The role of meson interactions in the $D_s^+ \to \pi^+\pi^+\pi^-\eta$ decay

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Outline

- **Introduction**
- **Theoretical formalism**
- **Results and discussion**
- **Summary**

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- Introduction
- Theoretical formalism
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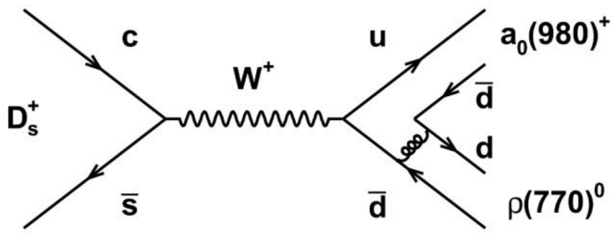
Introduction

- Experiment from *BESIII collaboration Phys.Rev.D 104 071101(2021)*

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



- Dynamic generation:
  - $a_0(980) \to \pi\eta$
  - $a_1(1260) \to \rho\pi$
  - …

- Motivation and goal: reproduce the six invariant mass distributions

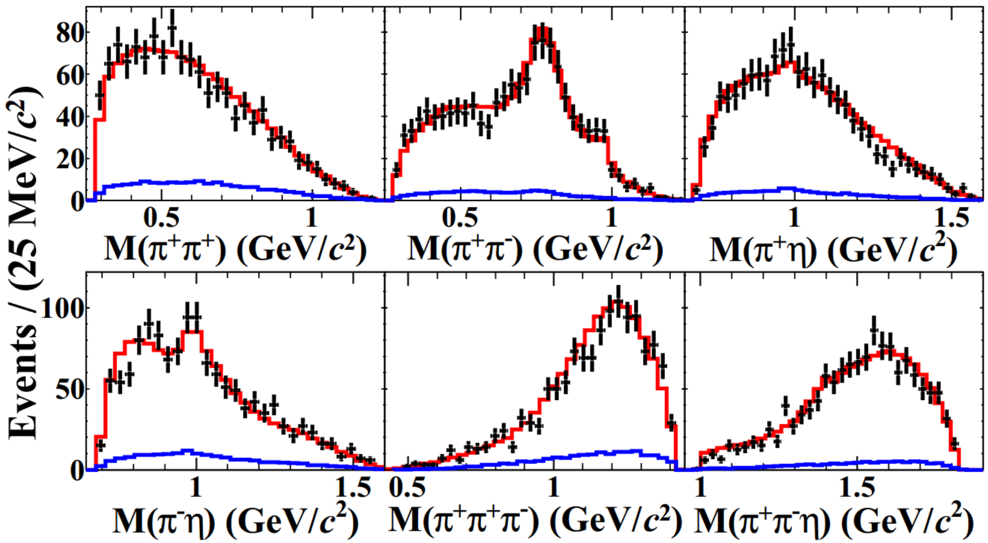


TABLE I. Phases and FFs for various intermediate processes. The first and the second uncertainties are statistical and systematic, respectively.

Amplitude	Phase	FF(%)
$a_1(1260)^+(\rho(770)^0\pi^+)\eta$	0.0(fixed)	$55.4 \pm 3.9 \pm 2.0$
$a_1(1260)^+(f_0(500)\pi^+)\eta$	$5.0 \pm 0.1 \pm 0.1$	$8.1 \pm 1.9 \pm 2.1$
$a_0(980)^+\rho(770)^0$	$2.5 \pm 0.1 \pm 0.1$	$6.7 \pm 2.5 \pm 1.5$
$\eta(1405)(a_0(980)^-\pi^+)\pi^+$	$0.2 \pm 0.2 \pm 0.1$	$0.7 \pm 0.2 \pm 0.1$
$\eta(1405)(a_0(980)^+\pi^-)\pi^+$	$0.2 \pm 0.2 \pm 0.1$	$0.7 \pm 0.2 \pm 0.1$
$f_1(1420)(a_0(980)^-\pi^+)\pi^+$	$4.3 \pm 0.2 \pm 0.4$	$1.9 \pm 0.5 \pm 0.3$
$f_1(1420)(a_0(980)^+\pi^-)\pi^+$	$4.3 \pm 0.2 \pm 0.4$	$1.7 \pm 0.5 \pm 0.3$
$[a_0(980)^-\pi^+]_S\pi^+$	$0.1 \pm 0.2 \pm 0.2$	$5.1 \pm 1.2 \pm 0.9$
$[a_0(980)^+\pi^-]_S\pi^+$	$0.1 \pm 0.2 \pm 0.2$	$3.4 \pm 0.8 \pm 0.6$
$[f_0(980)\eta]_S\pi^+$	$1.4 \pm 0.2 \pm 0.3$	$6.2 \pm 1.7 \pm 0.9$
$[f_0(500)\eta]_S\pi^+$	$2.5 \pm 0.2 \pm 0.3$	$12.7 \pm 2.6 \pm 2.0$

Outline

- Introduction
- **Theoretical formalism**

1. Hadronization of one $q\bar{q}$ pair
2. Rescattering from the tree level $\eta\rho^0\pi^+$ component
3. Two hadronizations: external and internal emission
4. Rescattering from the tree level $\eta f_0\pi^+$ component
5. Evaluation of the differential cross section: integral

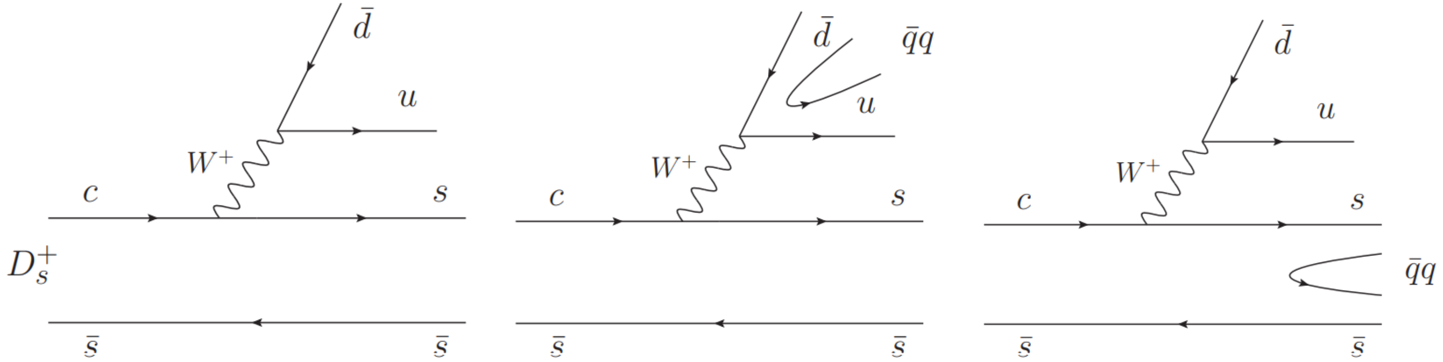
- Results and discussion
- Summary

1. Hadronization of one q$\bar{\text{q}}$ pair

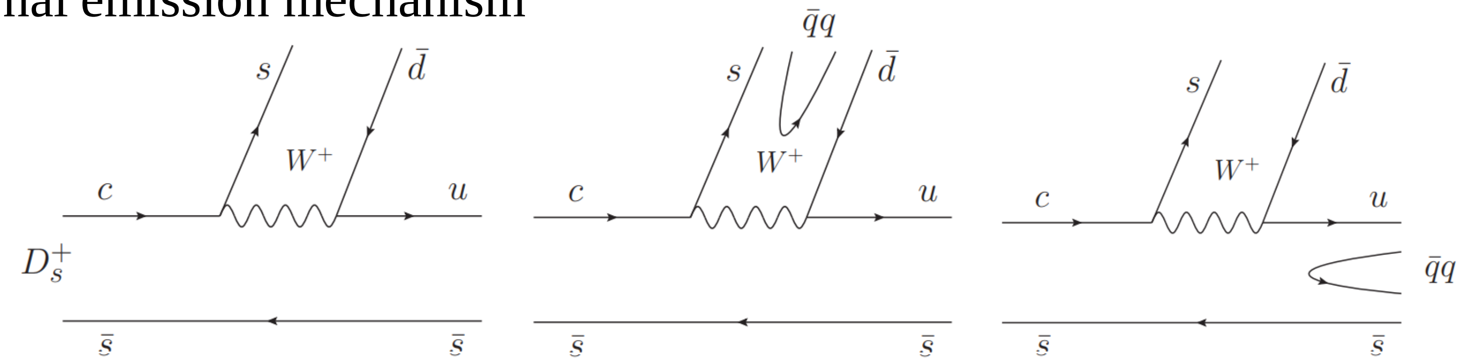
✓ Final states: G−parity: “−”; $\rho^0\pi\eta$ (**PPV**).

$$P = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{3}} + \frac{\eta'}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & \frac{-\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{3}} + \frac{\eta'}{\sqrt{6}} & K^0 \\ K^- & \bar{K}^0 & -\frac{\eta}{\sqrt{3}} + \frac{2\eta'}{\sqrt{3}} \end{pmatrix}, \quad V = \begin{pmatrix} \frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & \rho^+ & K^{*+} \\ \rho^- & \frac{-\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & K^{*0} \\ K^{*-} & \bar{K}^{*0} & \phi \end{pmatrix}$$

➢ External emission mechanism



➢ Internal emission mechanism

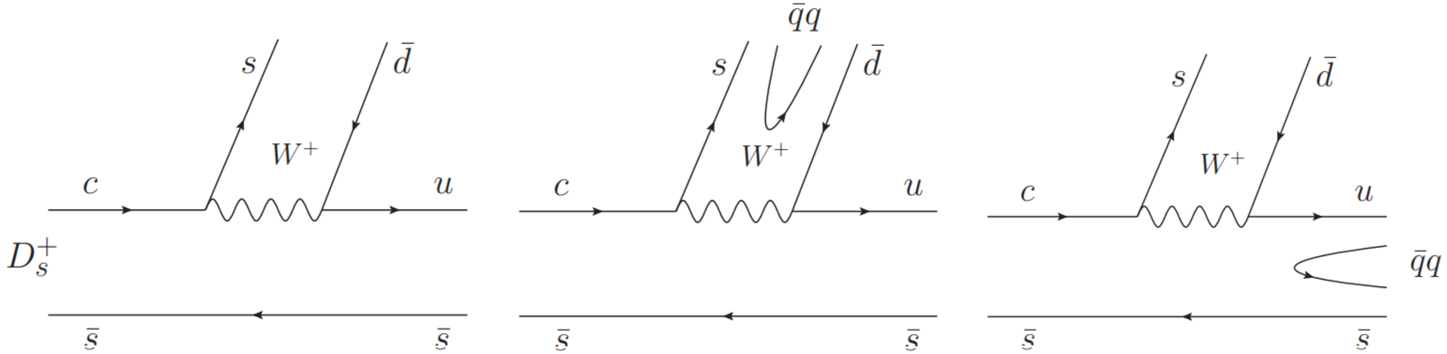


1. Hadronization of one qq̄ pair

✓ Final states: G–parity: "–"; $\rho^0\pi\eta$ (**PPV**).

$$P=\begin{pmatrix} \frac{\pi^0}{\sqrt{2}}+\frac{\eta}{\sqrt{3}}+\frac{\eta'}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & \frac{-\pi^0}{\sqrt{2}}+\frac{\eta}{\sqrt{3}}+\frac{\eta'}{\sqrt{6}} & K^0 \\ K^- & \bar{K}^0 & -\frac{\eta}{\sqrt{3}}+\frac{2\eta'}{\sqrt{3}} \end{pmatrix}, \quad V=\begin{pmatrix} \frac{\rho^0}{\sqrt{2}}+\frac{\omega}{\sqrt{2}} & \rho^+ & K^{*+} \\ \rho^- & \frac{-\rho^0}{\sqrt{2}}+\frac{\omega}{\sqrt{2}} & K^{*0} \\ K^{*-} & \bar{K}^{*0} & \phi \end{pmatrix}$$

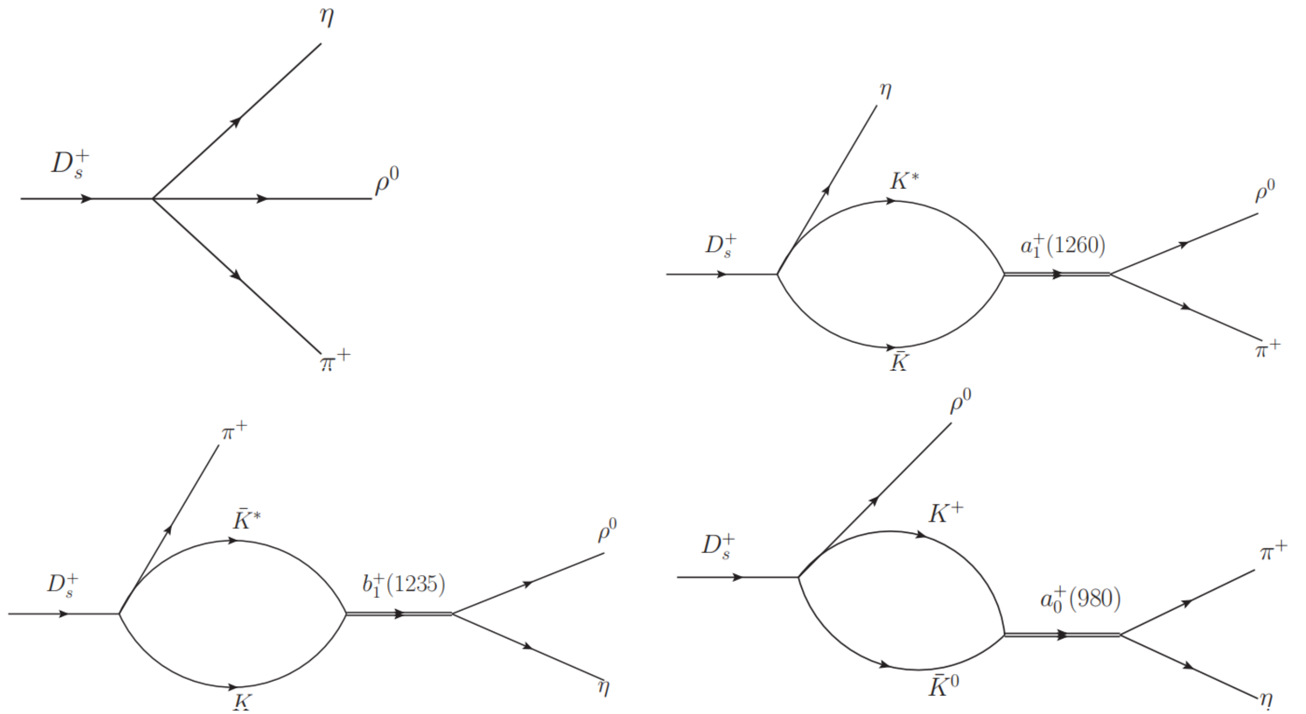
➢ Internal emission mechanism



1. Hadronize $s\bar{d}$ with PP and $u\bar{s}$ is a vector;
2. Hadronize $u\bar{s}$ to PP and $s\bar{d}$ is a vector;
3. Hadronize $s\bar{d}$ to VP, PV and $u\bar{s}$ is a pseudoscalar;
4. Hadronize $u\bar{s}$ to VP, PV and $s\bar{d}$ is a pseudoscalar.

1. Hadronization of one $q\bar{q}$ pair

- Ingredients



- Suitable states and the weights (α, β, γ)

C: Global normalization factor

$$|H1\rangle \equiv C\Big[-\sqrt{\frac{2}{3}}\eta\rho^0\pi^+ + \frac{\eta}{\sqrt{3}}(1+\alpha+\beta)(\bar{K}^{*0}K^+ - K^{*+}\bar{K}^0)$$
$$+\sqrt{2}\beta\rho^0K^+\bar{K}^0 + \alpha\pi^+(K^{*-}K^+ - K^{*0}\bar{K}^0) - \gamma\pi^+(\bar{K}^{*0}K^0 - K^{*+}K^-)\Big]$$

1. Hadronization of one $q\bar{q}$ pair

- Couplings

L. Roca et al.,Phys. Rev. D ***72****, 014002 (2005)*

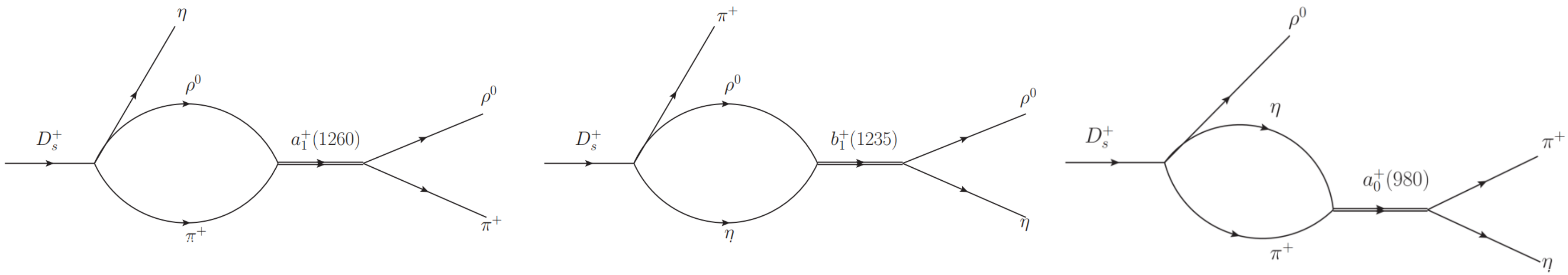
a_1		b_1	
$g_{\bar{K}^*K}$	$g_{\rho\pi}$	$g_{K^*\bar{K}}$	$g_{\rho\eta}$
$1872 - i1486$	$-3.795 + i2330$	$-3041 + i498$	$6172 - i75$

- Amplitude

$$
\begin{aligned}
t_{H1}(\pi^+\rho^0\eta) = C\Big[&-\sqrt{\frac{2}{3}} + \frac{\eta}{\sqrt{3}}(1+\alpha+\beta)G_{K^*\bar{K}}(M_{\rm inv}(\rho^0\pi^+))\frac{g_{a_1,K^*\bar{K}}\,g_{a_1,\rho\pi}}{M_{\rm inv}^2(\rho^0\pi^+) - M_{a_1}^2 + iM_{a_1}\Gamma_{a_1}} \\
&- \sqrt{2}\beta G_{K\bar{K}}(M_{\rm inv}(\pi^+\eta))\frac{g_{a_0,K\bar{K}}\,g_{a_0,\pi\eta}}{M_{\rm inv}^2(\pi^+\eta) - M_{a_0}^2 + iM_{a_0}\Gamma_{a_0}} \\
&- (\alpha+\gamma)G_{K^*\bar{K}}(M_{\rm inv}(\rho^0\eta))\frac{g_{b_1,K^*\bar{K}}\,g_{b_1,\rho\eta}}{M_{\rm inv}^2(\rho^0\eta) - M_{b_1}^2 + iM_{b_1}\Gamma_{b_1}}\Big]
\end{aligned}
$$

2. Rescattering from the tree level $\eta\rho^0\pi^+$ component

- Ingredients



- Couplings

L. Roca et al.,Phys. Rev. D ***72****, 014002 (2005)*

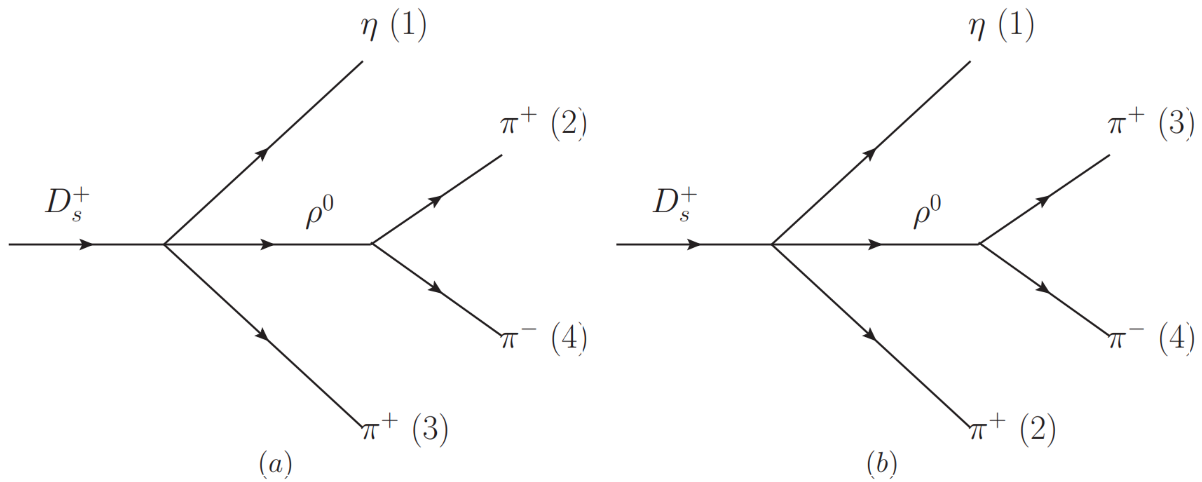
a_1		b_1	
$g_{\bar{K}^*K}$	$g_{\rho\pi}$	$g_{K^*\bar{K}}$	$g_{\rho\eta}$
$1872 - i1486$	$-3.795 + i2330$	$-3041 + i498$	$6172 - i75$

- Amplitude

$$t_{\text{RES}}(\rho^0\pi^+\eta) = -C\sqrt{\frac{2}{3}}G_{\rho\pi}(M_{\text{inv}}(\rho^0\pi^+))\frac{\frac{1}{\sqrt{2}}g_{a_1,\rho\pi}\frac{1}{\sqrt{2}}g_{a_1,\rho\pi}}{M^2_{\text{inv}}(\rho^0\pi^+) - M^2_{a_1} + iM_{a_1}\Gamma_{a_1}}$$
$$-C\sqrt{\frac{2}{3}}G_{\rho\eta}(M_{\text{inv}}(\rho^0\eta))\frac{g_{b_1,\rho\eta}g_{b_1,\rho\eta}}{M^2_{\text{inv}}(\rho^0\eta) - M^2_{b_1} + iM_{b_1}\Gamma_{b_1}} - C\sqrt{\frac{2}{3}}G_{\pi^+\eta}(M_{\text{inv}}(\pi^+\eta))\frac{g_{a_0,\pi\eta}g_{a_0,\pi\eta}}{M^2_{\text{inv}}(\pi\eta) - M^2_{a_0} + iM_{a_0}\Gamma_{a_0}}$$

2. Rescattering from the tree level $\eta\rho^0\pi^+$ component

- Symmetrized amplitude with ρ decaying to two pions.



- Amplitude

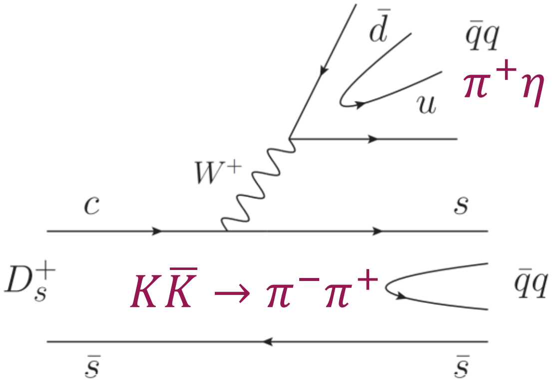
$$t_\rho = -C\left[P_{D_s}\cdot(p_4-p_2)\frac{1}{M_{\rm inv}^2(\rho,a)-M_\rho^2+iM_\rho\Gamma_\rho}t^{(a)}+P_{D_s}\cdot(p_4-p_3)\frac{1}{M_{\rm inv}^2(\rho,b)-M_\rho^2+iM_\rho\Gamma_\rho}t^{(b)}\right]$$

- ρ propagator: the sum over the ρ polarization

$$\sum_{pol} P_D^\mu \epsilon_\mu \epsilon_\nu (p_2-p_4)^\nu = P_D^\mu\left(-g_{\mu\nu}+\frac{q_\mu q_\nu}{m_{\rho^2}}\right)(p_2-p_4)^\nu$$

$$q=p_2+p_4;\ \mathrm{q}(p_2-p_4)=m_\pi^2-m_\pi^2=0$$

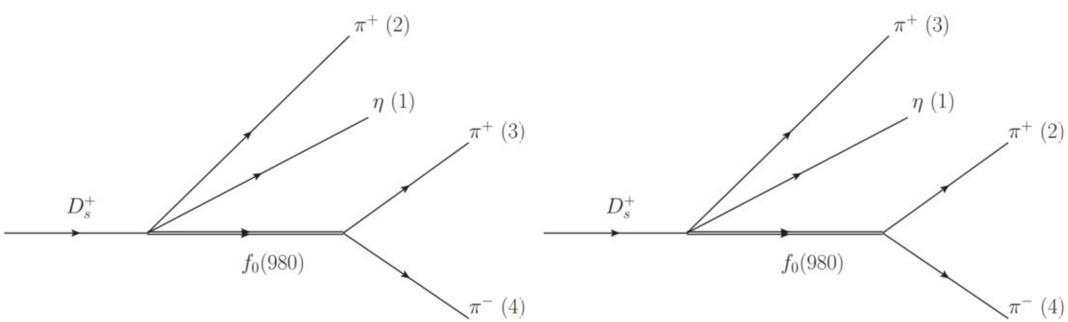
- Two hadronizations with external emission: $f_0(980)$ contribution



✓ Final states:

1. directly four pseudoscalars(**PPPP**)
2. G-parity: "–"

- Diagrams stemming from two hadronizations producing the $f_0(980)$ resonance.



- $f_0(980)$ propagator

$$D_{f_0} = \frac{1}{M^2_{\mathrm{inv}(\pi^-\pi^+(2))} - M^2_{f_0} + iM_{f_0}\Gamma_{f_0}}$$

$$\widetilde{D}_{f_0} = M_{f_0}\Gamma_{f_0}D_{f_0}$$

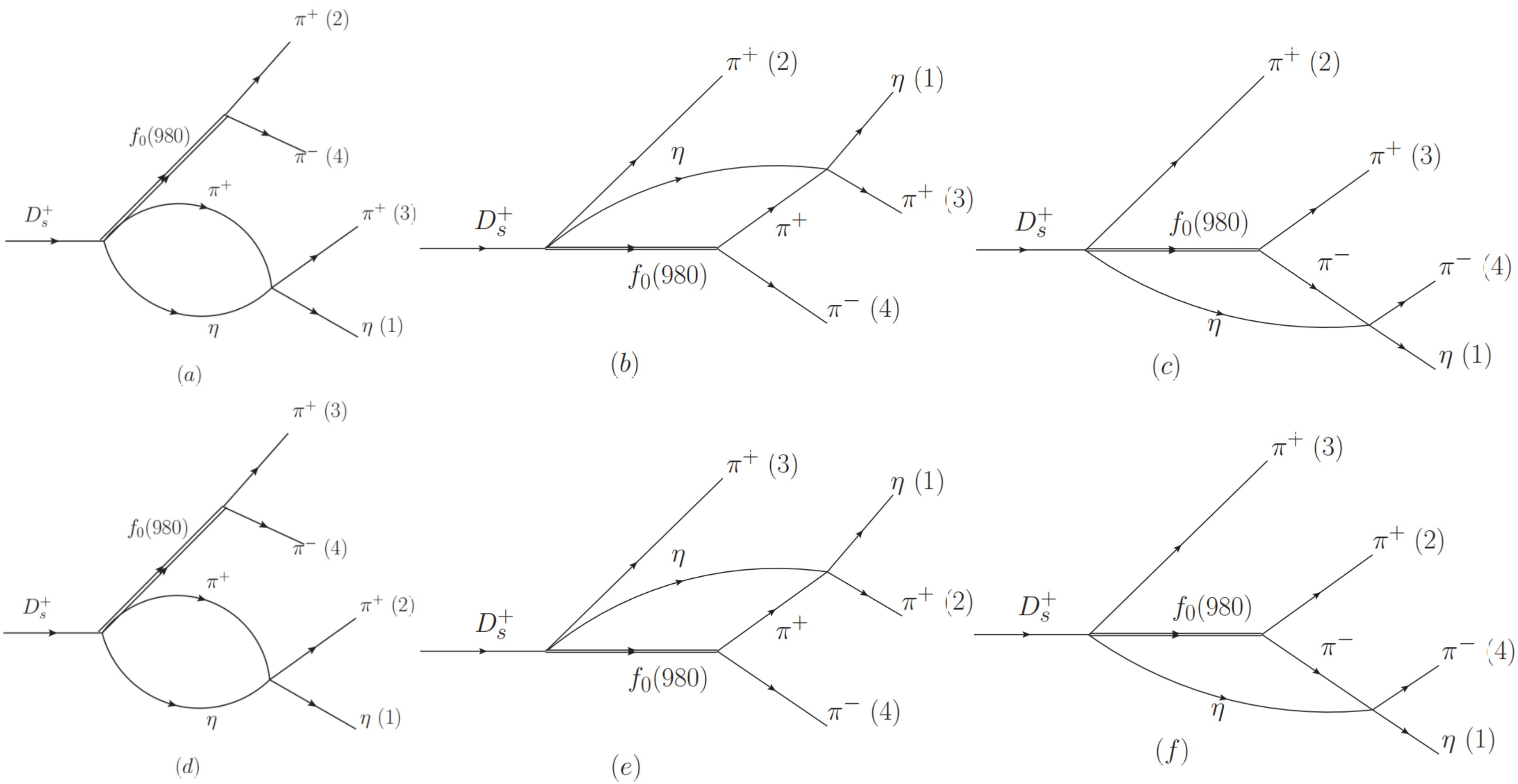
$\Gamma_{f_0} = 70\mathrm{MeV}$ (1~100 in PDG)

➢ Amplitude and the weight (μ)

$$t_1(f_0) = C\mu[\widetilde{D}_{f_0}\big(M_{\mathrm{inv}}(\pi^+(3)\pi^-)\big) + \widetilde{D}_{f_0}(M_{\mathrm{inv}}(\pi^+(2)\pi^-))]$$

4. Rescattering from the tree level $\eta f_0 \pi^+$ component

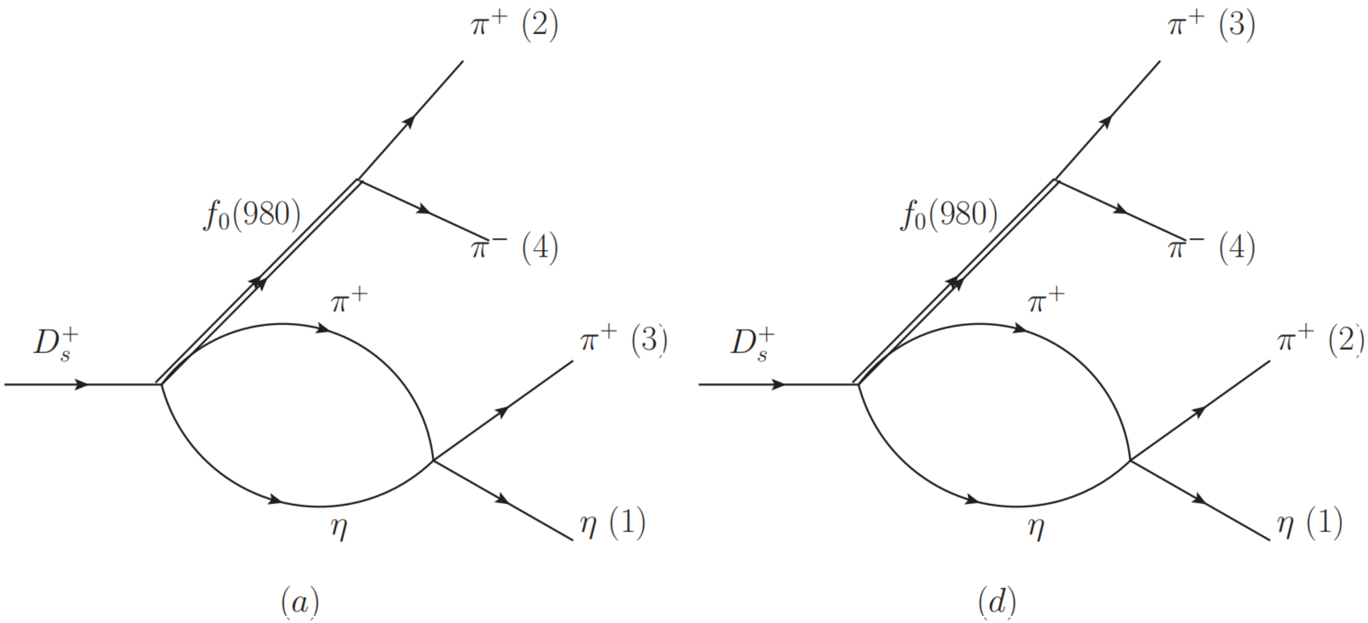
◆ Ingredients:



➢ Amplitude: $t_2(f_0) = t_{2a} + t_{2d} + t_{2b} + t_{2e} + t_{2c} + t_{2f}$

4. Rescattering from the tree level $\eta f_0 \pi^+$ component

➢ **Ingredient 1:**



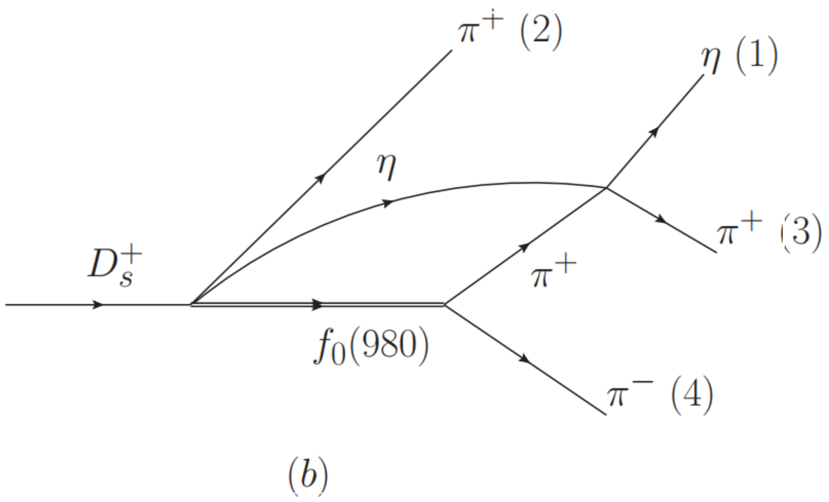
➢ Amplitude and the weight (μ)

$$t_{2a}(f_0) = C\mu\tilde{D}_{f_0}\left(M_{\rm inv}(\pi^+(2)\pi^-)\right)G_{\pi\eta}\left(M_{\rm inv}(\pi^+(3)\eta)\right)t_{\pi^+\eta,\pi^+\eta}\left(M_{\rm inv}(\pi^+(3)\eta)\right)$$

$$t_{2d}(f_0) = C\mu\tilde{D}_{f_0}\left(M_{\rm inv}(\pi^+(3)\pi^-)\right)G_{\pi\eta}\left(M_{\rm inv}(\pi^+(2)\eta)\right)t_{\pi^+\eta,\pi^+\eta}\left(M_{\rm inv}(\pi^+(2)\eta)\right)$$

4. Rescattering from the tree level $\eta f_0 \pi^+$ component

➢ Ingredient 2:



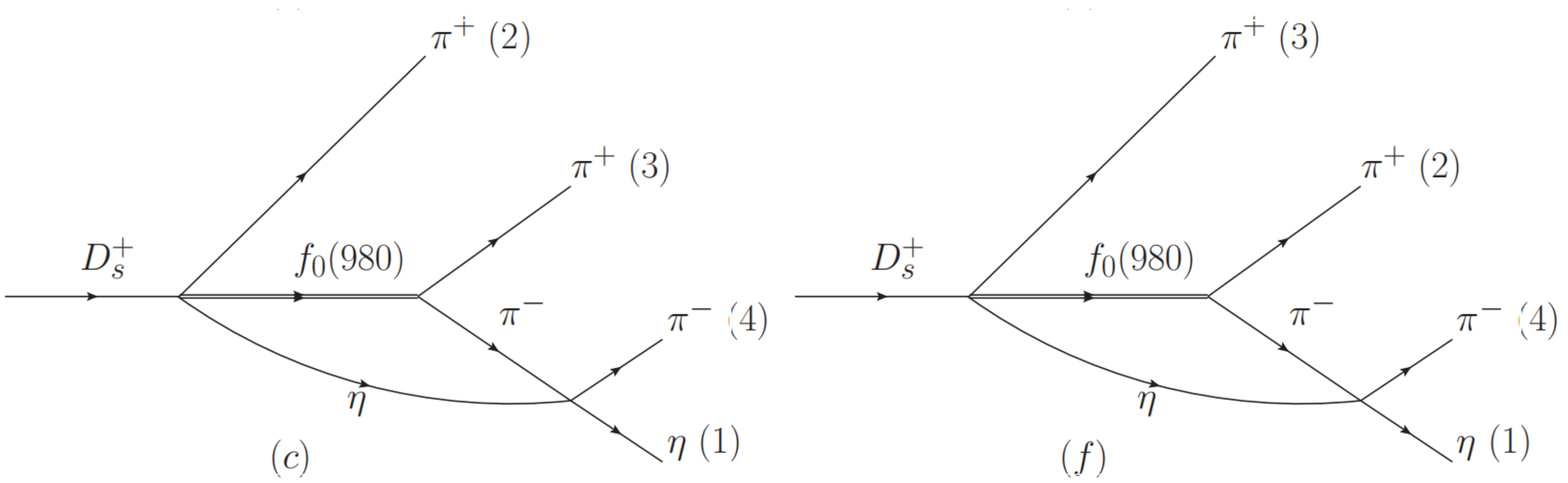
➢ Amplitude and the weight (μ)

$$t_{2b}(f_0) = C\mu\tilde{D}_{f_0}\left(M_{\rm inv}(\pi^-\pi^+_{\rm int})\right)G_{\pi\eta}\left(M_{\rm inv}(\pi^+(3)\eta)\right)t_{\pi^+\eta,\pi^+\eta}\left(M_{\rm inv}(\pi^+(3)\eta)\right)$$

$$t_{2c}(f_0) = C\mu\tilde{D}_{f_0}\left(M_{\rm inv}(\pi^+(3)\pi^-_{\rm int})\right)G_{\pi\eta}\left(M_{\rm inv}(\pi^-\eta)\right)t_{\pi^-\eta,\pi^-\eta}\left(M_{\rm inv}(\pi^-\eta)\right)$$

4. Rescattering from the tree level $\eta f_0 \pi^+$ component

➢ **Ingredient 3:**



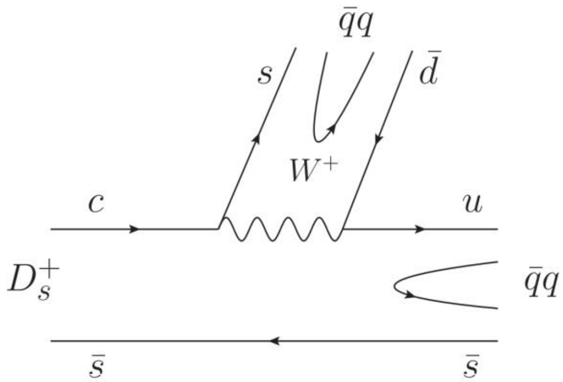
➢ Amplitude and the weight (μ)

$$t_{2e}(f_0) = C\mu\tilde{D}_{f_0}\left(M_{\rm inv}(\pi^-\pi^+_{\rm int})\right)G_{\pi\eta}\left(M_{\rm inv}(\pi^+(2)\eta)\right)t_{\pi^+\eta,\pi^+\eta}\left(M_{\rm inv}(\pi^+(2)\eta)\right)$$

$$t_{2f}(f_0) = C\mu\tilde{D}_{f_0}\left(M_{\rm inv}(\pi^+(2)\pi^-_{\rm int})\right)G_{\pi\eta}\left(M_{\rm inv}(\pi^-\eta)\right)t_{\pi^-\eta,\pi^-\eta}\left(M_{\rm inv}(\pi^-\eta)\right)$$

3. Two hadronizations: internal emission

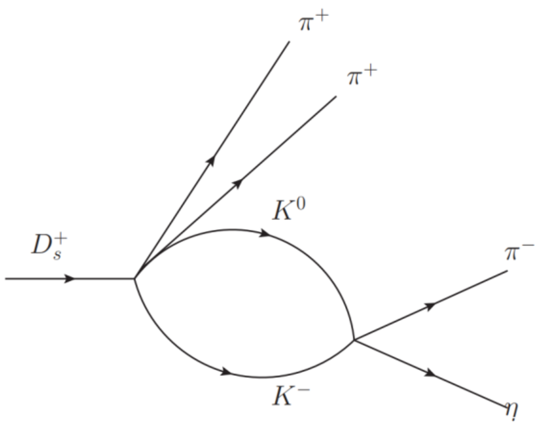
◆ Decay emission



◆ Mechanism contribution of $K^0K^- \to a_0^- \to \pi^-\eta$

Final states

1. directly 4 PPPP
2. G-parity: “–”



➢ Amplitude and the weight (ν)

$$t_{\mathrm{DIE}} = C\nu G_{K\bar{K}}(M_{\mathrm{inv}}(\pi^-\eta))t_{\pi^-\eta,\,K^0K^-}$$

◆ **Full amplitude:**

$$\boldsymbol{t = t_{\mathrm{H1}} + t_{\mathrm{RES}} + t_1(f_0) + t_2(f_0) + t_{\mathrm{DIE}}}$$

5. Evaluation of the differential cross section: integral

◆ The width for the D_s decay into $\pi^+\pi^+\pi^-\eta$

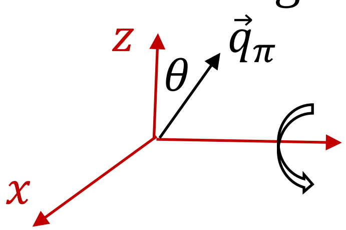
$$\Gamma = \frac{1}{2M_{D_s}}\frac{1}{2}\int\frac{\mathrm{d}^3p_\eta}{(2\pi)^3}\frac{1}{2E_\eta}\int\frac{\mathrm{d}^3p_{\pi^+}}{(2\pi)^3}\frac{1}{2E_{\pi^+}}\int\frac{\mathrm{d}^3p'_{\pi^+}}{(2\pi)^3}\frac{1}{2E'_{\pi^+}}\int\frac{\mathrm{d}^3p_{\pi^-}}{(2\pi)^3}\frac{1}{2E_{\pi^-}}(2\pi)^4\delta^{(4)}(P-p_\eta-p_{\pi^+}-p'_{\pi^+}-p_{\pi^-})|t|^2$$

- Define the η in the z direction:
  - ➢ $\delta()$ condition allows us to obtain the relation of $\cos\theta$ and variables:

$$\cos\theta \equiv A = \frac{1}{2P_\pi p_\eta}\left[(M_{D_s}-E_\eta-E_{\pi^+}-E'_{\pi^+})^2-m^2_{\pi^-}-\mathbf{P}^2_\pi-\mathbf{p}^2_\eta\right]$$

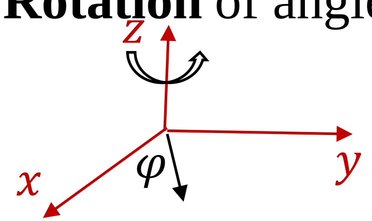
- Define the $\boldsymbol{P_\pi}$ in the z direction:

a. Rotation of angle θ in the xz plane, i.e. the $\boldsymbol{q_\pi}$ along to y-axis,



$$R_\theta\begin{pmatrix}1\\0\\0\end{pmatrix}=\begin{pmatrix}\sin\theta\\0\\\cos\theta\end{pmatrix}\quad R_\theta\begin{pmatrix}0\\1\\0\end{pmatrix}=\begin{pmatrix}0\\1\\0\end{pmatrix}\quad R_\theta\begin{pmatrix}1\\0\\0\end{pmatrix}=\begin{pmatrix}\sin\theta\\0\\\cos\theta\end{pmatrix}$$

b. Rotation of angle φ in the xy plane, i.e. the $\boldsymbol{q_\pi}$ along to z-axis,



$$R_\phi\begin{pmatrix}1\\0\\0\end{pmatrix}=\begin{pmatrix}\cos\phi\\\sin\phi\\0\end{pmatrix}\quad R_\phi\begin{pmatrix}0\\1\\0\end{pmatrix}=\begin{pmatrix}-\sin\phi\\\cos\phi\\0\end{pmatrix}\quad R_\phi\begin{pmatrix}0\\0\\1\end{pmatrix}=\begin{pmatrix}0\\0\\1\end{pmatrix}$$

- **The complete rotation: $q = R\tilde{q}$**

$$R = R_\phi R_\theta = \begin{pmatrix} \cos\phi & -\sin\phi & 0 \\ \sin\phi & \cos\phi & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{pmatrix} = \begin{pmatrix} \cos\phi\cos\theta & -\sin\phi & \cos\phi\sin\theta \\ \sin\phi\cos\theta & \cos\phi & \sin\phi\sin\theta \\ -\sin\theta & 0 & \cos\theta \end{pmatrix}$$

where, the other variables are:

$$\mathbf{p}_\eta = p_\eta \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}; \quad \mathbf{P}_\pi = P_\pi \begin{pmatrix} \sin\theta\cos\phi \\ \sin\theta\sin\phi \\ \cos\theta \end{pmatrix}, \quad (\cos\theta = A, \quad \sin\theta = \sqrt{1 - A^2})$$

$$\tilde{\mathbf{q}} = q \begin{pmatrix} \sin\tilde{\theta}_q \cos\tilde{\phi}_q \\ \sin\tilde{\theta}_q \sin\tilde{\phi}_q \\ \cos\tilde{\theta}_q \end{pmatrix}$$

$$\begin{aligned} E_{\pi^+} + E'_{\pi^+} &= \sqrt{m_\pi^2 + \frac{1}{4}(\mathbf{P}_\pi + \mathbf{q})^2} + \sqrt{m_\pi^2 + \frac{1}{4}(\mathbf{P}_\pi - \mathbf{q})^2} \\ &= \sqrt{m_\pi^2 + \frac{1}{4}P_\pi^2 + \frac{1}{4}q^2 + \frac{1}{2}P_\pi q\cos\tilde{\theta}_q} + \sqrt{m_\pi^2 + \frac{1}{4}P_\pi^2 + \frac{1}{4}q^2 - \frac{1}{2}P_\pi q\cos\tilde{\theta}_q} \end{aligned}$$

◆ Simplify, angle rotations, and variable substitution

$$\Gamma = \frac{1}{8M_{D_s}} \frac{1}{4\pi} \int \mathrm{d}E_\eta \int \frac{P_\pi \mathrm{d}P_\pi \mathrm{d}\phi}{(2\pi)^3} \int \frac{q^2 \mathrm{d}q \,\mathrm{d}\cos\tilde{\theta}_q \mathrm{d}\tilde{\phi}_q}{(2\pi)^3} \frac{1}{2E_{\pi^+}} \frac{1}{2E'_{\pi^+}} |t|^2 \theta(1 - A^2)\theta(M_{D_s} - E_\eta - E_{\pi^+} - E'_{\pi^+})$$

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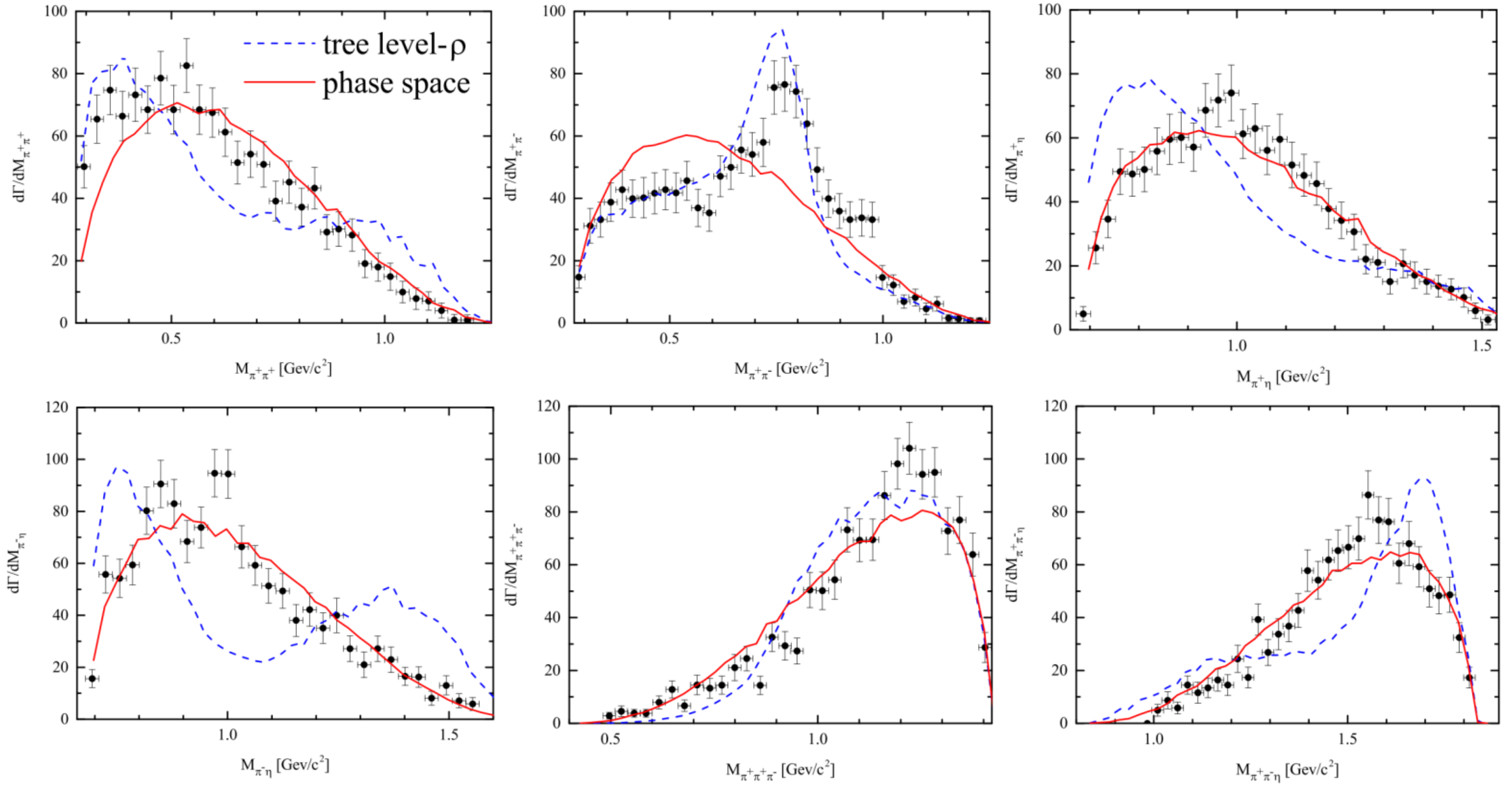
Results| Phase space and the tree-level of ρ

◆ Phase space: missing all the different structures which are visible in the experimental data.

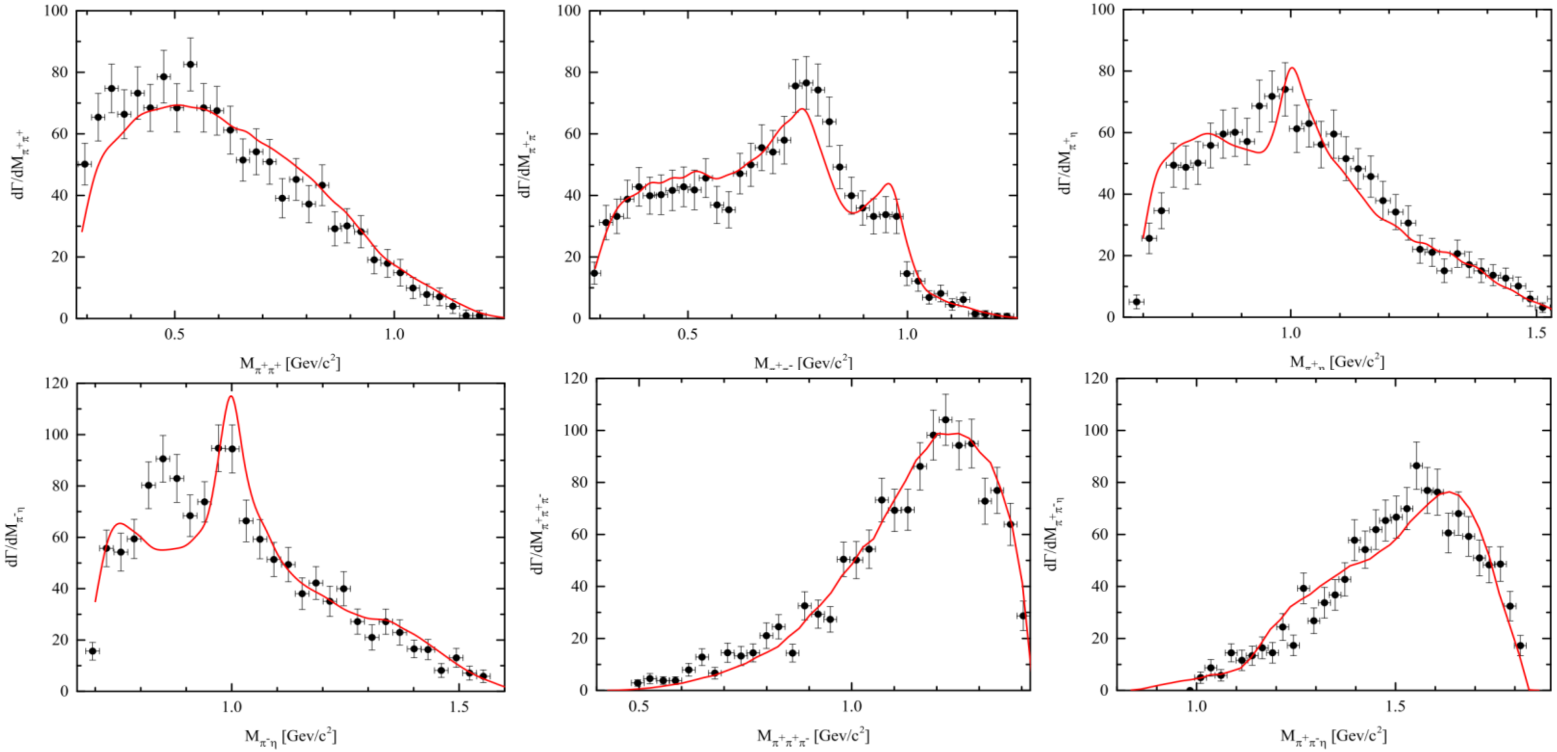


◆ the contribution of the $\eta\rho^0\pi^+$ term alone at the tree level.

1. ρ peak in the $M_{\pi^+\pi^-}$ distribution
2. A broad bump in $M_{\pi^+\pi^-}$ at 0.5 GeV. Not $f_0(500)$! (ρ term)

Results| the different mass distributions

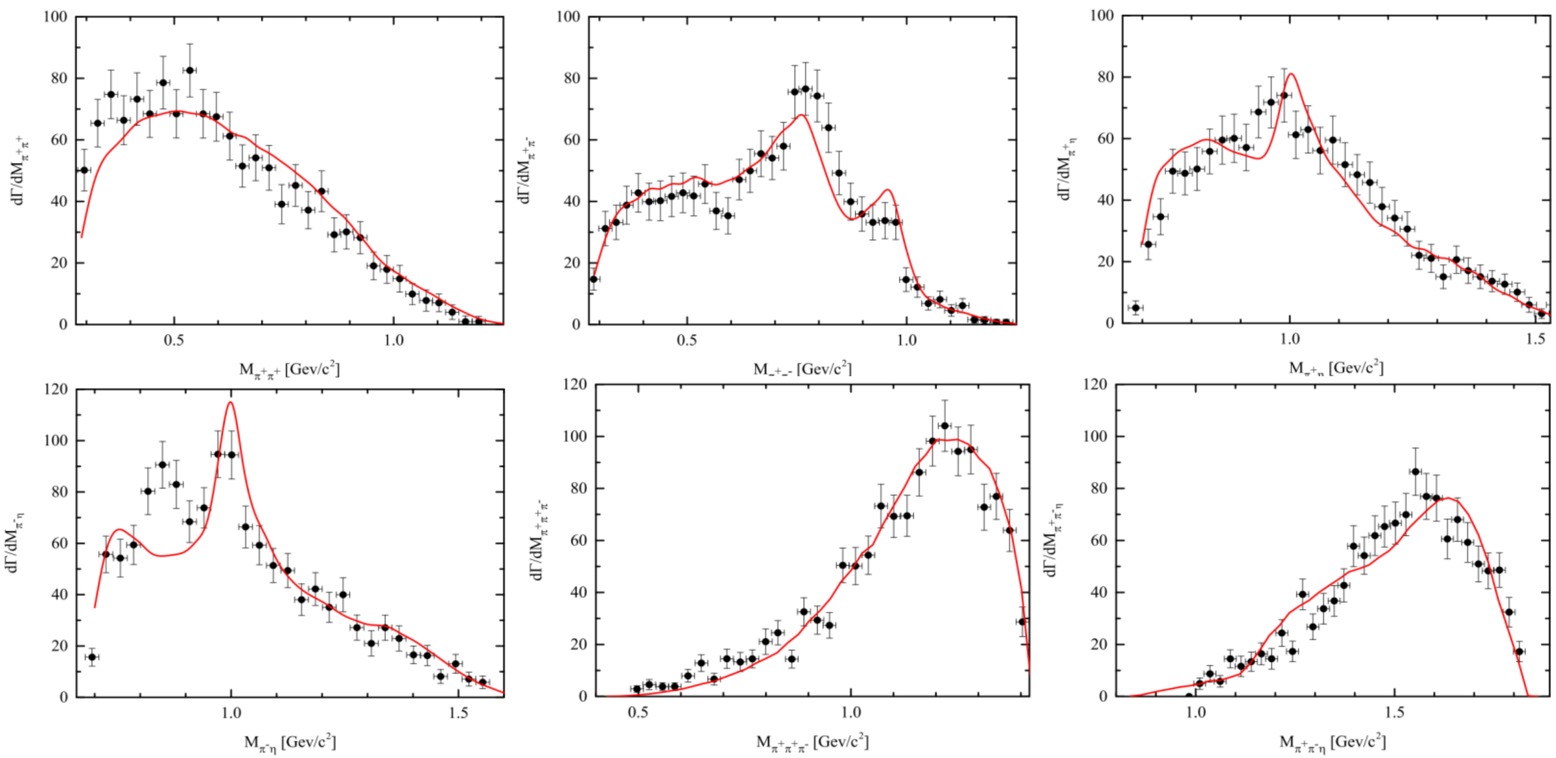
◆ Formalism comes from the systematic consideration of all possible mechanisms



◆ A best fit to all the six mass distributions

1. $\alpha = 4.2387, \beta = 2.8878, \gamma = -3.9334, \mu = -31.161, \nu = -39.092$ $(\chi^2/\mathrm{d.o.f} = 1.77)$
2. The improvement over the mass distributions of the tree level $\eta\rho^0\pi^+$ term is remarkable.

- Formalism comes from the systematic consideration of all possible mechanisms



- The low and high energy bump of the mass distribution is well reproduced

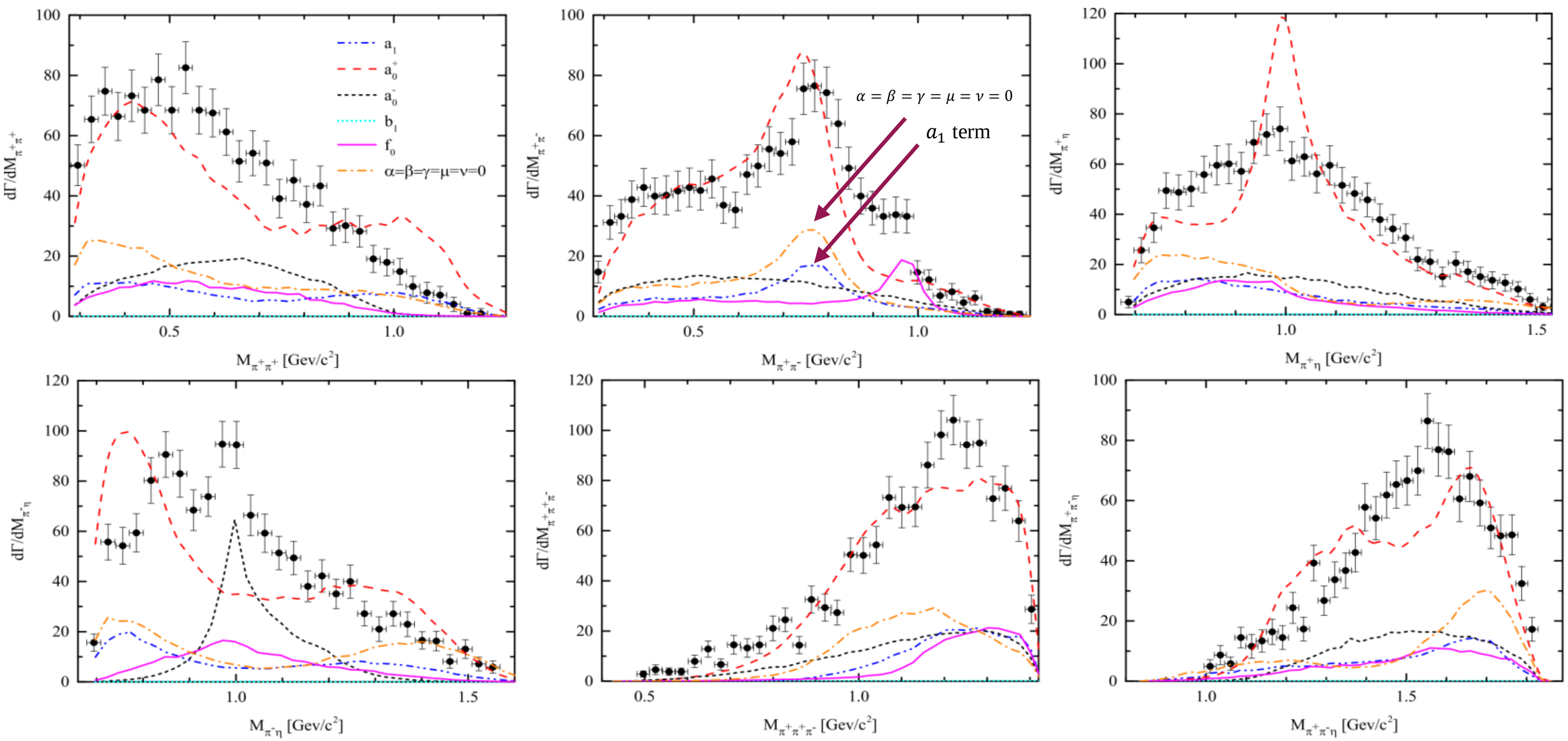
3. ρ^0, $f_0(980)$, $a_0^+(980)$, $a_0^-(980)$ peak in the $M_{\pi^+\pi^-}$, $M_{\pi^+\eta}$, $M_{\pi^-\eta}$distribution;

4. $M_{\pi^+\pi^+\pi^-}$, $M_{\pi^+\pi^-\eta}$distributions are also in good agreement with the experiment.

!! A peak around 0.85 GeV that we cannot reproduce and do not know its dynamical origin

Results| The contributions of a_1, a_0^+ , a_0^- , b_1, f_0, and external emission

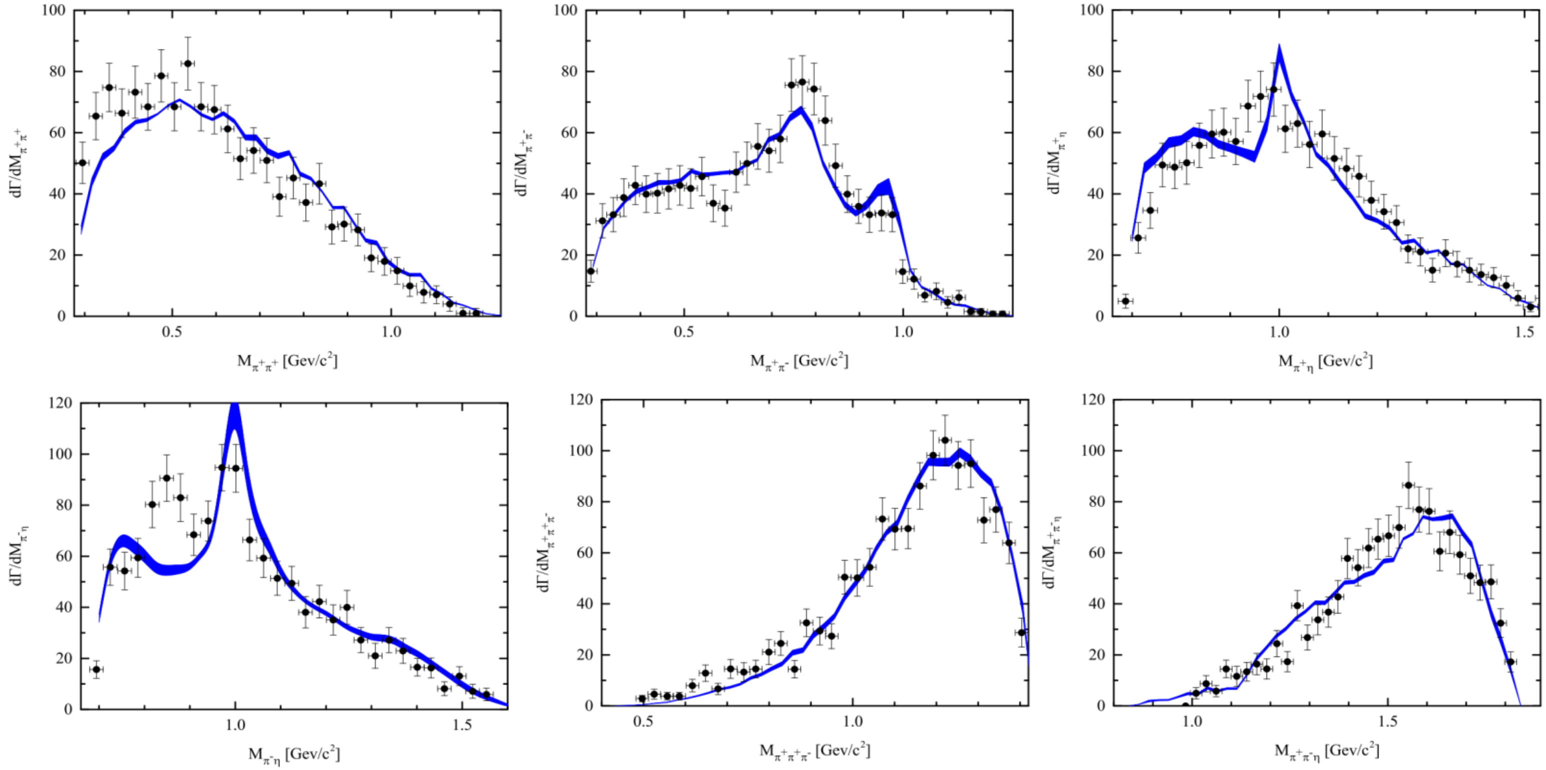
◆ The contribution of the different resonances



◆ The contributions to the mass distributions: interferences among the different amplitudes

1. The dominant contribution comes from a_0^+
2. $\alpha = \beta = \gamma = \mu = \nu = 0, a_1$ term: ρ peak appears
3. The strength of b_1^+ is practically negligible(mechanisms excitation without experiment!).

◆ Theoretical error bands vs. experimental data



◆ The parameters are different for each fit

1. The bands are so narrow: small uncertainties in the fit results.
2. Take care of the value of the parameters: the strong correlations of the parameters.

Outline

- Introduction
- Theoretical Formalism
- Results and discussion
- **Summary**

Summary

◆ The study of $D_s^+ \to \pi^+\pi^+\pi^-\eta$ reaction: final state interaction of pairs of mesons

1. The first time of $D_s^+ \to$ in quark level with external and internal emission.
2. We have made a theoretical study of the $D_s^+ \to \pi^+\pi^+\pi^-\eta$ reaction taking into account the **final state** interaction of pairs of mesons. (the filter of **G-parity**)
3. A support for the amplitudes studied by **chiral unitary approach**: we obtain a good reproduction of the 6 invariant mass distributions with **less freedom(5) than** the experiment analysis(19).
4. In these mass distributions: we could clearly see peaks for the ρ^0, a_1, a_0^+, a_0^-, f_0 in reasonable agreement with experiment.
5. The fit parameters have large uncertainties but there are strong correlations between them such that the uncertainties in the fit are small.

Thanks for your attention!