = \int \frac{d^4q}{(2\pi)^4} \mathcal{V}_1\mathcal{V}_2\mathcal{V}_3\mathcal{P}_1\mathcal{P}_2\mathcal{P}_E\mathcal{F}^2(q^2, m_E^2),$$

$\mathcal{F}(q^2, m_E^2)$ **is dipole form factor**

$$\mathcal{F}(q^2, m_E^2) = \left(\frac{m_E^2 - \Lambda^2}{q^2 - \Lambda^2}\right)^2,$$

where $\Lambda = m_E + \alpha\Lambda_{\mathrm{QCD}}$, $\Lambda_{\mathrm{QCD}} = 220\ \mathrm{MeV}$ **and** α **is cutoff parameter typically on the order of 1.**

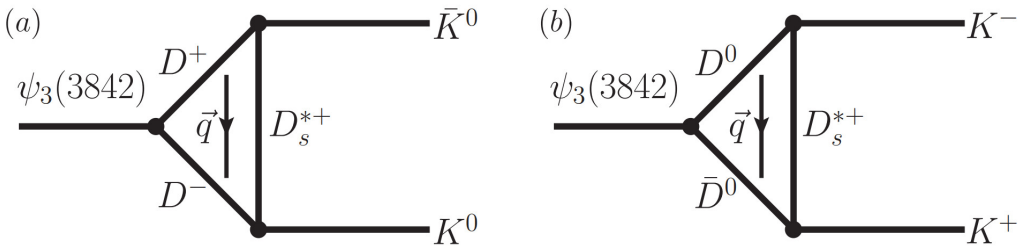
The non-$D\bar{D}$ **decay widths**

$$\Gamma = \frac{1}{7}\frac{|\vec{p}_1|}{8\pi m_{\psi_3(3842)}^2}\sum_{spin}\left|\mathcal{M}^{\mathrm{Total}}\right|^2,$$

where $\vec{p}_1$ **is the three-momentum of the final state.**

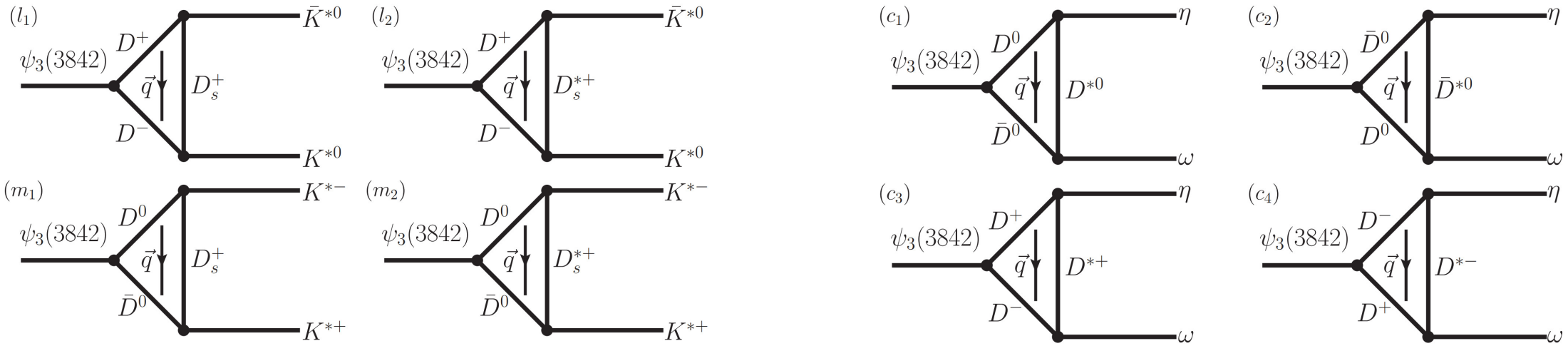
Specifically, the light-meson-pair decays of $\psi(3842)$ **include the following channels**

1. $\psi_3(3842) \to PP(K\bar{K})$

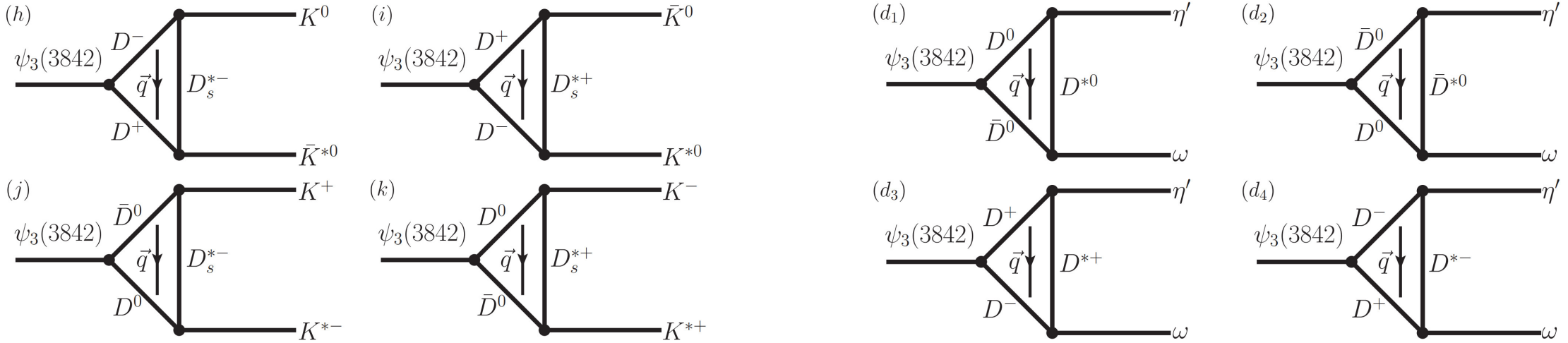


Framework

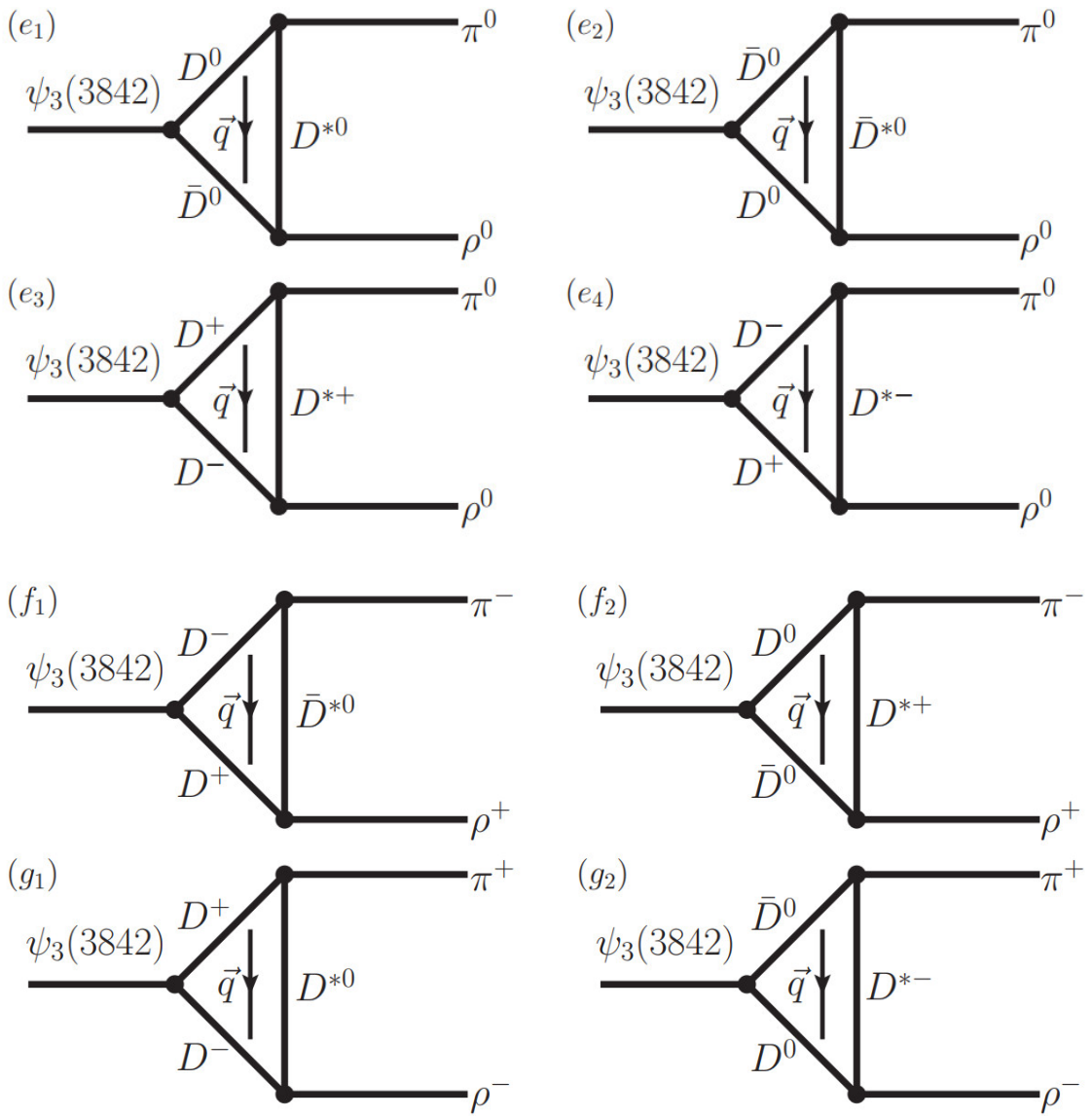
2. $\psi_3(3842) \to VV(K^*\bar{K}^*)$



3. $\psi_3(3842) \to PV(K\bar{K}^* + c.c., \omega\eta, \omega\eta' \text{ and } \rho\pi)$



► Framework



The effect Lagrangians related to each vertex as follow

$$\mathcal{L}_{\psi_3 DD} = ig_{\psi_3 DD}\psi_3^{\mu\alpha\beta}\left(\partial_\alpha\partial_\mu D^\dagger\partial_\beta D - \partial_\alpha D^\dagger\partial_\beta\partial_\mu D\right),$$

$$\mathcal{L}_{D_{(s)}^{(*)}D_{(s)}^{(*)}P} = ig_{DD^*P}\left(D_\mu^{*\dagger}D - D^\dagger D_\mu^*\right)\partial^\mu P$$
$$-g_{D^*D^*P}\varepsilon_{\mu\nu\alpha\beta}D^{*\dagger\nu}\partial^\beta D^{*\alpha}\partial^\mu P',$$

$$\mathcal{L}_{D_{(s)}^{(*)}D_{(s)}^{(*)}V} = -ig_{DDV}D_i^\dagger\overleftrightarrow{\partial^\mu}D^j\left(V_\mu\right)_j^i$$
$$-2f_{DD^*V}\varepsilon_{\mu\nu\alpha\beta}\partial^\nu\left(\mathcal{V}^\beta\right)_j^i\left(D_i^{*\dagger\mu}\overleftrightarrow{\partial^\alpha}D^j - D_i^\dagger\overleftrightarrow{\partial^\alpha}D^{*\mu j}\right)$$
$$+ig_{D^*D^*V}D_i^{*\dagger\nu}\overleftrightarrow{\partial^\mu}D_\nu^{*j}\left(\mathcal{V}_\mu\right)_j^i$$
$$+4if_{D^*D^*V}D_i^{*\dagger\mu}\left[\partial_\mu\mathcal{V}^\nu - \partial^\nu\mathcal{V}_\mu\right]_j^i D_\nu^{*j},$$

► Numerical Results

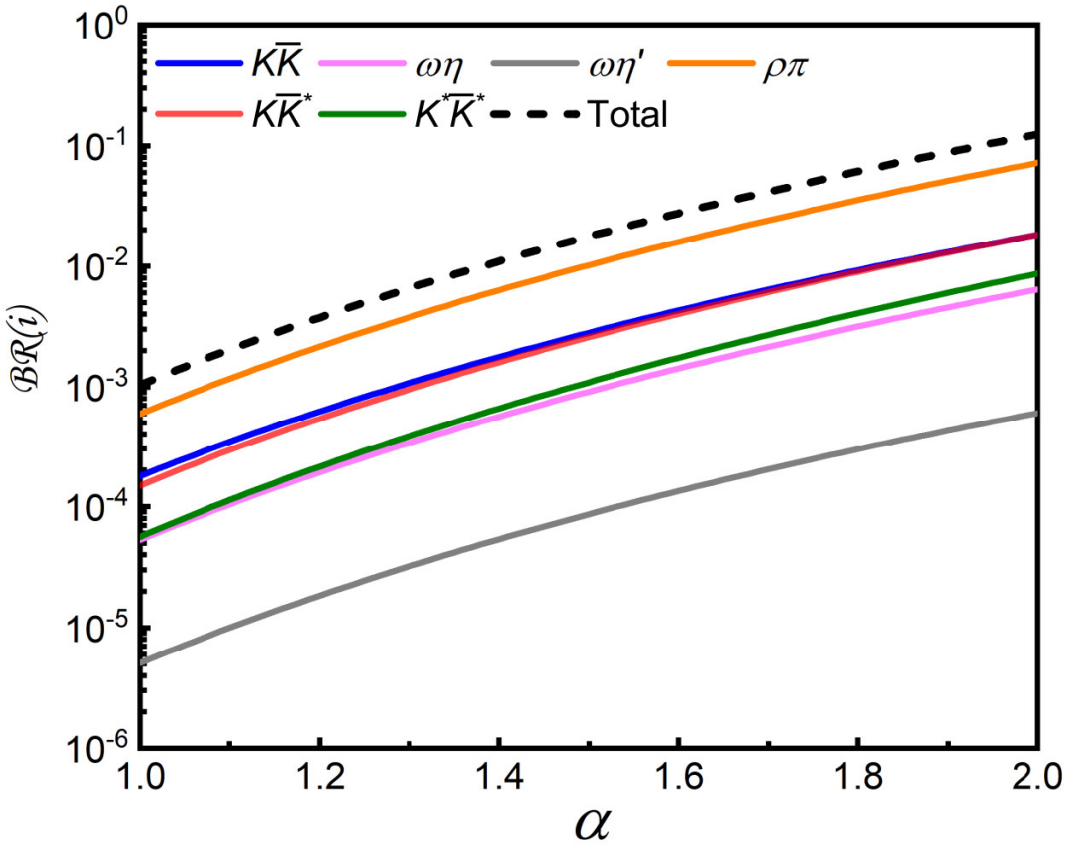


TABLE II: The branching ratios ($\mathcal{BR}$) of $\psi_3(3842)$ decays into allowed PP, PV, and VV final states for specific values of the α parameter.

$\mathcal{BR}(\%)$	$\alpha = 1.00$	$\alpha = 1.25$	$\alpha = 1.50$	$\alpha = 1.75$	$\alpha = 2.00$
$K\bar{K}$	0.02	0.08	0.28	0.77	1.83
$\omega\eta$	0.01	0.03	0.09	0.26	0.64
$\omega\eta'$	0	0	0.01	0.02	0.06
$\rho\pi$	0.06	0.29	1.02	2.93	7.21
$K\bar{K}^*$	0.01	0.07	0.26	0.74	1.83
$K^*\bar{K}^*$	0.01	0.02	0.11	0.33	0.87
Total	0.10	0.50	1.77	5.06	12.43

- **Decay width has a strong dependence on α.**
- **Hadronic loop can contribute a sizable branching ratio.**

- **$\rho\pi$ channel dominant the light meson pairs decay.**
- **Further demonstrates the similarity with $\psi(3770)$.**

► Numerical Results

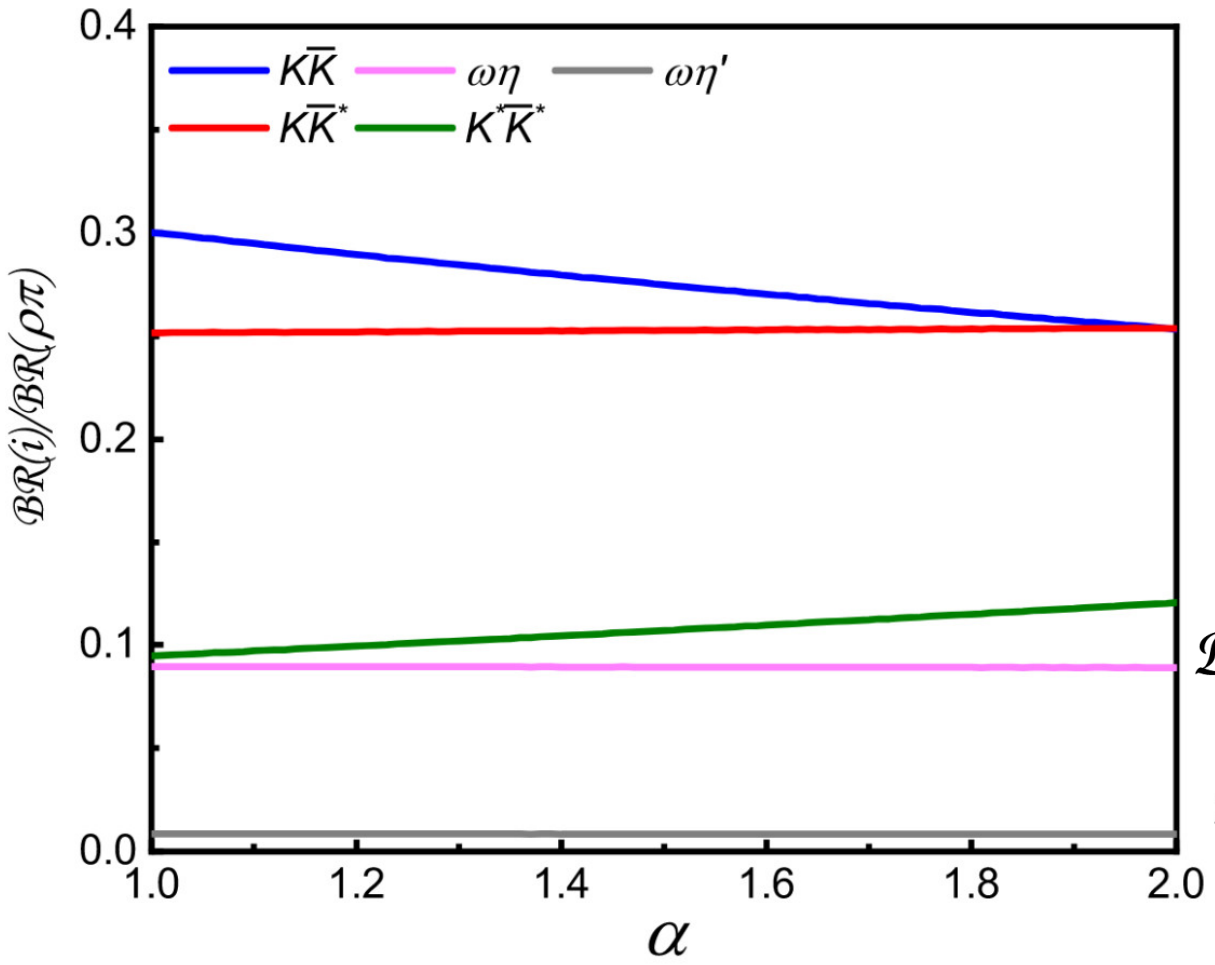


FIG. 4: The α parameter dependence of the ratios $\mathcal{BR}(i)/\mathcal{BR}(\rho\pi)$. Here, i represent the different final states of PP, PV, and VV.

$$\mathcal{BR}(K\bar{K})/\mathcal{BR}(\rho\pi) = (2.5 - 3.0) \times 10^{-1},$$
$$\mathcal{BR}(\omega\eta)/\mathcal{BR}(\rho\pi) = 8.9 \times 10^{-2},$$
$$\mathcal{BR}(\omega\eta')/\mathcal{BR}(\rho\pi) = (8.4 - 8.6) \times 10^{-3},$$
$$\mathcal{BR}(K\bar{K}^*)/\mathcal{BR}(\rho\pi) = 2.5 \times 10^{-1},$$
$$\mathcal{BR}(K^*\bar{K}^*)/\mathcal{BR}(\rho\pi) = (9.5 - 12.0) \times 10^{-2}.$$
$$\mathcal{BR}(\omega\eta) : \mathcal{BR}(\omega\eta') \approx 10 : 1$$
$$\boldsymbol{\alpha = 1}$$
$$\mathcal{BR}(K\bar{K}) : \mathcal{BR}(K\bar{K}^*) : \mathcal{BR}(K^*\bar{K}^*) = 3.2 : 2.7 : 1.0$$
$$\boldsymbol{\alpha = 2}$$
$$\mathcal{BR}(K\bar{K}) : \mathcal{BR}(K\bar{K}^*) : \mathcal{BR}(K^*\bar{K}^*) = 2.1 : 2.1 : 1.0$$

- **Ratios have a weak dependence on α.**
- **Provide useful references for experiments.**

► Summary

- Due to its similarities with $\psi(3770)$, $\psi_3(3842)$ very likely has a sizable non-$D\overline{D}$ decay branching ratio.
- By computing the hadronic loop contributions, our results confirm the inferred decay properties of $\psi_3(3842)$.
- Our results indicate the $\rho\pi$ channel dominant the light meson pairs decay.
- Despite a lack of relevant experimental data, the characteristic ratios we present still serve as valuable references for experiments.
- We hope our findings will aid future experiments, such as LHCb and BESIII, in further confirming $\psi_3(3842)$ and exploring its non-$D\overline{D}$ decay.

Thank you!