Triangle Singularity Enhancing Isospin Violation in $D_s^+ \to \pi^+\pi^0 f_0(980)$ and $\bar{B}_s^0 \to J/\psi\pi^0 f_0(980)$ Decays

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Based on: WHL, S. Sakai, J.J. Xie, E. Oset, CPC 42(2018)044101;
S. Sakai, E. Oset, WHL, PRD96 (2017) 074025.

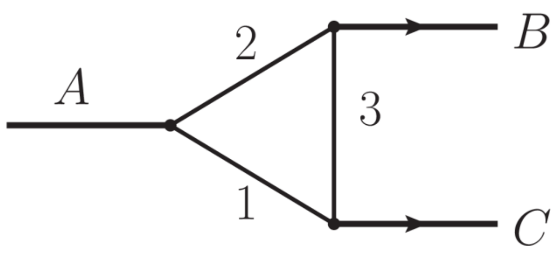
Outline

- Introduction and motivation
- Formalism
- Results and discussions
- Summary

◆ Introduction and motivation

• Triangle singularity (TS) in a reaction

$$A \to B + C$$



[Landau, Nucl. Phys. 13(1959)181]

[Coleman, Norton, Nuovo Cim. 38 (1965)438]

[Bayar, Aceti, Guo, Oset, PRD 94 (2016)074039]

When all the intermediate particles are placed on-shell and collinear in the rest frame of *A*, a singularity in the decay amplitude *T* develops.

If the internal particles have zero width, $|T| \to \infty$;
If the internal particles have non-zero width, $|T|$ **turns into a finite peak.**

$$\text{TS} \Rightarrow \begin{cases} \text{simulating a resonance;} \\ \text{providing a mechanism for the production} \\ \qquad\qquad \text{of particular modes in reactions;} \\ \cdots \end{cases}$$

Examples:

✓ The $a_1(1420)$ resonance, claimed by COMPASS, would not be a real state but the effect of TS in $a_1(1260) \to \pi f_0(980)$;

COMPASS, PRL115(2015)082001; X.H. Liu, M. Oka, Q. Zhao, PLB753(2016)297;

✓ $f_1(1420)$ corresponds to TS in $f_1(1285) \to \pi f_0(980)$;

Debastiani, Aceti, WHL, Oset, PRD95(2017)034015;

✓ $f_2(1810)$ peak comes from TS involving $K^* \bar{K}^*$ production;

Xie, Geng, Oset, PRD95(2017)034004;

…

◆ Introduction and motivation

- **$f_0(980)$-$a_0(980)$ mixing and isospin violation**

A recurrent topic shedding further light into the internal structure of $f_0(980)$ and $a_0(980)$.

Examples:

✓ The large isospin violation in $\eta(1405) \to \pi^0 f_0(980)$ is due to a TS;

BESIII, PRL108(2012)182001;

J.J. Wu, X.H. Liu, Q. Zhao, B.S. Zou , PRL108(2012)081803;

F. Aceti, WHL, E. Oset, B.S. Zou, PRD86(2012)114007;

✓ The isospin violation in $f_1(1285) \to \pi^0 f_0(980)$, $\pi^0 a_0(980)$ was studied theoretically, and was confirmed latter in a BESIII experiment.

Aceti, Dias, Oset, EPJA51(2015)48;

BESIII, PRD92(2015)012007;

◆ Introduction and motivation

• The purpose of our work:

To search for TS enhanced isospin-violating reactions producing the $f_0(980)$ and $a_0(980)$ resonances, to show the isospin violation as a function of the initial energy.

The selected reactions:

$$D_s^+ \to \pi^+\pi^0 a_0(980)(f_0(980)),$$

$$\bar{B}_s^0 \to J/\psi \pi^0 a_0(980)(f_0(980))$$

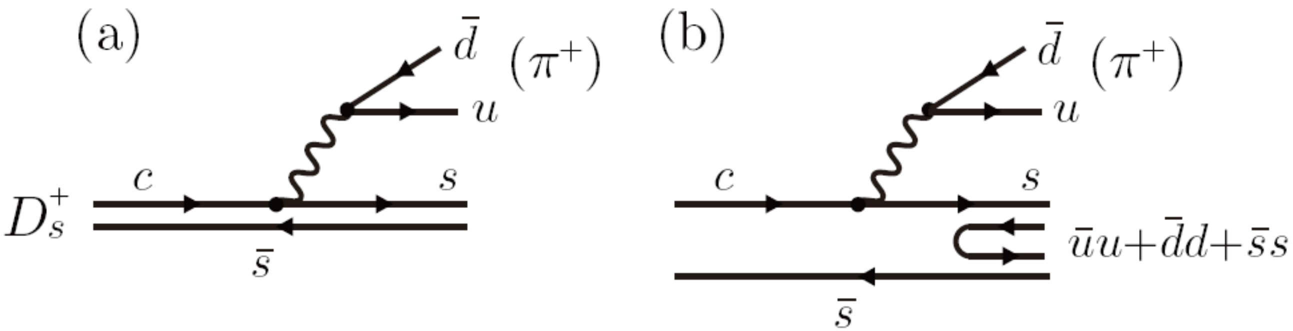
The $a_0(980)$ production mode is isospin-allowed, while the $f_0(980)$ production mode is isospin-forbidden.

Based on the notion that the $a_0(980)$ and $f_0(980)$ are generated from the interaction of pseudoscalar mesons, the results obtained will be tied to the molecular picture of the low lying scalar mesons.

◆ Formalism (for $D_s^+ \to \pi^+\pi^0 a_0(980)(f_0(980))$)

A. The $D_s^+ \to \pi^+ K^0 \bar{K}^{*0}$ reaction

Basic diagram at the quark level:



The hadronization produces a K and an anti-K*:

$$s\bar{s}(\bar{u}u + \bar{d}d + \bar{s}s) = K^+K^{*-} + K^0\bar{K}^{*0} + \cdots ,$$

where "$\cdots$" indicate terms inη, η' which play no role in the reaction that we study.

$$\frac{d\Gamma_{D_s^+ \to \pi^+ K^+ K^{*-}}}{dM_{\rm inv}(K^+ K^{*-})} = \frac{1}{(2\pi)^3} \frac{p_{\pi^+} \tilde{p}_{K^{*-}}}{4m_{D_s^+}^2} C^2 p'^2_{\pi^+},$$

C is a common factor containing contributions from weak vertex, determined by fitting the experimental data for $\mathrm{BR}(D_s^+ \to \pi^+ K^{*-} K^+)$

B. The $D_s^+ \to \pi^+ \pi^0 a_0(980)(f_0(980))$ reaction

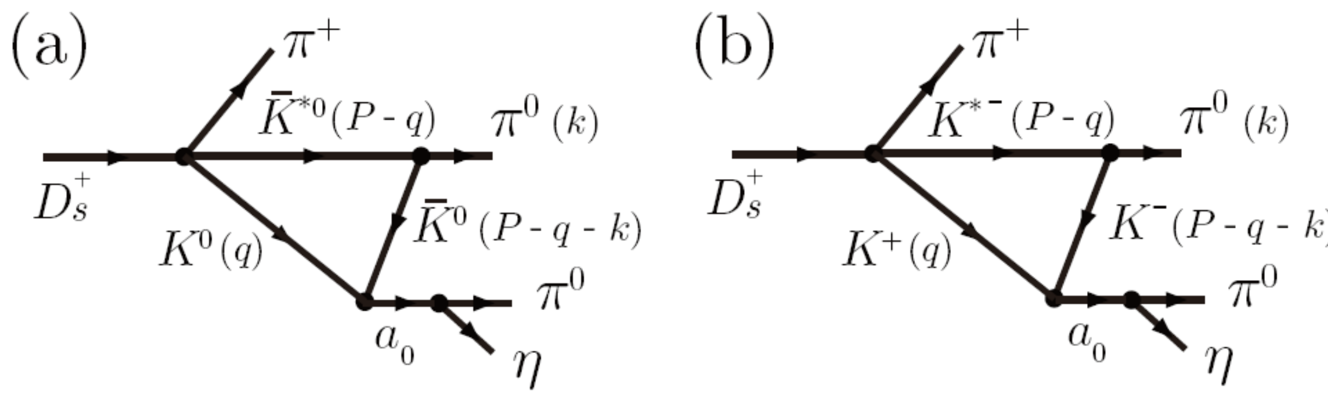


FIG. 2: Triangle mechanism which produces $\pi^+\pi^0 a_0(980)$. The $\pi^+\pi^0 f_0(980)$ channel could be seen replacing $\pi^0\eta$ by $\pi^+\pi^-$ at the end. The momenta of the particles are given in the brackets.

The double differential mass distribution for $D_s^+ \to \pi^+\pi^0 a_0(980)$ decay

$$\frac{d^2\Gamma}{dM_{\rm inv}(\pi^0 a_0)dM_{\rm inv}(\pi^0\eta)} = \frac{1}{(2\pi)^5}\frac{p_{\pi^+} k\,\tilde{p}_\eta}{4m^2_{D_s^+}}|t'_{\rm eff}|^2,$$

$$|t'_{\rm eff}|^2 = \frac{1}{6}C^2 g^2 p'^2_{\pi^+} k^2 \left| t_T(K^0\bar{K}^0\bar{K}^{*0}) t_{K^0\bar{K}^0,\pi^0\eta} - t_T(K^+K^-K^{*-}) t_{K^+K^-,\pi^0\eta}\right|^2 .$$

$$t_T = i\int \frac{d^4q}{(2\pi)^4}\frac{1}{q^2 - m^2_{K^0} + i\epsilon}\frac{1}{(P-q)^2 - m^2_{\bar{K}^{*0}} + i\epsilon} \cdot \frac{1}{(P-q-k)^2 - m^2_{\bar{K}^0} + i\epsilon}\left(2 + \frac{\vec{q}\cdot\vec{k}}{\vec{k}^2}\right) \quad (14)$$

For the case of $f_0(980)$ production, we use the same formula, substituting $\pi^0\eta$ in T matrices by $\pi^+\pi^-$.

Formalism (for $\bar{B}_s^0 \to J/\psi \pi^0 a_0(980)(f_0(980))$)

A. The $\bar{B}_s^0 \to \pi^+ K^{*0} \bar{K}^0$ decay

Basic diagram at the quark level:

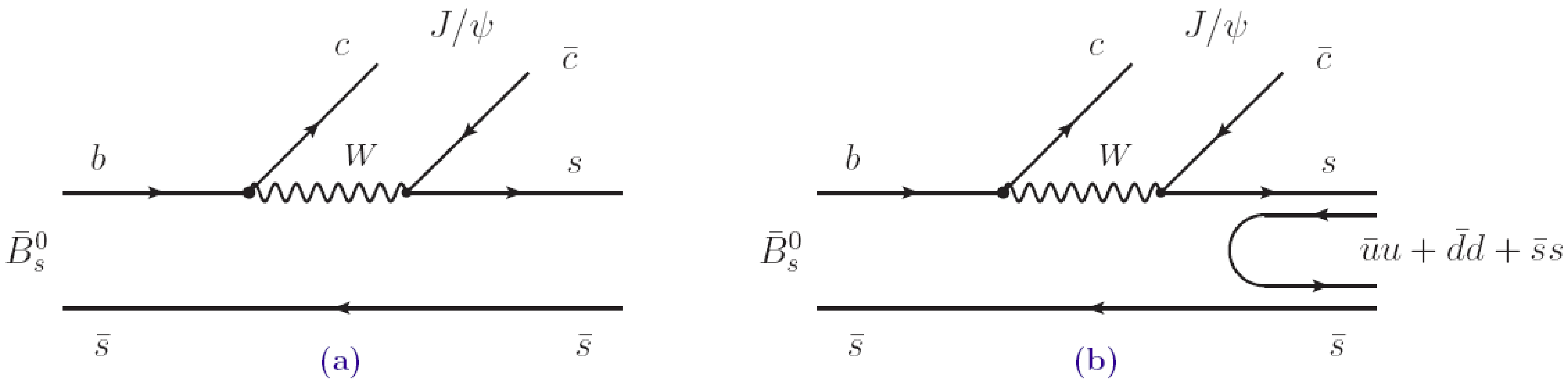
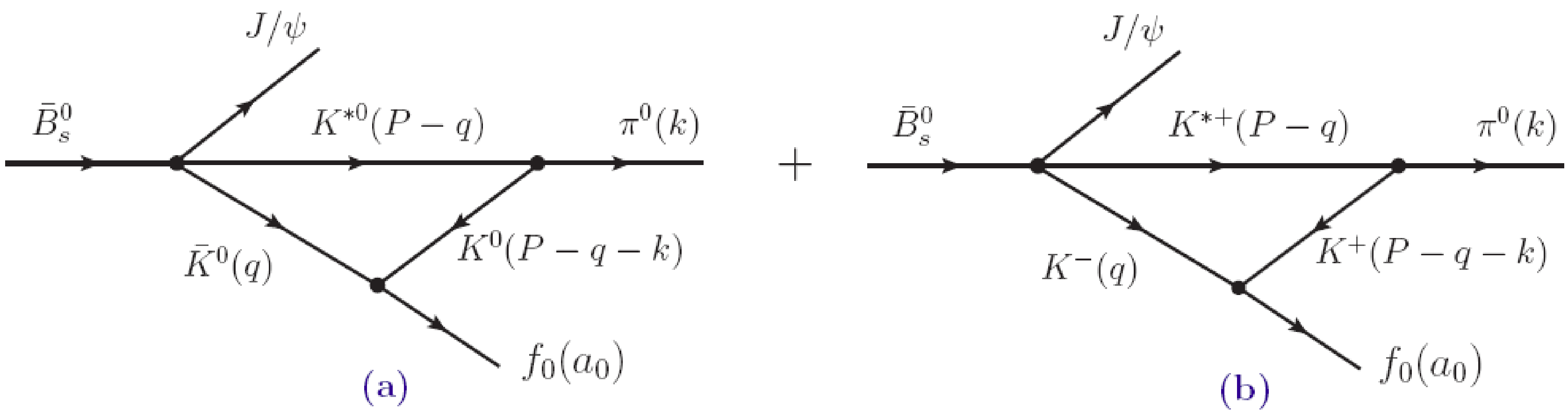


FIG. 1. Diagrammatic representation of $\bar{B}_s^0 \to J/\psi(c\bar{c})s\bar{s}$ at the quark level.

Formalism (for $\bar{B}_s^0 \to J/\psi\pi^0 a_0(980)(f_0(980))$)

B. The triangle diagram mechanism for $\bar{B}_s^0 \to J/\psi\pi^0 f_0(a_0)$



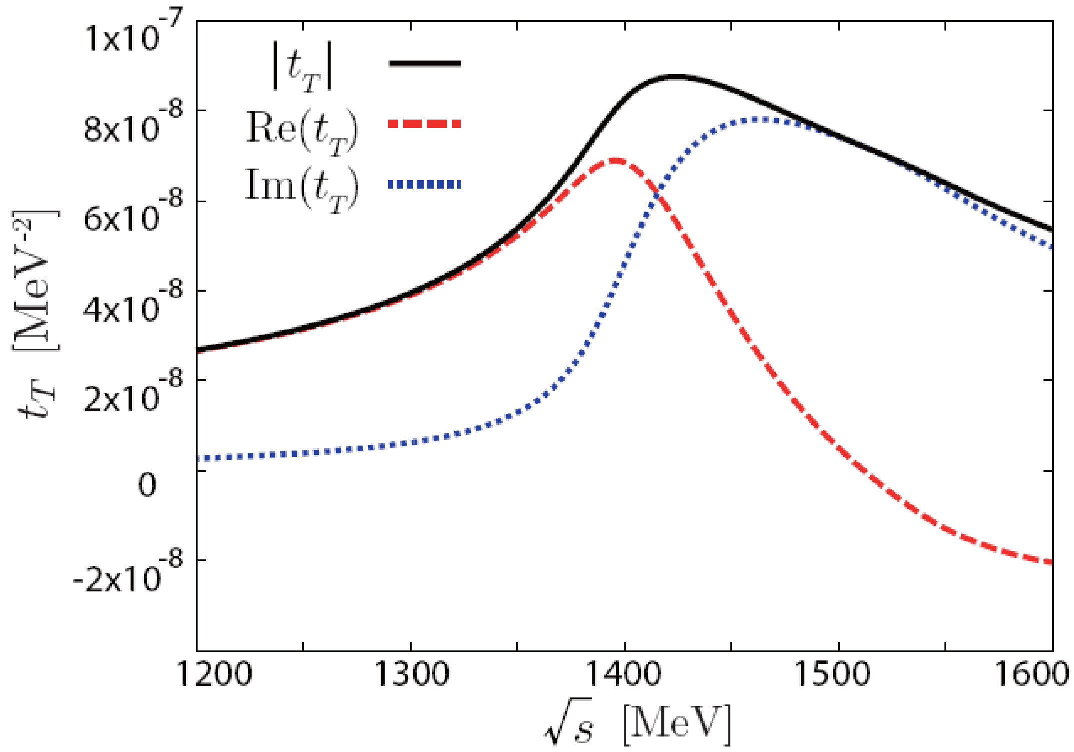
The formulas for $\bar{B}_s^0 \to J/\psi\pi^0 a_0(980)(f_0(980))$ can be obtained in a similar way.

◆ Results (for $D_s^+ \to \pi^+\pi^0 a_0(980)(f_0(980))$)

The results of t_T as a function of $\sqrt{s} \equiv m_{\rm inv}(\pi^0 a_0)$ taking for $m_{\rm inv}(\pi^0\eta)$ ($m_{\rm inv}(\pi^+\pi^-)$) the value of 980 MeV.

$|t_T|$ has a broad bump around 1420MeV.

Its origin is the TS developed by the amplitude.



$$\frac{d^2\Gamma_{D_s^+\to\pi^+\pi^0\pi^0\eta}}{dM_{\rm inv}(\pi^0 a_0)dM_{\rm inv}(\pi^0\eta)}\frac{1}{\Gamma_{D_s^+}} \quad \text{and}$$

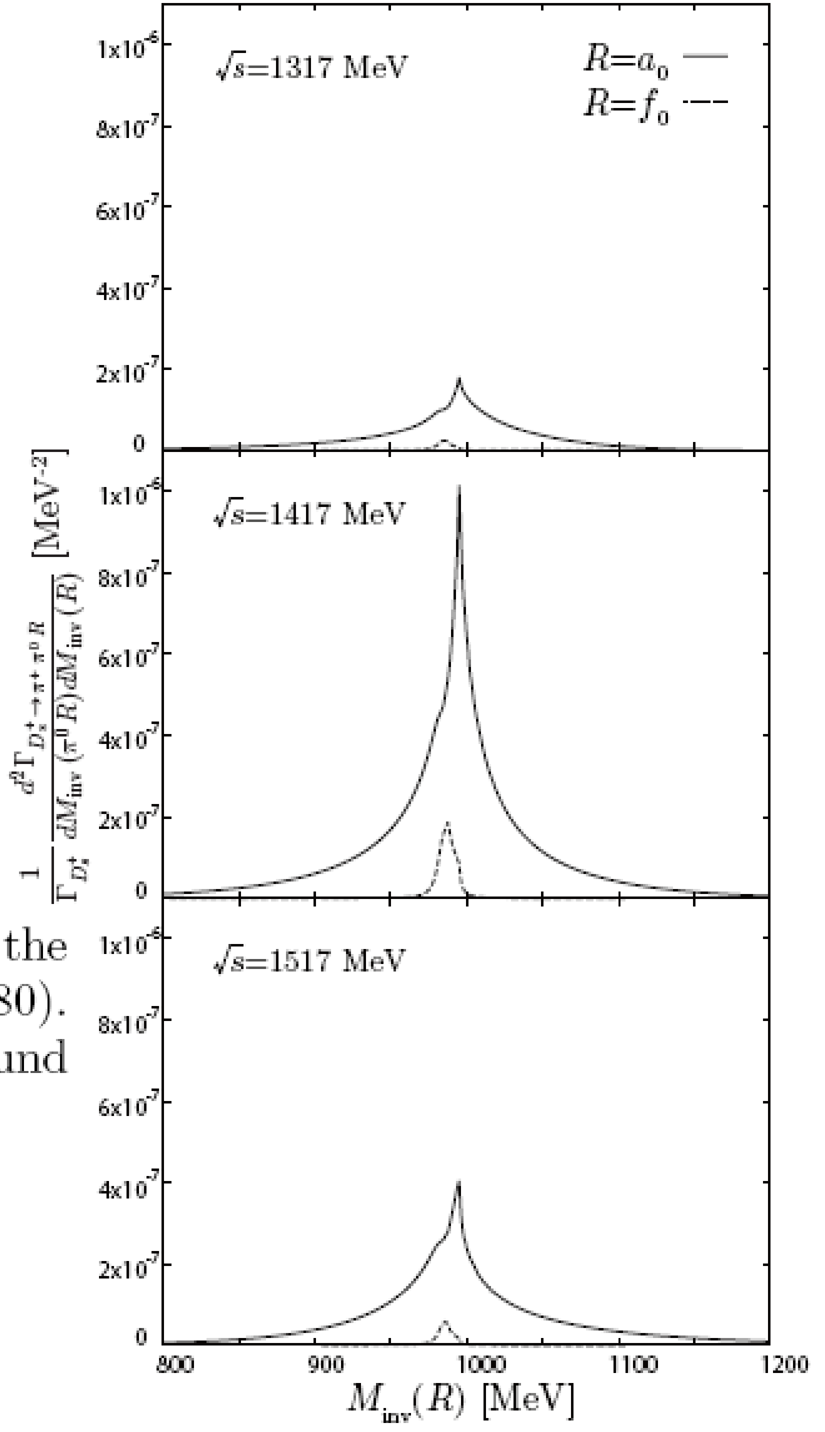
$$\frac{d^2\Gamma_{D_s^+\to\pi^+\pi^0\pi^+\pi^-}}{dM_{\rm inv}(\pi^0 f_0)dM_{\rm inv}(\pi^+\pi^-)}\frac{1}{\Gamma_{D_s^+}} \quad \text{as}$$

functions of $M_{\rm inv}(\pi^0\eta)$ or $M_{\rm inv}(\pi^+\pi^-)$

as 1317, 1417 and 1517 MeV.

we get two peaks,

corresponding to the typical $\pi^0\eta$ mass distribution of the $a_0(980)$ and the $\pi^+\pi^-$ mass distribution of the $f_0(980)$. The a_0 peaks around 995 MeV and the $f_0(980)$ around 985 MeV.



The rario o f0 to a0 production is strongly dependent on the \pi^0 R invariant mass.

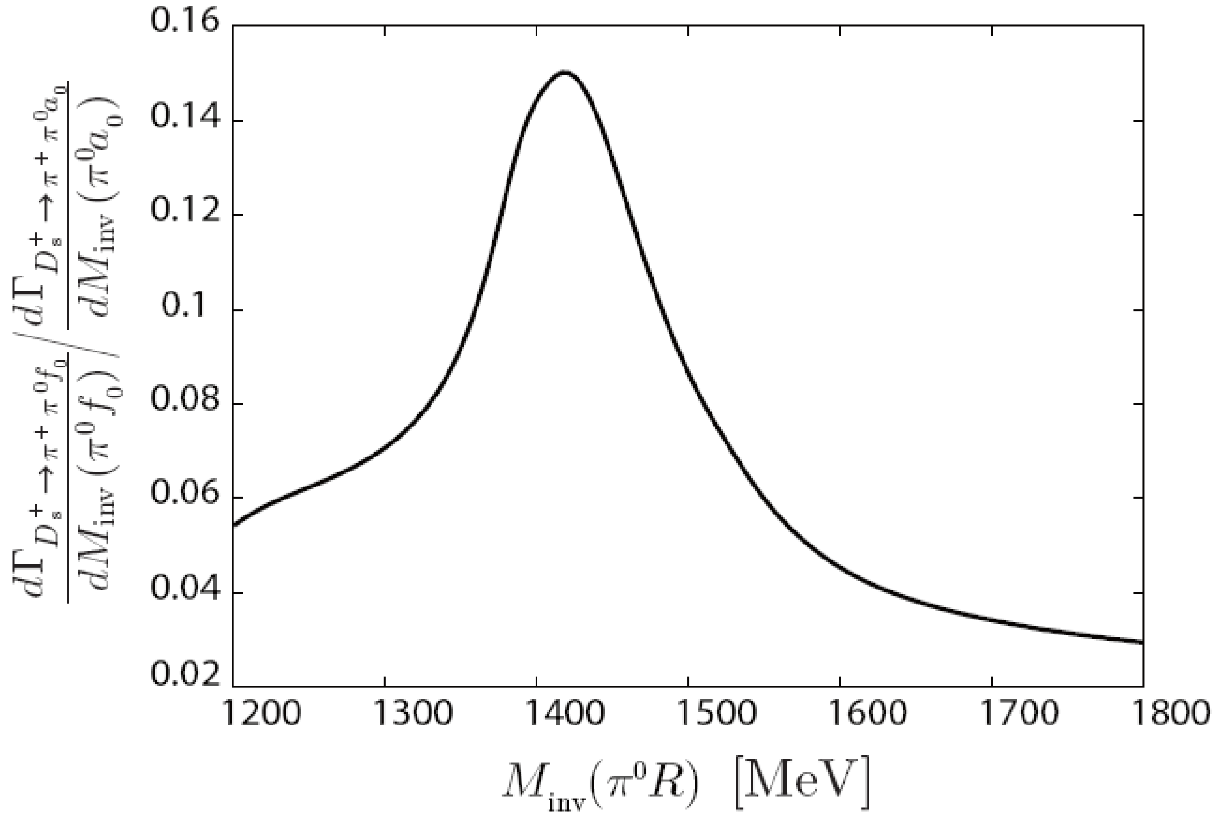


FIG. 6: Ratio of $d\Gamma/dM_{\rm inv}(\pi^0 a_0)$ and $d\Gamma/dM_{\rm inv}(\pi^0 f_0)$ as a function of $M_{\rm inv}(\pi^0 R)$ $(R = f_0, a_0)$.

TS acts as a magnifier for the isospin-violating \pi^0 f0 production process.

Finally, we would like to give numbers for the integrated rates of $\pi^+\pi^0 f_0$ and $\pi^+\pi^0 a_0$ production by integrating $d\Gamma/dM_{\rm inv}(\pi^0 R)$ in the range of invariant masses

We find the numbers

$$\begin{aligned} \text{BR}(D_s^+ \to \pi^+\pi^0 f_0) =& (4.91 \pm 0.46) \times 10^{-4}, \\ \text{BR}(D_s^+ \to \pi^+\pi^0 a_0) =& (3.85 \pm 0.36) \times 10^{-3}. \end{aligned} \quad (20)$$

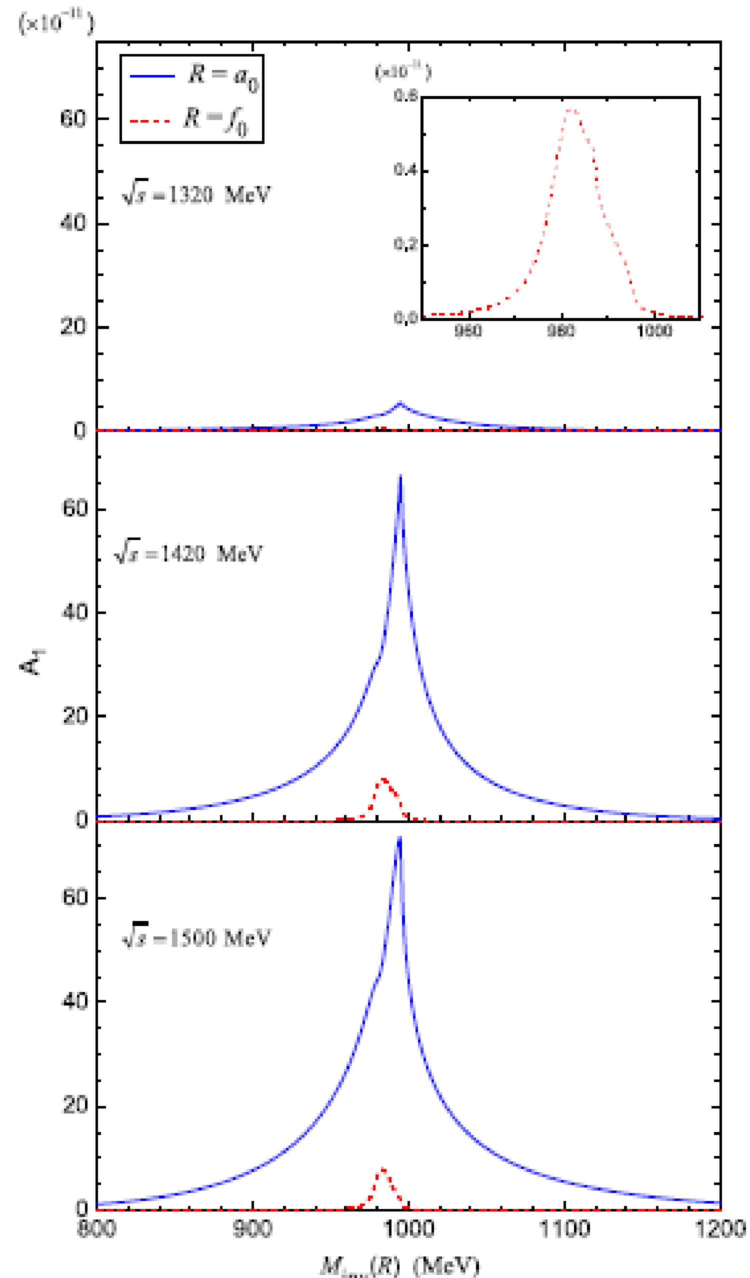
- The rates obtained are within present measurable range;
- Experimental messurment for this reaction will bring further light into the issue of f_0(980)-a_0(980) mixing and the nature of the low lying scalar mesons.

Results (for $\bar{B}_s^0 \to J/\psi \pi^0 a_0(980)(f_0(980))$)

The TS is expected to appear at

$M_{\text{inv}}(\pi^0 a_0)$ or $M_{\text{inv}}(\pi^0 f_0) \simeq 1424\,\text{MeV}$.

The double mass distribution as a function of M_R (i.e. $M_{\text{inv}}(\pi^0\eta)$ or $M_{\text{inv}}(\pi^+\pi^-)$) for fixed values of $M_{\text{inv}}(\pi^0 a_0)$ or $M_{\text{inv}}(\pi^0 f_0)$.



The ratio also peaks around the mass of the TS.

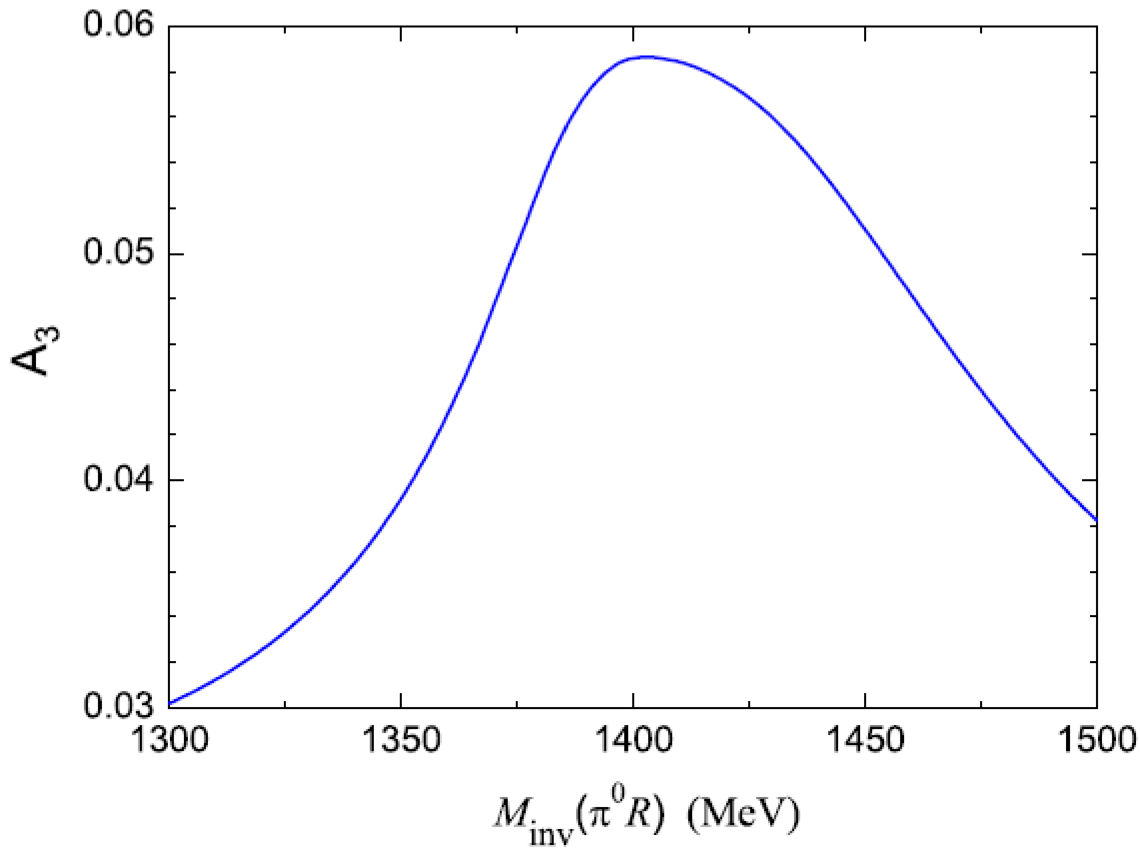


Fig. 6. (color online) Ratio of $d\Gamma/dM_{inv}(\pi^0 a_0)$ and $d\Gamma/dM_{inv}(\pi^0 f_0)$ as a function of $M_{inv}(\pi^0 R)$ $(R = f_0, a_0)$. Note: in this figure, the label of the longitudinal axis is $A_3 = \frac{d\Gamma_{\bar{B}_s^0 \to J/\psi\, \pi^0 f_0}}{dM_{inv}(\pi^0 f_0)} \Big/ \frac{d\Gamma_{\bar{B}_s^0 \to J/\psi\, \pi^0 a_0}}{dM_{inv}(\pi^0 a_0)}$.

We estimate the total rate for $\bar{B}_s^0 \to J/\psi\pi^0 f_0$ and $\bar{B}_s^0 \to J/\psi\pi^0 a_0$,

$$\mathrm{Br}(\bar{B}_s^0 \to J/\psi\pi^0 a_0) = 4.9 \times 10^{-6}.$$

$$\mathrm{Br}(\bar{B}_s^0 \to J/\psi\pi^0 f_0) = 3.3 \times 10^{-7}.$$

These rates are within present observation capacity at LHCb.

Summary

- We perform calculations for the $D_s^+ \to \pi^+\pi^0 f_0(980)(a_0(980))$ and $\bar{B}_s^0 \to J/\psi\pi^0 f_0(980)(a_0(980))$reactions, showing that the $a_0(980)$ mode is isospin-allowed while the $f_0(980)$ mode is isospin-suppressed.

- The triangle mechanism develops a TS around the $\pi^0 f_0(980)$or $\pi^0 a_0(980)$ invariant mass of 1420MeV, which enhance the isospin violation.

- We calculate absolute rates for the reactions and show that they are within present measurable range. The experimental measurement is encouraged, which will bring further light into the issue of f0(980)-a0(980) mixing and the nature of the light scalar mesons.

Thank you for your attention!