

# Strong decays of $D_{s1}(2700)^{\pm}$ and $D_{sJ}^*(2860)^{\pm}$

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# Outline

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**1. Introduction**



**2. Strong decays of  $D_{s1}(2700)^{\pm}$  and  $D_{sJ}^*(2860)^{\pm}$**



**3. Conclusions and discussions**

# 1. Introduction

## 1.1 Experiments

- ***S-wave and P-wave  $D_s$  is believed established***

States	$J^P$	$n^{2S+1}L_J$	$j^p$	PDG note
$D_S(1969)^\pm$	$0^-$	$1^1S_0$	$\frac{1}{2}^-$	
$D_S^*(2112)^\pm$	$1^-$	$1^3S_1$	$\frac{1}{2}^-$	$J^P = ?$ consistent with $1^-$
$D_{SJ}^*(2317)^\pm$	$0^+$	$1^3P_0$	$\frac{1}{2}^+$	J, P need confirmation
$D_{SJ}(2460)^\pm$	$1^+$	$1^1P_1$	$\frac{1}{2}^+$	
$D_{S1}(2536)^\pm$	$1^+$	$1^3P_1$	$\frac{3}{2}^+$	J, P need confirmation
$D_{S2}(2573)^\pm$	$2^+$	$1^3P_2$	$\frac{3}{2}^+$	$J^P = ?$ consistent with $2^+$

- ***Higher excited  $D_s$  is observed***

$D_{s1}(2700)^\pm$ ,  $D_{sJ}^*(2860)^+$ , and  $D_{sJ}(3040)^+$

# $D_{s1}(2700)^{\pm}$

**R**  
**BELLE**

**2006**

	$D_{sJ}^+(2700)$
$N_{\text{sig}}$	$182 \pm 30$
$M(\text{MeV}/c^2)$	$2715 \pm 11^{+11}_{-14}$
$\Gamma(\text{MeV}/c^2)$	$115 \pm 20^{+36}_{-32}$
$\mathcal{B}[B^+ \rightarrow R K^+ (\bar{D}^0 R)] \times \mathcal{B}[R \rightarrow \bar{D}^0 D^0 (D^0 K^+)] [10^{-4}]$ (or 90% C.L.)	$7.2 \pm 1.2^{+1.0}_{-2.9}$ <a href="https://arxiv.org/abs/hep-ex/0608031">hep-ex/0608031</a>

**BaBar**  
**2006**

[Phys.Rev.Lett.97,222001\(2006\)](https://arxiv.org/abs/Phys.Rev.Lett.97.222001)

$$m(X(2690)^+) = (2688 \pm 4 \pm 3) \text{ MeV}/c^2$$

$$\Gamma(X(2690)^+) = (112 \pm 7 \pm 36) \text{ MeV}/c^2.$$

**R**  
**BELLE**

**2008**

	$D_{sJ}(2700)^+$
$N_{\text{sig}}$ (Significance)	$182 \pm 30$ ( $8.4\sigma$ )
$M [\text{MeV}/c^2]$	$2708 \pm 9^{+11}_{-10}$
$\Gamma [\text{MeV}/c^2]$	$108 \pm 23^{+36}_{-31}$
Product $\mathcal{B}$ [ $10^{-4}$ ]	$11.3 \pm 2.2^{+1.4}_{-2.8}$

**BaBar**  
**2009**

[Phys.Rev.D 80,092003\(2009\)](https://arxiv.org/abs/Phys.Rev.D80.092003)

$$m(D_{s1}^*(2710)^+) = 2710 \pm 2_{\text{stat}} ({}^{+12}_{-7})_{\text{syst}} \text{ MeV}/c^2$$

$$\Gamma = 149 \pm 7_{\text{stat}} ({}^{+39}_{-52})_{\text{syst}} \text{ MeV},$$

$$\frac{\mathcal{B}(D_{s1}^*(2710)^+ \rightarrow D^* K)}{\mathcal{B}(D_{s1}^*(2710)^+ \rightarrow D K)} = 0.91 \pm 0.13_{\text{stat}} \pm 0.12_{\text{syst}}$$

**PDG**

Mass:  $2709^{+9}_{-6}$  MeV;

Decay width:  $125 \pm 30$  MeV;

Branching ratio:  $\Gamma(D^* K)/\Gamma(D K) = 0.91 \pm 0.18$ .

# $D_{sJ}^*(2860)^\pm$

2006

Phys.Rev.Lett.97,222001(2006)

$$m(D_{sJ}(2860)^+) = (2856.6 \pm 1.5 \pm 5.0) \text{ MeV}/c^2$$

$$\Gamma(D_{sJ}(2860)^+) = (47 \pm 7 \pm 10) \text{ MeV}/c^2.$$

BaBar

$$m(D_{sJ}^*(2860)^+) = 2862 \pm 2_{\text{stat}}^{+5}_{-2} {}_{\text{syst}} \text{ MeV}/c^2$$

$$\Gamma = 48 \pm 3_{\text{stat}} \pm 6_{\text{syst}} \text{ MeV},$$

$$\frac{\mathcal{B}(D_{sJ}^*(2860)^+ \rightarrow D^* K)}{\mathcal{B}(D_{sJ}^*(2860)^+ \rightarrow D K)} = 1.10 \pm 0.15_{\text{stat}} \pm 0.19_{\text{syst}}$$

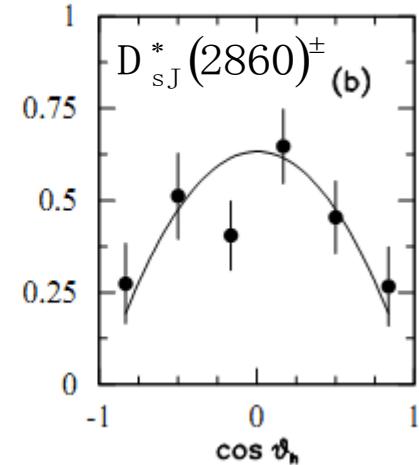
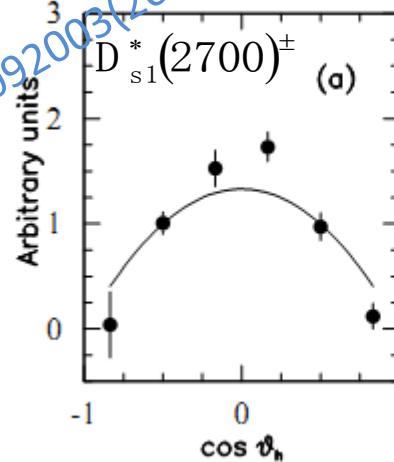
PDG

Mass:  $2862^{+5.4}_{-2.8}$  MeV;

Decay width:  $48 \pm 7$  MeV;

Branching ratio:  $\Gamma(D^* K)/\Gamma(D K) = 1.10 \pm 0.24$ .

Phys.Rev.D 80,092003(2009)



Natural spin-parity:  
 $J^P = 0^+, 1^-, \dots$

The observation of  $D_{sJ}(2860) \rightarrow D^* K$  by BaBar rules out the possibility of  $0^+$

## 1.2 Theories

### References

• Relativized quark model

- S. Godfrey and N. Isgur, *Phys. Rev. D* 32, 189(1985)
- S. Godfrey and R. Kokoski, *Phys. Rev. D* 43, 1679(1991)
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• Heavy quark symmetry theory

- E.J. Eichten, C.T. Hill and C. Quigg, *Phys. Rev. Lett.* 71, 4116(1993)

• Chiral quark model

- M. Di Pierro and E. Eichten, *Phys. Rev. D* 64, 114004(2001)

• Constituent quark model  
(heavy quark symmetry +  
light quark chiral symmetry)

- M.A. Nowak, M. Rho and I. Zahed, *Phys. Rev. D* 48, 4730(1993)
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• Mass loaded flux tube model

- T.J. Allen, T. Coleman, M.G. Olsson and S. Veleli, *Phys. Rev. D* 69, 074010(2004)
- Hong-Yun Shan and Ailin Zhang, *Chin. Phys. C* 34, 16(2010).
- Bing Chen, Deng-Xia Wang and Ailin Zhang, *Phys. Rev. D* 80, 071502(R)(2009)

## • Coupled channels models

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- *Yu.A. Simonov and J.A. Tjon, Phys. Rev. D70, 114013(2004)*
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## • Lattice QCD

- *J. Hein, et al., Phys. Rev. D62, 074503(2000)*

## • Other models

- *Yu.S. Kalashnikova, A.V. Nefediev and Yu. A. Simonov, Phys. Rev. D64, 014037(2001)*
- *J. Erdmenger, N. Evans and J. Grosse, JHEP 0701, 098(2007)*

## • Review

- *P. Colangelo, F. De Fazio and R. Ferrandes, Mod. Phys. Lett. A19, 2083(2004)*
- *E.S. Swanson, Phys. Rept. 429, 243(2006)*
- *J.L. Rosner, J. Phys. G34, S127(2007)*
- *Shi-Lin Zhu, Int. J. Mod. Phys. E17, 28(2008)*

## **Two kinds of classification schemes of $D_s$**

- Nonrelativistic:

$$n^{2S+1} L_J$$

- Heavy quark symmetric:

$$n j^P$$

• Physical states may not be the  $2S+1L_J$ , or the  $j^P$  eigenstates!

• Mixing between orbital P-wave

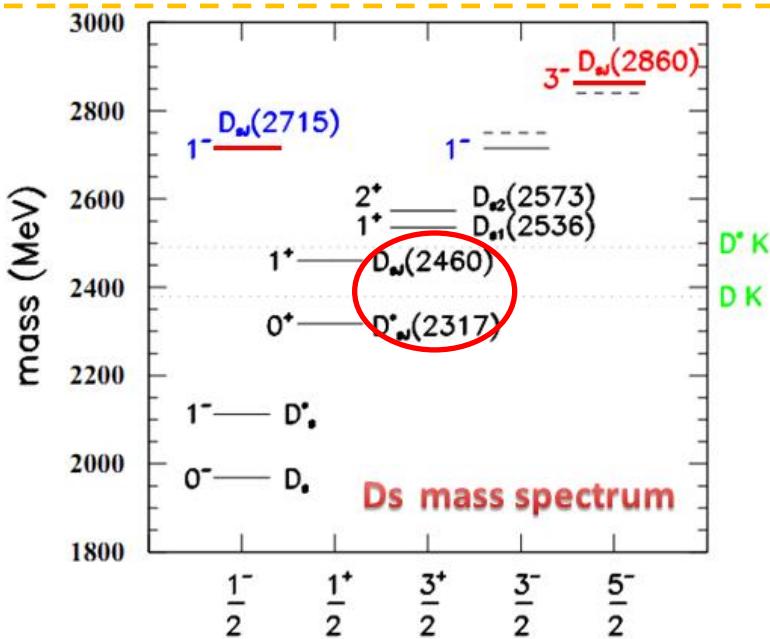


• Mixing between orbital D-wave



• Mixing between the orbital D-wave  $|1^-\rangle$  and the first radial S-wave  $|1^-\rangle$

$$\begin{aligned}|(SD)_1\rangle_L &= \cos\theta|2^3S_1\rangle - \sin\theta|1^3D_1\rangle \\|(SD)_1\rangle_R &= \sin\theta|2^3S_1\rangle + \cos\theta|1^3D_1\rangle,\end{aligned}$$



$D_{s1}(2700)^\pm$	Reference
$2^3 S_1 \left[ 2S(1^-, \frac{1}{2}) \right]$	CTLS[A-1]: Mass ✓, width ×; CWZ[A-2]: Mass ✓; Width ✓; ratio ?; CFNR[A-3]: Width ✓; ratio ✓;
$1^3 D_1 \left[ 1D(1^-, \frac{3}{2}) \right]$	ZLDZ[A-4]: Width ✓; ratio ×;
Mixing state	LM[A-5, 6]: Width ✓; ratio ✓ ; { $2^3 S_1$ } ZZ[A-7]: Width ✓; ratio ✓ ; { $1^3 D_1$ }

$D_{sJ}(2860)^\pm$	Reference
$2^3 P_0 \left[ 2P(0^+, \frac{1}{2}) \right]$	BR[B-1]: Mass ✓; CTLS[B-2]: Mass ✓, width ×;
$1^3 D_3 \left[ 1D(3^-, \frac{5}{2}) \right]$	CFN[B-3]: Mass ✓?; Width ✓; ratio ×; CWZ[B-4]: Mass ✓; Width ✓; ratio ?; ZLDZ[B-5]: Width ✓; ratio ×; ...
other	EFG[B-6]: (tetraquark) Mass ✓; EFG[B-7]: (Mixing state; two largely over-lapping resonances ) Mass ✓; decay width ✓; branching ratio ✓

$^3P_0$  model: the elementary process is described by the creation of a  $q \bar{q}$  pair with the quantum numbers of the vacuum,  $J^{PC} = 0^{++}$ , in the final state (A. Le Yaouanc, L. Oliver, O. Pene and J.C. Raynal, Phys. Rev. D8, 2223(1973); D 11, 1272(1975))

# literature :

$$D_{s1}(2700)^{\pm}$$

<b>[A-1]</b> F.E.Close, et al. a constituent quark potential model; the QPC model <i>Phys.Lett.B</i> 647, 159 (2007)
<b>[A-2]</b> B.Chen, et al. A mass loaded flux tube model <i>Phys. Rev. D</i> 80, 071502(R) (2009)
<b>[A-3]</b> P.Colangelo, et al. an effective Lagrangian based on the heavy quark expansion <i>Phys. Rev. D</i> 77, 014012 (2008)
<b>[A-4]</b> B.Zhang, et al. the QPC model <i>Eur.Phys.C</i> 50, 617(2007)
<b>[A-5]</b> D-M.Li and B. Ma the QPC model <i>Phys. Rev. D</i> 81, 014021 (2010)
<b>[A-7]</b> X.H.Zhong and Q.Zhao a constituent quark model with quark-meson effective Lagrangians <i>Phys. Rev. D</i> 81, 014031 (2010)

$$D_{sJ}^*(2860)^{\pm}$$

<b>[B-1]</b> E.V.Beveren and G.Rupp, a coupled-channel model, <i>phys.Rev.Lett</i> 97,202001(2006)
<b>[B-2]</b> F.E.Close, et al. a constituent quark potential model; the QPC model <i>Phys.Lett.B</i> 647, 159 (2007)
<b>[B-3]</b> P.Colangelo, et al. Regge trajectory; an effective Lagrangian based on the heavy quark expansion <i>Phys.Lett.B</i> 642, 48 (2006)
<b>[B-4]</b> B.Chen, et al. A mass loaded flux tube model <i>Phys. Rev. D</i> 80, 071502(R) (2009)
<b>[B-5]</b> B.Zhang, et al. the QPC model <i>Eur.Phys.C</i> 50, 617(2007)
<b>[B-6]</b> D. Ebert, et al. <i>Phys. Lett. B</i> 696 241(2011)
<b>[B-7]</b> X.H.Zhong and Qiang Zhao <i>Phys.Rev.D</i> 78,014029 (2008)

# Inconsistency within the ${}^3P_0$ model

F.E.Close, et al.

Phys.Lett.B 647,159 (2007)

$$|D_s^*(2690)\rangle \approx \frac{1}{\sqrt{5}}(-2|1S\rangle + 1|1D\rangle),$$

$$|D_s^*(2810)\rangle \approx \frac{1}{\sqrt{5}}(|1S\rangle + 2|1D\rangle)$$

a mixing angle consistent with  $-0.5$  radians.

D-M.Li and B. Ma

Phys. Rev. D 81, 014021 (2010)

$$|D_{s1}(2710)\rangle = \cos\theta|2{}^3S_1\rangle - \sin\theta|1{}^3D_1\rangle,$$

$$|D_{s1}(M_X)\rangle = \sin\theta|2{}^3S_1\rangle + \cos\theta|1{}^3D_1\rangle,$$

$1.12 \leq \theta \leq 1.38$  radians.

with a broad width, greater than 200 MeV.

## 2. Strong decays of $D_{s1}(2700)^\pm$ and $D_{sJ}^*(2860)^\pm$

The decay width for a process  $A \rightarrow BC$  is evaluated as follows

• Ling Yuan, Bing Chen and Ailin Zhang, arXiv:1203.0370

$$\Gamma = \pi^2 \frac{|\vec{K}|}{M_A^2} \sum_{JL} |M^{JL}|^2,$$

Relevant simple harmonic oscillator (SHO) wave functions

$$\begin{aligned}\Psi_{nLM_L} &= \frac{1}{\beta^{\frac{3}{2}}} \left[ \frac{2^{l+2-n} (2l+2n+1)!!}{\sqrt{\pi} n! [(2l+1)!!]^2} \right]^{\frac{1}{2}} \\ &\quad \times \left( \frac{k}{\beta} \right)^l \exp \left[ -\frac{1}{2} \left( \frac{k}{\beta} \right)^2 \right] \\ &\quad \times F(-n, l+3/2, (\frac{k}{\beta})^2) Y_{LM_L}(\Omega_p),\end{aligned}$$

## $2s+1L_J$ , or the $j^P$ eigenstates

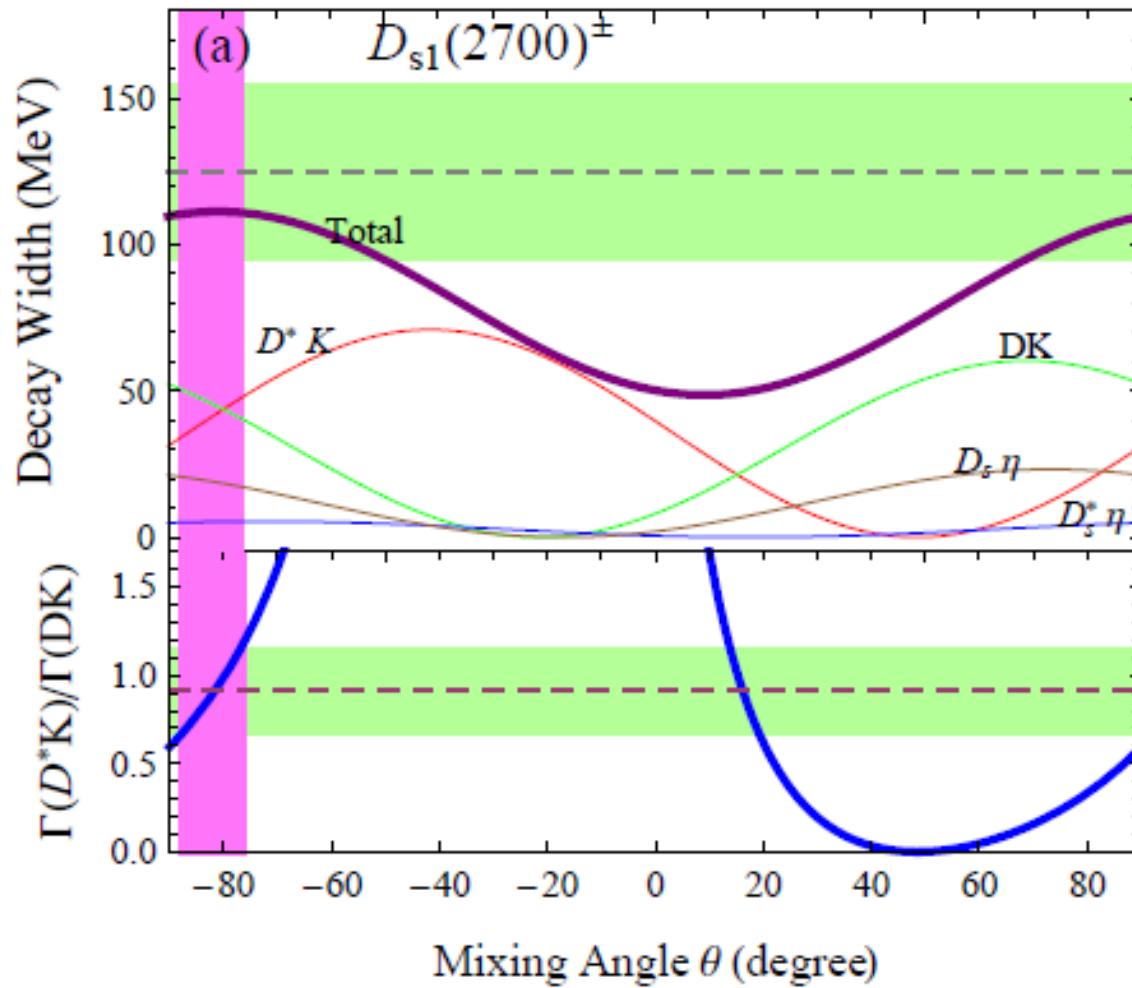
Mode	$D^*K$	$DK$	$D_s^*\eta$	$D_s\eta$	$DK^*$	$D_s\omega$	$\Gamma_{total}$	$\Gamma(D^*K)/\Gamma(DK)$
$D_{s1}(2700)[2^3S_1]$	41.4	9.4	2.0	2.0	-	-	54.8	4.4
$D_{s1}(2700)[1^3D_1]$	39.1	93.8	2.0	16.7	-	-	151.6	0.42
$D_{sJ}(2860)[1^3D_3]$	22.7	32.8	0.7	1.9	2.1	0.1	60.3	0.69

## Mixing states

**The way of choice of  $\beta$  plays an important role in the interpretation of these two states**

special for  $\theta$  each meson

## Decay widths and branching fraction ratio



$D_{s1}^*(2700)^{\pm}$

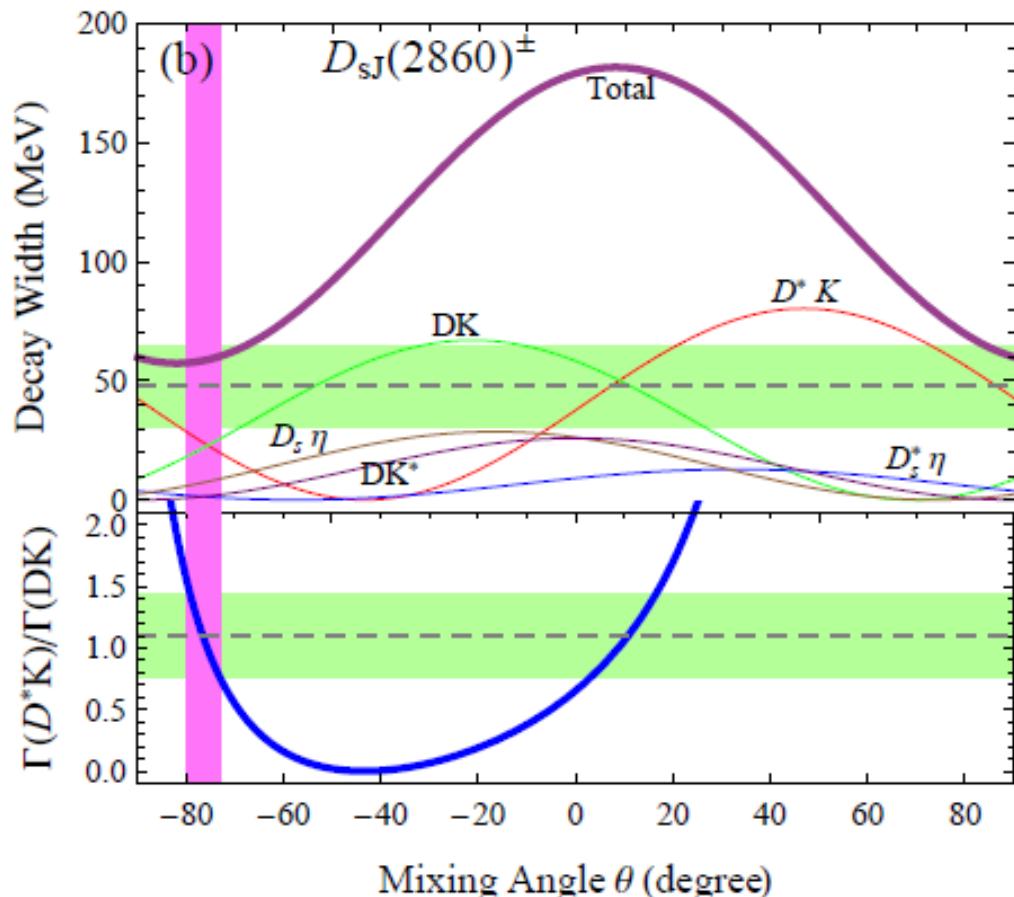


$|(SD)_1\rangle_L$

$$-88^\circ \leq \theta \leq -76^\circ.$$

special for 6 each meson

## Decay widths and branching fraction ratio



$D_{sJ}^*(2860)^{\pm}$

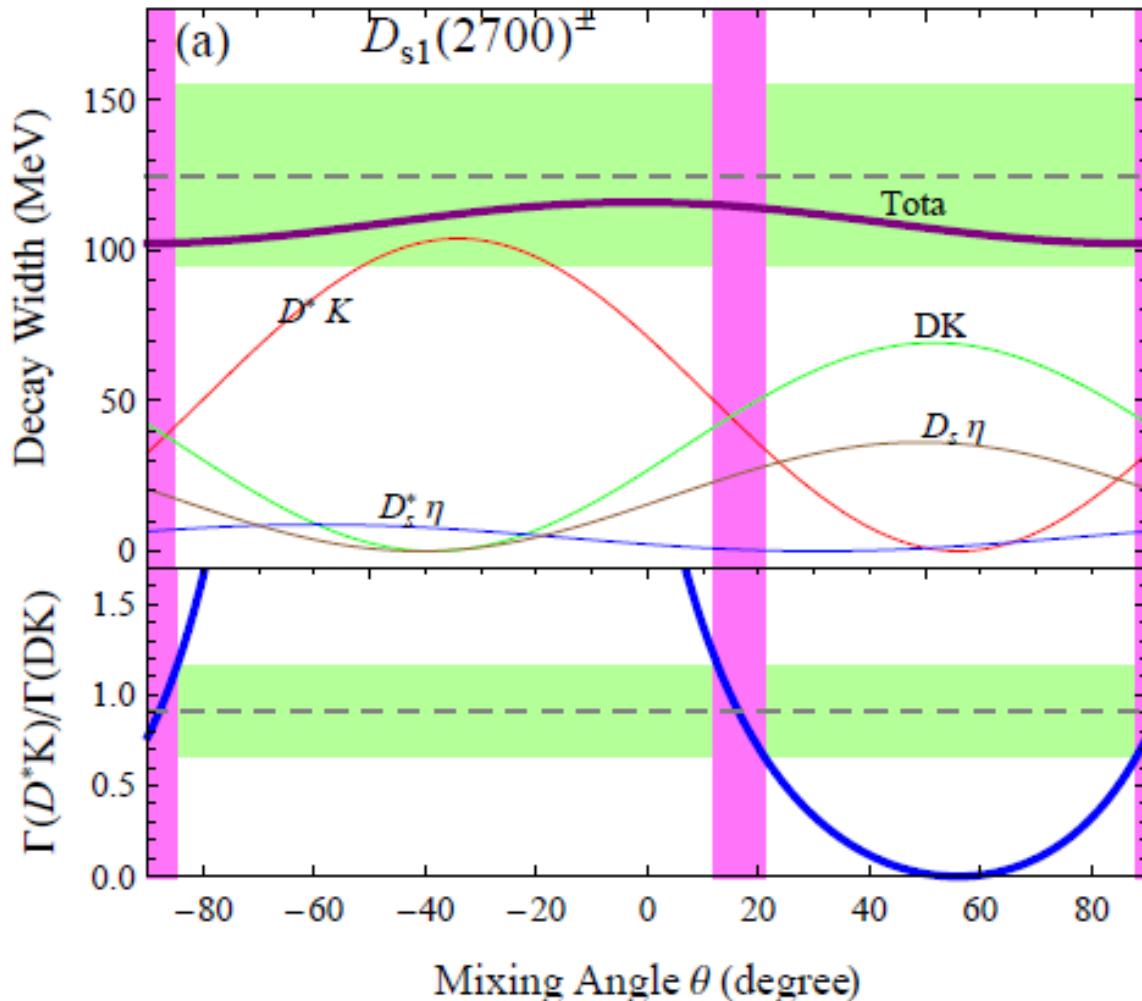


$|(SD)_1\rangle_R$

$$-80^\circ \leq \theta \leq -73^\circ.$$

*universal  $\theta$  for all mesons*

## Decay widths and branching fraction ratio



$D_{s1}^*(2700)^{\pm}$

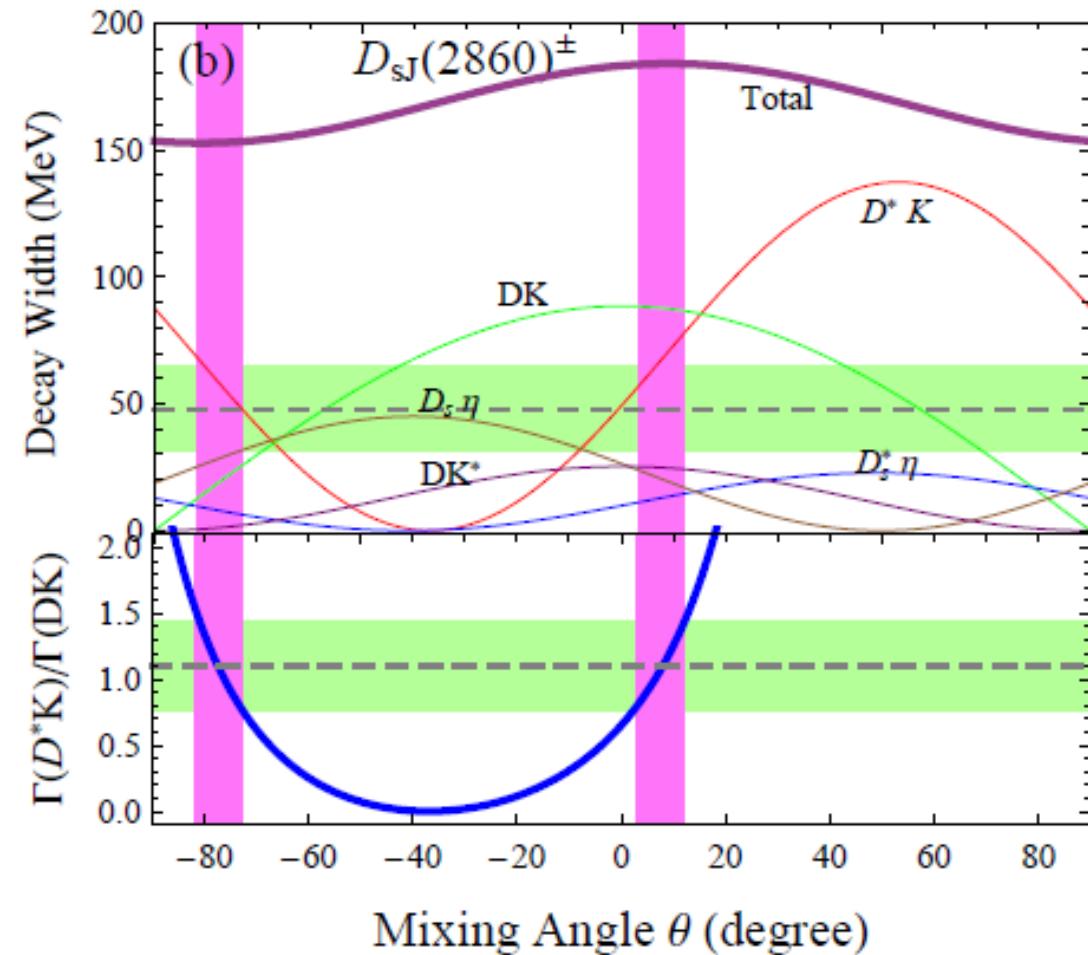
$\uparrow \downarrow$

$|(SD)_1\rangle_L$

$$12^\circ \leq \theta \leq 21^\circ$$

# universal $\theta$ for all mesons

## Decay widths and branching fraction ratio



$$D_{sJ}^*(2860)^{\pm}$$

$\neq$

$$|(SD)_1\rangle_R$$

Ling Yuang, Bing Chen and Ailin  
Zhang, arXiv: 1203.0370

### 3. Conclusions and discussions

There are some uncertainties within the  ${}^3P_0$  model, the way of choice of  $\beta$  plays an important role in the interpretation of these two states

The interpretations of  $D_{s1}(2700)^{\pm}$  and  $D_{sJ}^*(2860)^{\pm}$  are the same for different ways of choices of  $\beta$  when there is no mixing

If mixing between the two higher excited  $1^-$  states exist,  $D_{s1}(2700)^\pm$  and  $D_{sJ}^*(2860)^\pm$  could be interpreted as the two orthogonal mixed states with mixing angle  $\theta \approx -80^\circ$  in the case of a special  $\beta$  for each meson.

However, in the case of a universal  $\beta$  for all mesons,  $D_{s1}(2700)^\pm$  could be interpreted as the mixed state of  $2^3S_1$  and  $1^3D_1$  with mixing angle  $12^\circ < \theta < 21^\circ$  but  $D_{sJ}^*(2860)^\pm$  seems difficult to be interpreted as the orthogonal partner of  $D_{s1}(2700)^\pm$ .

**Be careful to draw conclusions within the  ${}^3P_0$  model**

**More experiment on other branching ratio is required**

$D_s^* \eta$  ,  $D_s \eta$

**Study in other models on strong decays for cross check**

**Study of other kinds of decays**

**Other analyses**

# Thanks !