# Scalar meson in charmed hadron decays

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EPJC80, 895 (2020),
EPJC81,1093 (2021),
PLB820, 136586 (2021)

Outline:
1. Introduction
2. Formalism
3. Results
4. Summary

# Introduction

## 2-body $D_s^+$ decay channels:

$D_s^+ \to PP, PV$ **and** $D_s^+ \to SP, SV$

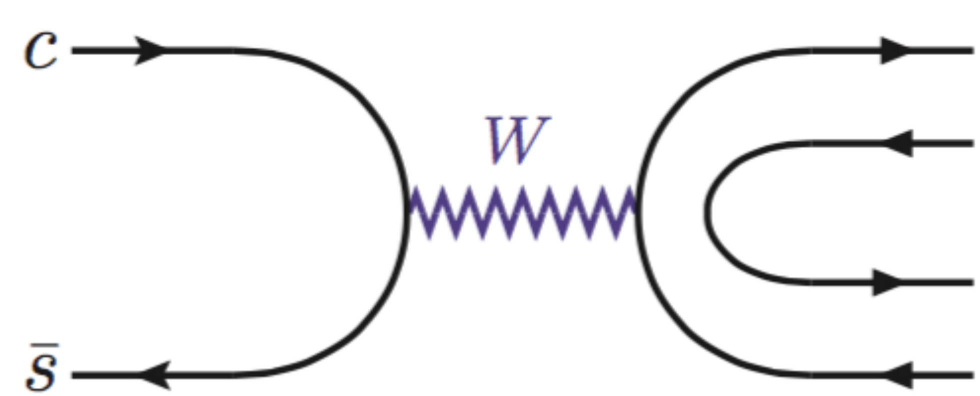
- $D_s^+ \to PP, PV$

$P(V)$: Strangeless pesudoscalar (vector) meson

Possible decay channels: $D_s^+ \to \pi^+\pi^0, \pi^+\rho^0, \pi^+\omega$

Short-distance $W$-boson annihilation (WA) process

$D_s^+(c\bar{s}) \to W^+ \to u\bar{d}$



## G parity analysis

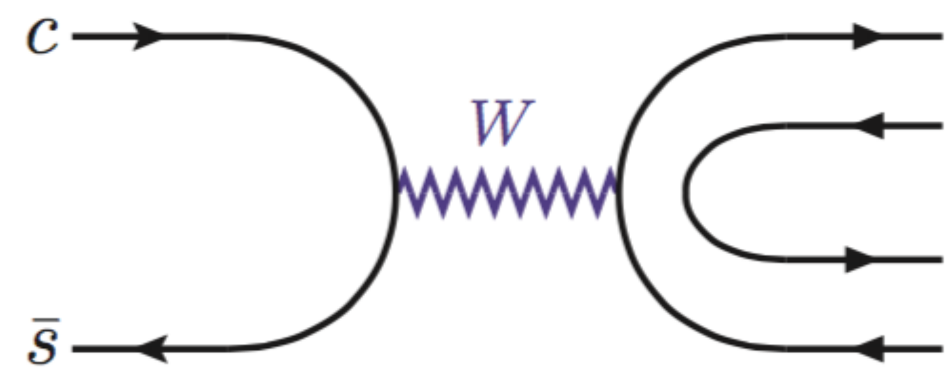
[H.Y. Cheng and C.W. Chiang, PRD81, 074021 (2010)]

$u\bar{d}$ (odd), $\pi^+\pi^0$ (even), $\pi^+\rho^0$ (odd), $\pi^+\omega$ (even)

$\mathcal{B}(D_s^+ \to \pi^+\pi^0) < 3.4 \times 10^{-4}$

$\mathcal{B}(D_s^+ \to \pi^+\rho^0) = (1.9 \pm 1.2) \times 10^{-4}$

$\mathcal{B}(D_s^+ \to \pi^+\omega) = (1.9 \pm 0.3) \times 10^{-3}$




SD WA for $\mathcal{B} \sim 10^{-4}$

FSI as LD annililation process for $\mathcal{B}(D_s^+ \to \pi^+\omega) \sim 10^{-3}$

[Fajfer, Prapotnik, Singer, Zupan, PRD68, 094012 (2003)]

[H.Y. Cheng and C.W. Chiang, PRD81, 074021 (2010)]

- $D_s^+ \to SP, SV$ decays

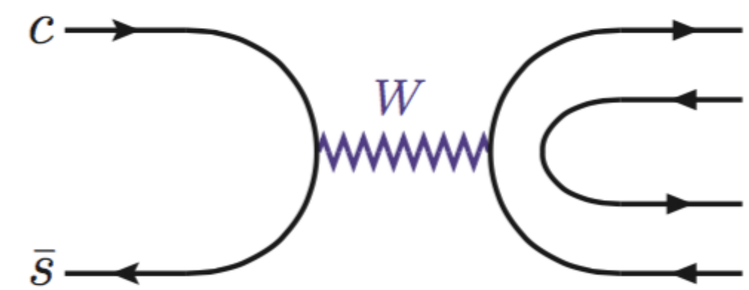
$S$: strangeless scalar meson, $a_0 \equiv a_0(980)$

Possible decay channels: $D_s^+ \to a_0^{0(+)}\pi^{+(0)}, a_0^{+(0)}\rho^{0(+)}, a_0^+\omega$

G parity analysis for WA process:

[Achasov, Shestakov, PRD96, 036013 (2017)]

$u\bar{d}$ (odd), $a_0\pi$ (even), $a_0\rho$ (odd), $a_0^+\omega$ (even)




BESIII presents that

$$\mathcal{B}(D_s^+ \to \pi^{+(0)}a_0^{0(+)}, a_0^{0(+)} \to \pi^{0(+)}\eta) = (1.46 \pm 0.15 \pm 0.23) \times 10^{-2}$$

$$\mathcal{B}_+(D_s^+ \to a_0^+\rho^0, a_0^+ \to \pi^+\eta) = (2.1 \pm 0.8 \pm 0.5) \times 10^{-3}$$

$$\mathcal{B}_0(D_s^+ \to a_0^0\rho^+, a_0^0 \to K^+K^-) = (0.7 \pm 0.2 \pm 0.1) \times 10^{-3}$$

10-100 times larger than $10^{-4}$, unlikely from WA,
$D_s^+ \to a_0^+\omega$ not measured yet.

**A careful study is needed.**

**Amplitude Analysis of $D_s^+ \to \pi^+\pi^0\eta$ and First Observation of the $W$-Annihilation Dominant Decays $D_s^+ \to a_0(980)^+\pi^0$ and $D_s^+ \to a_0(980)^0\pi^+$**

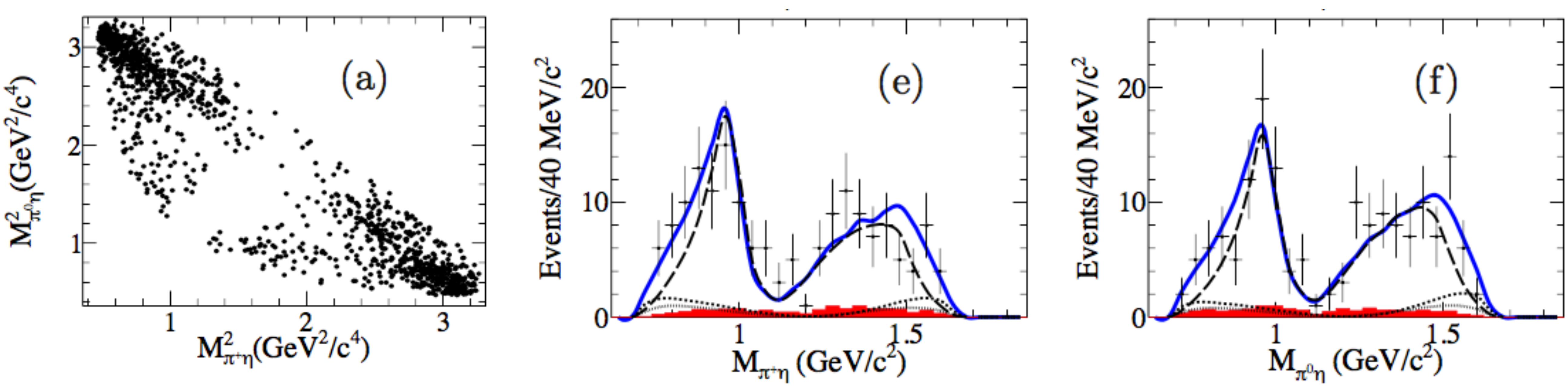
BESIII, PRL123, 112001 (2019),

$\mathcal{B}(D_s^+ \to \pi^+\pi^0\eta) = (9.50 \pm 0.28 \pm 0.41) \times 10^{-2}$,

$\mathcal{B}(D_s^+ \to \eta(\rho^0 \to)\pi^+\pi^0) = (7.44 \pm 0.52 \pm 0.38) \times 10^{-2}$,

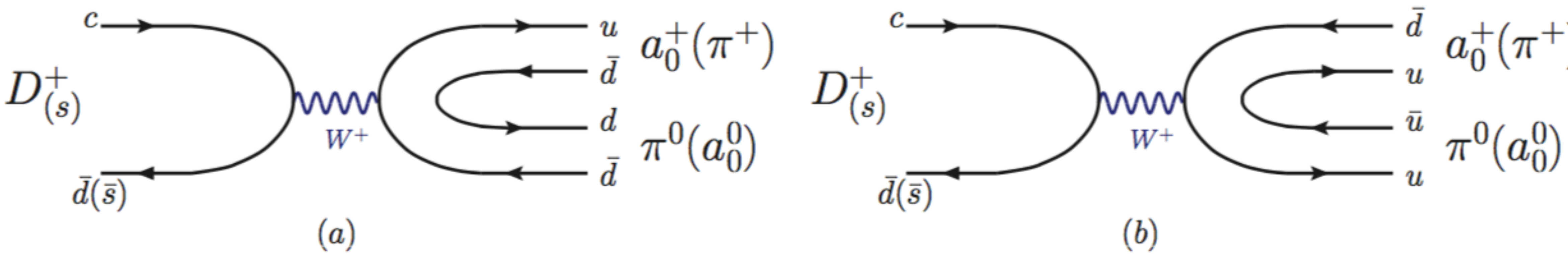
$\mathcal{B}(D_s^+ \to \pi^{+(0)}(a_0^{0(+)} \to)\pi^{0(+)}\eta) = (1.46 \pm 0.15 \pm 0.23) \times 10^{-2}$,

$M_{\pi^+\pi^0} > 1.0~\mathrm{GeV}/c^2$.



$D_s^+ \to \pi^{+(0)}(a_0^{0(+)} \to)\pi^{0(+)}\eta$

claimed as the $W$-annihilation process.




with the assumption that $a_0$ is a p-wave scalar meson.

Elimination of $\bar{s}$ in $D_s^+$.

Productions of $a_0^{+,0}$, equal sizes.

# Scalar mesons below 1 GeV

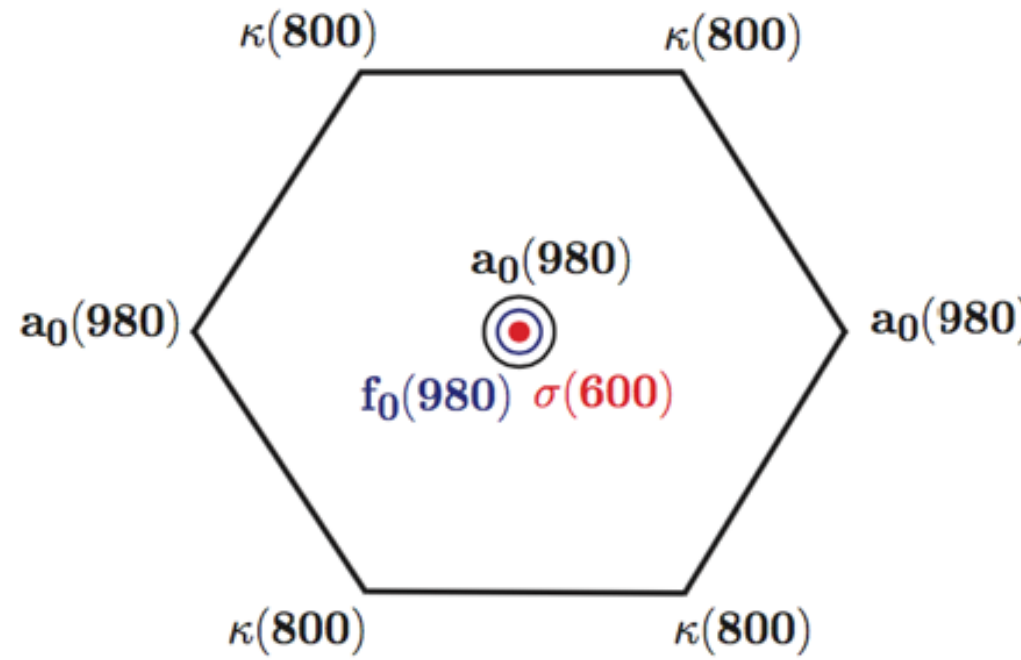
- Controversial identifications

$a_0^+$, $a_0^0$, $f_0(980)$

p-wave $(u\bar{d})$, $(u\bar{u} - d\bar{d})/\sqrt{2}$, $s\bar{s}$

compact $s\bar{s}(u\bar{d})$, $s\bar{s}(u\bar{u} - d\bar{d})/\sqrt{2}$,

$s\bar{s}(u\bar{u} + d\bar{d})/\sqrt{2}$ tetraquarks




- tetraquark, promising

$f_0(600)$, $ud\bar{u}\bar{d}$; $f_0(980)$, $us\bar{u}\bar{s}$;

lighter than 1 GeV

**PRL110, 261601 (2013), Steven Weinberg**

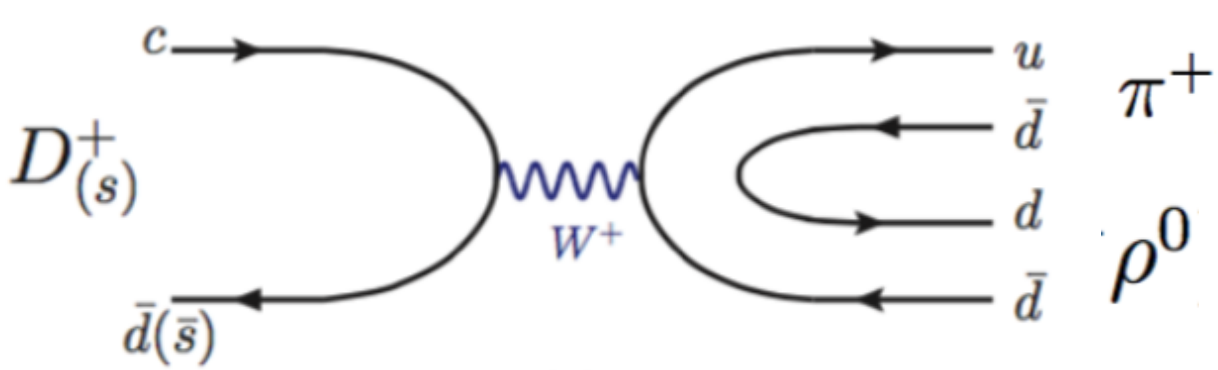
# Theoretical difficulties

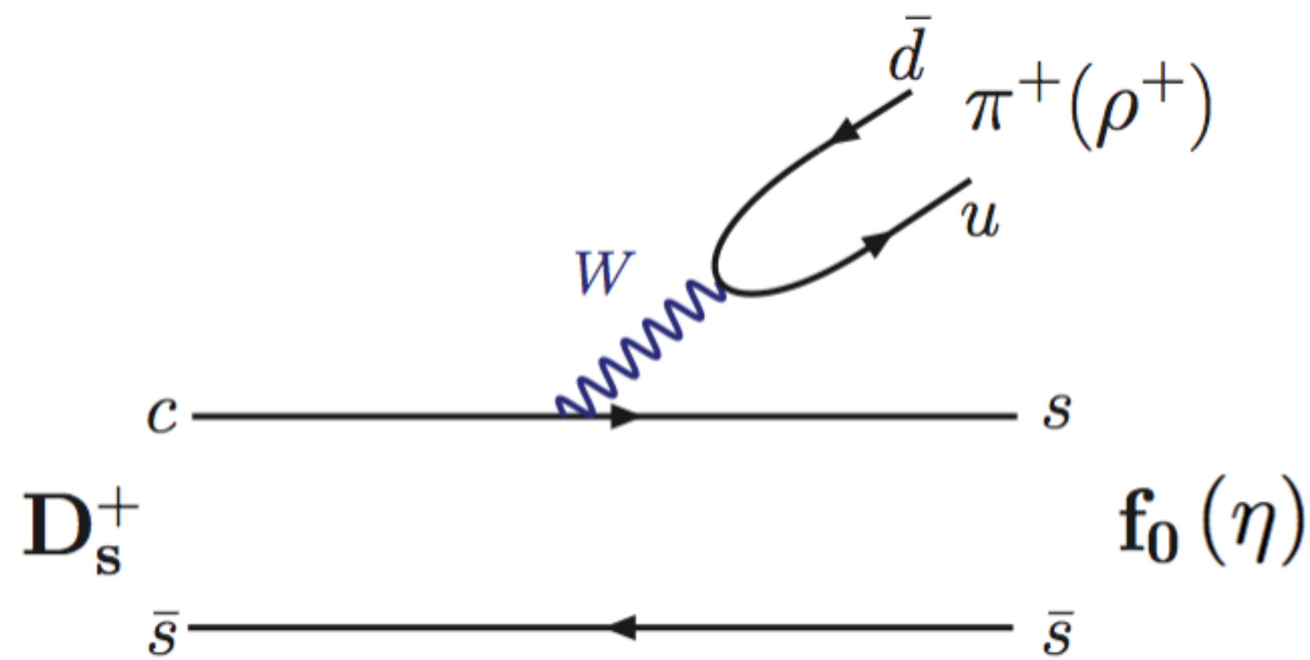
$$\mathcal{B}(D_s^+ \to \pi^+\rho^0) = (2.0 \pm 1.2) \times 10^{-4}$$

$$\mathcal{B}(D_s^+ \to \pi^{+(0)}(a_0^{0(+)} \to)\pi^{0(+)}\eta) = 1.46 \times 10^{-2}$$

$$\mathcal{B}(D_s^+ \to \pi^+\eta) = (1.70 \pm 0.09) \times 10^{-2}$$

$$\mathcal{B}(D_s^+ \to \pi^+ f_0(980)) \sim O(10^{-2})$$



• $G$-parity violation:

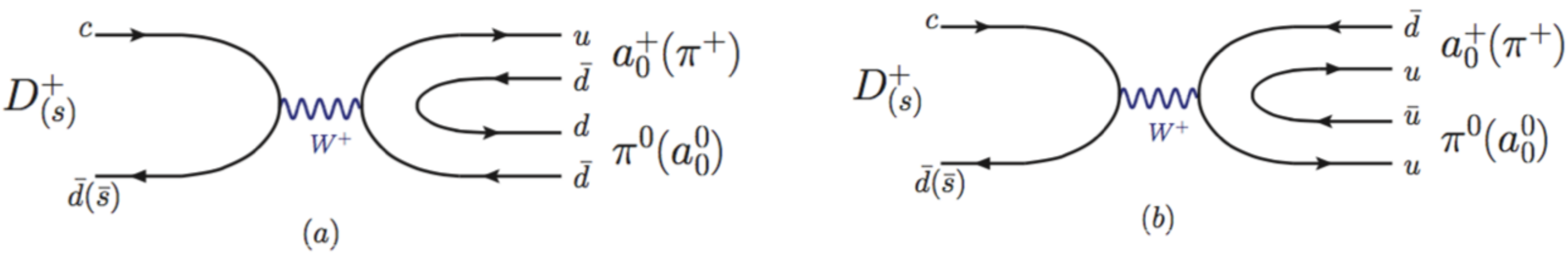
WA $c\bar{s} \to W^+ \to u\bar{d}$ decay

the $G$-parities of $u\bar{d}$ and $a_0\pi$, odd and even, respectively.

Cheng, Chiang, PRD81, 074021 (2010),

Achasov, Shestakov, PRD96, 036013 (2017).

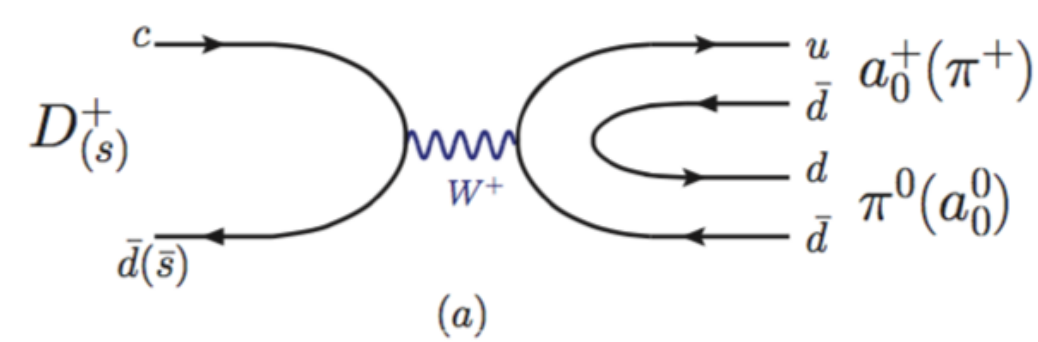
WA process for $D_s^+ \to a_0\pi$ should be suppressed.



# Estimation for $D^+ \to \pi^+\pi^0\eta$

- $\mathcal{B}(\eta) \equiv \mathcal{B}(D^+ \to \pi^+\pi^0\eta)$

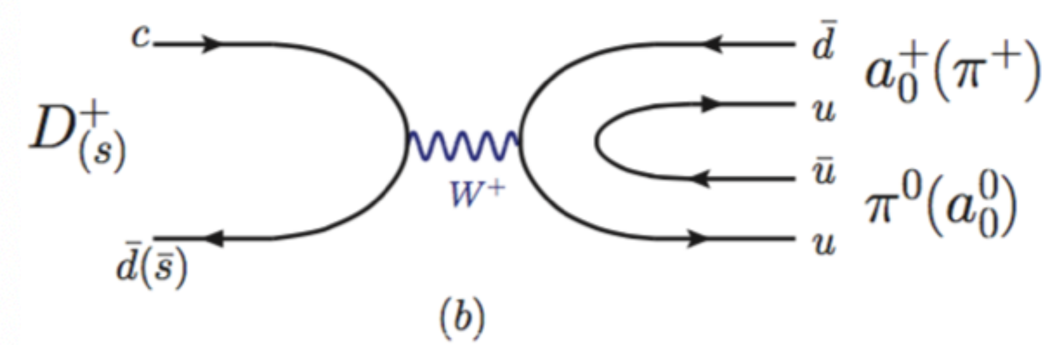
$= (1.4 \pm 0.4, 1.6 \pm 0.5) \times 10^{-3}$ [pdg].




- $\mathcal{B}(\eta) = \mathcal{B}_\rho(\eta) + \mathcal{B}_{\rm WA}(\eta)$

- $\mathcal{B}_\rho(\eta) \equiv \mathcal{B}(D^+ \to \eta(\rho^+ \to)\pi^+\pi^0)$

$\mathcal{B}_\rho(\eta) = (1.5 \pm 0.5) \times 10^{-3}$




Li, Lu, Qin, Yu, PRD89, 054006 (2014);
Cheng, Chiang, PRD100, 093002 (2019).

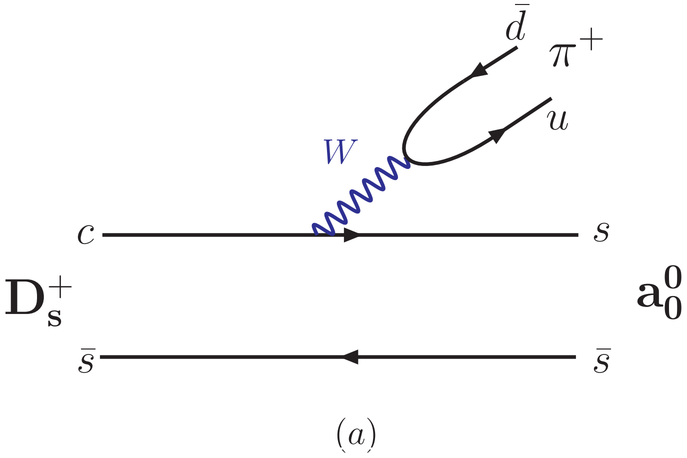
- $\mathcal{B}_{\rm WA}(\eta) \equiv \mathcal{B}(D^+ \to \pi^{+(0)}(a_0^{0(+)} \to)\pi^{0(+)}\eta)$

$$= \left(\frac{f_D}{f_{D_s}}\right)^2 \left(\frac{|V_{cd}|}{|V_{cs}|}\right)^2 \frac{\tau_D}{\tau_{D_s}} \left(\frac{m_{D_s}}{m_D}\right)^3 \times \mathcal{B}(D_s^+ \to \pi^{+(0)}(a_0^{0(+)} \to)\pi^{0(+)}\eta)$$

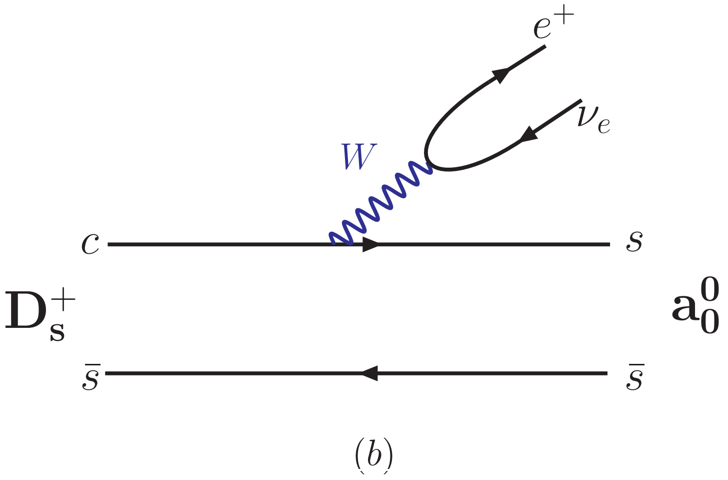
$= (1.2 \pm 0.2) \times 10^{-3}$

**Since you have eliminated the impossible, whatever remains, however improbable, must be the truth.**

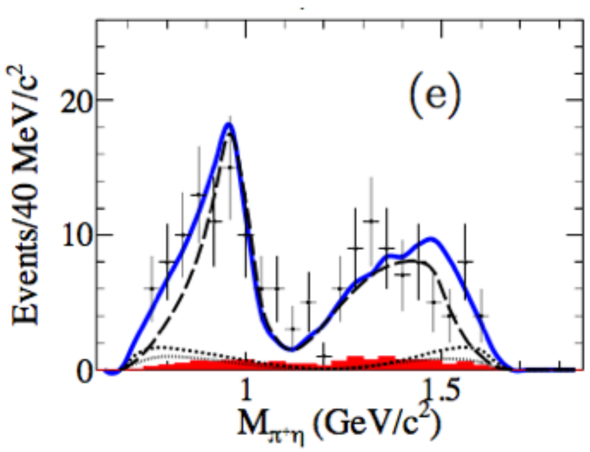
## Other short-distance effect?



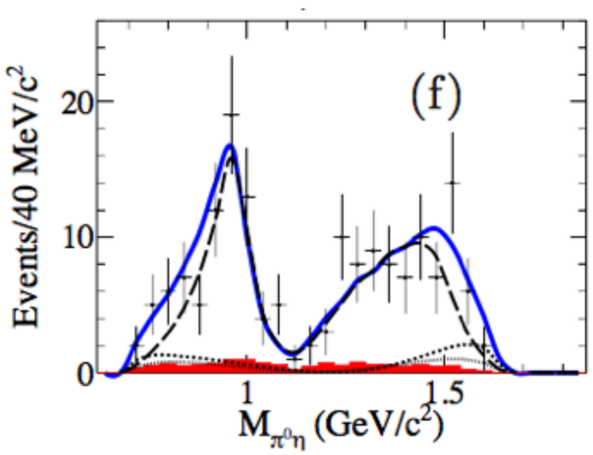

(a)




(b)

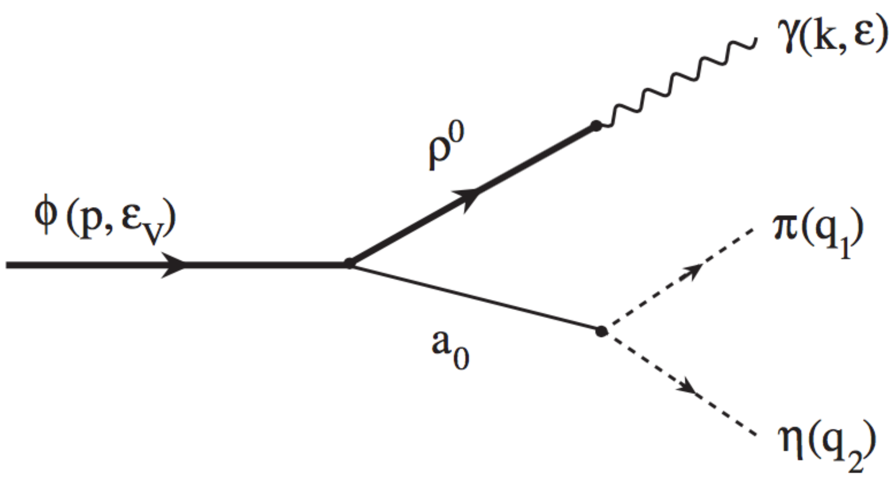



- $f_0 - a_0$ mixing   Wei Wang, PLB759, 501 (2016)
- not for $a_0^+$
- constraint from $D_s^+ \to a_0^0 e^+ \nu_e$



# Long-distance annihilation contribution?
# Triangle rescattering as FSI

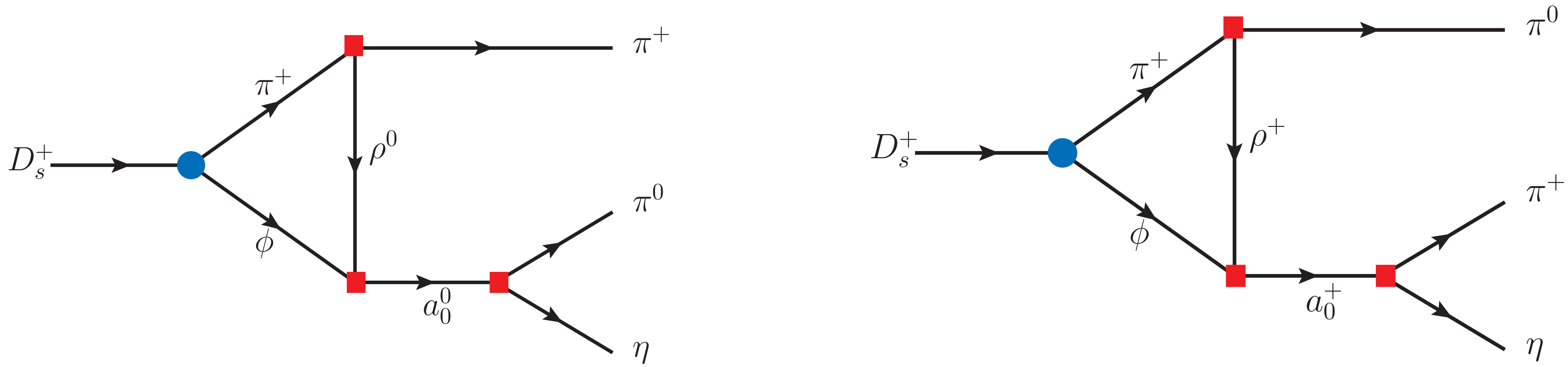
- $\phi \to a_0 \gamma$



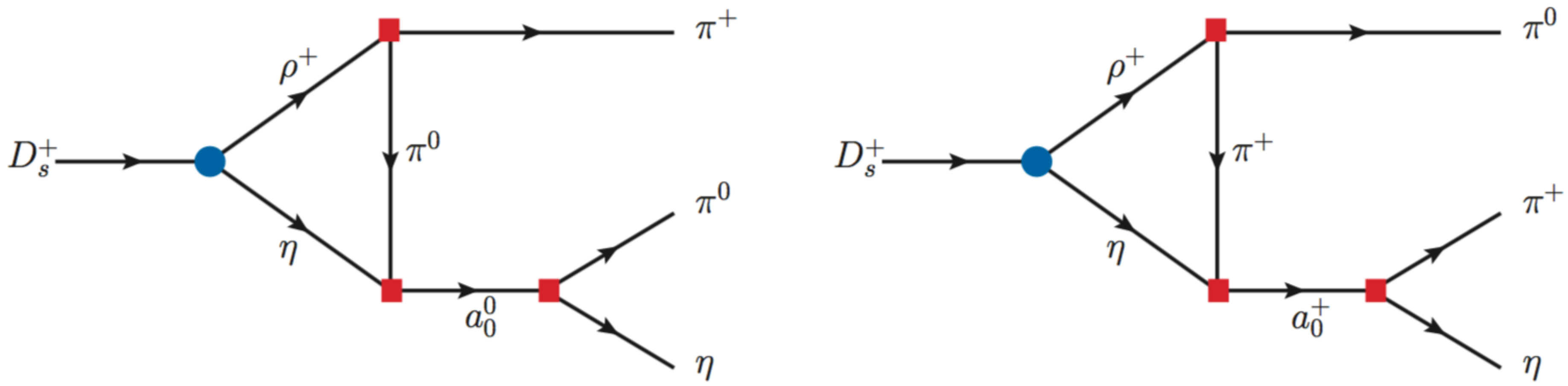

PHYSICAL REVIEW D **73,** 054017 (2006)

**Chiral approach to phi radiative decays**

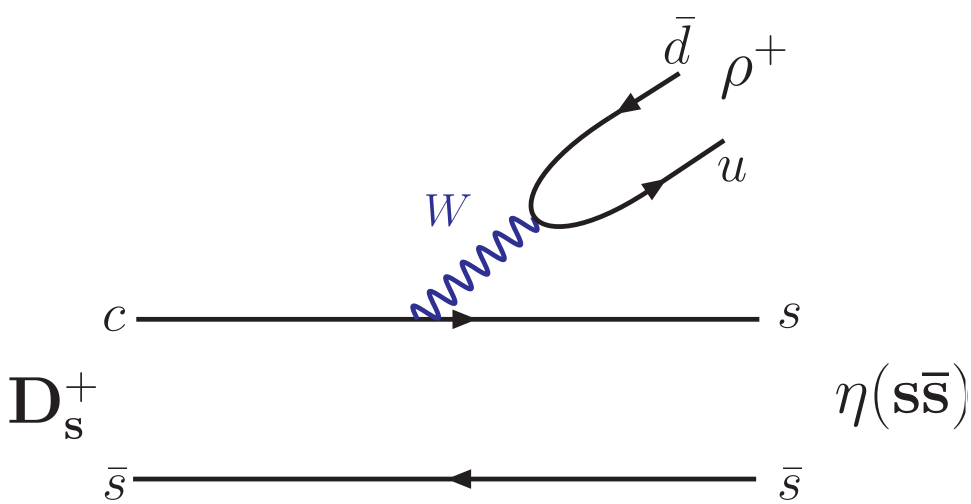
Deirdre Black,[1,*] Masayasu Harada,[2,†] and Joseph Schechter[3,‡]




$(a)$ $(b)$

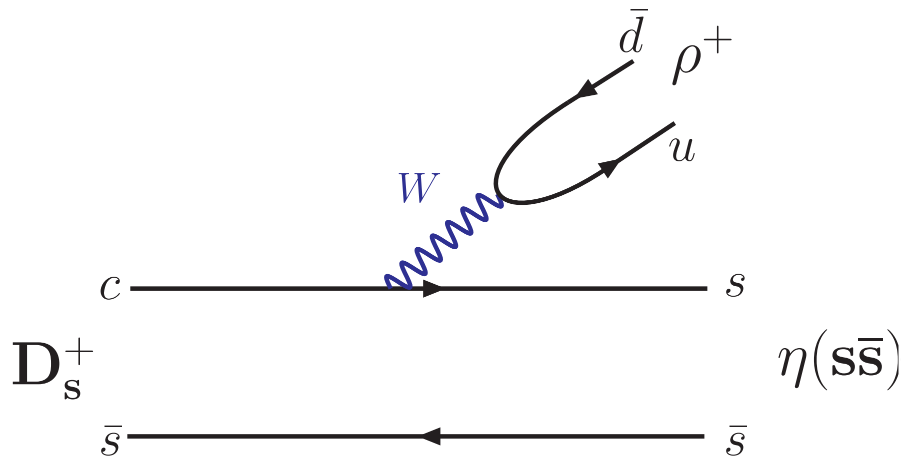



$(a)$ $(b)$




$(D_s^+ \to \eta\rho^+)$

$$\mathcal{B}(D_s^+ \to \rho^+\eta) = (7.4 \pm 0.6)\%$$




$(D_s^+ \to \eta\rho^+)$

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} V_{cs} V_{ud} [c_1 (\bar{u}d)(\bar{s}c) + c_2 (\bar{s}d)(\bar{u}c)]$$

$$\mathcal{A}(D_s^+ \to \eta\rho^+) = \frac{G_F}{\sqrt{2}} V_{cs} V_{ud} a_1 \langle \rho^+ | (\bar{u}d) | 0 \rangle \langle \eta | (\bar{s}c) | D_s^+ \rangle$$

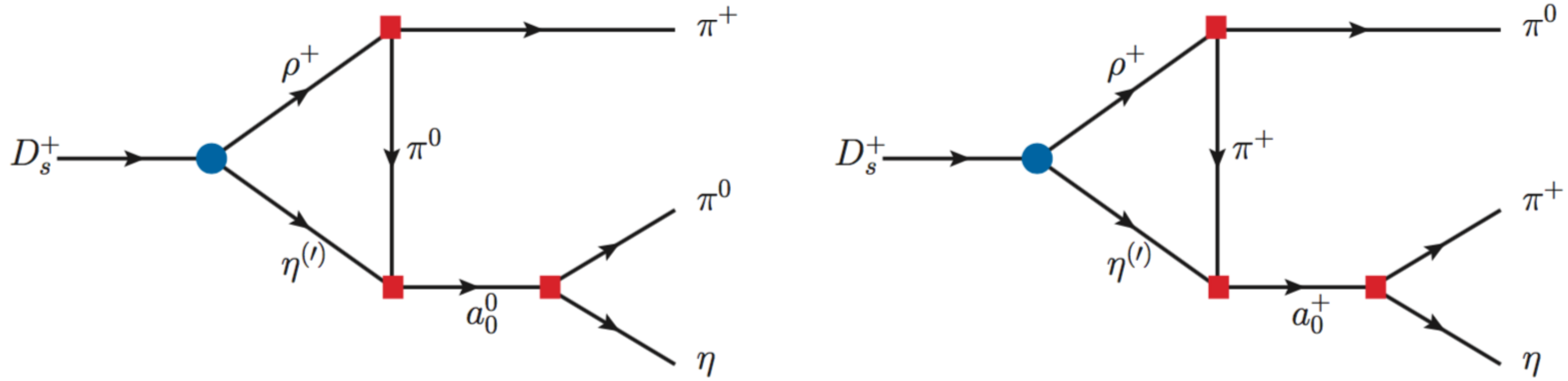
$$\langle \eta | (\bar{s}c) | D_s^+ \rangle = (p_{D_s} + p_\eta)_\mu F_+(t) + q_\mu F_-(t)$$

$$\langle \rho^+ | (\bar{u}d) | 0 \rangle = m_\rho f_\rho \epsilon_\mu^*$$

$$F(t) = \frac{F(0)}{1 - a(t/m_{D_s}^2) + b(t^2/m_{D_s}^4)}$$

$$a_1 = 0.93 \pm 0.04$$

$$\mathcal{B}(D_s^+ \to \rho^+ \eta) = (7.4 \pm 0.6)\%$$




$(a)$ $(b)$

$$\mathcal{A}^{(\prime)}_{a(b)} \equiv \mathcal{A}(D_s^+ \to \pi^{+(0)}(a_0^{0(+)} \to)\pi^{0(+)}\eta^{(\prime)}) = \frac{1}{D_0}\hat{\mathcal{A}}^{(\prime)}\mathcal{T}^{(\prime)}_{a(b)}\,,$$

$$\mathcal{T}^{(\prime)}_{a(b)} = -i\int\frac{d^4q}{(2\pi)^4}\frac{(2p_{D_s}-q)_\mu(-g^{\mu\nu}+\frac{q^\mu q^\nu}{q^2})(q-2p_{\pi^{+(0)}})_\nu}{D_1D_2D_3}\,,$$

$$\hat{\mathcal{A}} = G_{D_s\rho\eta}g^2_{a_0\eta\pi}g_{\rho\pi\pi}$$

$$\hat{\mathcal{A}}' = G_{D_s\rho\eta'}g_{a_0\eta'\pi}g_{a_0\eta\pi}g_{\rho\pi\pi}$$

$$\mathcal{A}(D_s^+ \to \eta^{(\prime)}\rho^+) = G_{D_s\rho\eta^{(\prime)}}\epsilon^*\cdot(p_{D_s}+p_{\eta^{(\prime)}})$$

$$G_{D_s\rho\eta^{(\prime)}} \equiv (G_F/\sqrt{2})V^*_{cs}V_{ud}a_1m_\rho f_\rho F_+^{(\prime)}(m_\rho^2)$$

$$\mathcal{A}(a_0 \to \eta\pi) = g_{a_0\eta\pi}$$

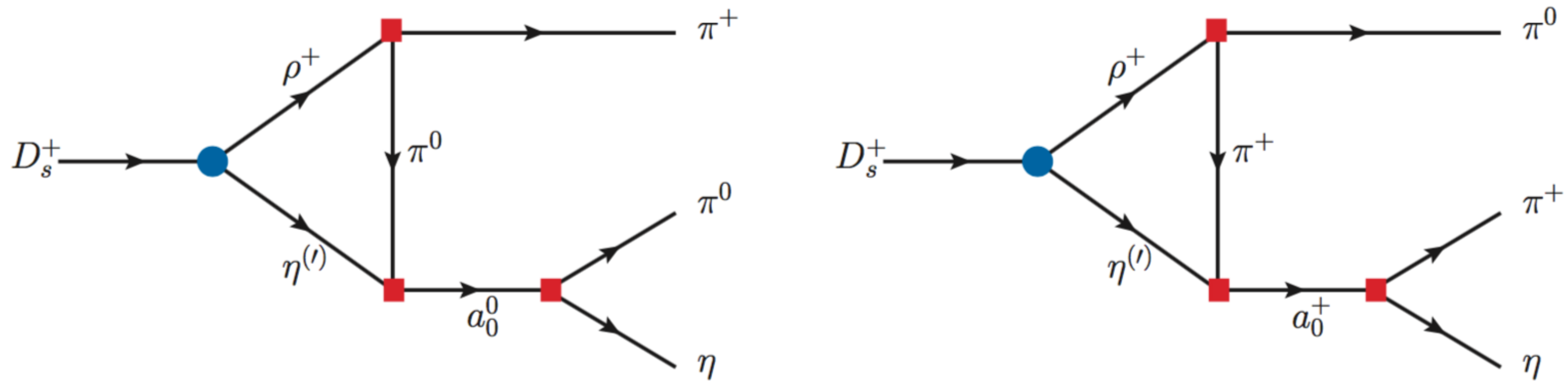
$$\mathcal{A}(\rho^+ \to \pi^+\pi^0) = g_{\rho\pi\pi}\epsilon\cdot(p_{\pi^+}-p_{\pi^0})$$

$$D_0 = x - m^2_{a_0} - \sum_{\alpha\beta}\left[\mathrm{Re}\Pi^{\alpha\beta}_{a_0}(m^2_{a_0}) - \Pi^{\alpha\beta}_{a_0}(x)\right],$$

$$D_1 = q^2 - m_\rho^2 + im_\rho\Gamma_\rho\,,$$

$$D_2 = (p_{\pi^{0(+)}}-q)^2 - m^2_{\pi^{0(+)}} + i\epsilon^+\,,$$

$$D_3 = (q-p_{\eta^{(\prime)}})^2 - m^2_{\eta^{(\prime)}} + i\epsilon^+\,,$$



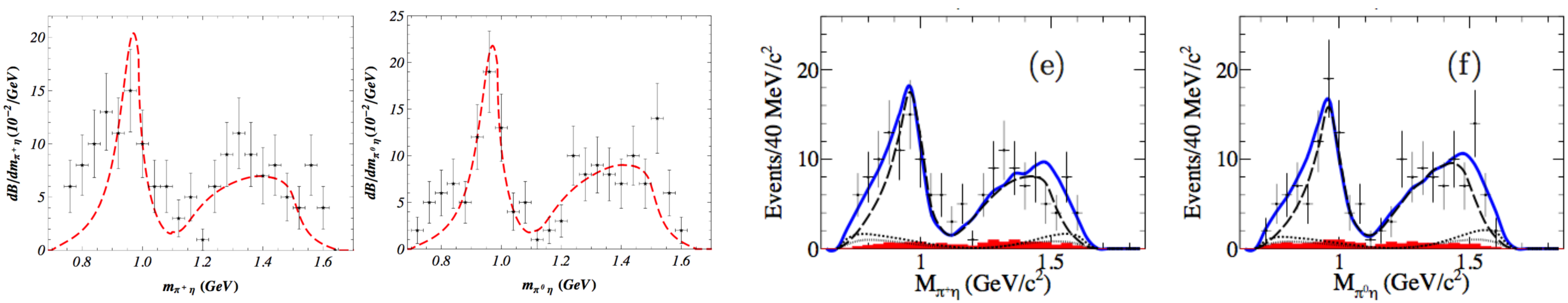

(a) (b)

$$D_0 = x - m_{a_0}^2 - \sum_{\alpha\beta} \left[ \mathrm{Re}\Pi_{a_0}^{\alpha\beta}(m_{a_0}^2) - \Pi_{a_0}^{\alpha\beta}(x) \right],$$

$$a_0 \to \eta^{(\prime)}\pi, K\bar{K}$$

$$f_0 \to \pi\pi, K\bar{K}$$

$$\Pi_{a_0}^{\alpha\beta}(x) = \frac{g_{a_0\alpha\beta}^2}{16\pi} \left\{ \frac{m_{\alpha\beta}^+ m_{\alpha\beta}^-}{\pi x} \log\left[\frac{m_\beta}{m_\alpha}\right] - \theta[x - (m_{\alpha\beta}^+)^2] \right.$$
$$\times \rho_{\alpha\beta} \left( i + \frac{1}{\pi} \log\left[ \frac{\sqrt{x - (m_{\alpha\beta}^+)^2} + \sqrt{x - (m_{\alpha\beta}^-)^2}}{\sqrt{x - (m_{\alpha\beta}^-)^2} - \sqrt{x - (m_{\alpha\beta}^+)^2}} \right] \right)$$
$$- \rho_{\alpha\beta} \left( 1 - \frac{2}{\pi} \arctan\left[ \frac{\sqrt{-x + (m_{\alpha\beta}^+)^2}}{\sqrt{x - (m_{\alpha\beta}^-)^2}} \right] \right) \left( \theta[x - (m_{\alpha\beta}^-)^2] - \theta[x - (m_{\alpha\beta}^+)^2] \right)$$
$$\left. + \rho_{\alpha\beta} \frac{1}{\pi} \log\left[ \frac{\sqrt{(m_{\alpha\beta}^+)^2 - x} + \sqrt{(m_{\alpha\beta}^-)^2 - x}}{\sqrt{(m_{\alpha\beta}^-)^2 - x} - \sqrt{(m_{\alpha\beta}^+)^2 - x}} \right] \theta[(m_{\alpha\beta}^-)^2 - x] \right\},$$




$$\mathcal{B}(D_s^+ \to a_0^{0(+)}\pi^{+(0)}) = (1.7 \pm 0.2 \pm 0.1) \times 10^{-2}\,,$$

$$\mathcal{B}(D_s^+ \to \pi^{+(0)}(a_0^{0(+)} \to)\pi^{0(+)}\eta) = (1.4 \pm 0.1 \pm 0.1) \times 10^{-2}\,,$$

$$\mathcal{B}(D_s^+ \to \pi^{+(0)}(a_0^{0(+)} \to)\pi^{0(+)}\eta) = (1.46 \pm 0.15 \pm 0.23) \times 10^{-2}$$

- $D_s^+ \to \pi^+(a_0^0 \to)\pi^0\eta$ and $D_s^+ \to \pi^0(a_0^+ \to)\pi^+\eta$

large interference with a relative phase of 180°

$\rho^+(q_4) \to \pi^0(q_3)\pi^+(q_4 - q_3)$, $\rho^+(q_4) \to \pi^+(q_3)\pi^0(q_4 - q_3)$

$\mathcal{A}_a(\rho^+ \to \pi^+\pi^0) = -\mathcal{A}_b(\rho^+ \to \pi^0\pi^+)$

30% cancellation to the total branching ratio.

## $D_s^+ \to SV$

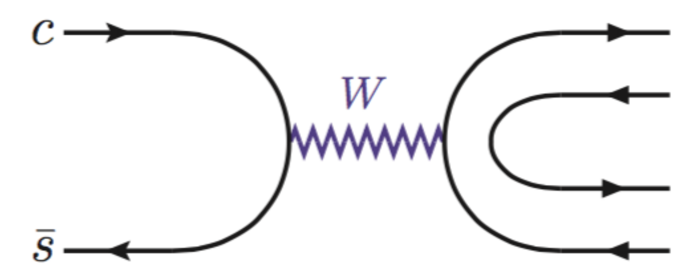
**Study of the Decay $D_s^+ \to \pi^+\pi^+\pi^-\eta$ and Observation of the W-annihilation Decay $D_s^+ \to a_0(980)^+\rho^0$**

BESIII, PRD104, 071101 (2021)

**Amplitude analysis and branching fraction measurement of $D_s^+ \to K^-K^+\pi^+\pi^0$**

BESIII, PRD104, 032011 (2021)

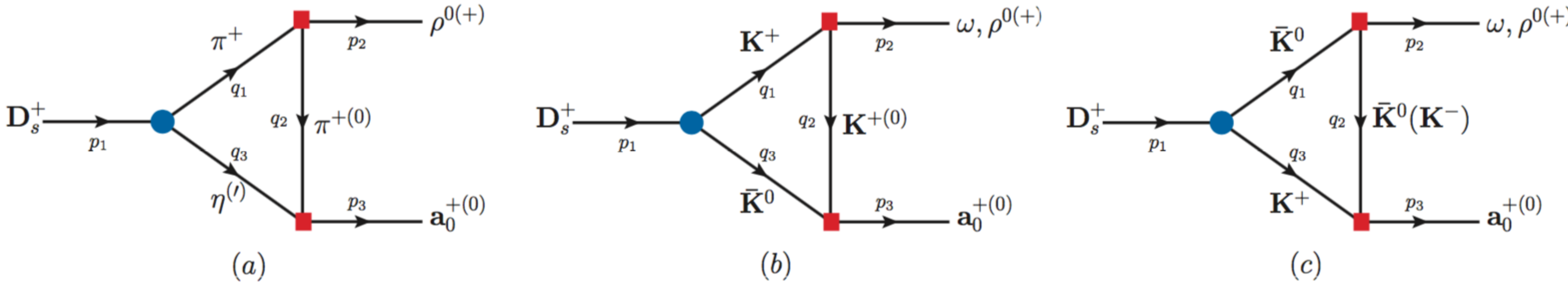
$$\mathcal{B}_+(D_s^+ \to a_0^+\rho^0, a_0^+ \to \pi^+\eta) = (2.1 \pm 0.8 \pm 0.5) \times 10^{-3},$$
$$\mathcal{B}_0(D_s^+ \to a_0^0\rho^+, a_0^0 \to K^+K^-) = (0.7 \pm 0.2 \pm 0.1) \times 10^{-3},$$

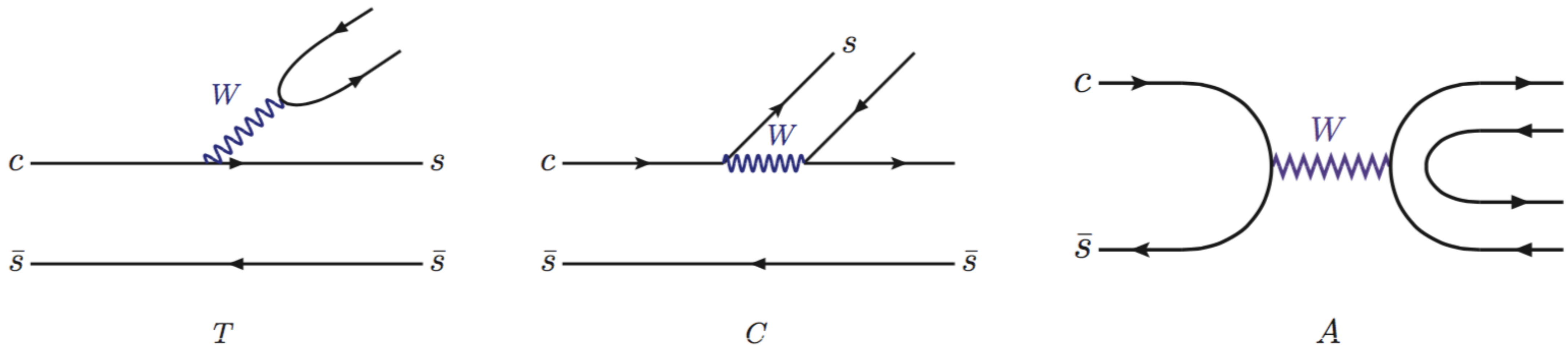



$D_s^+(c\bar{s}) \to W^+ \to u\bar{d}$

SD WA for $\mathcal{B} \sim 10^{-4}$

Study $D_s^+ \to \rho^{0(+)} a_0^{+(0)}$ and $D_s^+ \to \omega a_0^+$




$$\mathcal{M}_\eta(D_s^+ \to \pi^+\eta) = \frac{G_F}{\sqrt{2}} V_{cs}^* V_{ud}(\sqrt{2}A\cos\phi - T\sin\phi)\,,$$

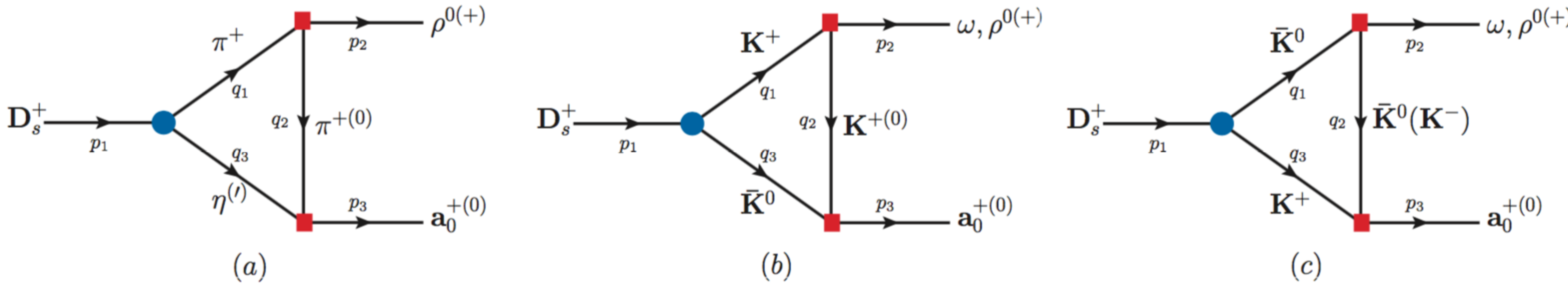
$$\mathcal{M}_{\eta'}(D_s^+ \to \pi^+\eta') = \frac{G_F}{\sqrt{2}} V_{cs}^* V_{ud}(\sqrt{2}A\sin\phi + T\cos\phi)\,,$$

$$\mathcal{M}_K(D_s^+ \to K^+\bar{K}^0) = \frac{G_F}{\sqrt{2}} V_{cs}^* V_{ud}(C + A)\,,$$

$$(|T|, |C|, |A|) = (0.363 \pm 0.001, 0.323 \pm 0.030, 0.064 \pm 0.004)\ \mathrm{GeV}^3\ \ ,$$

$$(\delta_C, \delta_A) = (-151.3 \pm 0.3, 23.0^{+7.0}_{-10.0})^\circ\,,$$

H.Y. Cheng and C.W. Chiang, Phys. Rev. D **100**, 093002 (2019)




$$\mathcal{M}_a = \int \frac{d^4q_1}{(2\pi)^4} \frac{\mathcal{M}_\eta \mathcal{M}_{\rho^{0(+)}\to\pi^+\pi^{-(0)}} \mathcal{M}_{a_0^{+(0)}\to\eta\pi^{+(0)}} F_\pi(q_2^2)}{(q_1^2 - m_\pi^2)[(q_1-p_2)^2 - m_\pi^2][(q_1-p_1)^2 - m_\eta^2]},$$

$$\mathcal{M}_b = \int \frac{d^4q_1}{(2\pi)^4} \frac{\mathcal{M}_K \mathcal{M}_{\rho^{0(+)}\to K^+K^-(K^+\bar{K}^0)} \mathcal{M}_{a_0^{+(0)}\to\bar{K}^0K^{+(0)}} F_K(q_2^2)}{(q_1^2 - m_K^2)[(q_1-p_2)^2 - m_K^2][(q_1-p_1)^2 - m_K^2]},$$

$$\mathcal{M}_c = \int \frac{d^4q_1}{(2\pi)^4} \frac{\mathcal{M}_K \mathcal{M}_{\rho^{0(+)}\to\bar{K}^0K^{0(+)}} \mathcal{M}_{a_0^{+(0)}\to\bar{K}^0K^{+(0)}} F_K(q_2^2)}{(q_1^2 - m_K^2)[(q_1-p_2)^2 - m_K^2][(q_1-p_1)^2 - m_K^2]},$$

$$\mathcal{M}(D_s^+ \to \rho^{0(+)} a_0^{+(0)}) = \mathcal{M}_a + \mathcal{M}_a' + \mathcal{M}_b + \mathcal{M}_c\,,$$

$$\mathcal{M}(D_s^+ \to \omega a_0^+) = \hat{\mathcal{M}}_b + \hat{\mathcal{M}}_c\,,$$

$$\mathcal{M}(D_s^+ \to \rho^0 a_0^+) = \mathcal{M}(D_s^+ \to \rho^+ a_0^0)\,,$$

$$\mathcal{M}(D_s^+ \to \omega a_0^+) = 0\,,$$

## Theoretical results

$$\mathcal{B}(D_s^+ \to \rho^{0(+)} a_0^{+(0)}) = (3.0 \pm 0.3 \pm 1.0) \times 10^{-3}\,,$$

$$\mathcal{B}(D_s^+ \to \omega a_0^+) = 0\,,$$

$$\mathcal{B}(D_s^+ \to \rho^{0(+)}(a_0^{+(0)} \to)\eta\pi^{+(0)}) = (1.6^{+0.2}_{-0.3} \pm 0.6) \times 10^{-3}\,,$$

$$\mathcal{B}(D_s^+ \to \rho^+(a_0^0 \to)K^+K^-, K^0\bar{K}^0) = (0.9^{+0.1}_{-0.1} \pm 0.4, 0.7^{+0.1}_{-0.1} \pm 0.3) \times 10^{-4}\,,$$

$$\mathcal{B}(D_s^+ \to \rho^0(a_0^+ \to)K^+\bar{K}^0) = (1.5^{+0.2}_{-0.3} \pm 0.6) \times 10^{-4}\,,$$

## Experimental data

$$\mathcal{B}_+(D_s^+ \to a_0^+\rho^0, a_0^+ \to \pi^+\eta) = (2.1 \pm 0.8 \pm 0.5) \times 10^{-3}\,,$$

$$\mathcal{B}_0(D_s^+ \to a_0^0\rho^+, a_0^0 \to K^+K^-) = (0.7 \pm 0.2 \pm 0.1) \times 10^{-3}\,,$$

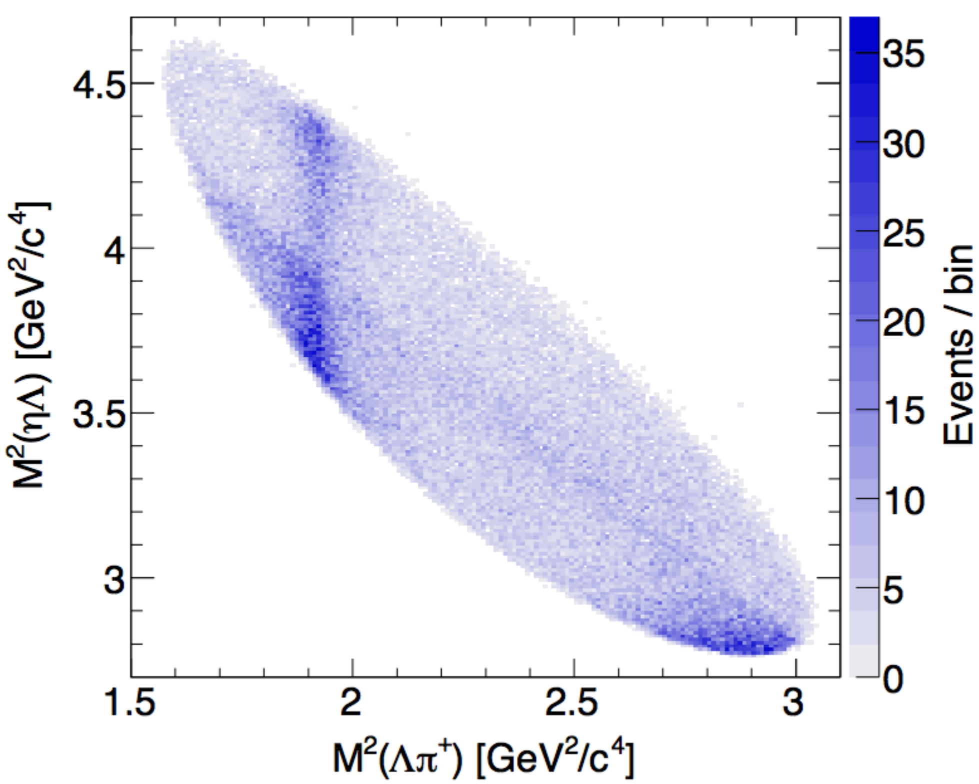
The total branching fraction [Belle, PRD103, 052005 (2021)]

$$\mathcal{B}(\Lambda_c^+ \to \Lambda\eta\pi^+) = (18.4 \pm 0.2 \pm 0.9 \pm 0.9) \times 10^{-3},$$

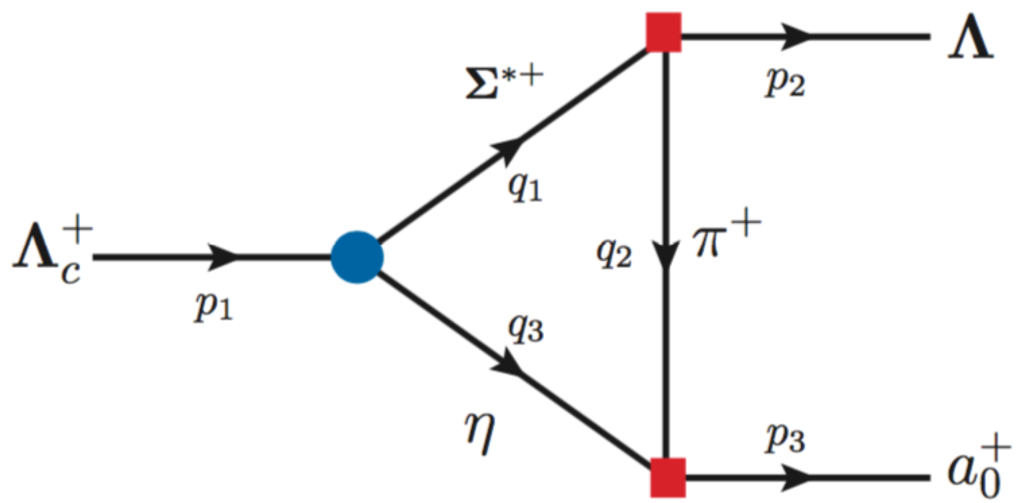
$$\mathcal{B}(\Lambda_c^+ \to \Lambda^*\pi^+, \Lambda^* \to \Lambda\eta) = (3.5 \pm 0.5) \times 10^{-3},$$

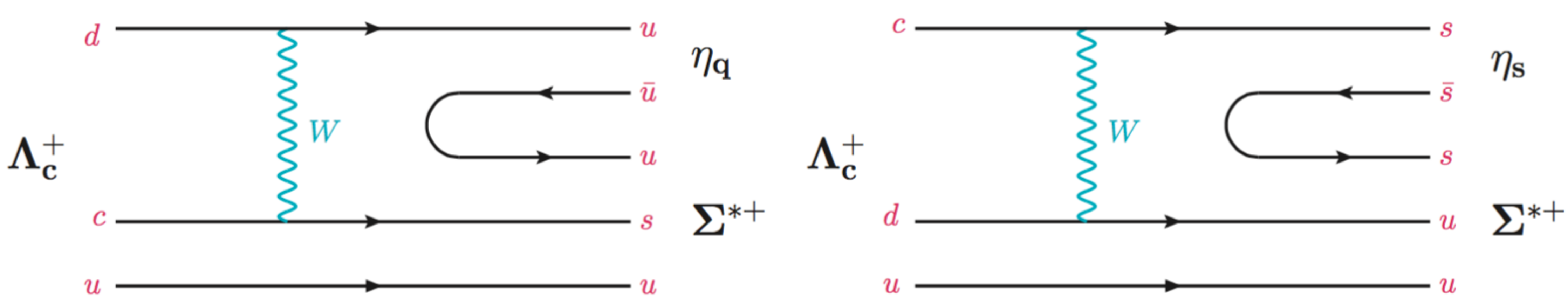
$$\mathcal{B}(\Lambda_c^+ \to \Sigma^{*+}\eta, \Sigma^{*+} \to \Lambda\pi^+) = (10.5 \pm 1.2) \times 10^{-3},$$

with $\Lambda^* \equiv \Lambda(1670)$ and $\Sigma^* \equiv \Sigma(1385)$.




A possible $\Lambda_c^+ \to \Lambda a_0^+, a_0^+ \to \eta\pi^+$ process.




$(a)\ E_{\mathbf{B}}$ $(b)\ E_M$

# Cabibbo-favored $\Lambda_c^+ \to \Lambda a_0(980)^+$ decay in the final state interaction

Yao Yu[1,*] and Yu-Kuo Hsiao[2,†]

PLB820, 136586 (2021)

$$\mathcal{B}(\Lambda_c^+ \to p f_0) = (3.5 \pm 2.3) \times 10^{-3}$$

measured in 1990

$$\mathcal{B}(\Lambda_c^+ \to \Lambda a_0^+) = (1.7^{+2.8}_{-1.0} \pm 0.3) \times 10^{-3}$$

## Summary

- We have studied the two-body $D_s^+$ decay channels: $D_s^+ \to a_0(\pi, \rho, \omega)$.
- In the rescatterining mechanism, we have obtained

$\mathcal{B}(D_s^+ \to \pi^{+(0)} a_0^{0(+)}, a_0^{0(+)} \to \pi^{0(+)}\eta) = (1.4 \pm 0.1 \pm 0.1) \times 10^{-2}$,

$\mathcal{B}(D_s^+ \to a_0^+ \rho^0, a_0^+ \to \pi^+\eta) = (1.6^{+0.2}_{-0.3} \pm 0.6) \times 10^{-3}$,

agreeing with the data; however,

$\mathcal{B}(D_s^+ \to \rho^+(a_0^0 \to)K^+K^-) = (0.9^{+0.1}_{-0.1} \pm 0.4) \times 10^{-4}$

is 10 times smaller than the observation.

- We have predicted

$\mathcal{B}(D_s^+ \to a_0^0\omega) \simeq \mathcal{B}(D_s^+ \to \pi^+\pi^0) < 3.4 \times 10^{-4}$

to be tested by future measurements.

# Thank You