Testing the molecular nature of $\phi(2170)$ (and K^* resonances with hidden charm)

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In collaboration with: Brenda B. Malabarba (University of São Paulo), Xiu-Lei Ren (University of Mainz), Kanchan P. Khemchandani (Federal University of São Paulo), Li-Sheng Geng (Beihang University)

INTRODUCTION

- $\phi(2170)$: observed by different collaborations (2006-2020) in processes like $e^+e^- \to K^+K^-\pi^{+(0)}\pi^{-(0)}, J/\psi \to \eta K^+K^-\pi^+\pi^-, e^+e^- \to \phi\eta'$ (PDG: $M = 2160 \pm 80$ MeV, $\Gamma = 125 \pm 65$ MeV)

- Different theoretical models trying to explain its nature and properties:

$s\bar{s}\,(n^{2S+1}L_J = 3^3S_1) \implies \Gamma \sim 300$ MeV

$s\bar{s}\,(2^3D_1) \implies \Gamma_{K^*(892)\bar{K}^*(892)}, \Gamma_{K^*(1410)\bar{K}} > \Gamma_{K(1460)\bar{K}}, \Gamma_{K_1(1400)\bar{K}}, \Gamma_{K_1(1270)\bar{K}}$

$s\bar{s}g \implies \Gamma_{K^*(1410)\bar{K}} \gtrsim \Gamma_{K_1(1270)\bar{K}}$, Mode $K(1460)\bar{K}$ forbidden (spin selection rule). Not supported by Lattice QCD and QCD Gaussian sum rules.

Tetraquark $\implies$ Difficulties in obtaining a compatible mass

BESIII collaboration (Phys. Rev. Lett. 124, 112001 (2020): $K^+(1460)K^-$, $K_1^+(1400)K^-$, $K^{*+}(1410)K^-$, $K_1^+(1270)K^-$, $K^{*+}(892)K^{*-}(892)$

1) Aubert et al., Phys. Rev. D74,091103(2006); Phys. Rev. D76, 012008(2007); 2) Ablikim et al., Phys. Rev. Lett, 100, 102003 (2008), Phys. Rev. D102, 012008 (2020); 3) Barnes et al., Phys. Rev. D68, 054014 (2003); 4) Ding and Yan, Phys. Lett. B657, 49(2007); Phys. Lett.B650, 390(2007); 5) Wang, Nucl. Phys. A791, 106(2007); 6) Dudek, Phys. Rev. D84, 074023 (2011);7) Ho et al., Phys. Rev. D100, 034012 (2019).

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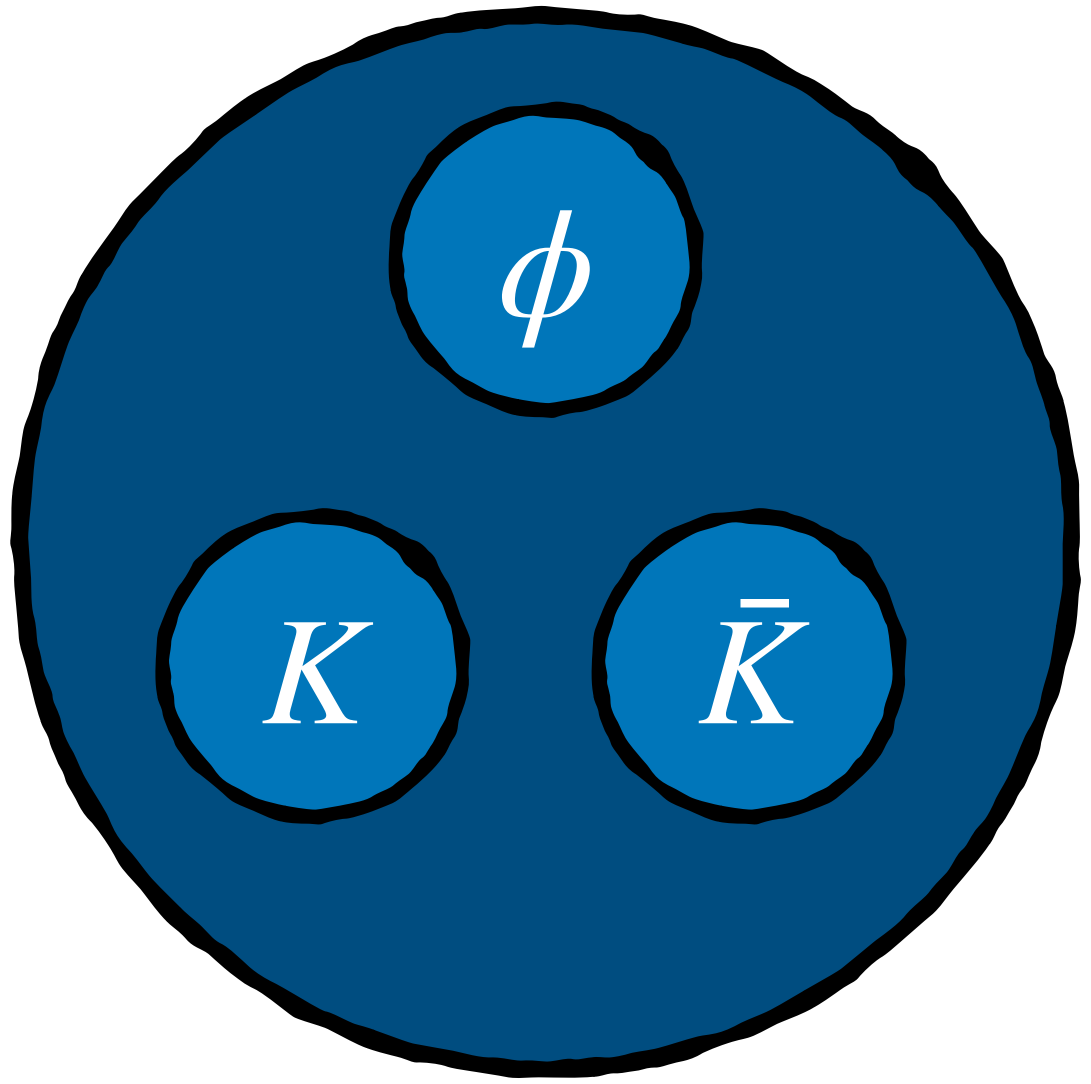
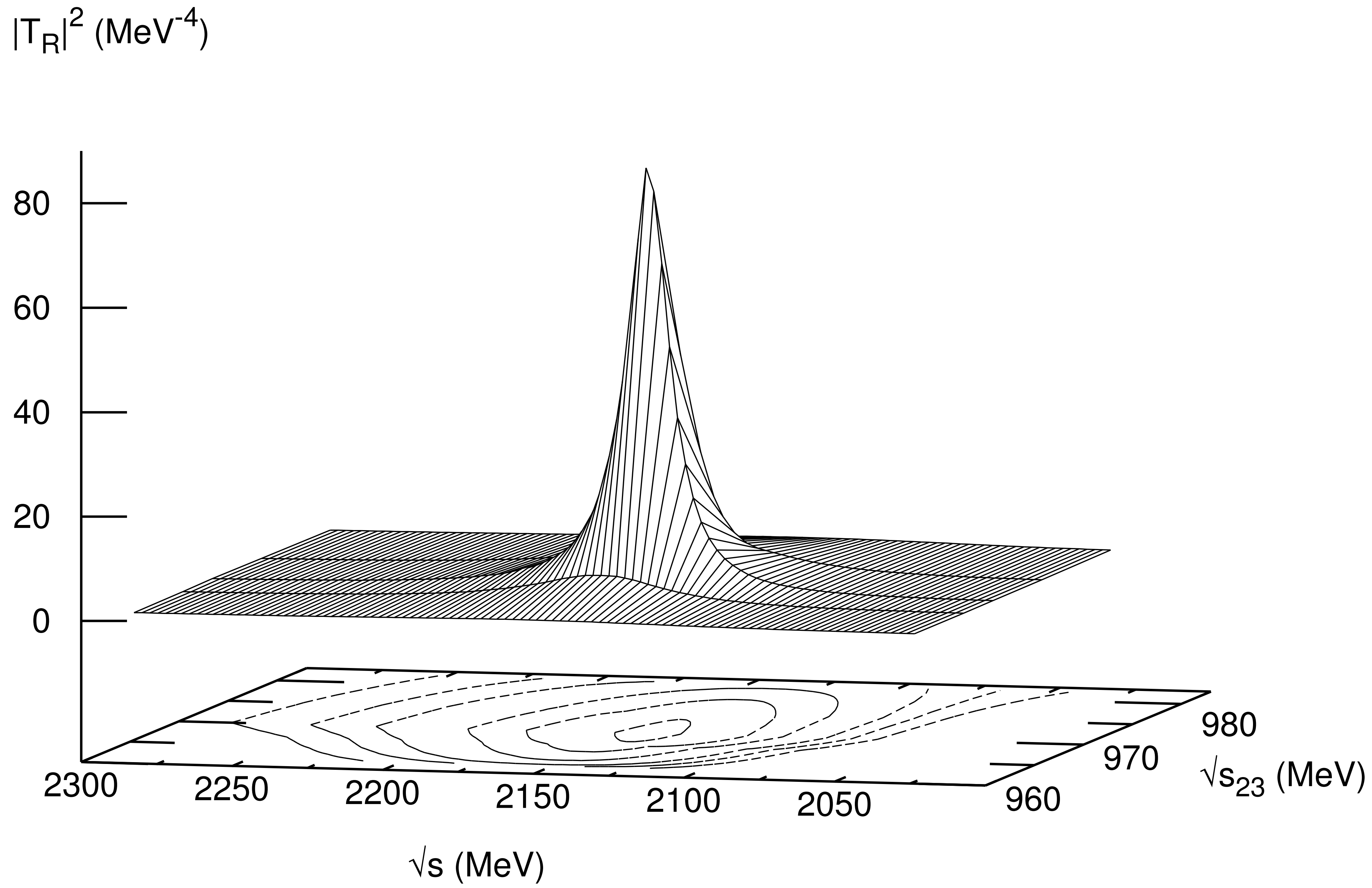
$\Longrightarrow$ Observed in the $\phi f_0(980)$ invariant mass distribution





8) A. Martínez Torres, K. P. Khemchandani, L. S. Geng, M. Napsuciale, E. Oset, Phys. Rev. D78, 074031 (2008); 9) M. Napsuciale, E. Oset, et al., Phys. Rev. D76, 074012 (2007). 10) J. A. Oller, E. Oset, Nucl. Phys. A620, 438 (1997); 11) L. Roca, E. Oset, J. Singh, Phys. Rev. D72, 014002 (2005); 12) L.S. Geng, E. Oset, L. Roca, J. A. Oller, Phys. Rev. D72, 014002 (2005).

INTRODUCTION

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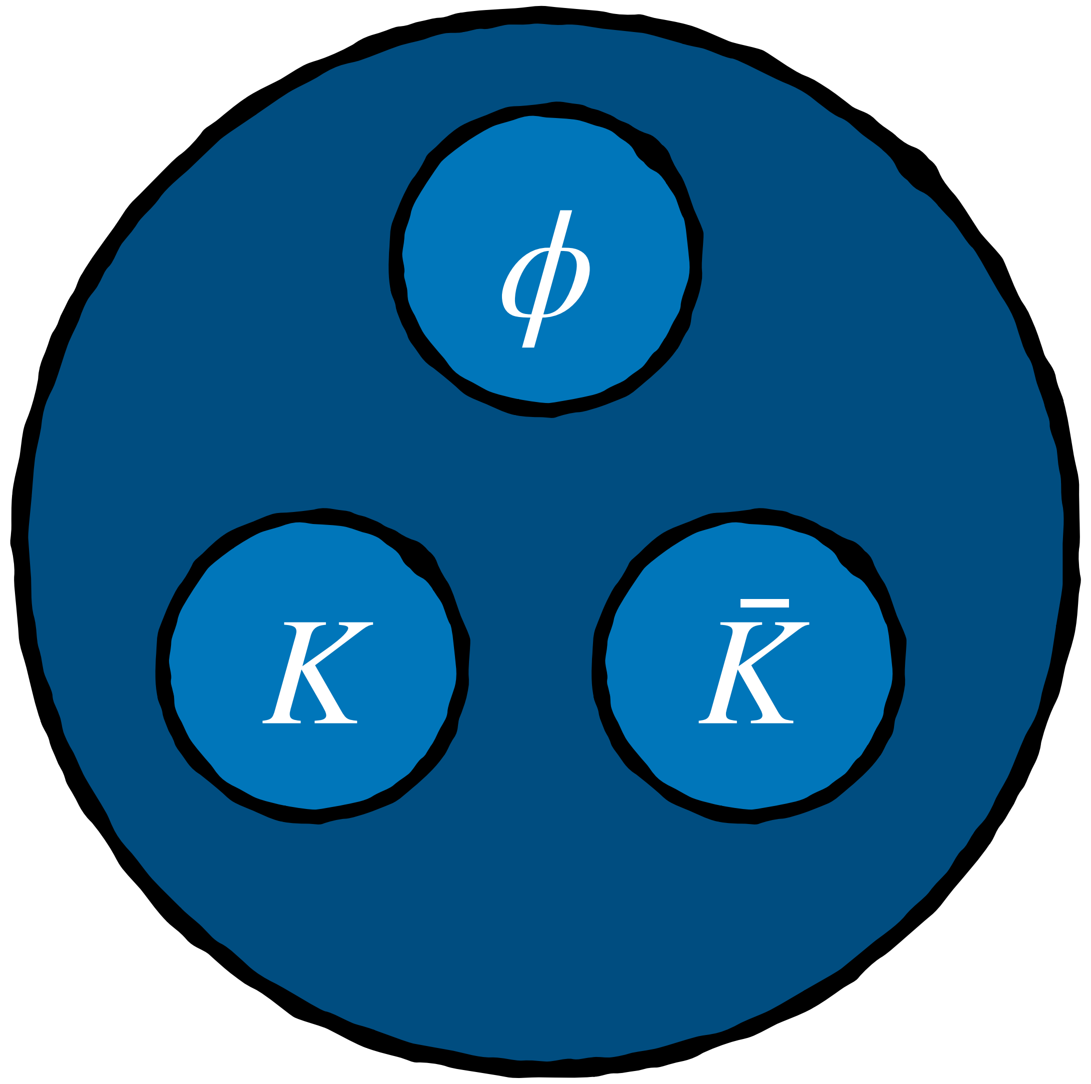
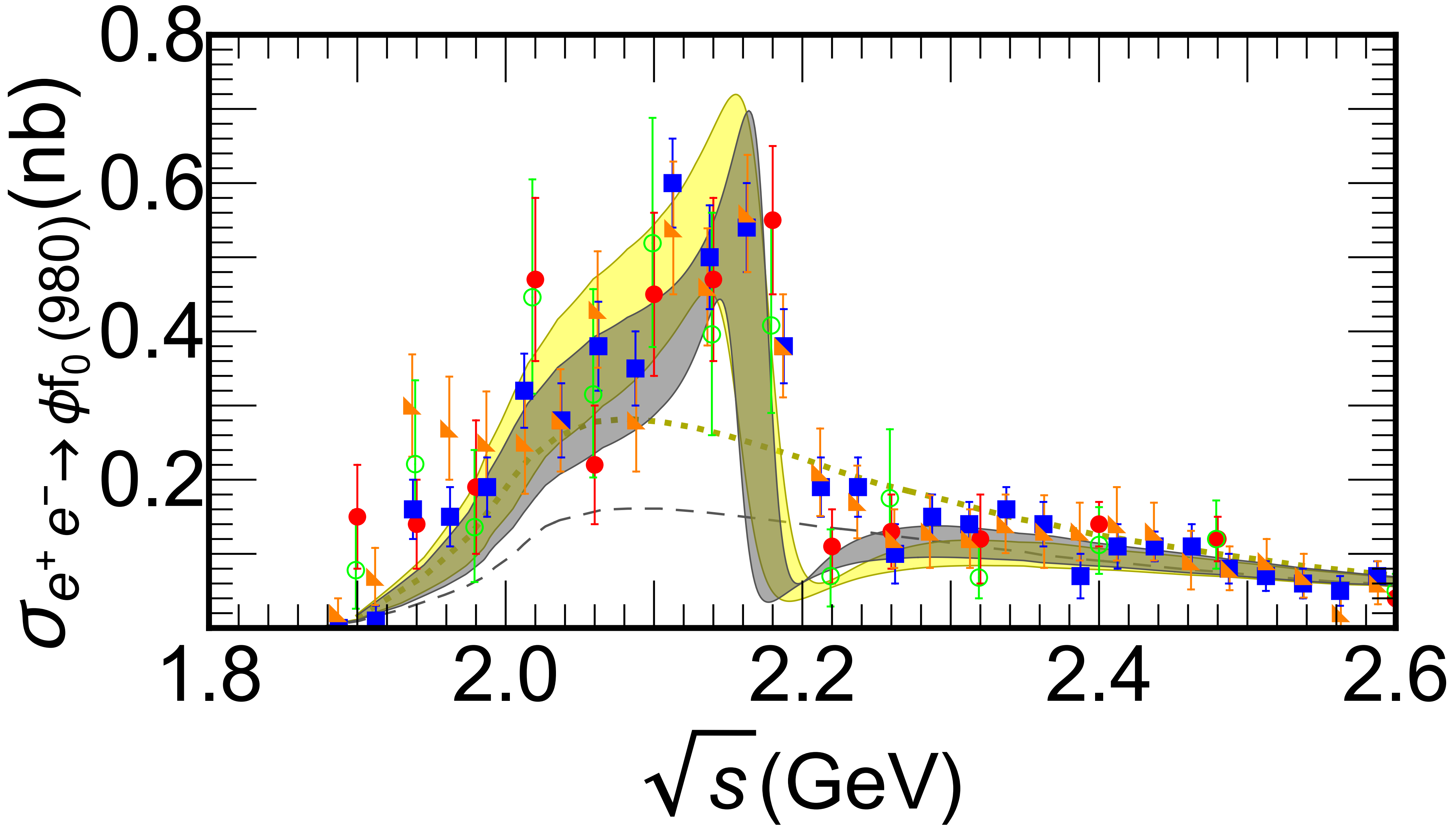


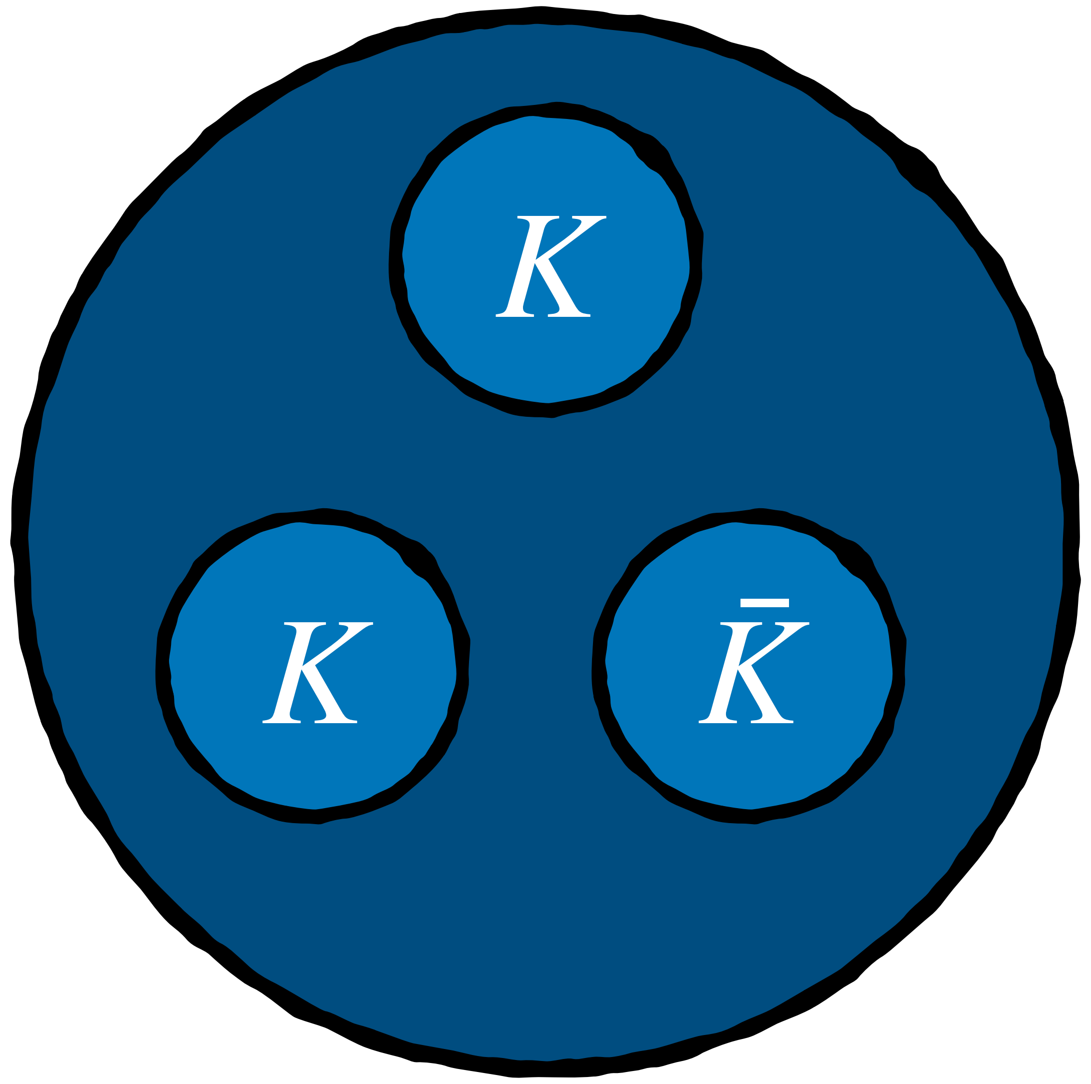


8) A. Martínez Torres, K. P. Khemchandani, L. S. Geng, M. Napsuciale, E. Oset, Phys. Rev. D78, 074031 (2008); 9) M. Napsuciale, E. Oset, et al., Phys. Rev. D76, 074012 (2007). 10) J. A. Oller, E. Oset, Nucl. Phys. A620, 438 (1997); 11) L. Roca, E. Oset, J. Singh, Phys. Rev. D72, 014002 (2005); 12) L.S. Geng, E. Oset, L. Roca, J. A. Oller, Phys. Rev. D72, 014002 (2005).

INTRODUCTION

- We have determined the decay width of $\phi(2170)$ to kaonic resonances: $K^+(1460)K^-$, $K_1^+(1400)K^-$, $K_1^+(1270)K^-$, $K^{*+}(892)K^{*-}(892)$.

$K(1460)$



$K_1(1270)$ & $K_1(1400)$

$\pi K^*(892), \phi K, \rho K \Longrightarrow K_1(1270)$, two poles

$z_1 = 1195 - i123$ MeV

$z_2 = 1284 - i73$ MeV

Mixing scheme $\Longrightarrow K_{1A}, K_{1B}$ belonging to the nonet of axials (mixing angles $29^\circ - 62^\circ$)

Phenomenological approach $\Longrightarrow$ Use of the data available in the PDG on their radiative decays

13) Brenda B. Malabarba, Xiu-Lei Ren, K. P. Khemchandani, A. Martínez Torres, Phys. Rev. D103, 016018 (2021); 14) A. Martínez Torres, D. Jido, Y. Kanada-En'yo; 15) Albaladejo, Oller, Roca, Phys. Rev. D82, 094019 (2010); 16) Shinmura, Hara, Yamada, JPS COnf. Proc, 26, 023003 (2019); 17) Filikhin, Kezerashvili, Suslov, et al., Phys. Rev. D102, 094027 (2020);18) Zhang, Hanhart, Meissner, Ju-Jun, arxiv: 2107.03168 [hep-ph]; 19) Palomar, Roca, Oset, Vacas, Nucl. Phys. A729, 743 (2003);

THE MODEL

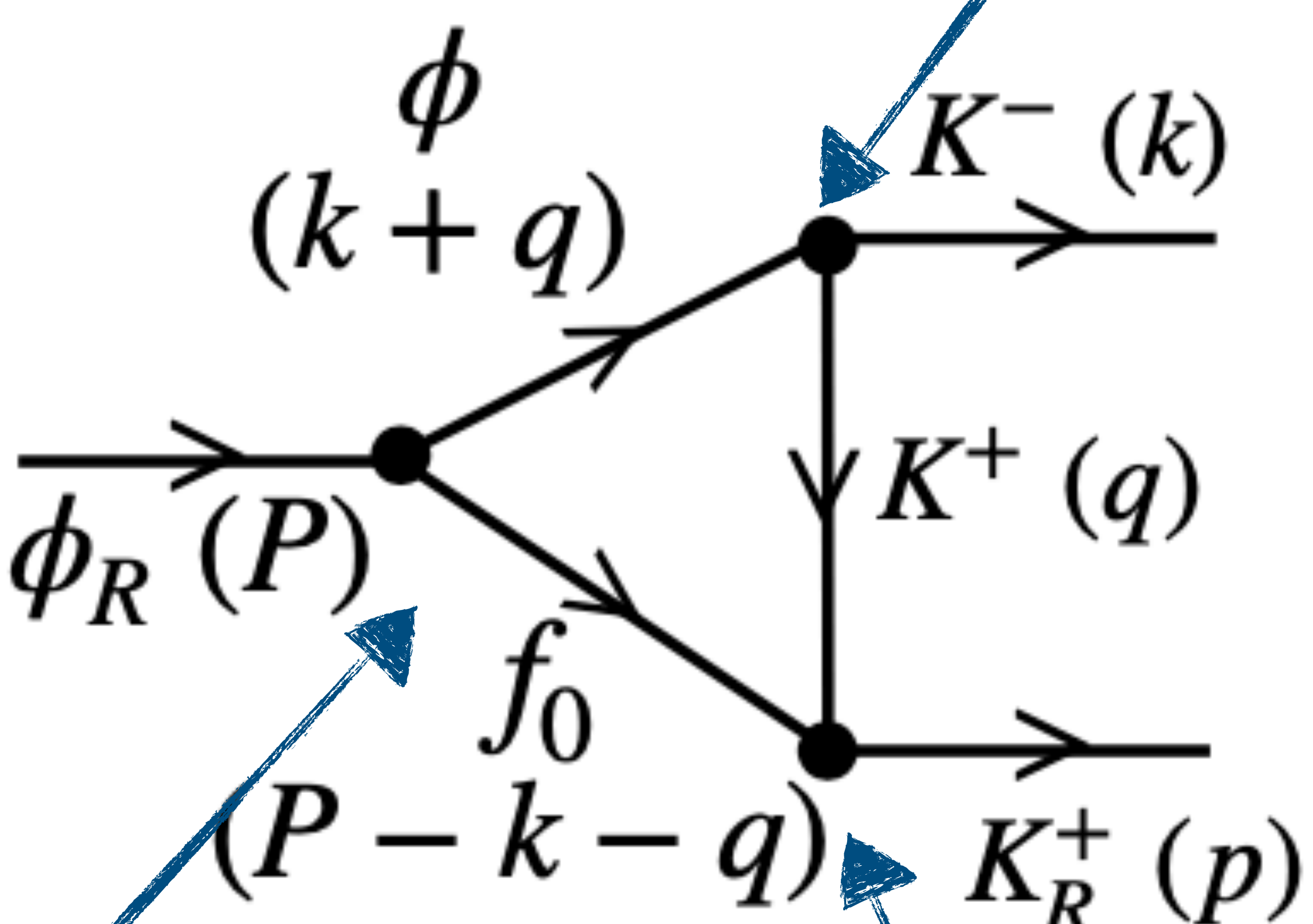
From $\mathscr{L}_{VPP} = -igV^{\mu}[\partial_{\mu}\Phi, \Phi]$,

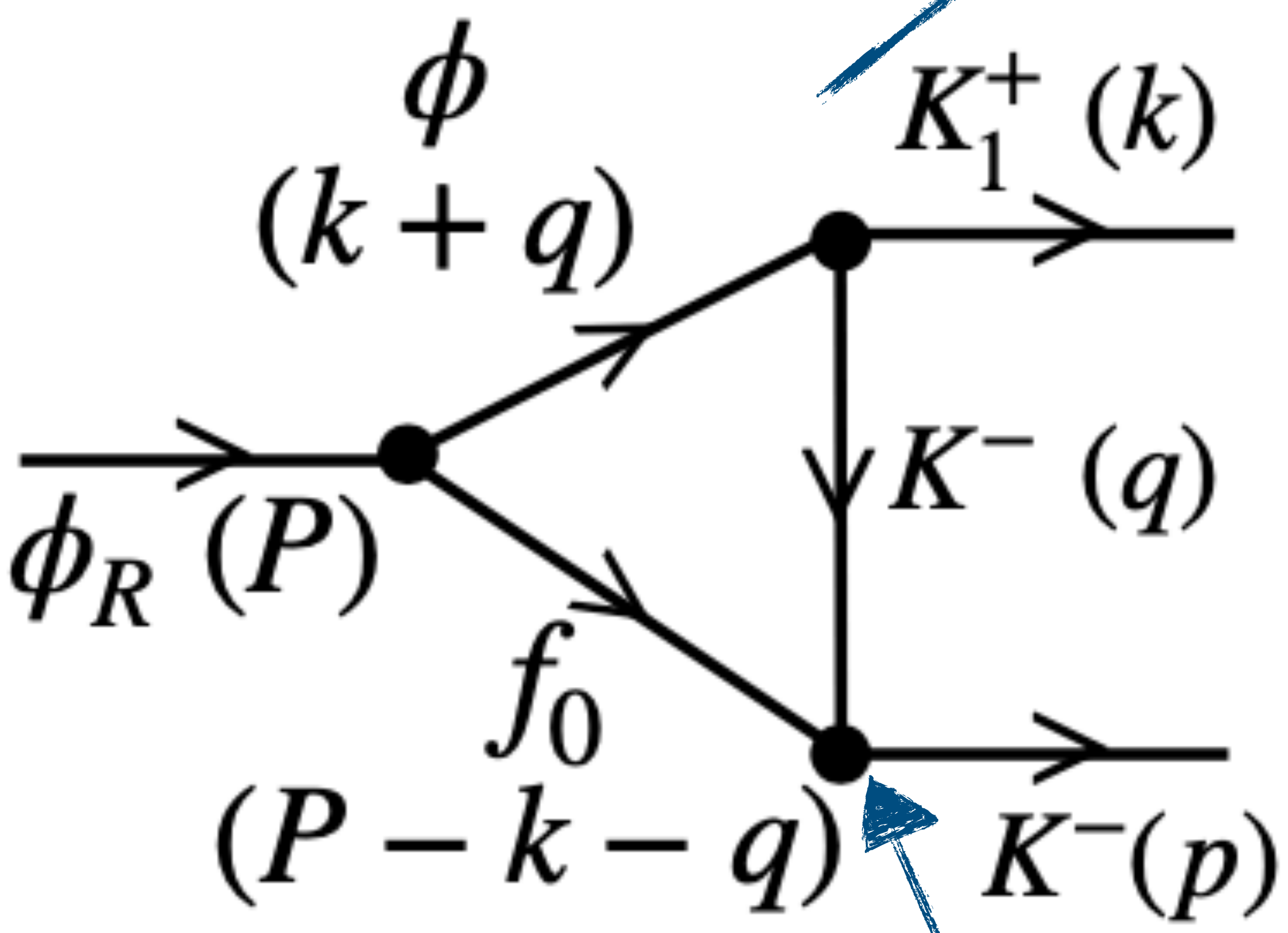
$V^{\mu} \equiv$ **Matrix vector meson octet fields**

$\Phi \equiv$ **Matrix pseudoscalar meson octet fields**

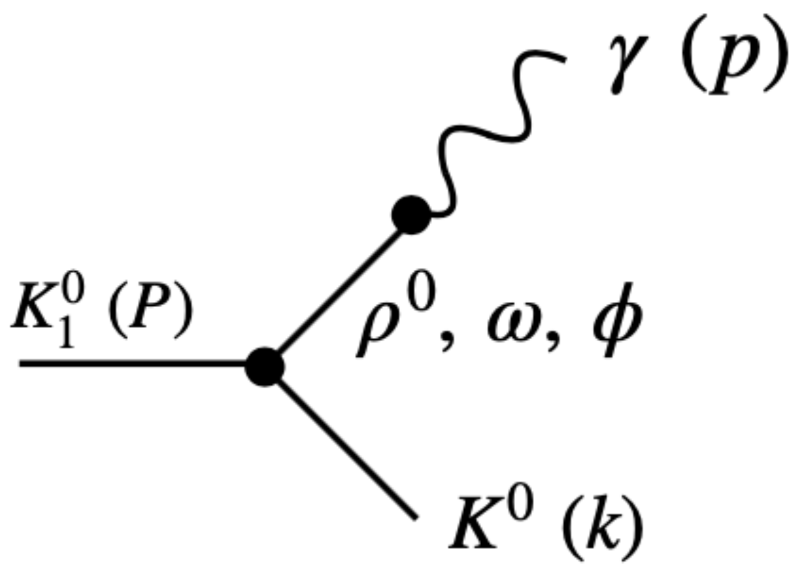
- Triangular loops:

$t_{K_1^+ \to \phi K^+} = g_{K_1^+ \to \phi K} \epsilon_{K_1^+} \cdot \epsilon_{\phi}$





1) $K_1(1270)$ **as a molecular state.**
2) $K_1(1270)$ & $K_1(1400)$ **as a mixture of** K_{1A}, K_{1B}.
3) **Phenomenological approach.**



$\phi(2170)$ **as a** $s-$**wave** $\phi f_0(980)$ **state:**

$t_{\phi_R} = g_{\phi_R \to \phi f_0} \epsilon_{\phi_R} \cdot \epsilon_{\phi}$

$K(1460)$ **couples to** $Kf_0(980)/Ka_0(980)$ **in** $s-$**wave:**

$t_{\phi_R} = g_{K_R^+ \to K^+ f_0}$

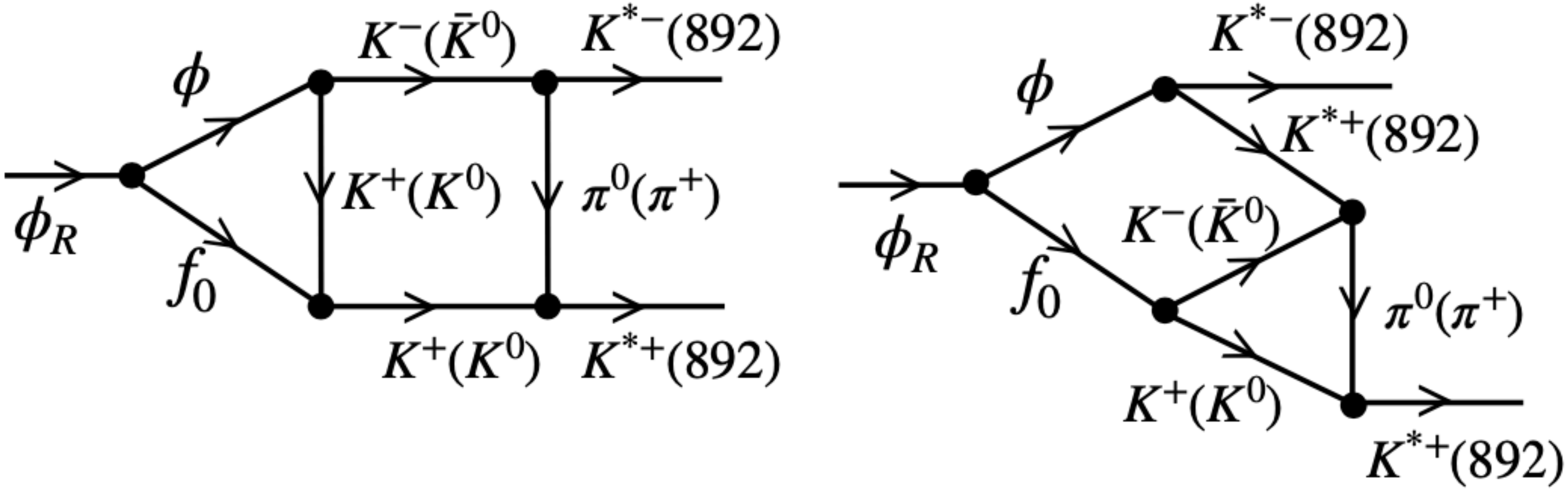
$f_0(980)$ **as a** $s-$**wave** $K\bar{K}, \pi\pi$ **state:**

$t_{f_0 \to K^+K^-} = g_{f_0 \to K^+K^-}$

20) Brenda B. Malabarba, Xiu-Lei Ren, K. P. Khemchandani, A. Martínez Torres, Phys. Rev. D103, 016018 (2021)

RESULTS

- BESIII collaboration: $\phi(2170) \to K^*(892)\bar{K}^*(892)$ is suppressed



RESULTS

Larger coupling to πK^*

Mass closer to 1270 MeV

$\phi(2170) \to K^+(1460)K^-$

Form factor	Decay width
Heaviside-Θ	1.5 ± 0.5
Monopole	1.3 ± 0.4
Exponential	1.3 ± 0.5

$\phi(2170) \to K_1^+(1270)K^-$

Form factor	Decay width						
	Model A			Model B	Model C		
	Poles z_1, z_2	Pole z_1	Pole z_2		Solution $\mathbb{S}_1$	Solution $\mathbb{S}_2$	Solution $\mathbb{S}_3$
Heaviside-Θ	1.5 ± 0.3	0.6 ± 0.1	0.22 ± 0.04	0.12 ± 0.04	1.6 ± 0.4	17 ± 3	41 ± 9
Monopole	0.8 ± 0.2	0.3 ± 0.1	0.12 ± 0.02	0.07 ± 0.02	0.9 ± 0.2	9 ± 2	23 ± 5
Exponential	1.0 ± 0.2	0.4 ± 0.1	0.15 ± 0.03	0.09 ± 0.02	1.1 ± 0.3	11 ± 2	28 ± 6

$\phi(2170) \to K_1^+(1400)K^-$

Form factor	Decay width	
	Model B	Model C
Heavise-Θ	2.6 ± 0.5	15 ± 4
Monopole	1.9 ± 0.4	11 ± 3
Exponential	2.1 ± 0.4	12 ± 3

Sizeable contributions

Model A: Molecular model for $K_1(1270)$

Model B: Mixing angle

Model C: Phenomenological (radiative decays)

RESULTS

- BESIII collaboration: $\mathscr{B}r\Gamma_R^{e^+e^-}$

$$\mathscr{B}r \equiv \text{Branching fraction } \phi(2170) \to RK^-$$

$$\Gamma_R^{e^+e^-} \equiv \text{Partial decay width of } \phi(2170) \to e^+e^-$$

$$B_1 \equiv \frac{\Gamma_{\phi_R \to K^+(1460)K^-}}{\Gamma_{\phi_R \to K_1^+(1400)K^-}} = \frac{\mathcal{B}r[\phi_R \to K^+(1460)K^-]}{\mathcal{B}r[\phi_R \to K_1^+(1400)K^-]}$$

$$B_2 \equiv \frac{\Gamma_{\phi_R \to K^+(1460)K^-}}{\Gamma_{\phi_R \to K_1^+(1270)K^-}} = \frac{\mathcal{B}r[\phi_R \to K^+(1460)K^-]}{\mathcal{B}r[\phi_R \to K_1^+(1270)K^-]}$$

$$B_3 \equiv \frac{\Gamma_{\phi_R \to K_1^+(1270)K^-}}{\Gamma_{\phi_R \to K_1^+(1400)K^-}} = \frac{\mathcal{B}r[\phi_R \to K_1^+(1270)K^-]}{\mathcal{B}r[\phi_R \to K_1^+(1400)K^-]}$$

$$\mathcal{B}r[\phi_R \to K^+(1460)K^-]\Gamma_R^{e^+e^-} = 3.0 \pm 3.8,$$

$$\mathcal{B}r[\phi_R \to K_1^+(1400)K^-]\Gamma_R^{e^+e^-} = \begin{cases} 4.7 \pm 3.3, & \text{Solution 1} \\ 98.8 \pm 7.8, & \text{Solution 2} \end{cases},$$

$$\mathcal{B}r[\phi_R \to K_1^+(1270)K^-]\Gamma_R^{e^+e^-} = \begin{cases} 7.6 \pm 3.7, & \text{Solution 1} \\ 152.6 \pm 14.2, & \text{Solution 2} \end{cases},$$

RESULTS

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$$B_1^{\text{exp}} = \begin{cases} 0.64 \pm 0.92, & \text{Solution 1,} \\ 0.03 \pm 0.04, & \text{Solution 2,} \end{cases}$$

$$B_2^{\text{exp}} = \begin{cases} 0.40 \pm 0.54, & \text{Solution 1,} \\ 0.02 \pm 0.03, & \text{Solution 2,} \end{cases}$$

$$B_3^{\text{exp}} = \begin{cases} 1.62 \pm 1.38, & \text{Solution 1,} \\ 1.55 \pm 0.19, & \text{Solution 2.} \end{cases}$$

RESULTS

$$B_1^{\rm exp} = \begin{cases} 0.64 \pm 0.92, & \text{Solution 1}, \\ 0.03 \pm 0.04, & \text{Solution 2}, \end{cases}$$

$$B_2^{\rm exp} = \begin{cases} 0.40 \pm 0.54, & \text{Solution 1}, \\ 0.02 \pm 0.03, & \text{Solution 2}, \end{cases}$$

$$B_3^{\rm exp} = \begin{cases} 1.62 \pm 1.38, & \text{Solution 1}, \\ 1.55 \pm 0.19, & \text{Solution 2}. \end{cases}$$

$$B_1 = \frac{\Gamma_{\phi_R \to K^+(1460)K^-}}{\Gamma_{\phi_R \to K_1^+(1400)K^-}} \qquad B_2 = \frac{\Gamma_{\phi_R \to K^+(1460)K^-}}{\Gamma_{\phi_R \to K_1^+(1270)K^-}}$$

$$B_3 = \frac{\Gamma_{\phi_R \to K^+(1270)K^-}}{\Gamma_{\phi_R \to K_1^+(1400)K^-}}$$

	B_1
Model B	0.62 ± 0.20
Model C	0.11 ± 0.04

	B_2	
	1.3 ± 0.4	(Poles z_1, z_2)
Model A	3.6 ± 1.2	(Pole z_1)
	8.8 ± 2.8	(Pole z_2)
Model B	16 ± 6	
	1.2 ± 0.4	(Solution $\mathbb{S}_1$)
Model C	0.12 ± 0.04	(Solution $\mathbb{S}_2$)
	0.05 ± 0.02	(Solution $\mathbb{S}_3$)

	B_3	
Model B	0.04 ± 0.01	
	0.09 ± 0.02	(Solution $\mathbb{S}_1$)
Model C	0.96 ± 0.16	(Solution $\mathbb{S}_2$)
	2.40 ± 0.40	(Solution $\mathbb{S}_3$)

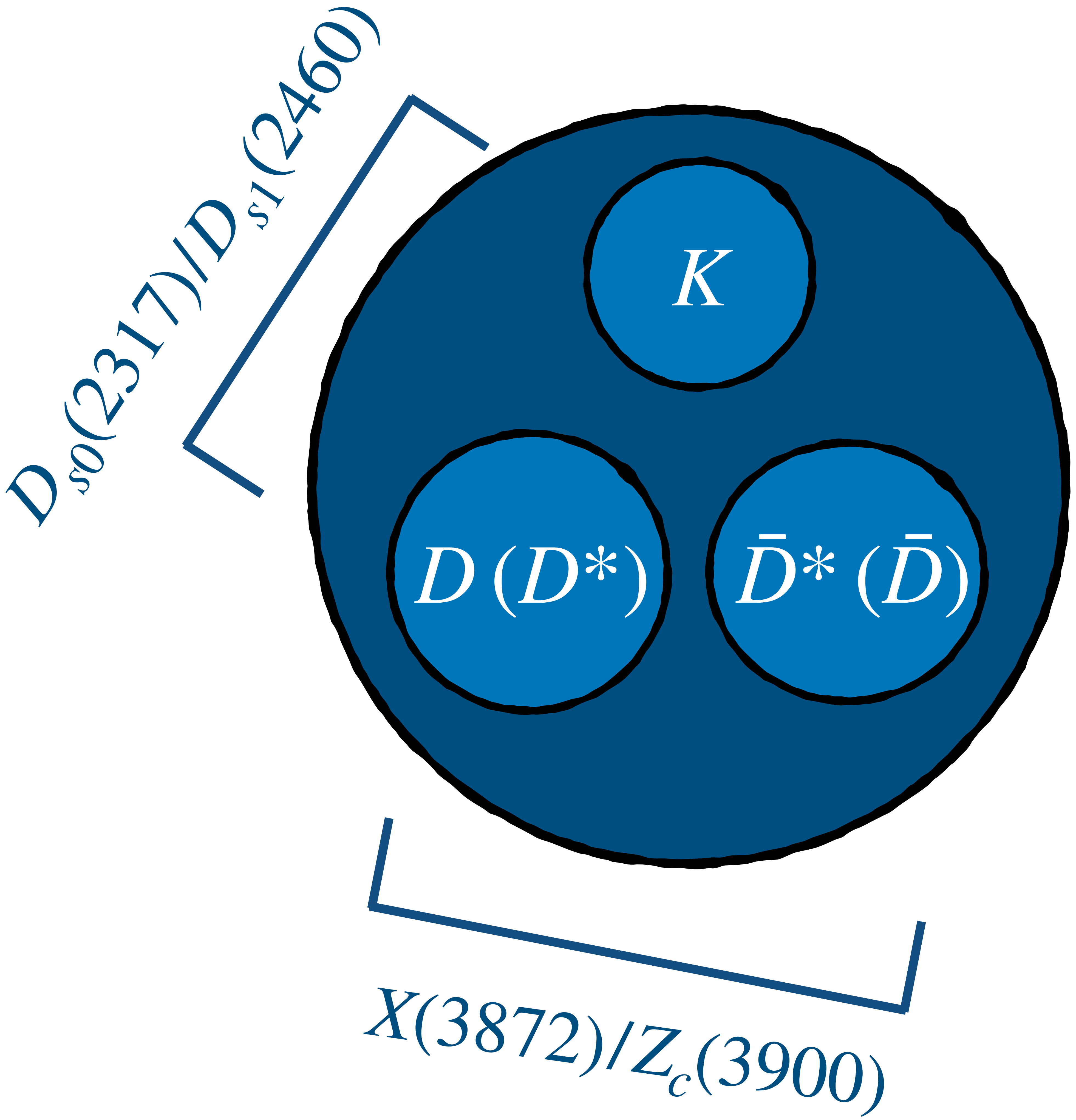
Model A: Molecular model for $K_1(1270)$

Model B: Mixing scheme

Model C: Phenomenological (radiative decays)

RESULTS K^*

More details in the talk of Brenda B. Malabarba, Thursday 12:40 (Exotic hadrons and candidates)



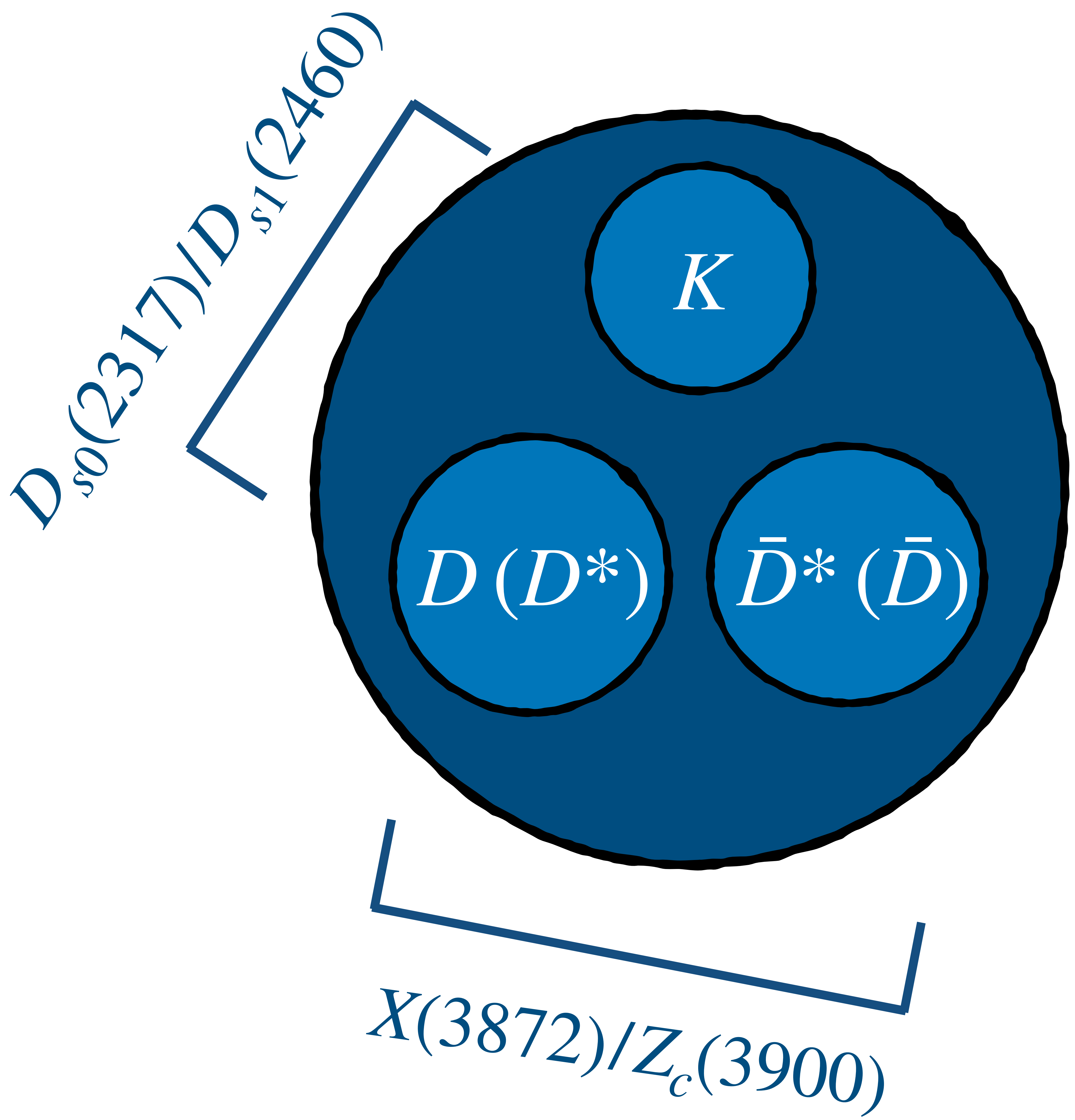
PDG Live

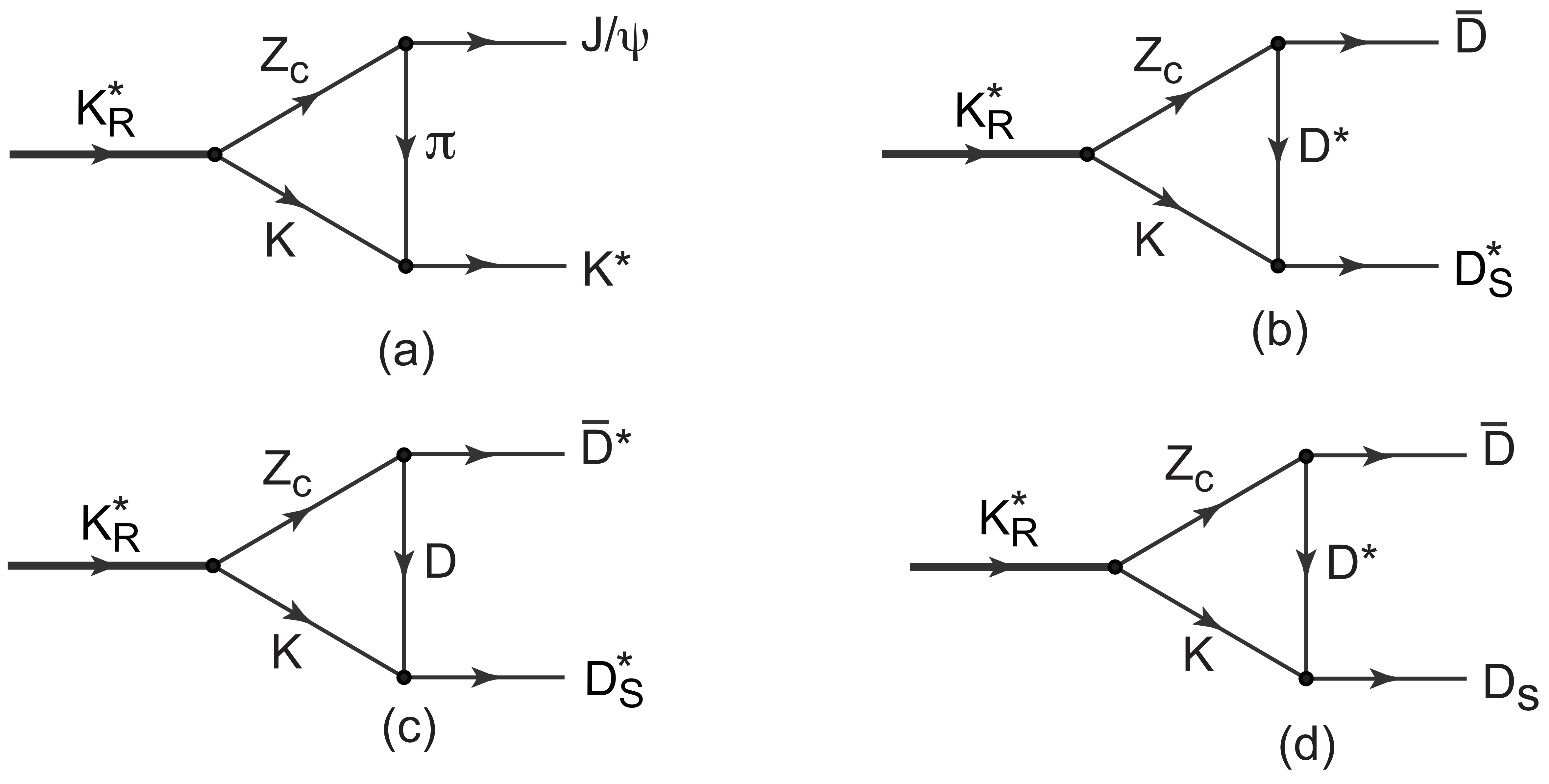
•	$K^*(1680)$	$1/2(1^-)$
•	$K_2(1770)$	$1/2(2^-)$
•	$K_3^*(1780)$	$1/2(3^-)$
•	$K_2(1820)$	$1/2(2^-)$
	$K(1830)$	$1/2(0^-)$
	$K_0^*(1950)$	$1/2(0^+)$
•	$K_2^*(1980)$	$1/2(2^+)$
•	$K_4^*(2045)$	$1/2(4^+)$
	$K_2(2250)$	$1/2(2^-)$
	$K_3(2320)$	$1/2(3^+)$
	$K_5^*(2380)$	$1/2(5^-)$
	$K_4(2500)$	$1/2(4^-)$
	$K(3100)$	$?^?(?^{??})$

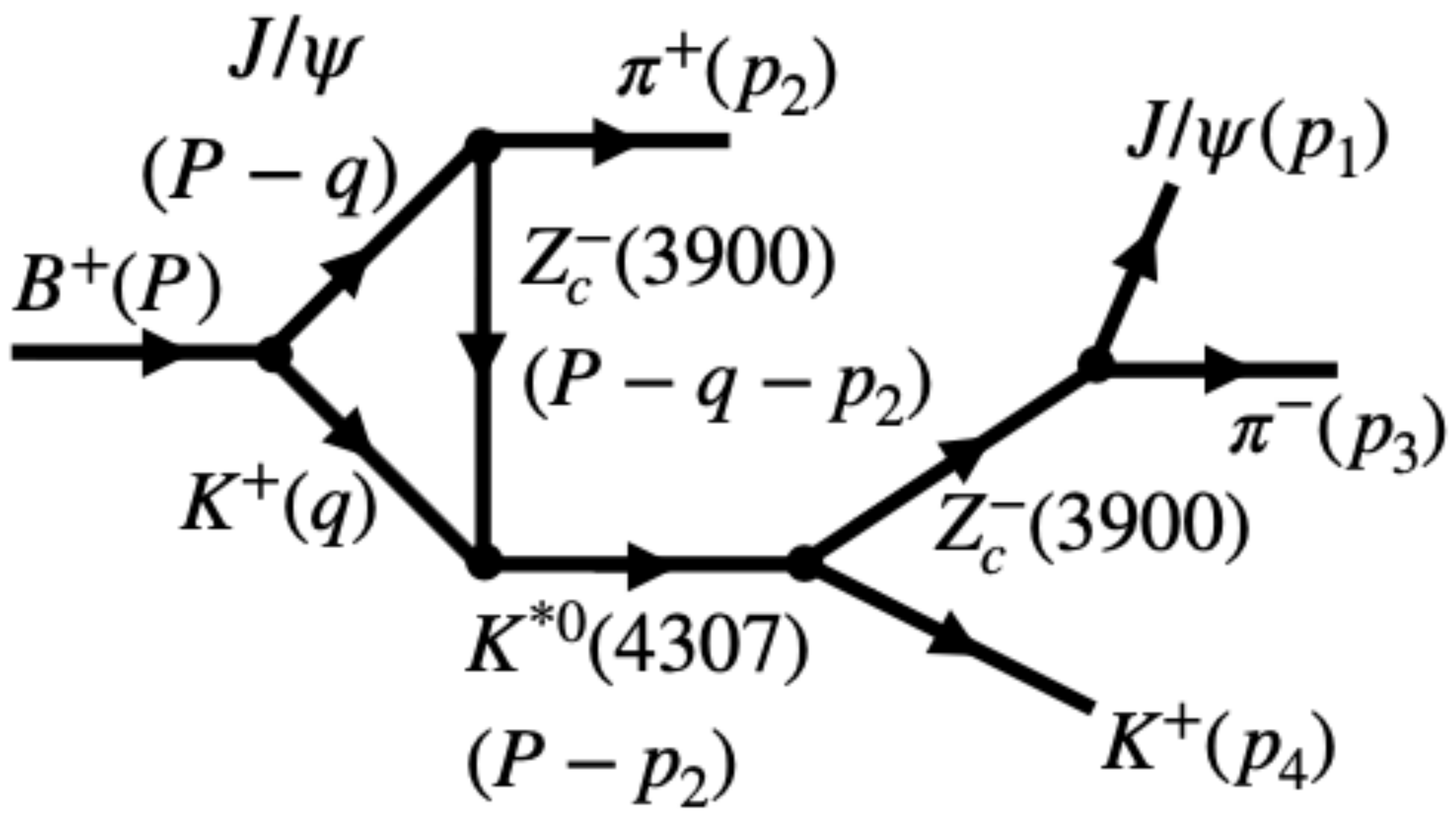
We find a narrow $K^*(4307)$

21) Xiu-Lei Ren, Brenda B. Malabarba, Li-Sheng Geng, K. P. Khemchandani, A. Martínez Torres, Phys. Lett. B785, 112-117 (2018); Xiu-Lei Ren, K. P. Khemchandani, A. Martínez Torres, JHEP 05, 103 (2019) and Phys. Rev. D102, 016005 (2020).

RESULTS K^*







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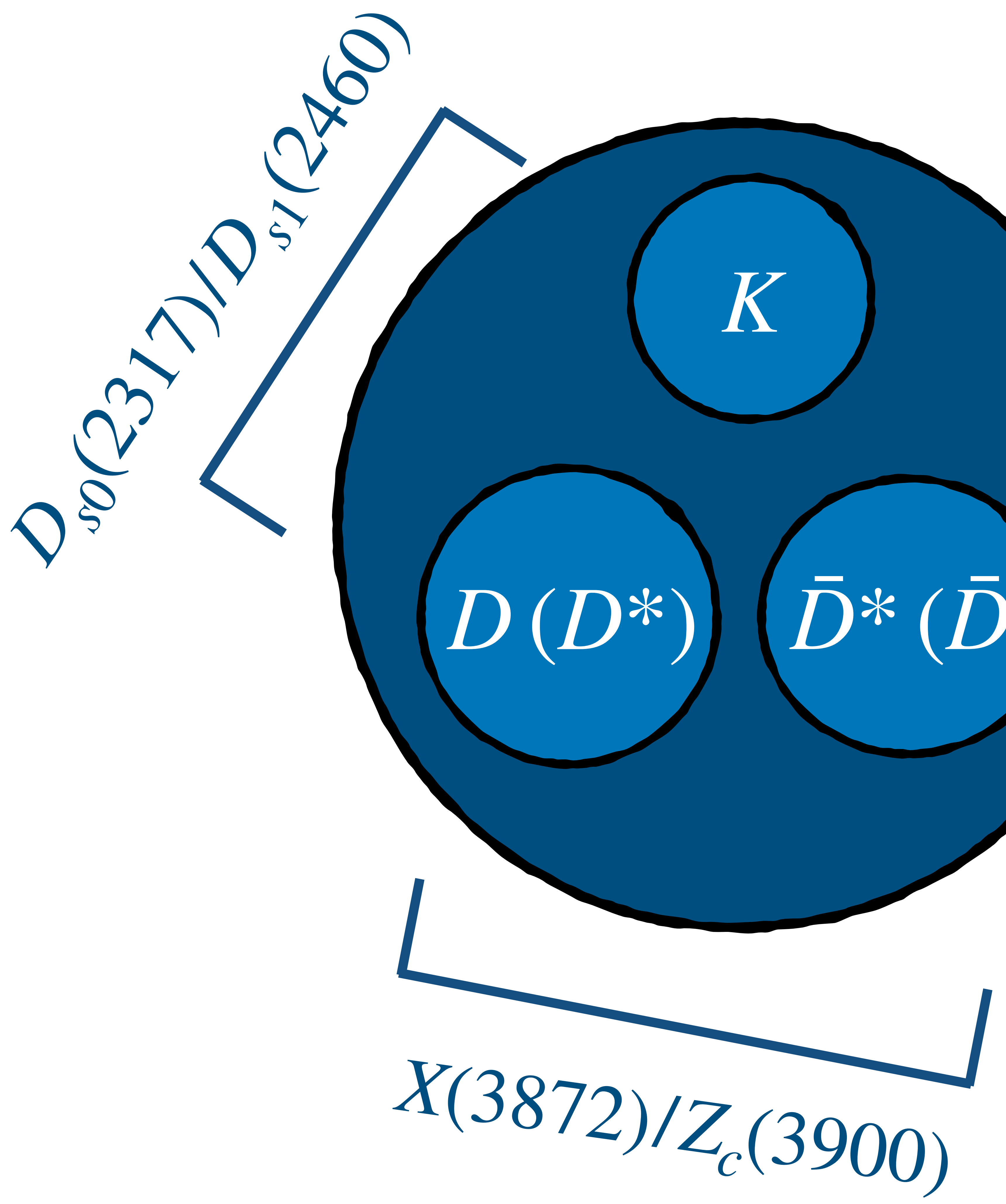
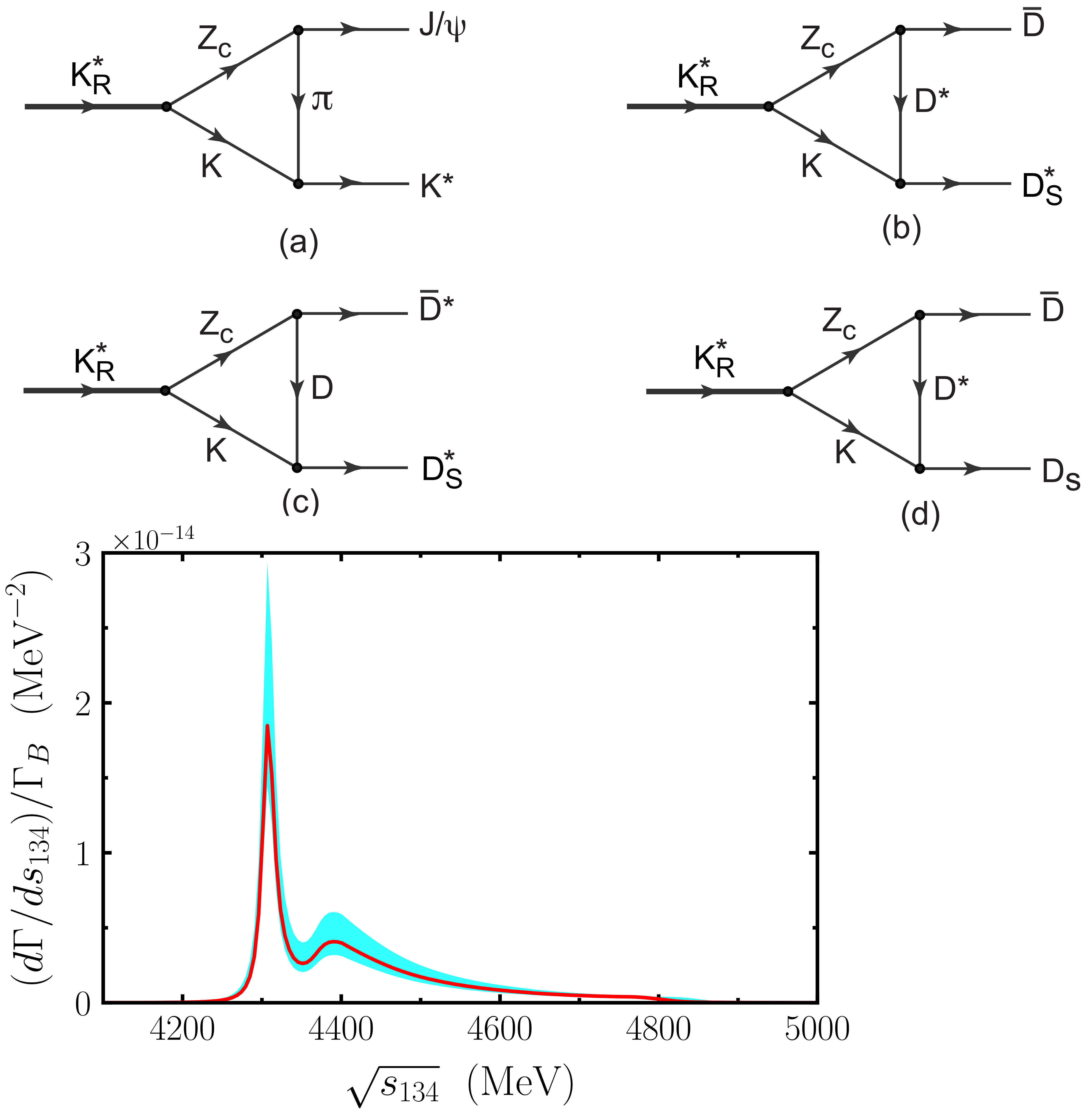
RESULTS K^*





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CONCLUSIONS

- $\phi(2170)$ as a $\phi f_0(980)$ state:

  - Explains its suppressed decay to $K*(892)\bar{K}*(892)$.

  - $K(1460)$ as a state which couples to Kf_0, $K_1(1400)$ mixing angle scheme/ phenomenological approach: compatible results for $B_1 = \frac{\Gamma_{\phi_R \to K^+(1460)K^-}}{\Gamma_{\phi_R \to K_1^+(1400)K^-}}$.

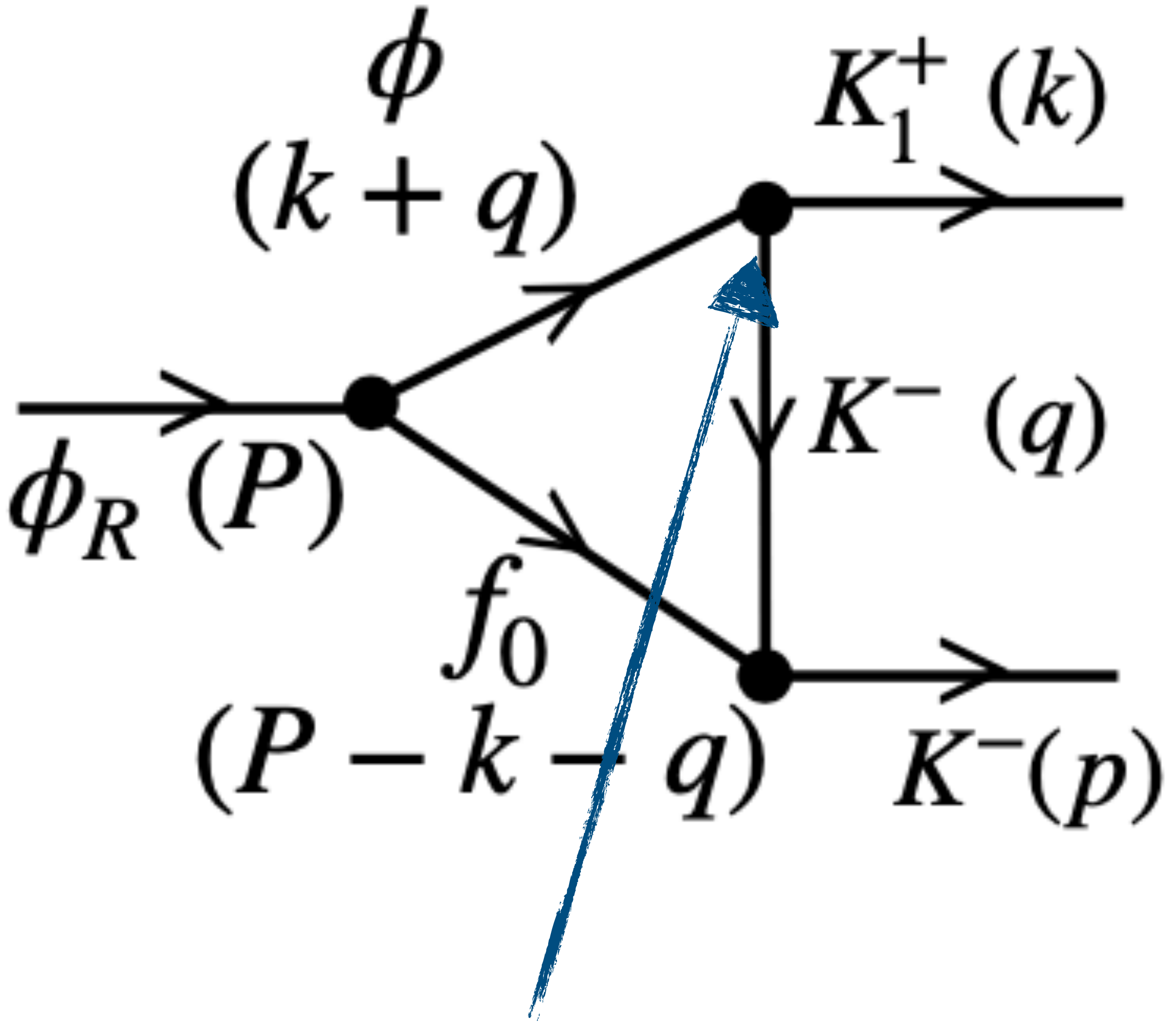
  - $K_1(1270)$ as state related to two poles arising from PV dynamics/ phenomenological approach for $K_1(1270)$ & $K_1(1400)$. Compatible results for $B_2 = \frac{\Gamma_{\phi_R \to K^+(1460)K^-}}{\Gamma_{\phi_R \to K_1^+(1270)K^-}}$. The mixing scheme considered for $K_1(1270)$ & $K_1(1400)$ is not compatible.

  - The ratio $B_3 = \frac{\Gamma_{\phi_R \to K^+(1270)K^-}}{\Gamma_{\phi_R \to K_1^+(1400)K^-}}$ is compatible with the mixing scheme/phenomenological approach.

- K^* resonance with hidden charm is predicted around 4307 MeV (also found by Ma, Wang, Meissner in Chin. Phys. C43, 014102 (2019) and by Tian-Wei Wu, Ming-Zhu Liu, Li-Sheng Geng in Phys. Rev. D103,3 (2021))

BACKUP SLIDES: SOME MORE DETAILS OF THE MODEL

- Triangular loops:



$t_{K_1^+ \to \phi K^+} = g_{K_1^+ \to \phi K} \epsilon_{K_1^+} \cdot \epsilon_\phi$

$K_1(1270)$ & $K_1(1400)$ as mixed states: K_{1A}, K_{1B}

- Tensor meson formalism for the vector mesons (rank 2)

- Couplings of $K_1(1270)$ & $K_1(1400)$ to ϕK are obtained

$$\Longrightarrow \quad \Gamma^T_{K_1^+ \to \phi K^+} = \frac{|g^T_{K_1^+ \to \phi K^+}|^2}{2\pi} \frac{1}{\mathcal{N}} \int_{M_{K_1} - a\Gamma_{K_1}}^{M_{K_1} + a\Gamma_{K_1}} d\tilde{M}_{K_1} (2\tilde{M}_{K_1}) \frac{|\vec{p}|}{\tilde{M}^2_{K_1}} \left[1 + \frac{2}{3} \frac{|\vec{p}|}{M^2_\phi}\right]$$

$$\times \operatorname{Im}\left[\frac{1}{\tilde{M}^2_{K_1} - M^2_{K_1} + iM_{K_1}\Gamma_{K_1}}\right] \theta(\tilde{M}_{K_1} - M_\phi - M_K)\theta(\tilde{M}_{K_1} - M_\pi - M_{K^*(892)})$$

$$\Gamma_{K_1^+ \to \phi K^+} = \frac{|g_{K_1^+ \to \phi K^+}|^2}{24\pi} \frac{1}{\mathcal{N}} \int_{M_{K_1} - a\Gamma_{K_1}}^{M_{K_1} + a\Gamma_{K_1}} d\tilde{M}_{K_1} (2\tilde{M}_{K_1}) \frac{|\vec{p}|}{\tilde{M}^2_{K_1}} \left[3 + \frac{|\vec{p}|^2}{M^2_\phi}\right]$$

$$\times \operatorname{Im}\left[\frac{1}{\tilde{M}^2_{K_1} - M^2_{K_1} + iM_{K_1}\Gamma_{K_1}}\right] \theta(\tilde{M}_{K_1} - M_\phi - M_K)\theta(\tilde{M}_{K_1} - M_\pi - M_{K^*(892)})$$

18) Palomar, Roca, Oset, Vacas, Nucl. Phys. A729, 743 (2003)

BACKUP SLIDES: SOME MORE DETAILS OF THE MODEL

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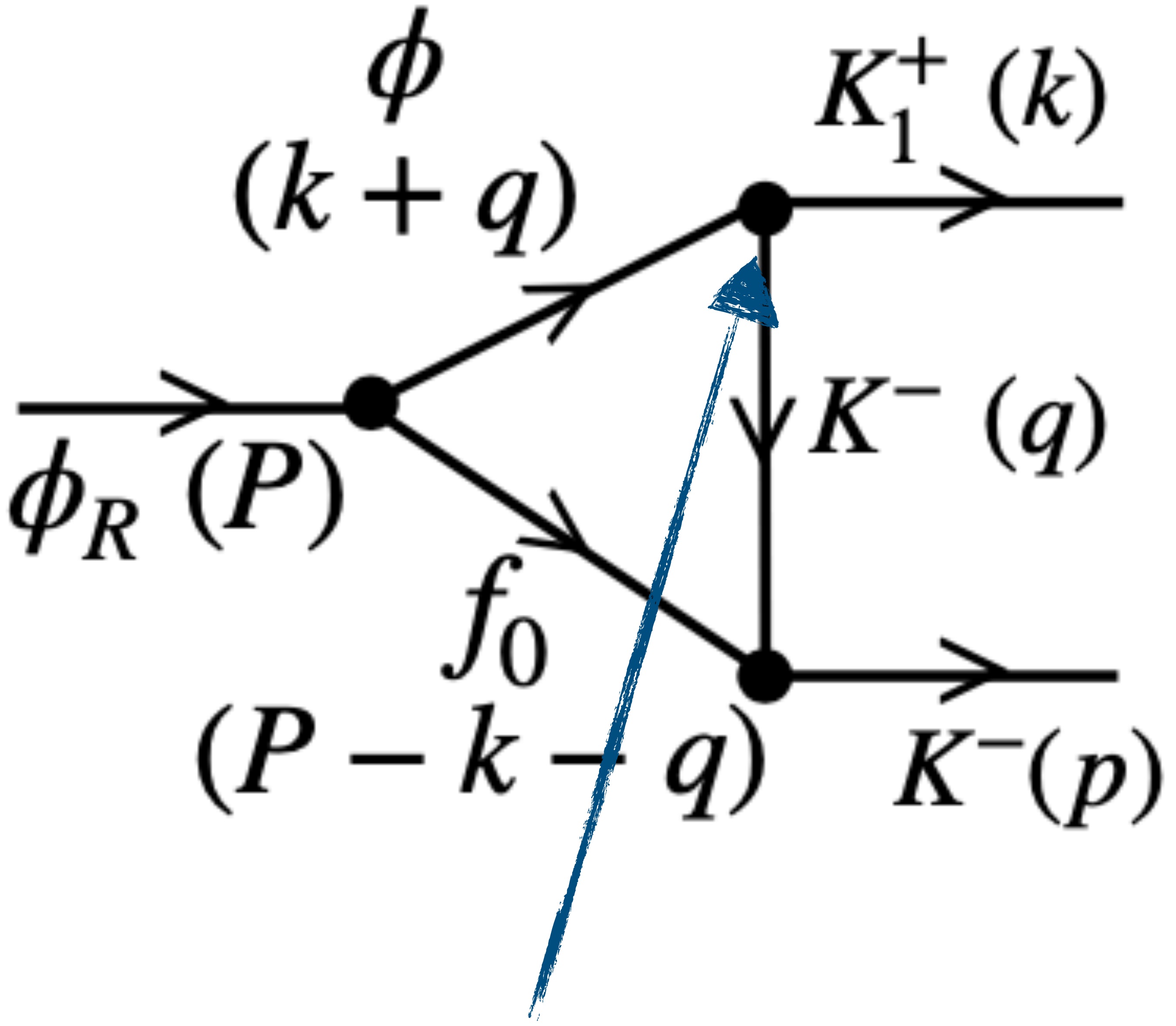
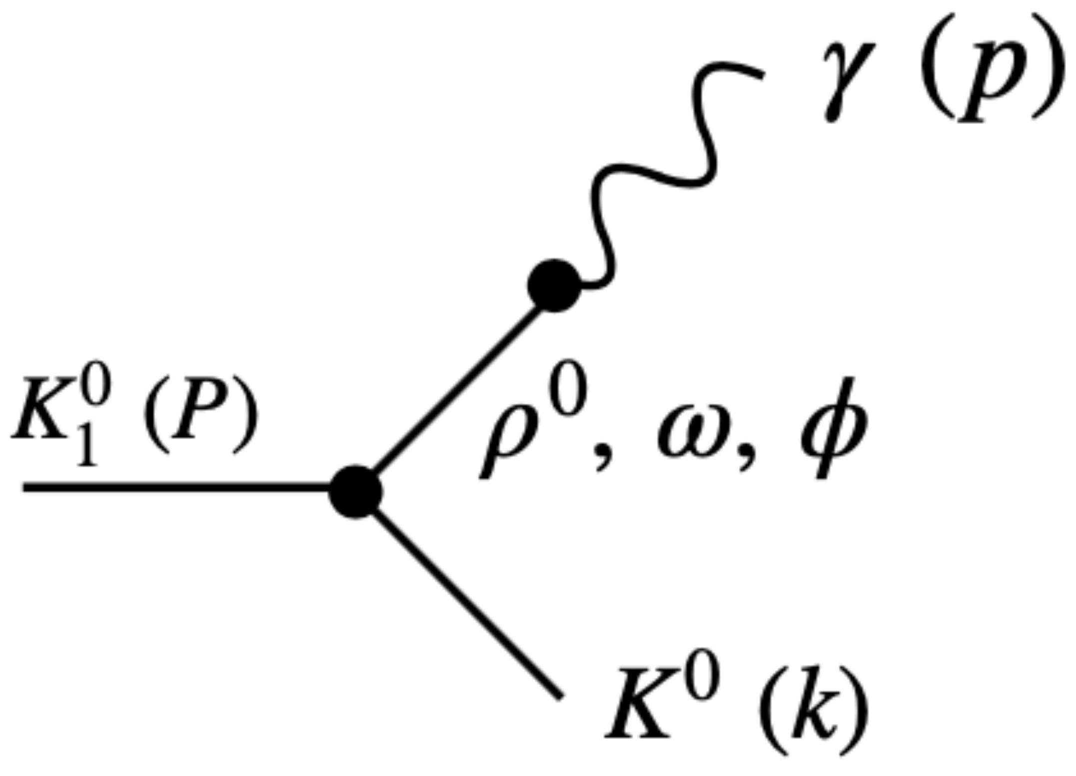


$$t_{K_1^+\to\phi K^+} = g_{K_1^+\to\phi K}\epsilon_{K_1^+}\cdot\epsilon_\phi$$

Phenomenological approach for $K_1(1270)$ & $K_1(1400)$:

- Available data on the radiative decays
- Vector meson dominance: Couplings of $K_1(1270)$ & $K_1(1400)$ to ϕK are obtained



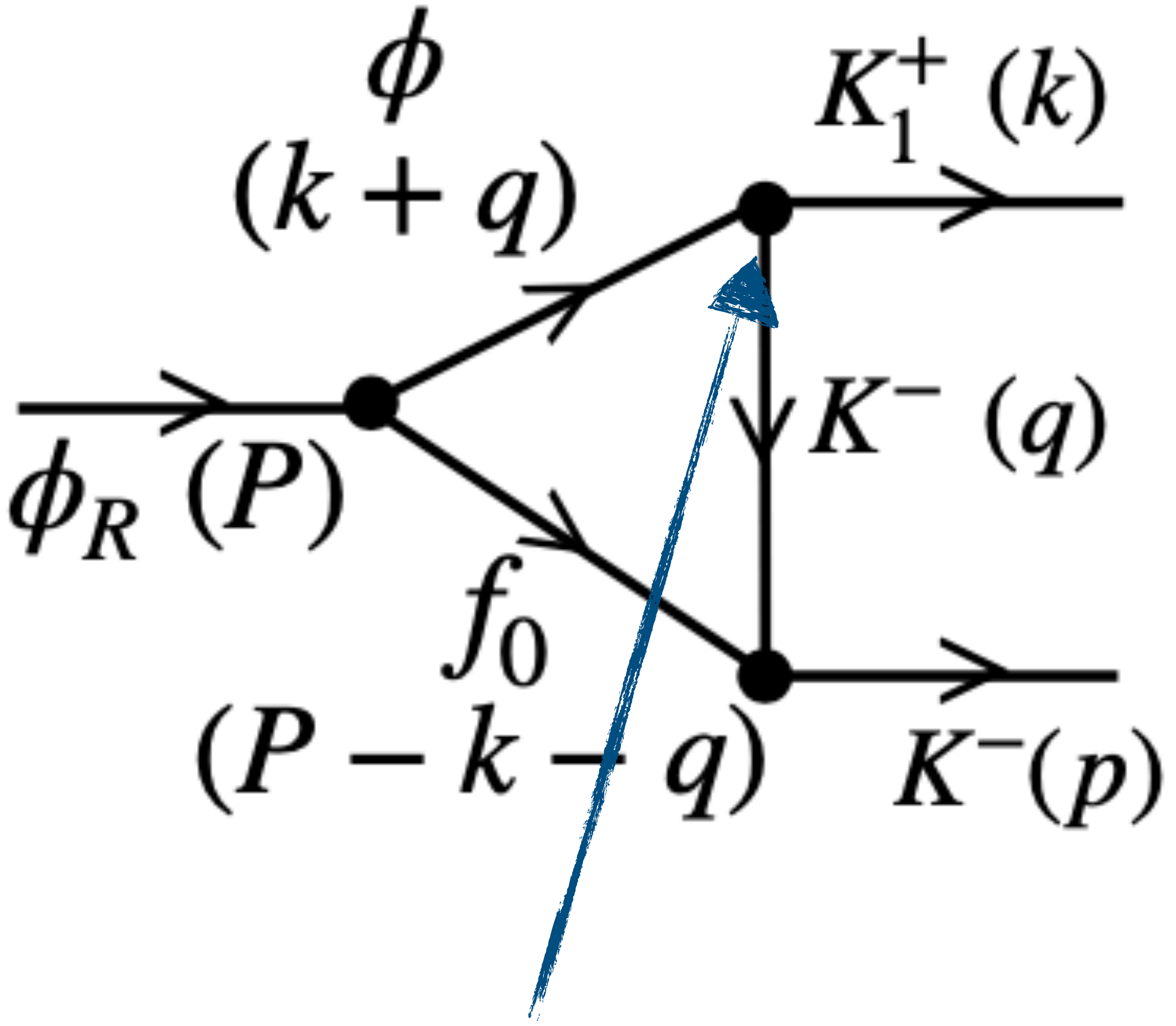
We use the tensor formalism for vector mesons: Tree level term is gauge invariant

$$t^T_{K_1^0\to\gamma K^0} = -\frac{2eF_V}{M_{K_1^0}}\Big[\frac{g^T_{K_1^0\to\rho^0K^0}}{M^2_{\rho^0}} + \frac{g^T_{K_1^0\to\omega K^0}}{3M^2_\omega} - \frac{\sqrt{2}g^T_{K_1^0\to\phi K^0}}{3M^2_\phi}\Big]$$
$$\times\Big[(P\cdot p)(\epsilon_{K_1^0}(P)\cdot\epsilon_\gamma(p)) - (P\cdot\epsilon_\gamma(p))(p\cdot\epsilon_{K_1^0}(P))\Big]$$

18) Palomar, Roca, Oset, Vacas, Nucl. Phys. A729, 743 (2003)

BACKUP SLIDES: SOME MORE DETAILS OF THE MODEL

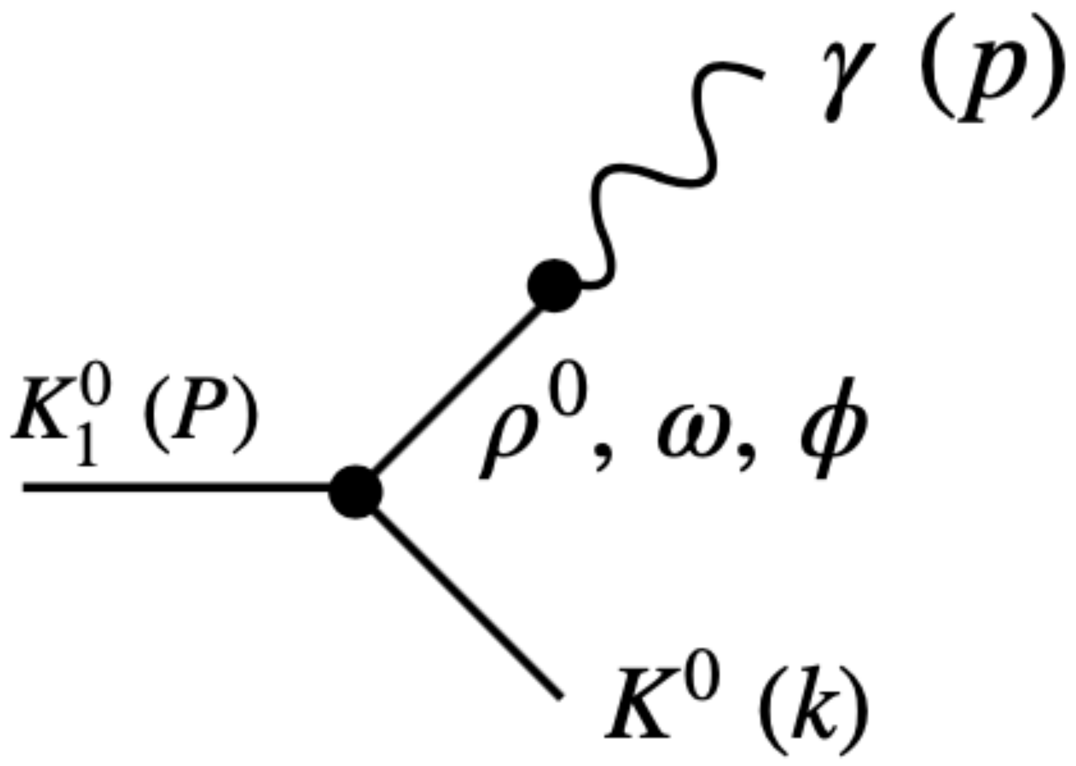
- Triangular loops:



$$t_{K_1^+ \to \phi K^+} = g_{K_1^+ \to \phi K} \epsilon_{K_1^+} \cdot \epsilon_\phi$$

Phenomenological approach for $K_1(1270)$ & $K_1(1400)$:

- Available data on the radiative decays
- Vector meson dominance: Couplings of $K_1(1270)$ & $K_1(1400)$ to ϕK are obtained



We use the tensor formalism for vector mesons: Tree level term is gauge invariant

Fixed to reproduce the experimental data on the decay width

$$\Gamma^T_{K_1^0 \to \gamma K^0} = \frac{|\vec{p}|^3}{3\pi M^2_{K_1^0}} e^2 |F_V|^2 \left| \frac{g^T_{K_1^0 \to \rho^0 K^0}}{M^2_{\rho^0}} + \frac{g^T_{K_1^0 \to \omega K^0}}{3M^2_\omega} - \frac{\sqrt{2} g^T_{K_1^0 \to \phi K^0}}{3M^2_\phi} \right|^2$$

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18) Palomar, Roca, Oset, Vacas, Nucl. Phys. A729, 743 (2003)

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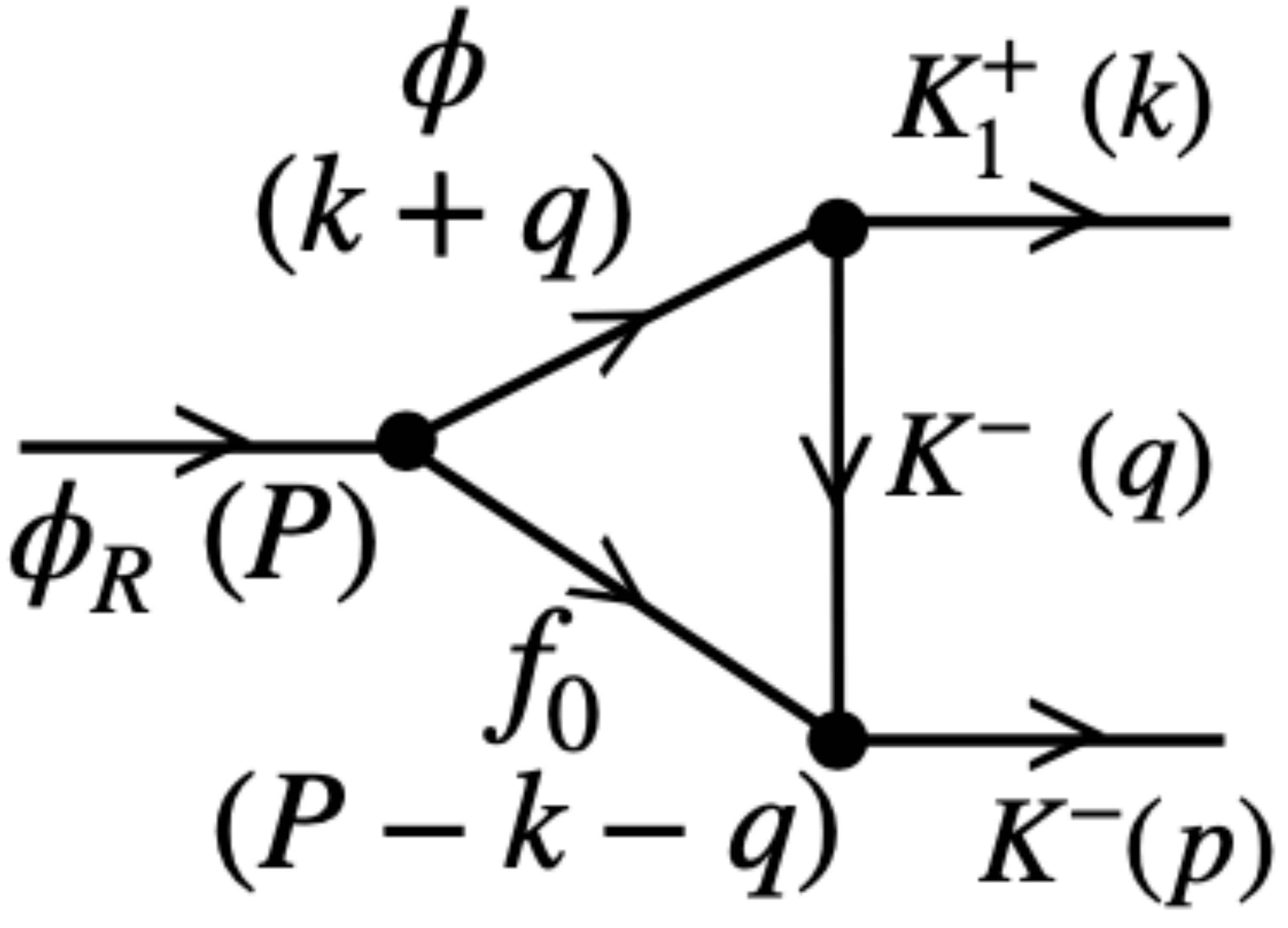

$\Gamma^T_{K_1\to\phi K} \sim \Gamma_{K_1\to\phi K}$: we can determine $|g_{K_1\to\phi K}|$

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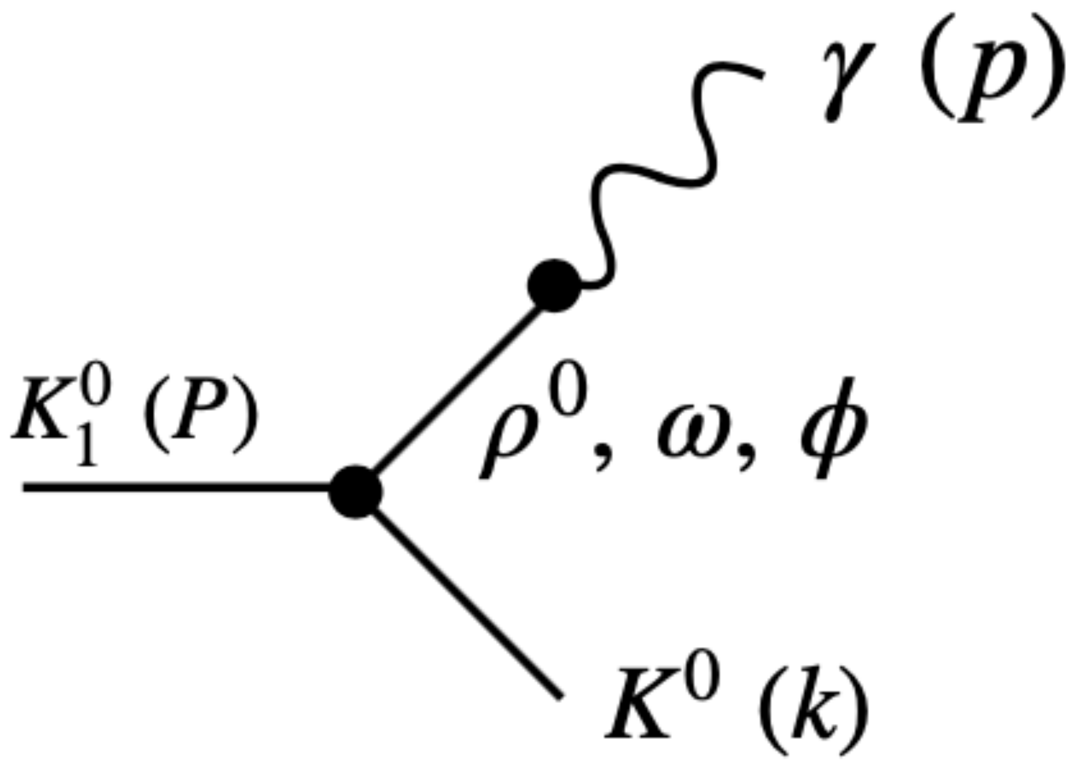

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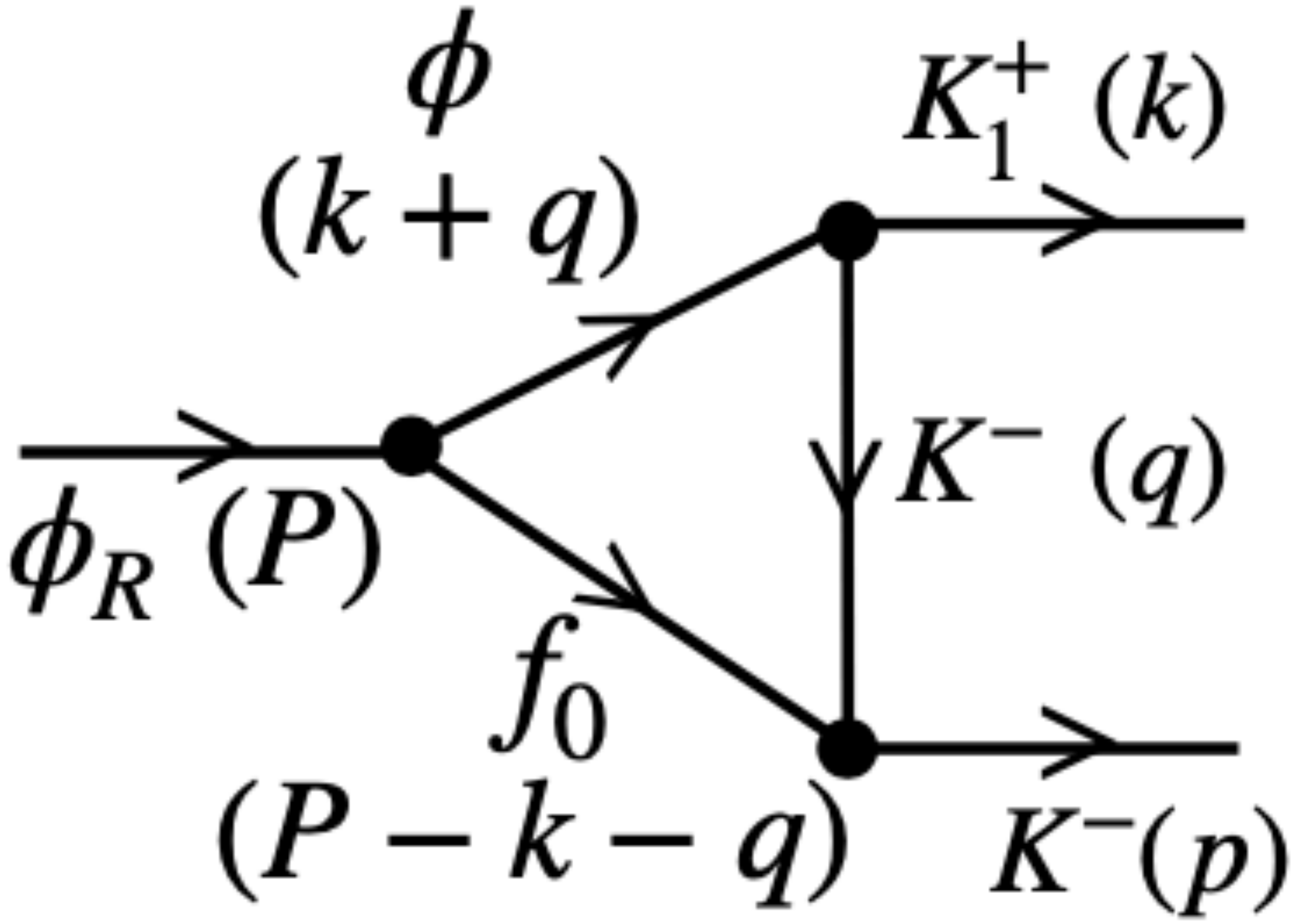

Phenomenological approach for $K_1(1270)$ & $K_1(1400)$:

$$|g_{K_1^+(1270)\to\phi K^+}| = \begin{cases} 3967 \pm 419\ \mathrm{MeV}, & \mathrm{Solution}\ \mathbb{S}_1, \\ 12577 \pm 763\ \mathrm{MeV}, & \mathrm{Solution}\ \mathbb{S}_2, \\ 19841 \pm 1177\ \mathrm{MeV}, & \mathrm{Solution}\ \mathbb{S}_3. \end{cases}$$

$$|g_{K_1^+(1400)\to\phi K^+}| = 8480 \pm 1333\ \mathrm{MeV}$$

No direct measurement of $K_1 \to K\gamma$