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Chiral study of exotic charmed hadrons

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Outline:

1. Introduction

2. Scalar charmed meson resonances:

   Ds*0(2317)、D*0(2400)

3. Possible exotic doubly charmed baryons

4. Summary

Introduction

Thriving studies on the EXOTIC hadrons with heavy flavors

- **Hidden heavy flavor mesons: Zc(3900), Zb(10610)/Zb(10650) ..**
- **Open heavy flavor mesons: $D^*_{s0}(2317)$, $D_{s1}(2460)$ ...**
- **Hidden heavy flavor baryons: Pc(4450), Pc(4380) ...**
- **Singly heavy flavor baryons: Λc(2940) , Σc(2800) ...**
- **Doubly heavy flavor baryons: ? ? ?**
- **Triply heavy flavor baryons: ? ? ?**

Status of ground-state doubly heavy flavored baryons

Only doubly charmed baryons are observed now.

Long standing experimental puzzle:

- **SELEX:** $\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+}$, $p\, D^{+} K^{-}$

  [SELEX Coll., PRL'02, PLB'05]

  mass $3519 \div 2$ MeV

- **However the results are NOT confirmed by FOCUS, Belle, BaBar !**

  [Ratti, NPPS'03, BaBar Coll., PRD'06, Belle Coll.,PRL'06]

- **New measurements from LHCb:**

$\Xi_{cc}^{++} \to \Lambda_c^{+} K^{-} \pi^{+} \pi^{+}$, mass $3621.40 \div 0.78$ MeV

[LHCb Coll., PRL'17]

Our exploratory work aims at pushing forward the study of the EXCITED doubly charmed baryons.

- **Methodology:** **Scattering of ground-state doubly charmed baryons (Ξ_{cc}^{++}, Ξ_{cc}^{+}, Ω_{cc}^{+}) and light pseudoscalar mesons (π, K, η)**
- **Theoretical framework:**

($\Xi_{cc}^{++} = ccu$, $\Xi_{cc}^{+} = ccd$, $\Omega_{cc}^{+} = ccs$) : charm quarks behave like static color source. The dynamics is governed by the light flavors.

Then chiral EFT is a perfect tool to study such processes.

- **Benefits:** **Our results could provide useful guides for future experimental measurements and lattice QCD simulations !**

$D^*_{s0}(2317)$: a hot topic at B-Factory

1. **The BaBar detector**
(2145) BaBar Collaboration (Bernard Aubert (Annecy, LAPP) *et al.*). Apr 2001. 119 pp.
Published in **Nucl.Instrum.Meth. A479 (2002) 1-116**
SLAC-PUB-8569, BABAR-PUB-01-08
DOI: 10.1016/S0168-9002(01)02012-5
e-Print: **hep-ex/0105044** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service; BaBar Publications Database; BaBar Password Protected Publications Data
Detailed record - Cited by 2145 records 1000+

2. **Observation of CP violation in the B^0 meson system**
(867) BaBar Collaboration (Bernard Aubert (Annecy, LAPTH) *et al.*). Jul 2001. 8 pp.
Published in **Phys.Rev.Lett. 87 (2001) 091801**
SLAC-PUB-8904, BABAR-PUB-01-18
DOI: 10.1103/PhysRevLett.87.091801
e-Print: **hep-ex/0107013** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service; OSTI.gov Server; BaBar Publications Database; BaBar Password Protected
Document Server
Detailed record - Cited by 867 records 500+

3. **Observation of a narrow meson decaying to $D_s^+\pi^0$ at a mass of 2.32-GeV/c^2**
(823) BaBar Collaboration (B. Aubert (Annecy, LAPP) *et al.*). Apr 2003.
Published in **Phys.Rev.Lett. 90 (2003) 242001**
SLAC-PUB-9711, BABAR-PUB-03-011
DOI: 10.1103/PhysRevLett.90.242001
e-Print: **hep-ex/0304021** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac |
ADS Abstract Service; OSTI.gov Server; BaBar Publications
Document Server
Detailed record - Cited by 823 records 500+

Top 3 @BaBar

5. **Measurements of the meson - photon transition form-factors of light pseudosca**
(610) CLEO Collaboration (J. Gronberg (UC, Santa Barbara) *et al.*). Jul 1997. 30 pp.
Published in **Phys.Rev. D57 (1998) 33-54**
SLAC-PUB-9838, CLNS-97-1477, CLEO-97-7
DOI: 10.1103/PhysRevD.57.33
e-Print: **hep-ex/9707031** | PDF
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
KEK scanned document; ADS Abstract Service; Cornell U., LNS Server; SLAC Document Server; SLA
Data: INSPIRE | HepData
Detailed record - Cited by 610 records 500+

6. **Observation of a narrow resonance of mass 2.46-GeV/c**2 decaying to D*+(s) pi**
(575) CLEO Collaboration (D. Besson (Kansas U.) *et al.*). May 2003. 16 pp.
Published in **Phys.Rev. D68 (2003) 032002**, Erratum: **Phys.Rev. D75 (2007) 119908**
CLNS-03-1826, CLEO-03-09, CLNS03-1826
DOI: 10.1103/PhysRevD.68.032002, 10.1103/PhysRevD.75.119908
e-Print: **hep-ex/0305100** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service
Detailed record - Cited by 575 records 500+

Top 6 @CLEO

7. **Observation of B Meson Semileptonic Decays to Noncharmed Final States**
(419) CLEO Collaboration (R. Fulton *et al.*). Nov 1989. 14 pp.
Published in **Phys.Rev.Lett. 64 (1990) 16-20**
CLNS-89/951, CLEO-89-14
DOI: 10.1103/PhysRevLett.64.16
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
OSTI.gov Server
Detailed record - Cited by 419 records 250+

BELLE-PREPRINT-2006-11
DOI: 10.1103/PhysRevLett.97.251802
e-Print: **hep-ex/0604018** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service
Detailed record - Cited by 347 records 250+

16. **Study of B- ---> D**0 pi- (D**0 ---> D(*)+ pi-) decays**
(338) Belle Collaboration (Kazuo Abe (KEK, Tsukuba) *et al.*). Jul 2003. 20 pp.
Published in **Phys.Rev. D69 (2004) 112002**
DOI: 10.1103/PhysRevD.69.112002
e-Print: **hep-ex/0307021** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service
Detailed record - Cited by 338 records 250+

Top 20 @Belle

17. **Observation of the D(sJ)(2317) and D(sJ)(2457) in B decays**
(337) Belle Collaboration (P. Krokovny (Novosibirsk, IYF) *et al.*). Aug 2003. 6 pp.
Published in **Phys.Rev.Lett. 91 (2003) 262002**
DOI: 10.1103/PhysRevLett.91.262002
e-Print: **hep-ex/0308019** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service
Detailed record - Cited by 337 records 250+

18. **Observation of double c anti-c production in e+ e- annihilation at**
(337) Belle Collaboration (Kazuo Abe (KEK, Tsukuba) *et al.*). May 2002. 7 pp.
Published in **Phys.Rev.Lett. 89 (2002) 142001**
BELLE-PREPRINT-2002-13, KEK-PREPRINT-2002-27
DOI: 10.1103/PhysRevLett.89.142001
e-Print: **hep-ex/0205104** | **PDF**

Continuing efforts from LHCb, Belle-II, PANDA,…

and also Lattice QCD

Theoretical interpretations

recent reviews: H.X.Chen, et al., Rept.Prog.Phys.2017; F.K.Guo, et al., Rev.Mod.Phys.2018

- $c\bar{s}$ **state: Y.B.Dai, et al., PRD2003 ; S.Narison, PLB2005;**

  E. van Beveren, et al., PRL 2003; ……

- **Hadronic molecular state: T.Barnes, et al., PRD'03; F.K.Guo, et al., PLB'06; Altenbuchinger, et al., PRD'14; Du, et al., 1712.07957; Albaladejo, et al. 1805.07104 … See also F.K.Guo's talk**

- **Four-quark state: H.Y.Cheng, et al., PRD 2003; K. Terasaki, PRD2003; L.Maiani et.al., PRD2005; M.Bracco, et al., PLB2005;……**

- **Mixing of molecular and four-quark states:**

  T. Browder, et al., PLB2004;……

- **……**

Our focus:

Scalar Charmed states from $D_{(s)} + \pi(K,\eta,\eta')$ scattering

& their Nc and m_π dependences

Scalar charmed meson resonances:

Ds*0(2317) and D*0(2400)

Theoretical framework

LO ChPT with heavy-light mesons

$$\mathcal{L}^{(1)}_{D\phi} = \mathcal{D}_\mu D \mathcal{D}^\mu D^\dagger - \overline{M}^2_D D D^\dagger$$

NLO ChPT with heavy-light mesons [F.K.Guo,et al.,PLB'08]

$$\begin{aligned}\mathcal{L}^{(2)}_{D\phi} &= D\left(-h_0\langle\chi_+\rangle - h_1\chi_+ + h_2\langle u_\mu u^\mu\rangle - h_3 u_\mu u^\mu\right) D^\dagger \\ &+\mathcal{D}_\mu D\left(h_4\langle u_\mu u^\nu\rangle - h_5\{u^\mu, u^\nu\}\right)\mathcal{D}_\nu D^\dagger\ ,\end{aligned}$$

with $u_\mu = i\left(u^\dagger \partial_\mu u - u\,\partial_\mu u^\dagger\right)$ $u = \exp\left(\dfrac{i\phi}{\sqrt{2}F_0}\right)$ $\chi_\pm = u^\dagger \chi u^\dagger \pm u\chi u$

It is essential to generalize to U(3) case to study the Nc behaviors:

$$\phi = \begin{pmatrix} \dfrac{\sqrt{3}\pi^0+\eta_8}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & \dfrac{-\sqrt{3}\pi^0+\eta_8}{\sqrt{6}} & K^0 \\ K^- & \bar{K}^0 & \dfrac{-2\eta_8}{\sqrt{6}} \end{pmatrix} \longrightarrow \begin{pmatrix} \dfrac{\sqrt{3}\pi^0+\eta_8+\sqrt{2}\eta_0}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & \dfrac{-\sqrt{3}\pi^0+\eta_8+\sqrt{2}\eta_0}{\sqrt{6}} & K^0 \\ K^- & \bar{K}^0 & \dfrac{-2\eta_8+\sqrt{2}\eta_0}{\sqrt{6}} \end{pmatrix}$$

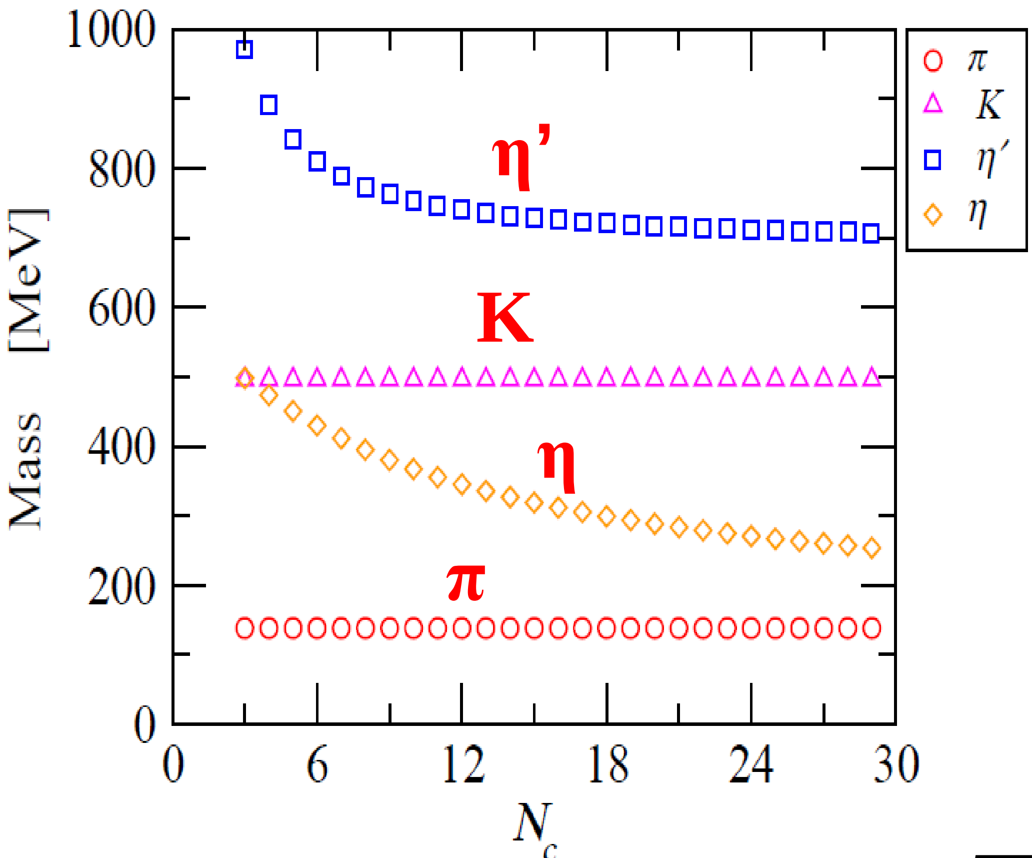
Possible new operators with singlet η_0 can appear, but they are much less relevant in the present analysis.

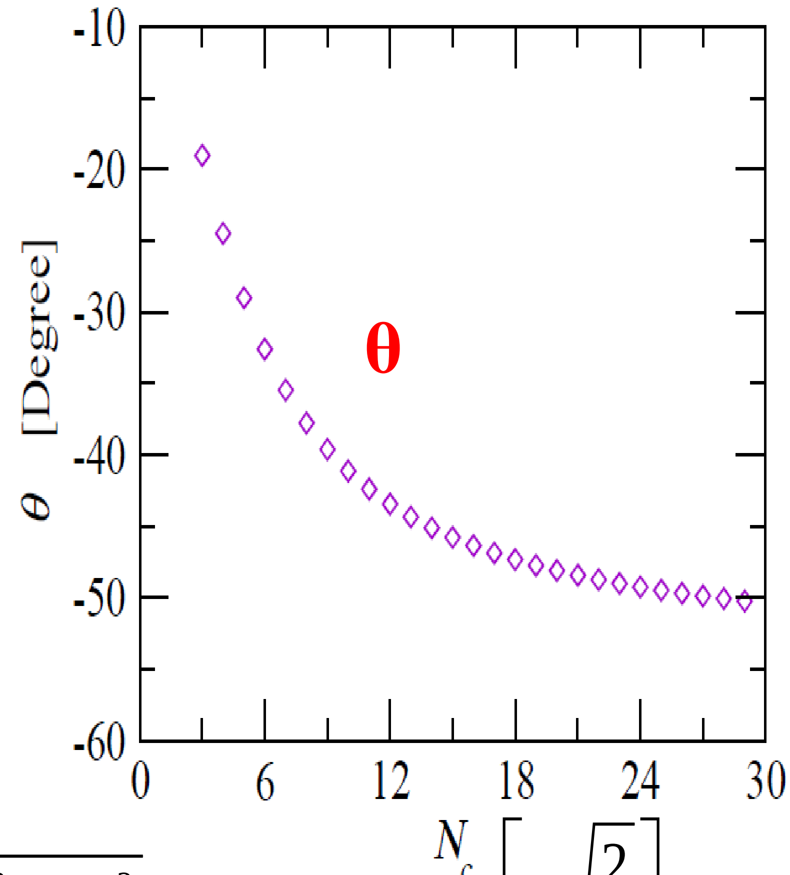
Chiral Lagrangian for pseudo-Goldstone with $U_A(1)$ anomaly

$$\mathcal{L}_\chi = \frac{F^2}{4}\langle u_\mu u^\mu \rangle + \frac{F^2}{4}\langle \chi_+ \rangle + \boxed{\frac{F^2}{3} M_0^2 \ln^2 \det u}$$

Leads to a massive η_0

$$M_0^2 \to 1/Nc, \quad m_\pi^2, m_K^2 \to Const.$$





$$\mathbf{Nc} \to \infty: \quad m_\eta \to m_\pi, \quad m_{\eta'} \to \sqrt{2m_K^2 - m_\pi^2}, \quad ,\theta \to \mathrm{Arcsin}\left[-\sqrt{\frac{2}{3}}\right]$$

$D_{(s)}$ and light pseudoscalar meson scattering amplitudes

$$V^{(S,I)}_{D_1\phi_1\to D_2\phi_2}(s,t,u)=\frac{1}{F^2}\left[\frac{C_{\rm LO}}{4}(s-u)-4C_0h_0+2C_1h_1\ -2C_{24}H_{24}(s,t,u)+2C_{35}H_{35}(s,t,u)\right]$$

(S,I)	Channels	$C_{\rm LO}$	C_0	C_1	C_{24}	C_{35}
$(-1,0)$	$D\bar K\to D\bar K$	-1	M_K^2	M_K^2	1	-1
$(-1,1)$	$D\bar K\to D\bar K$	1	M_K^2	$-M_K^2$	1	1
$(2,\frac{1}{2})$	$D_sK\to D_sK$	1	M_K^2	$-M_K^2$	1	1
$(0,\frac{3}{2})$	$D\pi\to D\pi$	1	M_π^2	$-M_\pi^2$	1	1
$(1,1)$	$D_s\pi\to D_s\pi$	0	M_π^2	0	1	0
	$DK\to DK$	0	M_K^2	0	1	0
	$DK\to D_s\pi$	1	0	$-(M_K^2+M_\pi^2)/2$	0	1
$(1,0)$	$DK\to DK$	-2	M_K^2	$-2M_K^2$	1	2
	$DK\to D_s\eta$	$-\sqrt{3}c_\theta$	0	$C_1^{1,0\ DK\to D_s\eta}$	0	$C_{35}^{1,0\ DK\to D_s\eta}$
	$D_s\eta\to D_s\eta$	0	$C_0^{1,0\ D_s\eta\to D_s\eta}$	$C_1^{1,0\ D_s\eta\to D_s\eta}$	1	$C_{35}^{1,0\ D_s\eta\to D_s\eta}$
	$DK\to D_s\eta'$	$-\sqrt{3}s_\theta$	0	$C_1^{1,0\ DK\eta\to D_s\eta'}$	0	$C_{35}^{1,0\ DK\eta\to D_s\eta'}$
	$D_s\eta\to D_s\eta'$	0	$C_0^{1,0\ D_s\eta\to D_s\eta'}$	$C_1^{1,0\ D_s\eta\to D_s\eta'}$	0	$C_{35}^{1,0\ D_s\eta\to D_s\eta'}$
	$D_s\eta'\to D_s\eta'$	0	$C_0^{1,0\ D_s\eta'\to D_s\eta'}$	$C_1^{1,0\ D_s\eta'\to D_s\eta'}$	1	$C_{35}^{1,0\ D_s\eta'\to D_s\eta'}$
$(0,\frac{1}{2})$	$D\pi\to D\pi$	-2	M_π^2	$-M_\pi^2$	1	1
	$D\eta\to D\eta$	0	$C_0^{0,\frac{1}{2}\ D\eta\to D\eta}$	$C_1^{0,\frac{1}{2}\ D\eta\to D\eta}$	1	$C_{35}^{0,\frac{1}{2}\ D\eta\to D\eta}$
	$D_s\bar K\to D_s\bar K$	-1	M_K^2	$-M_K^2$	1	1
	$D\eta\to D\pi$	0	0	$M_\pi^2(\sqrt{2}s_\theta-c_\theta)$	0	$c_\theta-\sqrt{2}s_\theta$
	$D_s\bar K\to D\pi$	$-\frac{\sqrt{6}}{2}$	0	$-\sqrt{6}(M_K^2+M_\pi^2)/4$	0	$\frac{\sqrt{6}}{2}$
	$D_s\bar K\to D\eta$	$-\frac{\sqrt{6}}{2}c_\theta$	0	$C_1^{0,\frac{1}{2}\ D_sK\to D\eta}$	0	$C_{35}^{0,\frac{1}{2}\ D_sK\to D\eta}$
	$D\eta'\to D\pi$	0	0	$-M_\pi^2(\sqrt{2}c_\theta+s_\theta)$	0	$s_\theta+\sqrt{2}c_\theta$
	$D\eta\to D\eta'$	0	$C_0^{0,\frac{1}{2}\ D\eta\to D\eta'}$	$C_1^{0,\frac{1}{2}\ D\eta\to D\eta'}$	0	$C_{35}^{0,\frac{1}{2}\ D\eta\to D\eta'}$
	$D_s\bar K\to D\eta'$	$-\frac{\sqrt{6}}{2}s_\theta$	0	$C_1^{0,\frac{1}{2}\ D_s\bar K\to D\eta'}$	0	$C_{35}^{0,\frac{1}{2}\ D_s\bar K\to D\eta'}$
	$D\eta'\to D\eta'$	0	$C_0^{0,\frac{1}{2}\ D\eta'\to D\eta'}$	$C_1^{0,\frac{1}{2}\ D\eta'\to D\eta'}$	1	$C_{35}^{0,\frac{1}{2}\ D\eta'\to D\eta'}$

Partial wave projection

$$\mathcal{V}^{(S,I)}_{J,D_1\phi_1\to D_2\phi_2}(s) = \frac{1}{2}\int_{-1}^{+1} \mathrm{d}\cos\varphi P_J(\cos\varphi) V^{(S,I)}_{D_1\phi_1\to D_2\phi_2}(s, t(s,\cos\varphi))$$

Unitarization

$$T(s) = \frac{1}{1-\mathcal{V}^{(S,I)}_\ell \cdot g(s)} \cdot \mathcal{V}^{(S,I)}_\ell ,$$

$$g(s) = \mathrm{diag}\{g(s)_{i=D_i\phi_i}\} \qquad \mathrm{Im}\ g(s) = -\rho(s)$$

$$g(s) = g(s_0) - \frac{s-s_0}{\pi}\int_{s_{\mathrm{th}}}^{\infty} \frac{\rho(s')}{(s'-s)(s'-s_0)} ds',$$

$$16\pi^2 g(s) = \boxed{a_{SL}(\mu)} + \log\frac{m_b^2}{\mu^2} - x_+ \log\frac{x_+ - 1}{x_+} - x_- \log\frac{x_- - 1}{x_-}$$

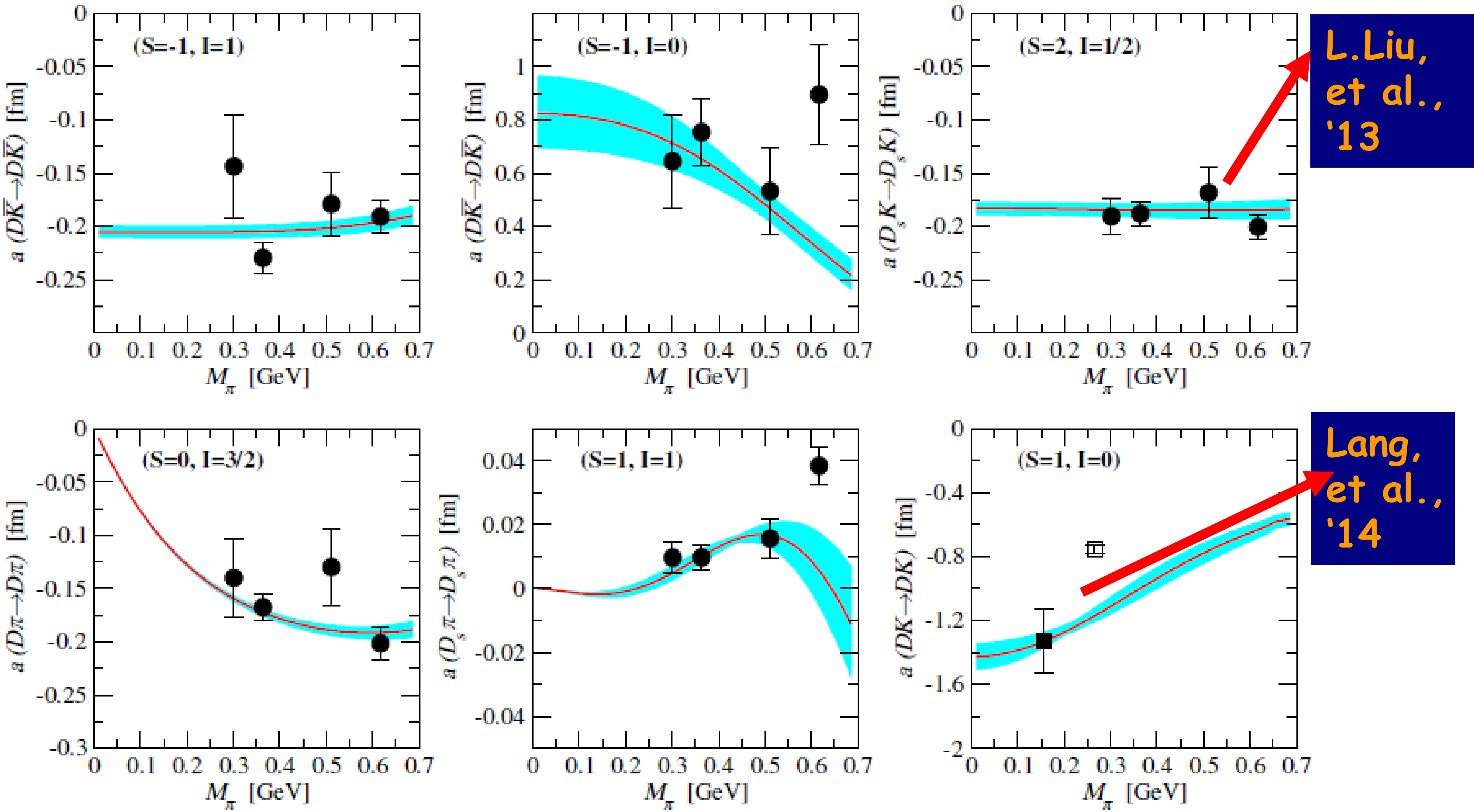
Free parameters

h_0, h_1, h_2, h_3, h_4, h_5: chiral LECs, enter in all channels

$a_{SL,\,i}$: subtraction constant, exclusively affects a specific channel

$D\,(-h_0\langle\chi_+\rangle - h_1\chi_+\ )\,D^\dagger$ h_0 h_1 determined by masses of D and Ds

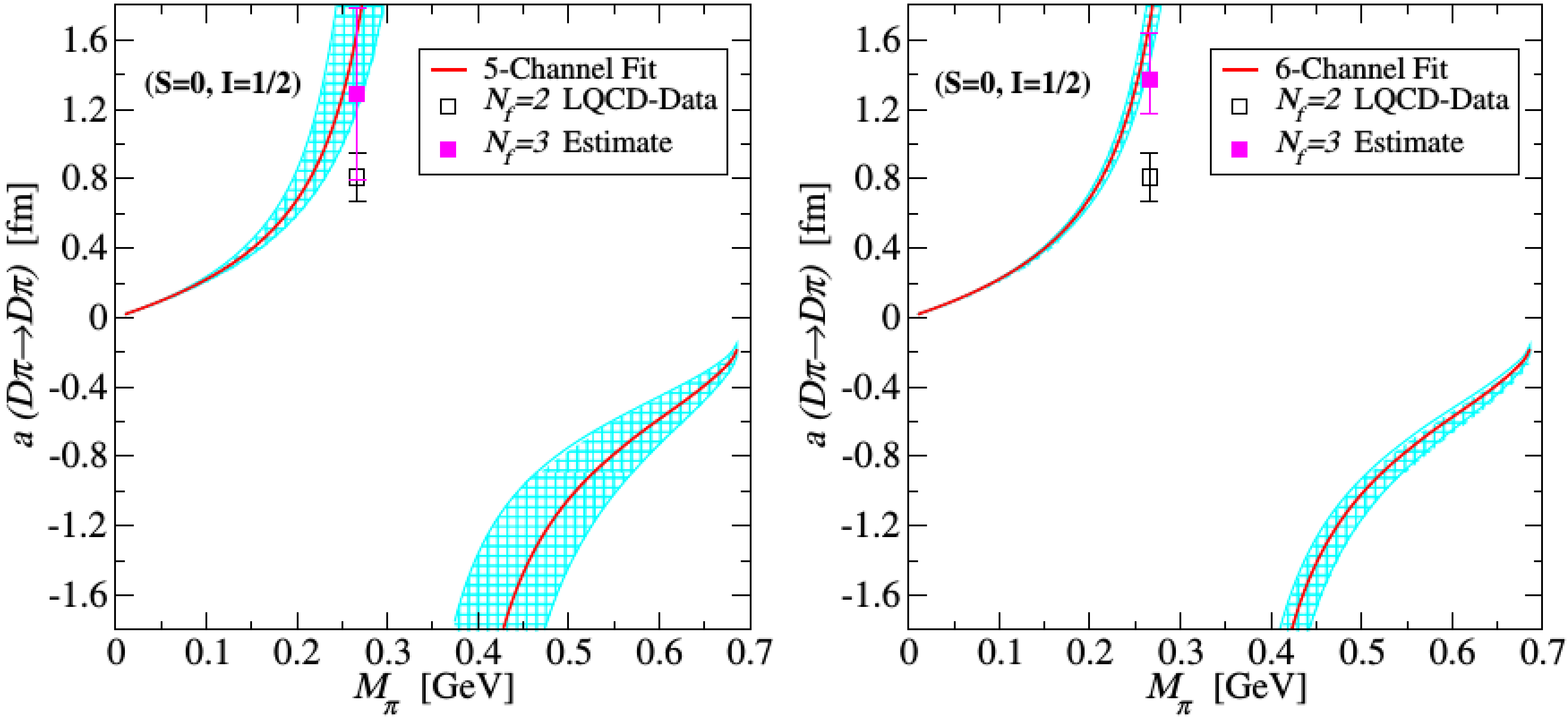
Six-channel fit (6c): 4 LECs and 1 common a_{SL}



Radical Assmuption

All the channels, regardless of the quantum numbers and the dynamical states, share a common subtraction constant in the unitarized amplitudes !

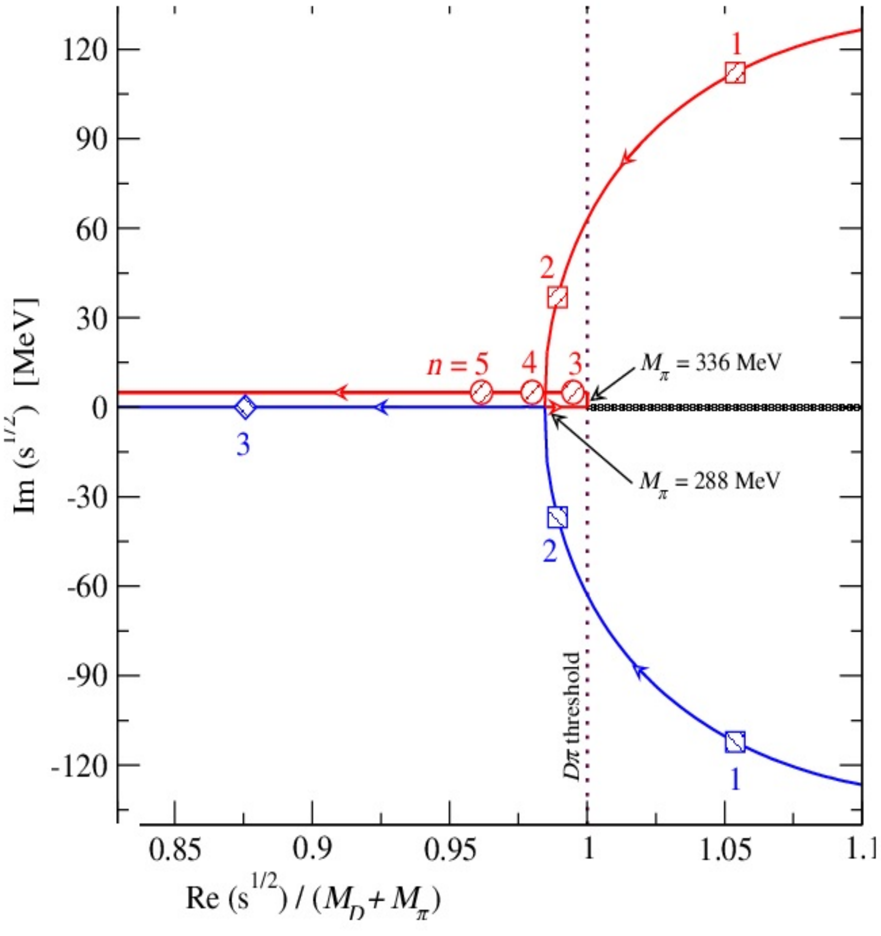
Prediciton of scattering lengths for (S,I)=(0,1/2) channel

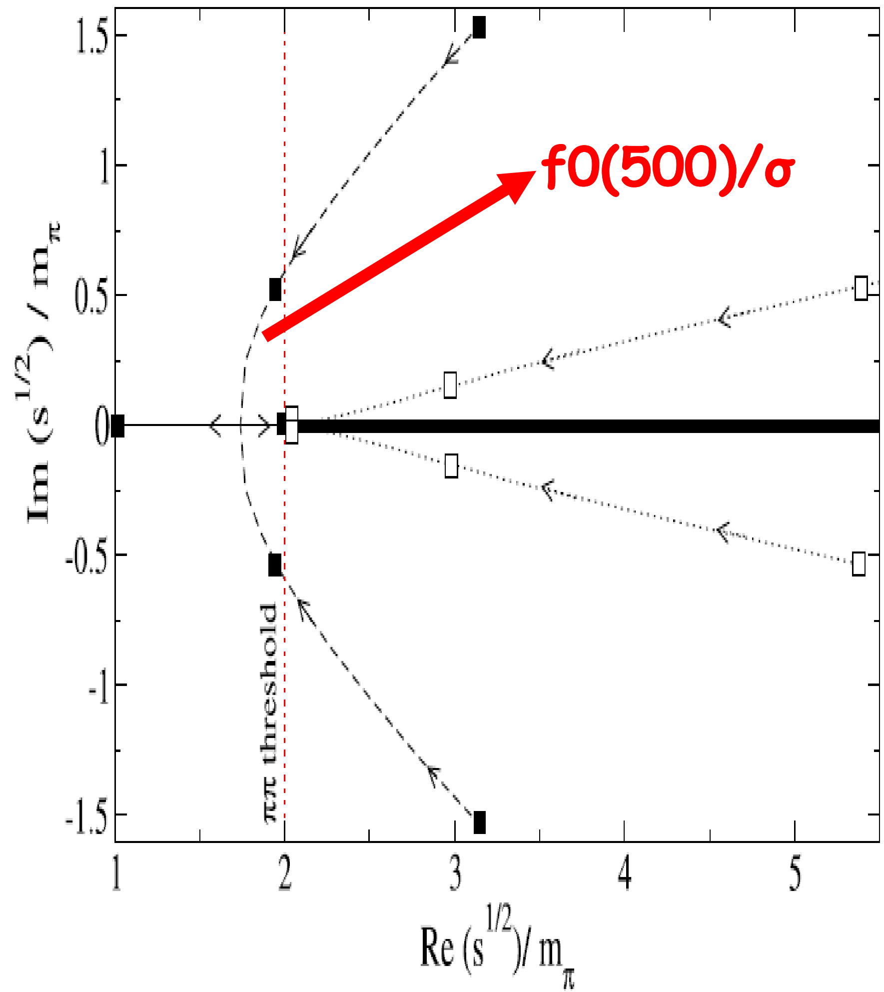


It clearly indicates that "exotics" things happen around m_π=0.3~0.4GeV

Pole trajectories with varying m_π

[ZHG,Meissner, Yao, PRD'15]





(S,I)=(0,1/2) channel

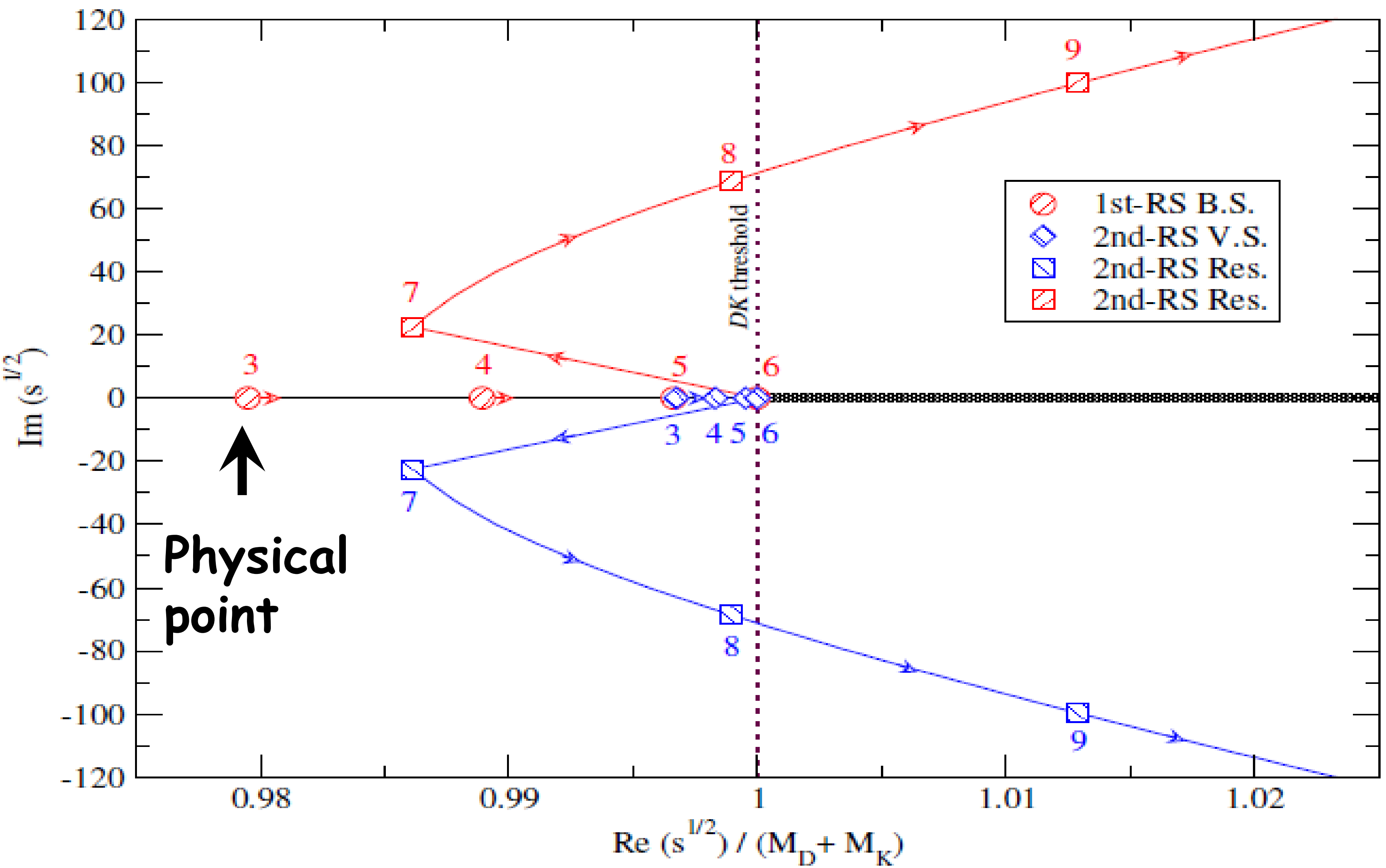
Hanhart, et al., PLB14

(S,I)	RS	$\sqrt{s_{pole}}$ [MeV]	$\lvert\text{Residue}\rvert^{1/2}$ [GeV]	Ratios	
$(-1,0)$	II	2333^{+15}_{-36}	$7.45^{+3.56}_{-1.38}(D\bar{K})$		
$(0,\frac{3}{2})$	II	$2033^{+3}_{-3}-i\,251^{+3}_{-3}$	$6.64^{+0.04}_{-0.04}(D\pi)$		
$(1,1)$	II	$2466^{+32}_{-27}-i\,271^{+4}_{-5}$	$6.95^{+0.60}_{-0.37}(D_s\pi)$	$1.72^{+0.12}_{-0.15}(DK/D_s\pi)$	
	III	$2225^{+12}_{-9}-i\,178^{+19}_{-17}$	$7.35^{+0.19}_{-0.13}(D_s\pi)$	$0.80^{+0.04}_{-0.04}(DK/D_s\pi)$	
$(1,0)$	I	2321^{+6}_{-3}	$9.30^{+0.04}_{-0.12}(DK)$	$0.77^{+0.02}_{-0.02}(D_s\eta/DK)$	$0.43^{+0.15}_{-0.13}(D_s\eta'/DK)$
	II	2356^{+1}_{-1}	$2.85^{+0.08}_{-0.13}(DK)$	$0.69^{+0.01}_{-0.01}(D_s\eta/DK)$	$0.38^{+0.12}_{-0.11}(D_s\eta'/DK)$
$(0,\frac{1}{2})$	II	$2114^{+3}_{-3}-i\,111^{+8}_{-7}$	$9.66^{+0.15}_{-0.13}(D\pi)$	$0.31^{+0.03}_{-0.03}(D\eta/D\pi)$	$0.46^{+0.02}_{-0.02}(D_s\bar{K}/D\pi)$
				$0.49^{+0.08}_{-0.08}(D\eta'/D\pi)$	
	III	$2473^{+29}_{-22}-i\,140^{+8}_{-7}$	$5.36^{+0.40}_{-0.28}(D\pi)$	$1.09^{+0.06}_{-0.05}(D\eta/D\pi)$	$2.12^{+0.06}_{-0.08}(D_s\bar{K}/D\pi)$
				$1.12^{+0.18}_{-0.16}(D\eta'/D\pi)$	

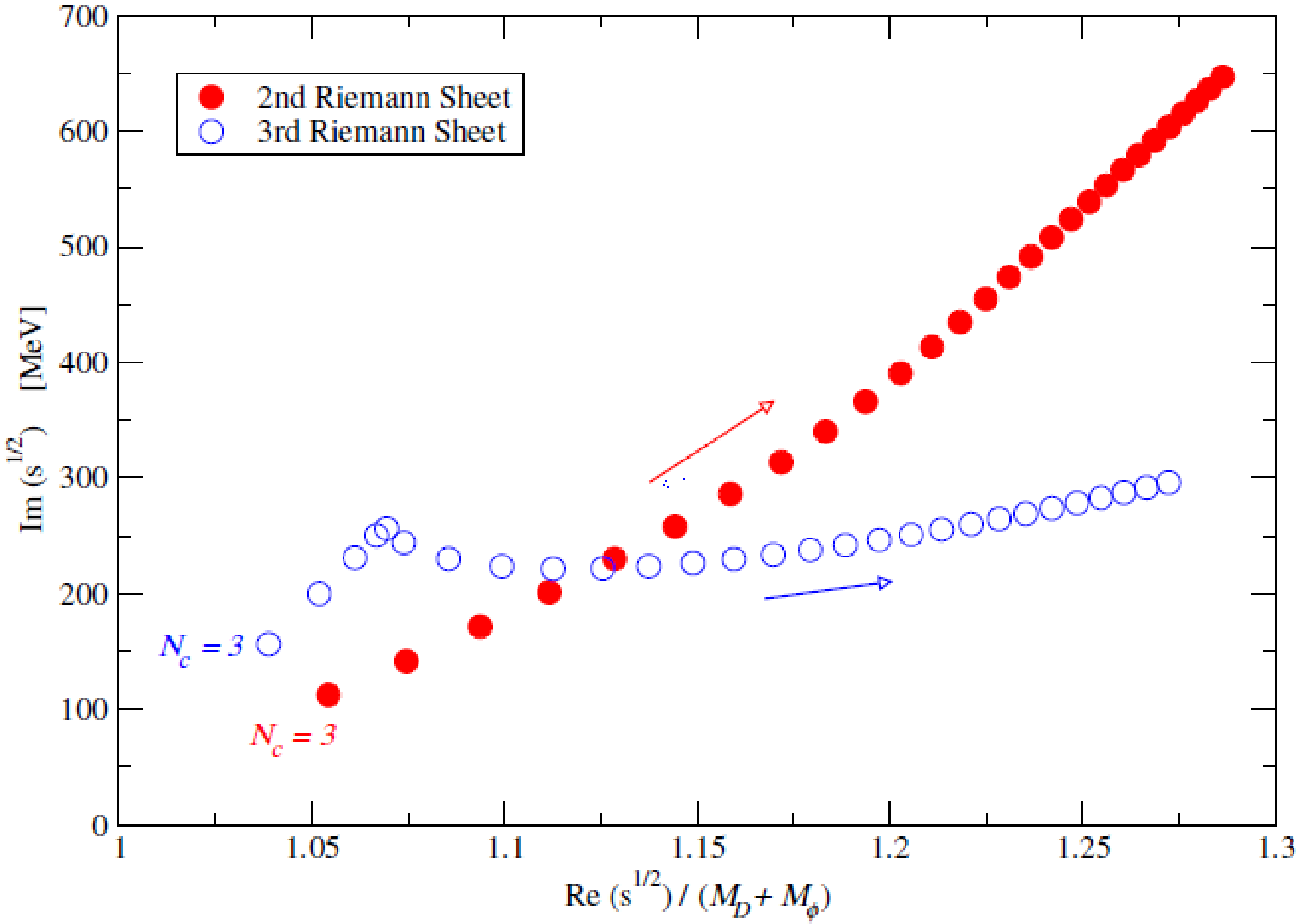
May explain the enhancement of the D^0 K^+ channel: 1506.00600

Pole positions and their residues with physical masses

Nc trajectories for $D^*_{s0}(2317)$ [ZHG,Meissner, Yao, PRD'15]

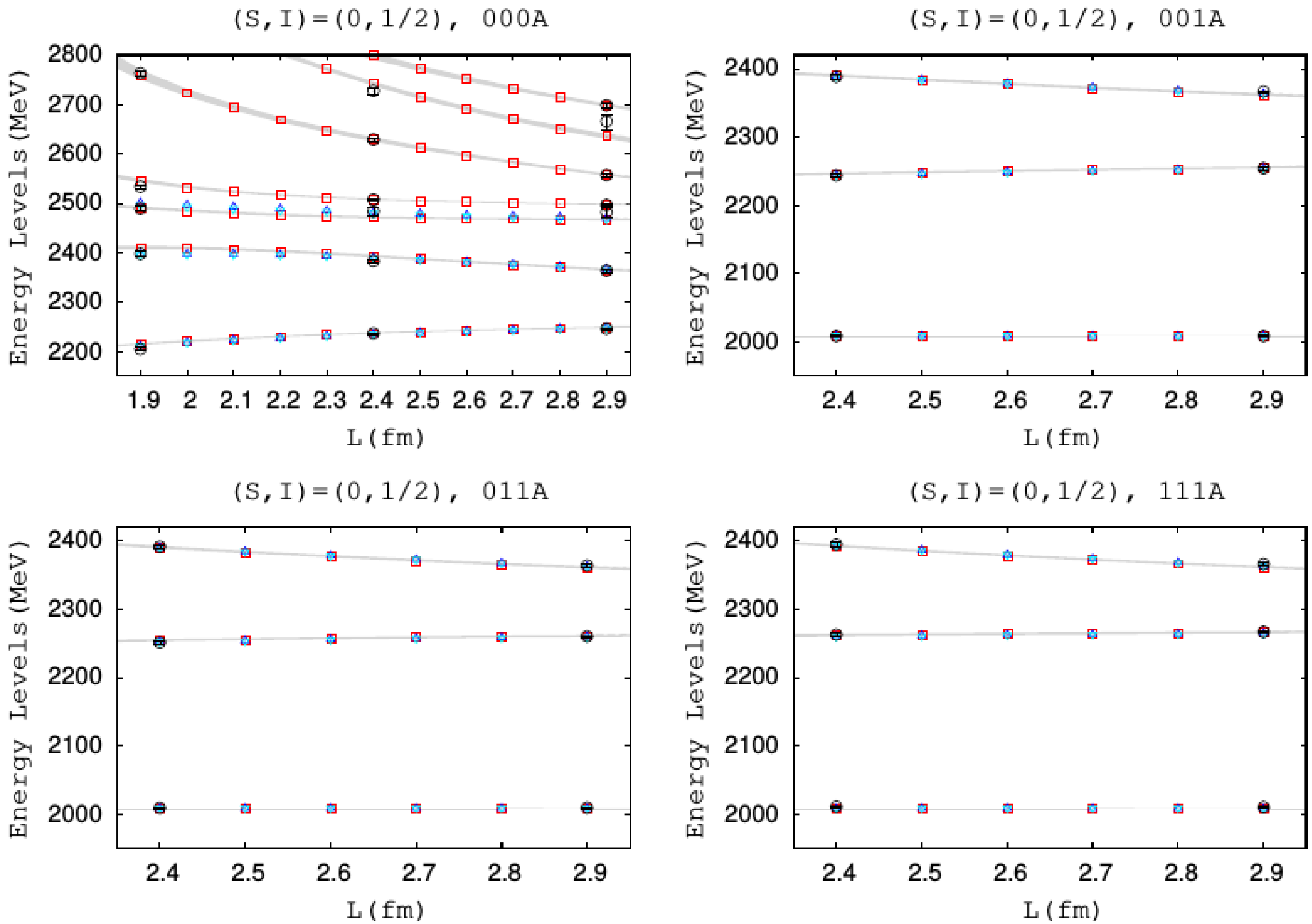


Nc trajectories for D^*_0 pole in (S,I)=(0,1/2) channel



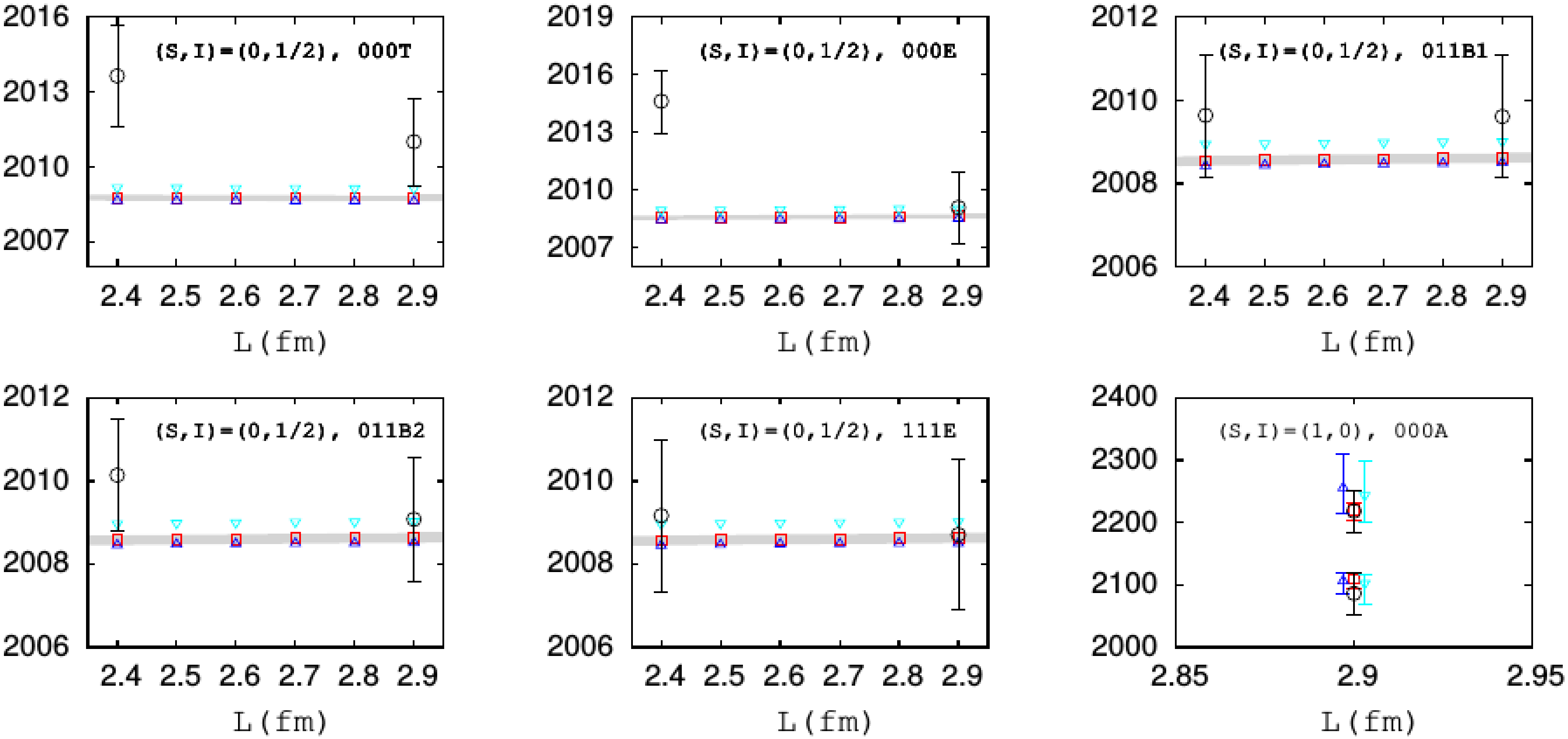
To further constrain the scattering amplitudes using the recent lattice simulation data of the finite-volume energy levels

[Moir,Peardon,Ryan,Thomas, Wilson, JHEP'16]



Preliminary

[ZHG, et al., in preparation]



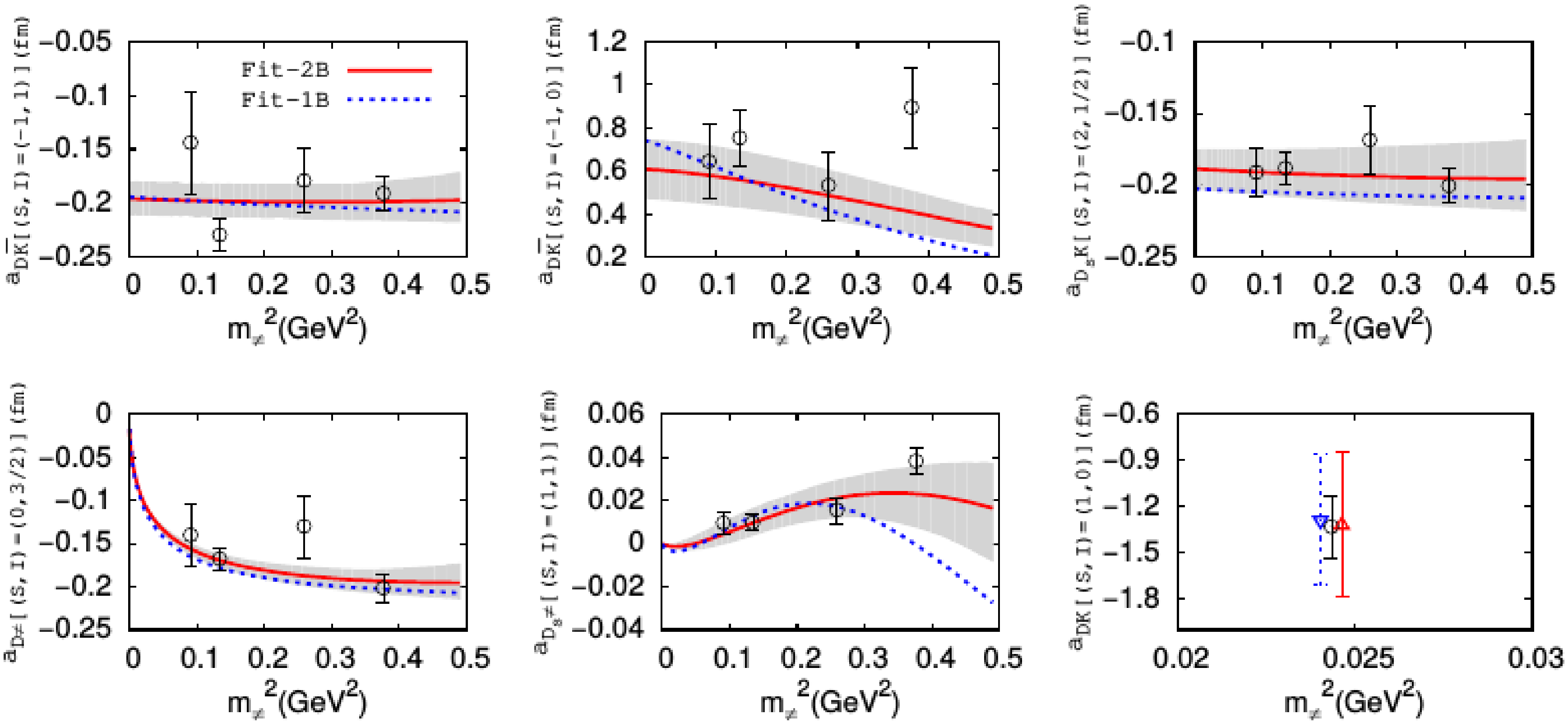
Preliminary

[Moir,Peardon,Ryan,Thomas, Wilson, JHEP'16]

[Lang,Leskovec,Mohler,Prelovsek,Woloshyn,PRD'14]

Reproduction of scattering lengths

[L.Liu,Orginos,F.K.Guo,Meissner, PRD'13]
[Lang,Leskovec,Mohler,Prelovsek,Woloshyn,PRD'14]



Preliminary

[ZHG, et al., in preparation]

Exploratory study of exotic doubly charmed baryons

Construction of the leading order chiral Lagrangian

- **Ground-state doubly charmed baryons form a chiral triplet**

$$\psi_{cc} = \begin{pmatrix} \Xi_{cc}^{++} \\ \Xi_{cc}^{+} \\ \Omega_{cc}^{+} \end{pmatrix}$$

- **Light pseudoscalar mesons identified as pseudo Nambu-Goldstone bosons**

$$U = u^2 \quad = \quad e^{i\sqrt{2}\Phi/F}$$

$$\Phi = \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & \pi^+ & K^+ \\ \pi^- & \frac{-1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & K^0 \\ K^- & \bar{K}^0 & \frac{-2}{\sqrt{6}}\eta \end{pmatrix}$$

➢ The leading order Lagrangian

$$D_\mu = \partial_\mu + \frac{1}{2}\left[u^\dagger \partial_\mu u + u \partial_\mu u^\dagger\right], \; u_\mu = i u^+ D_\mu U u^+$$

$$\mathcal{L} = \bar{\psi}_{cc}\left(i \not{D} - m_0 + \frac{g_A}{2}\gamma^\mu \gamma_5 u_\mu\right)\psi_{cc}$$

(wt) (s) (u)

$$T^{Ai\to Bj} = T_{wt}^{Ai\to Bj} + T_s^{Ai\to Bj} + T_u^{Ai\to Bj} \,,$$

$$T^{Ai\to Bj} = T_{wt}^{Ai\to Bj} + T_s^{Ai\to Bj} + T_u^{Ai\to Bj}\,,$$

$$T_{wt}^{Ai\to Bj} = -\mathcal{F}_{wt}\frac{1}{F^2}\bar{u}_B(\not{q}+\not{q}')u_A\,,$$

$$T_s^{Ai\to Bj} = -\mathcal{F}_s\frac{g_A^2}{F^2}\bar{u}_B\not{q}'\gamma_5\frac{1}{\not{p}_C-m_C}\not{q}\gamma_5u_A\,,$$

$$T_u^{Ai\to Bj} = -\mathcal{F}_u\frac{g_A^2}{F^2}\bar{u}_B\not{q}\gamma_5\frac{1}{\not{p}_C-m_C}\not{q}'\gamma_5u_A\,,$$

(S,I)	Processes	$\mathcal{F}_{wt}$	$\mathcal{F}_s\ (C)$	$\mathcal{F}_u\ (C)$	(S,I)	Processes	$\mathcal{F}_{wt}$	$\mathcal{F}_s\ (C)$	$\mathcal{F}_u\ (C)$
$(-2,\frac{1}{2})$	$\Omega_{cc}\bar{K}\to\Omega_{cc}\bar{K}$	$\frac{1}{4}$	0	$\frac{1}{2}\ (\Xi_{cc})$	$(1,0)$	$\Xi_{cc}K\to\Xi_{cc}K$	$-\frac{1}{4}$	0	$-\frac{1}{2}\ (\Omega_{cc})$
$(0,\frac{3}{2})$	$\Xi_{cc}\pi\to\Xi_{cc}\pi$	$\frac{1}{4}$	0	$\frac{1}{2}\ (\Xi_{cc})$	$(1,1)$	$\Xi_{cc}K\to\Xi_{cc}K$	$\frac{1}{4}$	0	$\frac{1}{2}\ (\Omega_{cc})$
$(-1,1)$	$\Omega_{cc}\pi\to\Omega_{cc}\pi$	0	0	0	$(0,\frac{1}{2})$	$\Xi_{cc}\pi\to\Xi_{cc}\pi$	$-\frac{1}{2}$	$\frac{3}{4}\ (\Xi_{cc})$	$-\frac{1}{4}\ (\Xi_{cc})$
	$\Xi_{cc}\bar{K}\to\Xi_{cc}\bar{K}$	0	0	0		$\Xi_{cc}\eta\to\Xi_{cc}\eta$	0	$\frac{1}{12}\ (\Xi_{cc})$	$\frac{1}{12}\ (\Xi_{cc})$
	$\Omega_{cc}\pi\to\Xi_{cc}\bar{K}$	$\frac{1}{4}$	0	$\frac{1}{2}\ (\Xi_{cc})$		$\Omega_{cc}K\to\Omega_{cc}K$	$-\frac{1}{4}$	$\frac{1}{2}\ (\Xi_{cc})$	0
$(-1,0)$	$\Xi_{cc}\bar{K}\to\Xi_{cc}\bar{K}$	$-\frac{1}{2}$	$1\ (\Omega_{cc})$	0		$\Xi_{cc}\pi\to\Xi_{cc}\eta$	0	$\frac{1}{4}\ (\Xi_{cc})$	$\frac{1}{4}\ (\Xi_{cc})$
	$\Omega_{cc}\eta\to\Omega_{cc}\eta$	0	$\frac{1}{3}\ (\Omega_{cc})$	$\frac{1}{3}\ (\Omega_{cc})$		$\Xi_{cc}\pi\to\Omega_{cc}K$	$-\frac{\sqrt{3}}{4\sqrt{2}}$	$\frac{\sqrt{3}}{2\sqrt{2}}\ (\Xi_{cc})$	0
	$\Xi_{cc}\bar{K}\to\Omega_{cc}\eta$	$\frac{\sqrt{3}}{4}$	$-\frac{1}{\sqrt{3}}\ (\Omega_{cc})$	$\frac{1}{2\sqrt{3}}\ (\Xi_{cc})$		$\Xi_{cc}\eta\to\Omega_{cc}K$	$-\frac{\sqrt{3}}{4\sqrt{2}}$	$\frac{1}{2\sqrt{6}}\ (\Xi_{cc})$	$-\frac{1}{\sqrt{6}}\ (\Omega_{cc})$

[ZHG, PRD2017]

Partial-wave projection and the unitarization

- **S-wave partial-wave projection formula for baryon-meson scattering**

$$\mathcal{T}(W) = \frac{1}{8\pi}\sum_{\sigma=1,2}\int d\Omega\, T(W,\Omega;\sigma,\sigma)$$

- **Unitarization: to take into account the possible strong interactions of the two-body scattering**

$$\mathrm{Im}\mathbb{T} = -\rho(s) \qquad \rho(s)_i = q(s)_i/8\pi\sqrt{s}$$ **($q(s)$: CM three-momentum)**

$$\boxed{\mathbb{T}(s) = \left[1 - \mathcal{T}(s)\cdot G(s)\right]^{-1}\cdot\mathcal{T}(s)}$$

✓ **G(s) takes care of the right-hand/unitarity cuts**

$$G(s) = \frac{1}{i}\int\frac{\mathrm{d}^4q}{(2\pi)^4}\frac{1}{(q^2-m_1^2+i\epsilon)[(P-q)^2-m_2^2+i\epsilon]}$$

$$G^{\Lambda}(s) = -\int^{|\vec{q}|<\Lambda}\frac{\mathrm{d}^3\vec{q}}{(2\pi)^3}\frac{w_1+w_2}{2w_1w_2\left[s-(w_1+w_2)^2\right]}\,, \qquad \left(w_i = \sqrt{|\vec{q}|^2+m_i^2}\right)$$

✓ $\mathcal{T}(s)$ **contains the remaining contributions except the right-hand cuts**

Inputs

$$m_{\Xi_{cc}^{++}} = m_{\Xi_{cc}^{+}} = 3621.4\ \mathrm{MeV}$$ [LHCb, PRL'17 & Isospin symmetry]

$$m_{\Omega_{cc}^{+}} = 3700\ \mathrm{MeV}$$ [Chen, et al., PRD'17]

$$F = F_{\pi} = 92.1\ \mathrm{MeV}$$ [PDG, CPC'16]

$$|g_A| = 0.2, \quad g_A = 0$$ [Sun, Vicente Vacas, PRD'16]

(The final results are barely affected by the g_A term.)

- **The most sensitive parameter: cutoff scale Λ**

Our conservative estimation: $\Lambda = 1.0 \div 0.2$ GeV

Scattering lengths

$$a^{S,I}_{\psi_{cc}\phi\to\psi_{cc}\phi} = \frac{1}{8\pi(m_{\psi_{cc}}+m_\phi)}\mathbb{T}^{S,I}_{\psi_{cc}\phi\to\psi_{cc}\phi}(s_{\rm thr})$$

$(S,\,I)$	Processes	Scattering lengths (fm)
$(-2,1/2)$	$\Omega_{cc}\bar{K}\to\Omega_{cc}\bar{K}$	$-0.19^{+0.02}_{-0.02}$
$(1,0)$	$\Xi_{cc}K\to\Xi_{cc}K$	$-1.4,\,-3.6,\,5.2$
$(1,1)$	$\Xi_{cc}K\to\Xi_{cc}K$	$-0.19^{+0.02}_{-0.02}$
$(0,3/2)$	$\Xi_{cc}\pi\to\Xi_{cc}\pi$	$-0.095^{+0.003}_{-0.004}$
$(-1,1)$	$\Omega_{cc}\pi\to\Omega_{cc}\pi$	$0.03^{+0.01}_{-0.01}$
	$\Xi_{cc}\bar{K}\to\Xi_{cc}\bar{K}$	$-0.22^{+0.14}_{-0.14}+i0.45^{+0.00}_{-0.09}$
$(-1,0)$	$\Xi_{cc}\bar{K}\to\Xi_{cc}\bar{K}$	$-0.49^{+0.10}_{-0.19}$
	$\Omega_{cc}\eta\to\Omega_{cc}\eta$	$-0.26^{+0.03}_{-0.03}+i\,0.02^{+0.02}_{-0.01}$
$(0,1/2)$	$\Xi_{cc}\pi\to\Xi_{cc}\pi$	$0.55^{+0.16}_{-0.10}$
	$\Xi_{cc}\eta\to\Xi_{cc}\eta$	$-0.72^{+0.21}_{-0.17}+i\,0.30^{+1.10}_{-0.18}$
	$\Omega_{cc}K\to\Omega_{cc}K$	$-0.55^{+0.11}_{-0.16}+i\,0.13^{+0.19}_{-0.07}$

Resonance poles in the complex energy plane

[ZHG, PRD'17]

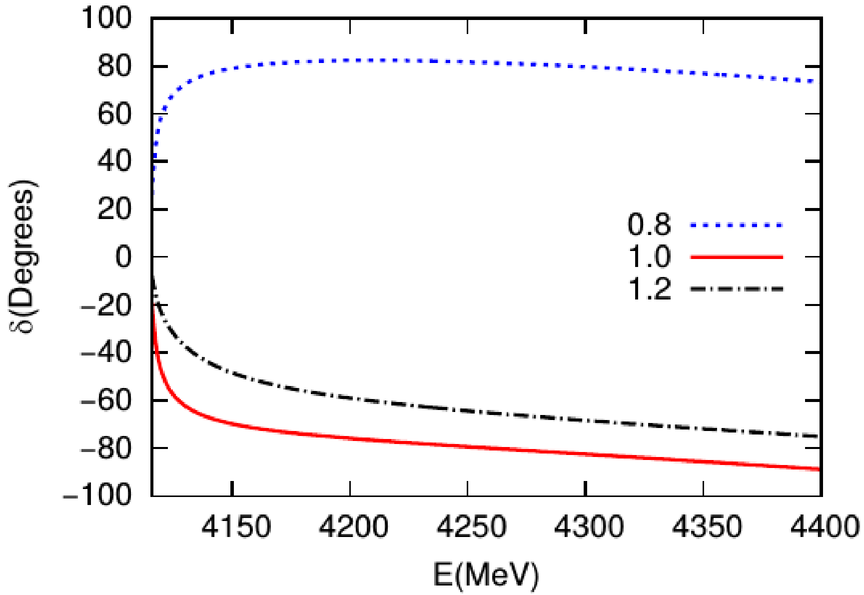
(S,I)	RS	Mass (MeV)	Width/2 (MeV)	$\lvert\text{Residue}\rvert_{11}^{1/2}$ (GeV)	$\lvert\text{Residue}\rvert_{22}^{1/2}$ (GeV)	$\lvert\text{Residue}\rvert_{33}^{1/2}$ (GeV)
$(1,0)$				$\Xi_{cc}K$		
	I	$(--, 4112, 4096)$	0	$(--, 10.0, 14.9)$		
	II	$(4114, 4115, 4113)$	0	$(6.5, 3.9, 4.1)$		
$(-1,1)$				$\Omega_{cc}\pi$	$\Xi_{cc}\bar{K}$	
	II	$(4191, 4134, 4090)$	$(89, 83, 74)$	$(15.7, 14.5, 13.2)$	$(21.0, 18.3, 16.4)$	
$(-1,0)$				$\Xi_{cc}\bar{K}$	$\Omega_{cc}\eta$	
	I	$(4018, 3957, 3907)$	0	$(22.4, 21.7, 19.8)$	$(13.4, 12.5, 11.1)$	Resembles $\Lambda(1405)$ & $D^*_{s0}(2317)$
	II	$(4105, 4095, 4083)$	0	$(5.7, 6.6, 7.4)$	$(3.0, 3.2, 3.3)$	
$(0,\frac{1}{2})$				$\Xi_{cc}\pi$	$\Xi_{cc}\eta$	$\Omega_{cc}K$
	II	$(3830, 3816, 3800)$	$(76, 50, 33)$	$(15.7, 14.6, 13.4)$	$(1.0, 1.2, 1.2)$	$(8.3, 7.6, 6.9)$
	II	$(4170, 4146, 4116)$	$(8, 18, 22)$	$(4.4, 5.7, 6.4)$	$(9.9, 12.1, 13.2)$	$(12.0, 13.6, 14.1)$

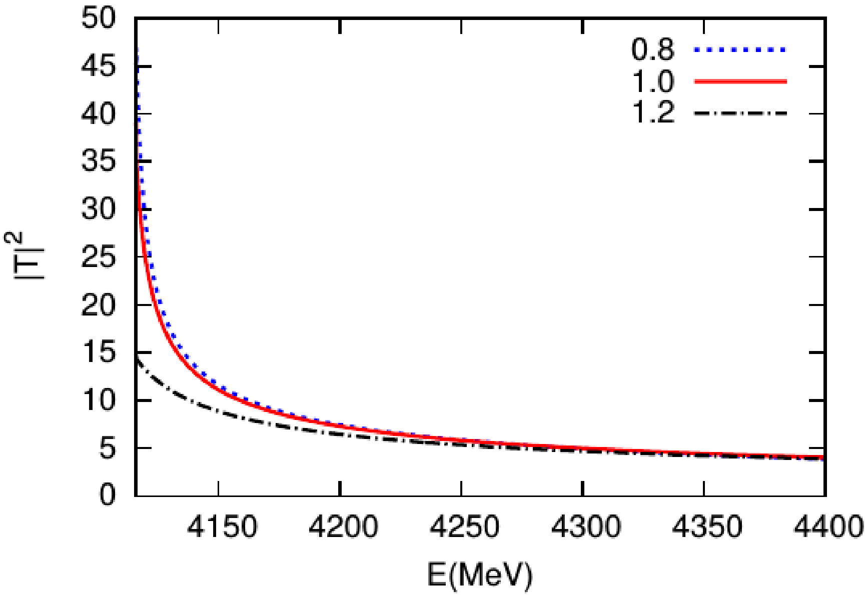
See also a pioneer study of the bound state pole in the Ξ_{cc}Kbar scattering by F.K.Guo & Ulf.-G.Meissner, PRD'11; and a following detailed study by M.J.Yuan, et al., 1805.10972 and J.M.Dias et al., 1805.03286

Phase shifts, inelasticities, line shapes

$\Xi_{cc}K \to \Xi_{cc}K$ scattering with $(S, I) = (1, 0)$

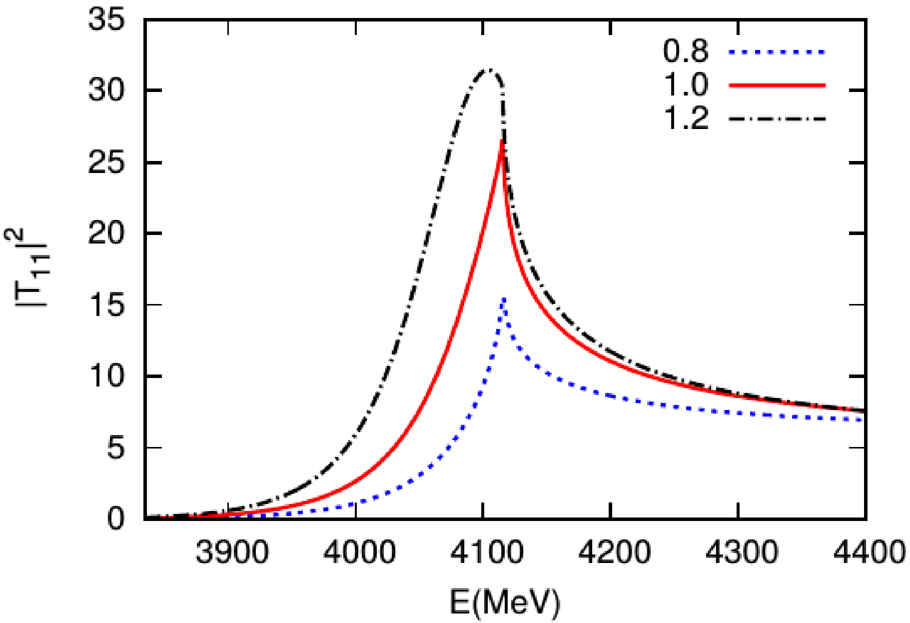
(S, I)	RS	Mass(MeV)	Width/2(MeV)	$\lvert\text{Residue}\rvert_{11}^{1/2}$(GeV)
$(1, 0)$	I	$(--,\ 4112,\ 4096)$	0	$(--,\ 10.0,\ 14.9)$
	II	$(4114,\ 4115,\ 4113)$	0	$(6.5,\ 3.9,\ 4.1)$

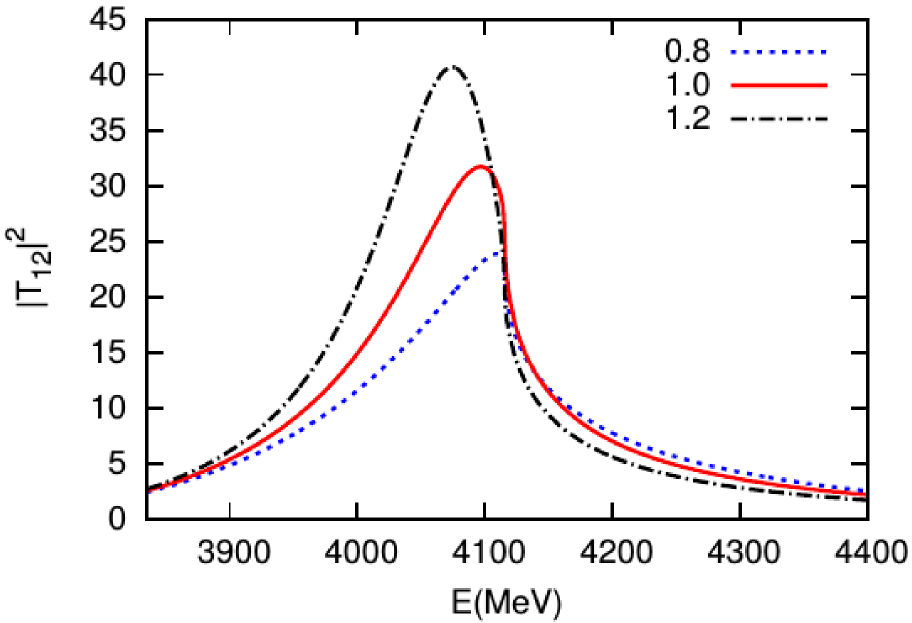




$\Omega_{cc}\pi \to \Omega_{cc}\pi$ and $\Omega_{cc}\pi \to \Xi_{cc}\bar{K}$ scattering with $(S, I) = (-1, 1)$

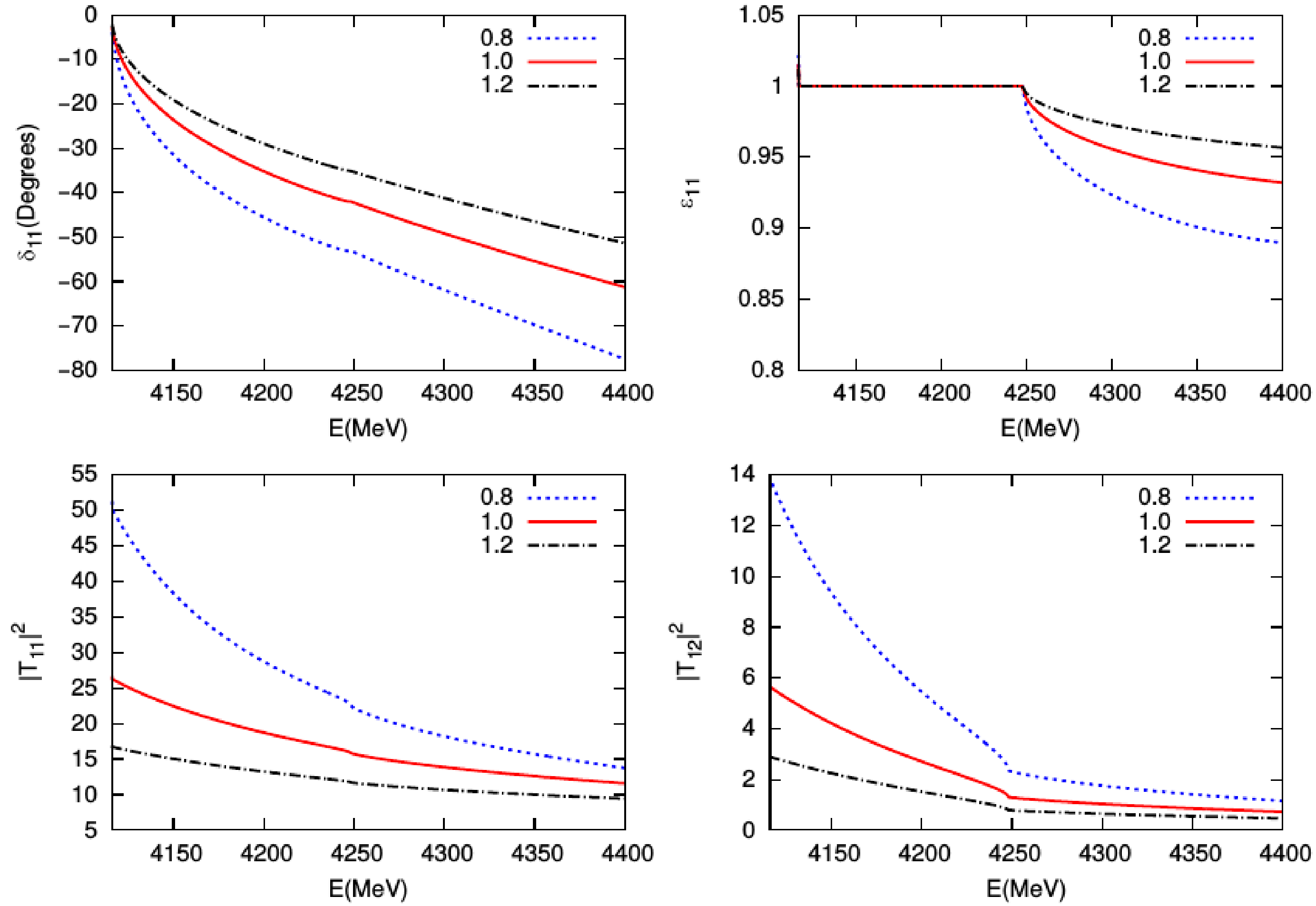
(S, I)	RS	Mass(MeV)	Width/2(MeV)	$\lvert\text{Residue}\rvert_{11}^{1/2}$(GeV)	$\lvert\text{Residue}\rvert_{22}^{1/2}$(GeV)
$(-1, 1)$	II	(4191, 4134, 4090)	(89, 83, 74)	(15.7, 14.5, 13.2)	(21.0, 18.3, 16.4)





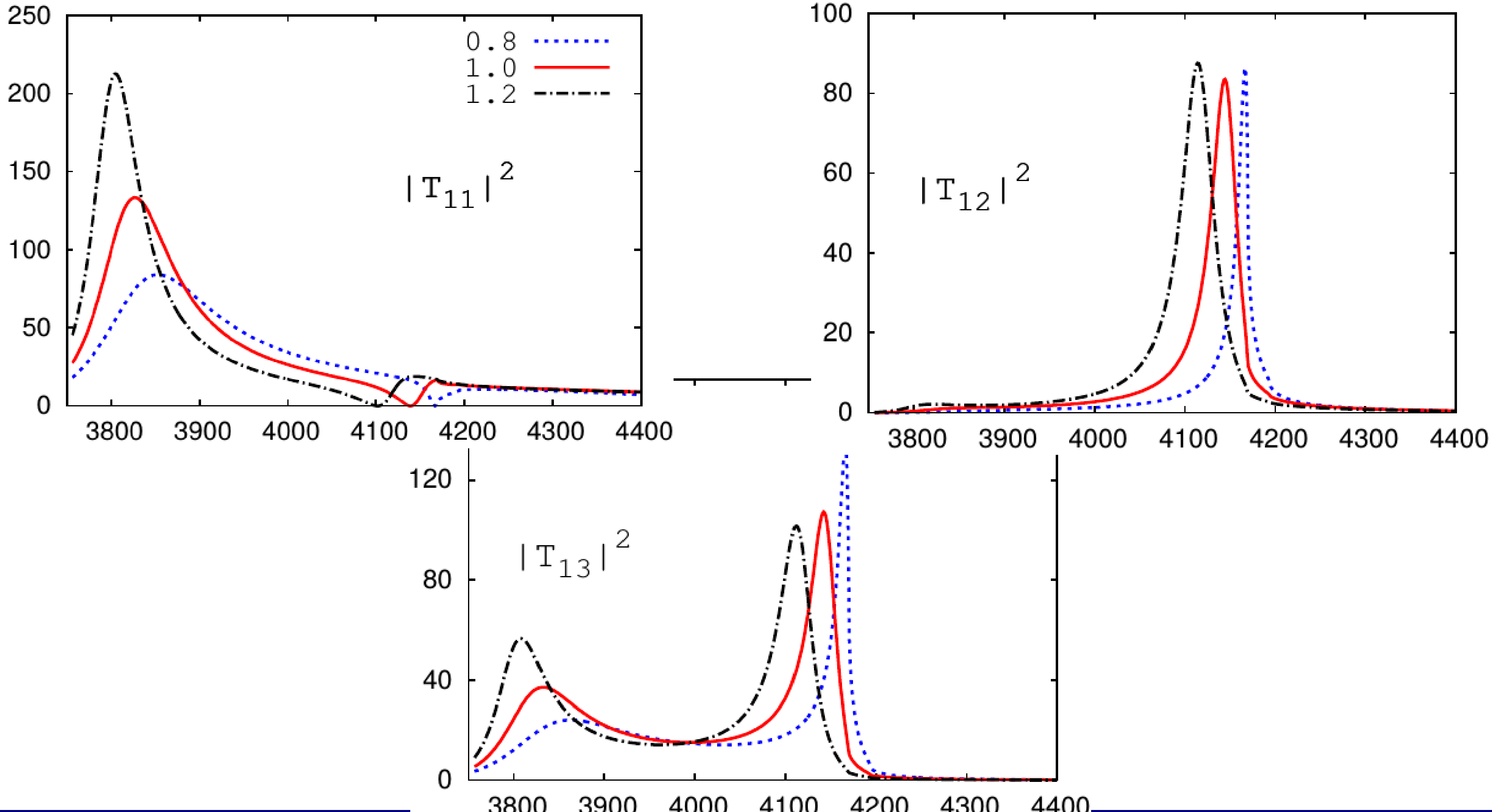
$\Xi_{cc}\bar{K} \to \Xi_{cc}\bar{K}$ and $\Xi_{cc}\bar{K} \to \Omega_{cc}\eta$ scattering with $(S, I) = (-1, 0)$

(S, I)	RS	Mass(MeV)	Width/2(MeV)	$\lvert\text{Residue}\rvert_{11}^{1/2}$(GeV)	$\lvert\text{Residue}\rvert_{22}^{1/2}$(GeV)
$(-1, 0)$	I	(4018, 3957, 3907)	0	(22.4, 21.7, 19.8)	(13.4, 12.5, 11.1)
	II	(4105, 4095, 4083)	0	(5.7, 6.6, 7.4)	(3.0, 3.2, 3.3)



$\Xi_{cc}\pi$, $\Xi_{cc}\eta$ and $\Omega_{cc}K$ coupled-channel scattering with $(S, I) = (0, 1/2)$

(S, I)	RS	Mass(MeV)	Width/2(MeV)	$\lvert\text{Residue}\rvert_{11}^{1/2}$(GeV)	$\lvert\text{Residue}\rvert_{22}^{1/2}$(GeV)	$\lvert\text{Residue}\rvert_{33}^{1/2}$(GeV)
$(0, \frac{1}{2})$	II	(3830, 3816, 3800)	(76, 50, 33)	(15.7, 14.6, 13.4)	(1.0, 1.2, 1.2)	(8.3, 7.6, 6.9)
	II	(4170, 4146, 4116)	(8, 18, 22)	(4.4, 5.7, 6.4)	(9.9, 12.1, 13.2)	(12.0, 13.6, 14.1)



Summary

• Chiral EFT provides a useful tool to study the charmed hadron spectra.

• Pole trajectories with varying m_π for the (S,I)=(0,1/2) channel are found to be quite similar as those from f0(500).

• Pole trajectories with varying Nc for $D^*_{s0}(2317)$ and the (S,I)=(0,1/2) channel are given.

• To further constrain the scatteing amplitudes using lattice finite-volume energy levels and scattering lengths is in preparation !

- **Two clearly exotic doubly charmed baryons are predicted, due to their exotic quantum numbers of (S,I)=(1,0) and (-1,1).**

- **Two resonance poles in the $\Xi_{cc}\pi, \Xi_{cc}\eta, \Omega_{cc}K$ coupled-channel scattering with (S,I)=(0,1/2) are predicted.**

- **Similar to the Λ(1405) in $\bar{K}N$ and D^{*}_{s0}(2317) in DK scattering, one bound/virtual state pole is found below the $\Xi_{cc}\bar{K}$ threshold with (S,I)=(-1,0).**

- **These findings can provide useful guides for future experimental and lattice studies.**

Thank you!

谢谢各位！