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Combined analysis of the singly-Cabbibo-suppressed decays of $D^0 \to VP$

第八届全国重味物理和量子色动力学研讨会

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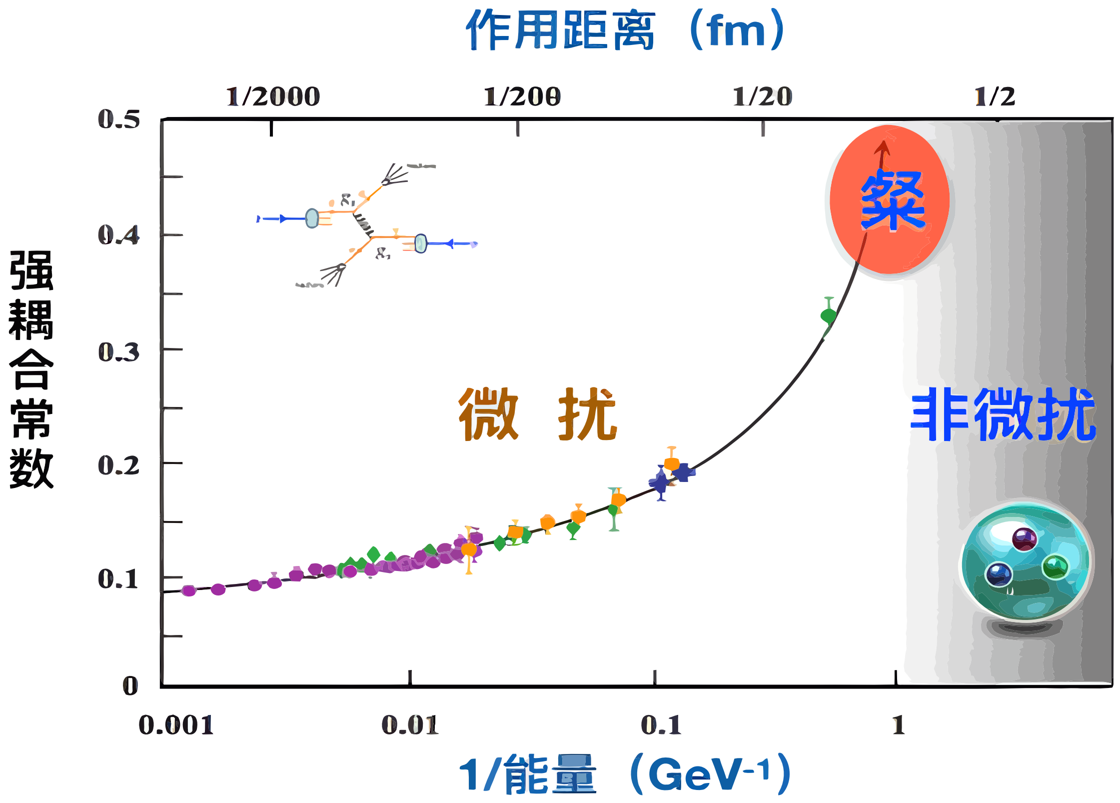
Outline

01 | Introduction

Motivation

- For B mesons, the b quark is sufficiently heavy, and perturbative methods can effectively describe their decay processes.
  V. L. Chernyak and A. R. Zhitnitsky, Phys. Rept., 112, 173; V. L. Chernyak and A. R. Zhitnitsky, Nucl. Phys. B, 201, 492; S. J. Brodsky and G. P. Lepage, Phys. Rev. D, 24, 2848

  The charm quark mass $m_c \sim 1.5\,\mathrm{GeV}$
- lies at the boundary between the perturbative and non-perturbative energy regions.
- Non-perturbative effects play a significant role in charm meson decays.



H.-Y. Cheng and C.-W. Chiang, Phys. Rev. D, 104, 073003 ,
Y. Cao, Y. Cheng, and Q. Zhao, Phys. Rev. D, 109, 073002 ($D^0 \to VV$),
Y. Cao and Q. Zhao, Phys. Rev. D, 109, 093005 ($D^0 \to V\gamma$)

Motivation

- The two-body non-leptonic decays of D^0 mesons have abundant experimental data. S. Navas and others, Phys. Rev. D, 110, 030001
- The study of weak decays of D^0 mesons can provide deeper insights into non-perturbative effects.

A. Branching Ratios of $D^0 \to VP$

Cabibbo-favored (CF) decay channels

TABLE I: Branching ratios of Cabibbo-favored (CF) $D^0 \to VP$ decay channels in units of 10^{-2}

Decay channels	$D^0 \to K^{*-}\pi^+$	$D^0 \to K^-\rho^+$	$D^0 \to \bar{K}^{*0}\pi^0$	$D^0 \to \bar{K}^0\rho^0$	$D^0 \to \bar{K}^{*0}\eta$	$D^0 \to \bar{K}^{*0}\eta'$	$D^0 \to \bar{K}^0\omega$	$D^0 \to \bar{K}^0\phi$
BR	$5.67^{+0.49}_{-0.38}$	11.2 ± 0.7	3.15 ± 0.31	$1.28^{+0.12}_{-0.16}$	1.41 ± 0.12	< 0.1	2.27 ± 0.07	0.832 ± 0.036

Singly Cabibbo-suppressed (SCS) decay channels

TABLE II: Branching ratios of singly Cabibbo-suppressed (SCS) $D^0 \to VP$ decay channels in units of 10^{-3}

Decay channels	$D^0 \to \rho^+\pi^-$	$D^0 \to \rho^-\pi^+$	$D^0 \to \pi^0\rho^0$	$D^0 \to K^{*+}K^-$	$D^0 \to K^{*-}K^+$	$D^0 \to K^{*0}\bar{K}^0$	$D^0 \to \bar{K}^{*0}K^0$
BR	10.1 ± 0.5	5.15 ± 0.26	3.86 ± 0.24	5.36 ± 0.61	1.82 ± 0.20	0.342 ± 0.063	0.249 ± 0.048
Decay channels	$D^0 \to \pi^0\omega$	$D^0 \to \pi^0\phi$	$D^0 \to \eta\omega$	$D^0 \to \eta\phi$	$D^0 \to \eta'\omega$	$D^0 \to \eta\rho^0$	$D^0 \to \eta'\rho^0$
BR	0.117 ± 0.035	1.17 ± 0.04	1.98 ± 0.18	0.18 ± 0.05	...	...	...

Doubly Cabibbo-suppressed (DCS) decay channels

TABLE III: Branching ratios of doubly Cabibbo-suppressed (DCS) $D^0 \to VP$ decay channels in units of 10^{-4}

Decay channels	$D^0 \to K^{*+}\pi^-$	$D^0 \to K^+\rho^-$	$D^0 \to K^{*0}\pi^0$	$D^0 \to K^0\rho^0$	$D^0 \to K^{*0}\eta$	$D^0 \to K^{*0}\eta'$	$D^0 \to K^0\omega$	$D^0 \to K^0\phi$
BR	$3.45^{+1.80}_{-1.02}$	...	...	...	...	...	...	...

- Weak decays of D^0 mesons are often accompanied by contributions from intermediate strong decays. Investigating D^0 weak decays can help improve our understanding of strong interactions, such as exotic states .

S. Rahmani, W. Liang, Y.-W. Peng, Y. Lu, D.-L. Yao, and C.-W. Xiao, Phys. Rev. D, 112, 036001 .

Theoretical methods

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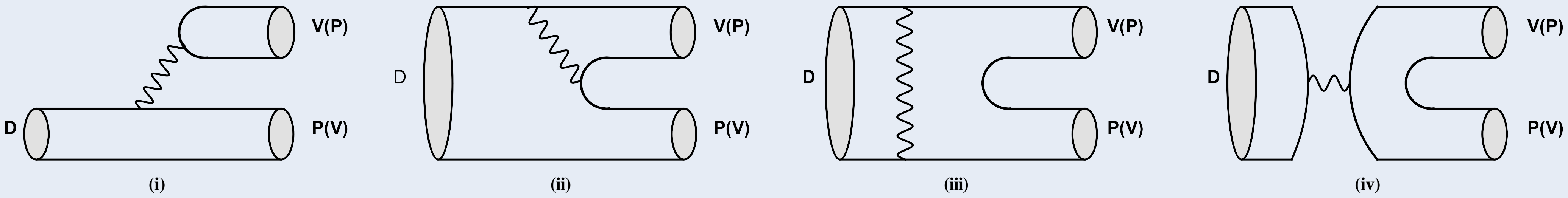
Topological diagram approach (TDA)



H.-Y. Cheng and C.-W. Chiang, Phys. Rev. D, 86, 014014; H.-Y. Cheng and C.-W. Chiang, Phys. Rev. D, 85, 034036; H.-Y. Cheng and C.-W. Chiang, Phys. Rev. D, 109, 073008

Our works: Weak effective hamiltonian + quark model

$$\mathcal{H}_W(V-A) + \text{Nonrelativistic Constituent Quark Model}$$

Y. Cao, Y. Cheng, and Q. Zhao, Phys. Rev. D, 109, 073002; Y. Cao and Q. Zhao, Phys. Rev. D, 109, 093005; P.-Y. Niu, J.-M. Richard, Q. Wang, and Q. Zhao, Phys. Rev. D, 102, 073005

02 | Formalism

Decay channels

- **Six singly Cabibbo-suppressed (SCS) channels :**

$D^0 \to \rho^+\pi^-$, $\rho^-\pi^+$, $K^{*+}K^-$, $K^{*-}K^+$, $K^{*0}\bar{K}^0$, and $\bar{K}^{*0}K^0$.

- **Direct emission (DE) process**

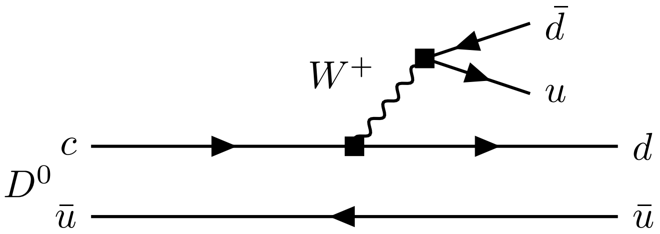
(a) Direct emission (DE) process

(b) Internal conversion (IC) process

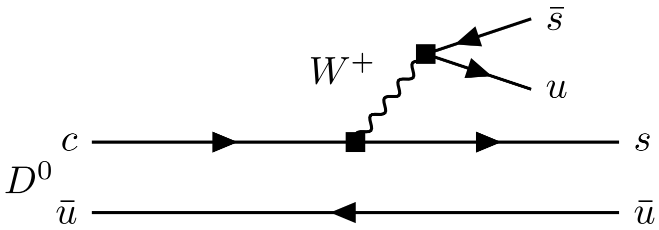
Figure: Schematic diagrams for $D^0 \to VP$ processes.

- **Calculate the contribution of the DE process and extract the contribution of the IC process by fitting experimental data.**

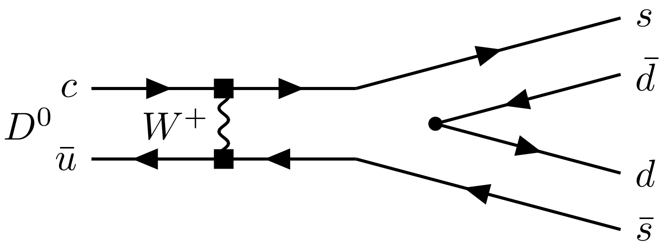
Diagrams for different channels



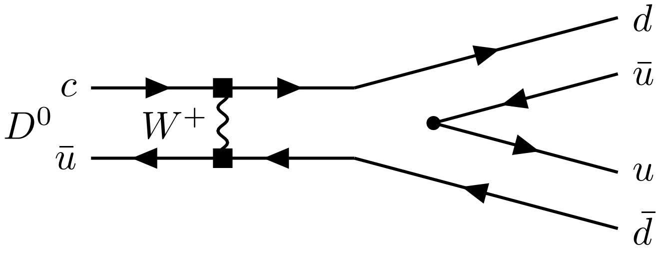
(a) $D^0 \to \rho^\pm \pi^\mp$ D E process



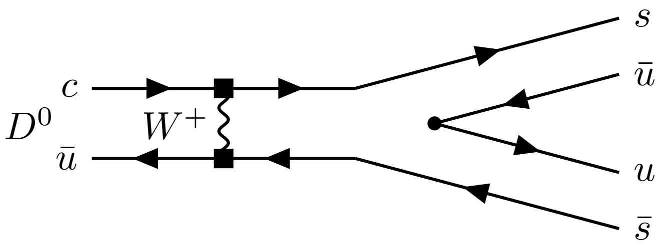
(b) $D^0 \to K^{*\pm} K^\mp$ DE process



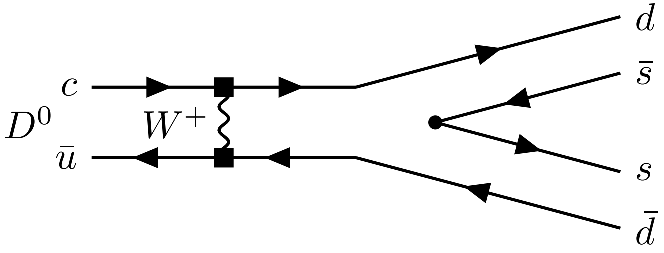
(c) $D^0 \to K^{(*)0} \bar{K}^{(*)0}$ IC process $s\bar{s}$



(d) $D^0 \to \rho^\pm \pi^\mp$ IC process



(e) $D^0 \to K^{*\pm} K^\mp$ IC process



(f) $D^0 \to K^{(*)0} \bar{K}^{(*)0}$ IC process $s\bar{s}$

Figure: Schematic diagrams for $D^0 \to VP$ processes.

Weak Hamiltonian

Effective weak Hamiltonian

$$\mathcal{H}_W = \frac{G_F}{\sqrt{2}} \int d^3\mathbf{x} \frac{1}{2} \{ J^{-,\mu}(\mathbf{x}), J^{+}_{\mu}(\mathbf{x}) \} = \mathcal{H}_W^{PV} + \mathcal{H}_W^{PC}$$

P.-Y. Niu, J.-M. Richard, Q. Wang, and Q. Zhao, Phys. Rev. D, 102, 073005

Parity violating (PV) and parity conserving (PC)

$$\mathcal{H}_W = \mathcal{H}_W^{PC} + H_W^{PC}$$

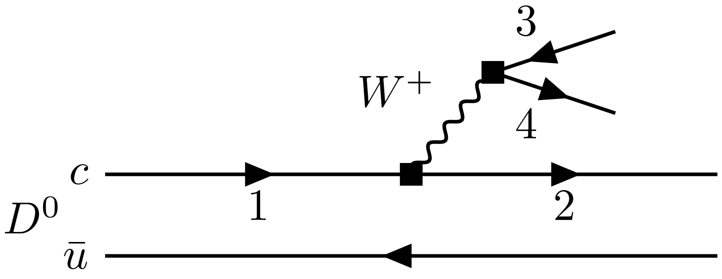
For $D^0 \to VP$ decays, only the parity-conserving part $\mathcal{H}_W^{PC}$ contributes to the decay amplitude.

Parity conserving (PC)

$$\mathcal{H}_W^{PC} = \frac{G_F}{\sqrt{2}} \int d^3\mathbf{x} j^{-}_{\mu}(\mathbf{x}) j^{+,\mu}(\mathbf{x}) + j^{-}_{5,\mu}(\mathbf{x}) j_5^{+,\mu}(\mathbf{x})$$

Nonrelativistic Limits

At the quark level, for the DE process, the $\mathcal{H}_W^{PC}$ corresponds to a $1 \to 3$ quark transition.



$$\mathcal{H}_{W,1\to3}^{PC} = \frac{G_F}{\sqrt{2}} V_{cd} V_{ud} \frac{1}{(2\pi)^3} \delta^3(\mathbf{p}_1 - \mathbf{p}_2 - \mathbf{p}_3 - \mathbf{p}_4) \Big\{ \langle s_2 | I | s_1 \rangle \langle s_4 \bar{s}_3 | \boldsymbol{\sigma} | 0 \rangle \cdot \left(\frac{\mathbf{p}_3}{2m_3} + \frac{\mathbf{p}_4}{2m_4} \right)$$
$$+ \langle s_2 | \boldsymbol{\sigma} | s_1 \rangle \cdot \left(\frac{\mathbf{p}_1}{2m_1} + \frac{\mathbf{p}_2}{2m_2} \right) \langle s_4 \bar{s}_3 | I | 0 \rangle$$
$$- \langle s_4 \bar{s}_3 | \boldsymbol{\sigma} | 0 \rangle \cdot \left[\langle s_2 | I | s_1 \rangle \left(\frac{\mathbf{p}_1}{2m_1} + \frac{\mathbf{p}_2}{2m_2} \right) - i \langle s_2 | \boldsymbol{\sigma} | s_1 \rangle \times \left(\frac{\mathbf{p}_1}{2m_1} - \frac{\mathbf{p}_2}{2m_2} \right) \right]$$
$$- \langle s_2 | \boldsymbol{\sigma} | s_1 \rangle \cdot \left[\langle s_4 \bar{s}_3 | I | 0 \rangle \left(\frac{\mathbf{p}_3}{2m_3} + \frac{\mathbf{p}_4}{2m_4} \right) \right] - i \langle s_4 \bar{s}_3 | \boldsymbol{\sigma} | 0 \rangle \times \left(\frac{\mathbf{p}_3}{2m_3} - \frac{\mathbf{p}_4}{2m_4} \right) \Big\}$$

Decay amplitude

Amplitude at the quark level

$$\mathcal{M}^q_{\mathrm{DE}}(D^0 \to VP) = \langle P(\mathbf{P}_3)V(\mathbf{P}_2)|\hat{H}_{1\to 3}|D^0(\mathbf{P}_1)\rangle$$

Calculated by using the non-relativistic constituent quark model (NRCQM) wave functions

R. Kokoski and N. Isgur, Phys. Rev. D, 35, 907; S. Godfrey and N. Isgur, Phys. Rev. D, 32, 189–231; S. Godfrey and R. Kokoski, Phys. Rev. D, 43, 1679–1687; P.-Y. Niu, Q. Wang, and Q. Zhao, Phys. Rev. D, 111, 093004

Amplitude at the hadronic level

$$\mathcal{M}^h_{\mathrm{DE}} = -8\pi^{\frac{3}{2}}\sqrt{m_{D^0}E_V E_P}\mathcal{M}^q_{\mathrm{DE}}$$

Effective coupling constant

$$\mathcal{M}^h_{\mathrm{DE}}(D^0 \to VP) \equiv V_{cq}V_{uq}\mathcal{G}^{\mathrm{DE}}\varepsilon_2 \cdot p_3$$

Decay amplitude

DE coupling constant

$$\mathcal{G}^{\rm DE}_{\rho^+\pi^-} = \frac{2G_F m_\rho (R_\pi R_D R_\rho)^{3/2} e^{-\frac{|\mathbf{p}|^2}{8(R_D^2+R_\pi^2)}} \sqrt{E_\pi E_\rho m_{D^0}}}{\pi^{3/4} m_c m_{D^0} (R_D^2 + R_\pi^2)^{5/2} m_q^3},$$
$$\times \left(2m_c(R_D^2 + R_\pi^2)m_q^2 + m_c(R_D^2 + 2R_\pi^2)m_q^2 - R_D^2 m_q^3\right),$$

$$\mathcal{G}^{\rm DE}_{K^{*+}K^-} = \frac{2G_F m_{K^*} (R_D R_K R_{K^*})^{3/2} e^{-\frac{|\mathbf{p}|^2}{8(R_D^2+R_K^2)}} \sqrt{E_K E_{K^*} m_{D^0}}}{\pi^{3/4} m_c m_{D^0} m_q m_s^2 (R_D^2 + R_K^2)^{5/2}},$$
$$\times \left(m_c m_s(R_D^2 + R_K^2)(m_q + m_s) + m_c m_q m_s(R_D^2 + 2R_K^2) - R_D^2 m_q m_s^2\right),$$

$$\mathcal{G}^{\rm DE}_{\rho^-\pi^+} = \mathcal{G}^{\rm DE}_{\rho^+\pi^-}(R_\rho \leftrightarrow R_\pi), \qquad \mathcal{G}^{\rm DE}_{K^{*-}K^+} = \mathcal{G}^{\rm DE}_{K^{*+}K^-}(R_{K^*} \leftrightarrow R_K),$$

$R_{\cdots}$ are the harmonic-oscillator parameters for the mesons. $|\mathbf{p}|$ is the three-momentum of the final-state mesons in the D^0 rest frame.

Total amplitude

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DE+IC amplitude

$$\mathcal{M}(D^0 \to V(\varepsilon_2, p_2)P(p_3)) = V_{cq}V_{uq}(\mathcal{G}^{\mathrm{DE}} + \mathcal{G}^{\mathrm{IC}})\varepsilon_2 \cdot p_3 \equiv \mathcal{G}^{\mathrm{total}}\varepsilon_2 \cdot p_3$$

Total effective coupling constants for different channels

$$\mathcal{G}^{\mathrm{total}}(D^0 \to \rho^{\pm}\pi^{\mp}) = V_{cd}V_{ud}\left(\mathcal{G}^{\mathrm{DE}}_{\rho^{\pm}\pi^{\mp}} + \mathcal{G}^{\mathrm{IC}}_{d\bar{d}}\right), \mathcal{G}^{\mathrm{IC}}_{d\bar{d}} = \left|\mathcal{G}^{\mathrm{IC}}_{d\bar{d}}\right| e^{i\theta_{d\bar{d}}}$$

$$\mathcal{G}^{\mathrm{total}}(D^0 \to K^{*\pm}K^{\mp}) = V_{cs}V_{us}\left(\mathcal{G}^{\mathrm{DE}}_{K^{*\pm}K^{\mp}} + \mathcal{G}^{\mathrm{IC}}_{s\bar{s}}\right), \mathcal{G}^{\mathrm{IC}}_{s\bar{s}} = \left|\mathcal{G}^{\mathrm{IC}}_{s\bar{s}}\right| e^{i\theta_{s\bar{s}}}$$

$$\mathcal{G}^{\mathrm{total}}(D^0 \to K^{(*)0}\bar{K}^{(*)0}) = V_{cs}V_{us}\mathcal{G}^{\mathrm{IC}}_{s\bar{s}} + e^{i\theta_{ds}}V_{cd}V_{ud}\mathcal{G}^{\mathrm{IC}}_{d\bar{d}},$$

Decay width

$$\Gamma(D^0 \to VP) = \frac{|\mathbf{p}|^3}{8\pi m_V^2}\left|\mathcal{G}^{\mathrm{total}}\right|^2.$$

03 | Results and Discussion

Input parameters

Paramters in the quark model

Table 1: Harmonic oscillator strengths for meson wavefunctions and the constituent quark masses
S. Godfrey and N. Isgur, Phys. Rev. D, 32, 189–231; S. Godfrey, Phys. Rev. D, 70, 054017; S. Godfrey and R. Kokoski, Phys. Rev. D, 43, 1679–1687; S. Godfrey and K. Moats, Phys. Rev. D, 93, 034035 .

HO Strength	Values (MeV)	Quark mass	Values (MeV)
R_D	660	m_c	1628
R_{K^*}	480	m_s	419
R_K	710	m_u	220
R_ρ	450	m_d	220
R_π	750		

HO parameters

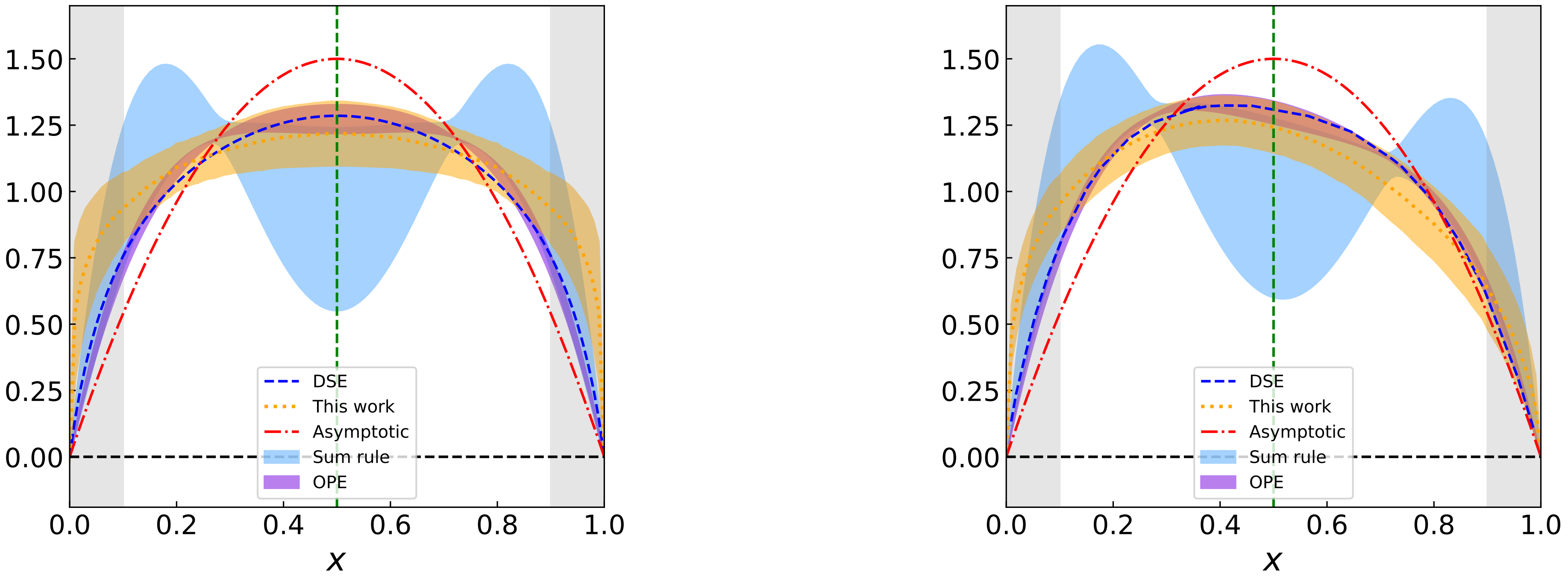

Figure: LCDAs for π(left) and K(right). J. Hua et al., Phys. Rev. Lett., 129, 132001

In momentum space, the wavefunctions of pseudoscalar mesons exhibit a relatively broad distribution. Therefore, when approximating them with harmonic oscillator wavefunctions, larger values are chosen.

Fitted branching ratios

Fitted results

Table 2: Experimental (PDG) and fitted branching ratios for the relevant decay channels.

Decay channels	$D^0 \to \rho^+\pi^-$	$D^0 \to \rho^-\pi^+$	$D^0 \to K^{*+}K^-$	$D^0 \to K^{*-}K^+$	$D^0 \to K^{*0}\overline{K}^0$	$D^0 \to \overline{K}^{*0}K^0$
$\mathcal{B}_{\rm exp}(\times 10^{-3})$	10.1 ± 0.5	5.15 ± 0.26	5.36 ± 0.61	1.82 ± 0.20	0.342 ± 0.063	0.249 ± 0.048
$\mathcal{B}_{\text{fit-1}}(\times 10^{-3})$	10.3 ± 0.3	5.27 ± 0.21	5.80 ± 0.27	1.79 ± 0.19	0.290 ± 0.139	0.290 ± 0.139
$\mathcal{B}_{\text{fit-2}}(\times 10^{-3})$	10.3 ± 0.3	5.27 ± 0.21	5.80 ± 0.27	1.79 ± 0.19	0.290 ± 0.055	0.290 ± 0.055

Numerical results

DE contribution

Table 3: Numerical results of the effective coupling constants $\mathcal{G}^{\mathrm{DE}}$ for the direct emission processes.

Decay channels	$D^0 \to \rho^+\pi^-$	$D^0 \to \rho^-\pi^+$	$D^0 \to K^{*+}K^-$	$D^0 \to K^{*-}K^+$
$\mathcal{G}^{\mathrm{DE}}(\times 10^{-5})$	0.805	1.391	0.683	1.059

Asymptotic behavior of DE coupling constants

$$\mathcal{G}^{\mathrm{DE}}_{V^+P^-} \propto \frac{3R_D^2 + 4R_P^2}{\left(R_D^2 + R_P^2\right)^{\frac{5}{2}}}, \quad \mathcal{G}^{\mathrm{DE}}_{V^-P^+} \propto \frac{3R_D^2 + 4R_V^2}{\left(R_D^2 + R_V^2\right)^{\frac{5}{2}}}, \quad \frac{\mathcal{G}^{\mathrm{DE}}_{V^-P^+}}{\mathcal{G}^{\mathrm{DE}}_{V^+P^-}} \simeq 1.5$$

Numerical results

Fitted parameters

Table 4: Fitted values of the parameters

Parameters	$\lvert\mathcal{G}^{\rm IC}_{d\bar{d}}\rvert(\times 10^{-5})$	$\theta_{d\bar{d}}(^\circ)$	$\lvert\mathcal{G}^{\rm IC}_{s\bar{s}}\rvert(\times 10^{-5})$	$\theta_{s\bar{s}}(^\circ)$	$\theta_{ds}()$	$\chi^2/{\rm d.o.f}$
Fit−1	1.146 ± 0.004	180.0 ± 2.3	1.053 ± 0.007	167.5 ± 0.7	192.5 ± 3.7	2.3
Fit−2	1.146 ± 0.004	\	1.053 ± 0.007	167.5 ± 0.7	\	0.7

Coupling constants expressions

Table 5: Coupling constants for different fits schemes

Coupling constant	Fit−1	Fit−2
$\mathcal{G}^{\rm total}(D^0 \to \rho^\pm\pi^\mp)$	$V_{cd}V_{ud}\left(\mathcal{G}^{\rm DE}_{\rho^\pm\pi^\mp} + \mathcal{G}^{\rm IC}_{d\bar{d}}\right)$	$V_{cd}V_{ud}\left(\mathcal{G}^{\rm DE}_{\rho^\pm\pi^\mp} - \lvert\mathcal{G}^{\rm IC}_{d\bar{d}}\rvert\right)$
$\mathcal{G}^{\rm total}(D^0 \to K^{*\pm}K^\mp)$	$V_{cs}V_{us}\left(\mathcal{G}^{\rm DE}_{K^{*\pm}K^\mp} + \mathcal{G}^{\rm IC}_{s\bar{s}}\right)$	
$\mathcal{G}^{\rm total}\left(D^0 \to K^{(*)0}\overline{K}^{(*)0}\right)$	$V_{cs}V_{us}\mathcal{G}^{\rm IC}_{s\bar{s}} + e^{i\theta_{ds}}V_{cd}V_{ud}\mathcal{G}^{\rm IC}_{d\bar{d}}$	$V_{cs}V_{us}\lvert\mathcal{G}^{\rm IC}_{s\bar{s}}\rvert - V_{cd}V_{ud}\lvert\mathcal{G}^{\rm IC}_{d\bar{d}}\rvert$

Fitted branching ratios

Fitted results

Table 6: Experimental (PDG) and fitted branching ratios for the relevant decay channels.

Decay channels	$D^0 \to \rho^+\pi^-$	$D^0 \to \rho^-\pi^+$	$D^0 \to K^{*+}K^-$	$D^0 \to K^{*-}K^+$	$D^0 \to K^{*0}\overline{K}^0$	$D^0 \to \overline{K}^{*0}K^0$
$\mathcal{B}_{\rm exp}(\times 10^{-3})$	10.1 ± 0.5	5.15 ± 0.26	5.36 ± 0.61	1.82 ± 0.20	0.342 ± 0.063	0.249 ± 0.048
$\mathcal{B}_{\text{fit-1}}(\times 10^{-3})$	10.3 ± 0.3	5.27 ± 0.21	5.80 ± 0.27	1.79 ± 0.19	0.290 ± 0.139	0.290 ± 0.139
$\mathcal{B}_{\text{fit-2}}(\times 10^{-3})$	10.3 ± 0.3	5.27 ± 0.21	5.80 ± 0.27	1.79 ± 0.19	0.290 ± 0.055	0.290 ± 0.055

Discussions

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- Comparison with TDA H.-Y. Cheng and C.-W. Chiang, Phys. Rev. D, 109, 073008

Comparison

Table 7: The coupling constants size are quoted in units of 10^{-6}, phase angle are presented in units of $^\circ$.

Parameters	$\mathcal{G}^{\mathrm{DE}}_{\rho^+\pi^-}(\lvert T_P\rvert)$	$\backslash\left(\delta_{T_P}\right)$	$\mathcal{G}^{\mathrm{IC}}_{\rho^+\pi^-}(\lvert E_V\rvert)$	$\theta_{d\bar{d}}\left(\delta_{E_V}\right)$	$\mathcal{G}^{\mathrm{DE}}_{\rho^-\pi^+}(\lvert T_V\rvert)$	$\mathcal{G}^{\mathrm{IC}}_{\rho^-\pi^+}(\lvert E_P\rvert)$	$\theta_{d\bar{d}}\left(\delta_{E_P}\right)$
Our works	8.05	$\backslash$	11.46 ± 0.04	180.0 ± 2.3	13.91	11.46	180.0 ± 2.3
TDA	3.58 ± 0.06	327^{+5}_{-4}	0.92 ± 0.04	92 ± 2	2.17 ± 0.03	1.65 ± 0.03	253 ± 3

- The relative phase between the DE and IC processes differs in our work and the TDA.
  - In our work, the relative phase between DE and IC is close to 180°, indicating a destructive interference.
  - While in TDA, the relative phase is around 90°, suggesting a more complex interference pattern.

Discussions

- The magnitudes of the DE and IC contributions in our work are larger than those in the TDA results, with the IC contribution being nearly an order of magnitude greater.
- The contribution of IC is comparable to that of DE, and for certain decay channels, the IC contribution is even larger.
  - The phase of the IC process is close to 180°, and $\mathcal{G}^{\rm IC}$ is approximately a real number.

$$\mathcal{G}^{\rm IC} \propto \sum_R \frac{g_R}{m_D^2 - m_R^2 + i m_R \Gamma_R} = \sum_R \frac{m_D^2 - m_R^2 - i m_R \Gamma_R}{(m_D^2 - m_R^2)^2 + (m_R \Gamma_R)^2} g_R$$

$$\mathrm{Im}\ \mathcal{G}^{\rm IC} \propto -\sum_R \frac{m_R \Gamma_R}{(m_D^2 - m_R^2)^2 + (m_R \Gamma_R)^2} g_R \sim 0\,.$$

The intermediate resonances contributing to the IC process are primarily low-width ground states.

- The total amplitude arises from the cancellation of large contributions from DE and IC.

04 | Summary

Summary and Outlook

Summary

- The six SCS decay channels of $D^0 \to VP$ have been studied within the framework of the quark model.
- The fitted branching ratios are in good agreement with experimental data.
- The DE contributions obtained from calculations and the IC contributions derived from fitting experimental data and compared to the results obtained via the TDA method through global fitting.
- IC contributions play a significant role in $D^0 \to VP$ processes.

Summary and Outlook

Outlook

- Explain the IC contributions in our work.
- Further studies on the remaining decay channels of $D^0 \to VP$ are needed.
- Analyze potential intermediate resonances that may contribute to the IC process.
- Investigate CP violation in $D^0 \to VP$ processes within the current theoretical framework.

Thanks for your attention!

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