A new interpretation for the $D^*_{s2}(2573)$, the prediction of novel exotic charmed mesons and narrow N^*, Λ^* resonances around 4.3 GeV

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Outline

Introduction

Formalism: The VV interaction

- Convolution
- The PP decay mode

Results

- VV resonances
- Prediction of narrow N^* and Λ^* resonances above 4.2 GeV

Conclusions

Introduction

- Heavy quark symmetry framework (HQS): with $l = 1$ two doublets of D_s states are generated:
  - light quark $\rightarrow j_l = 3/2$, total angular momentum: $J^P = 1^+, 2^+$
  - light quark $\rightarrow j_l = 1/2$, total angular momentum: $J^P = 0^+, 1^+$
- The doublet with $J^P = 1^+, 2^+$ is identified with the $D_{s1}(2536)$ and $D_{s2}(2573)$ in HQS
- However, the doublet with $J^P = 0^+, 1^+$ and very broad states cannot be identified with the narrow states discovered: the $D^*_{s0}(2317)$ and the $D_{s1}(2460)$ (100 MeV lower in mass than the predictions)
- $D^*_{s0}(2317)$: strong s-wave Coupling to DK, E. van Beveren and G. Rupp, PRL (2003); Couple Channels: $D^*_{s0}(2317) \sim DK$, D. Gamermann, E. Oset, D. Strottmann, M. J. Vicente Vacas , PRD (2007); $D_{s1}(2460) \sim KD^*(\eta D^*_s)$, $D_{s1}(2536) \sim DK^*(D_s\omega))$ D. Gamermann and E. Oset, EPJA (2007)

The VV interaction Bando, Kugo, Yamawaki

$$\mathcal{L}_{III} = -\frac{1}{4}\langle V_{\mu\nu} V^{\mu\nu}\rangle$$

→

$$\mathcal{L}_{III}^{(3V)} = ig\langle(\partial_\mu V_\nu - \partial_\nu V_\mu)V^\mu V^\nu\rangle$$

$$\mathcal{L}_{III}^{(c)} = \frac{g^2}{2}\langle V_\mu V_\nu V^\mu V^\nu - V_\nu V_\mu V^\mu V^\nu\rangle$$

$V_{\mu\nu}$, g

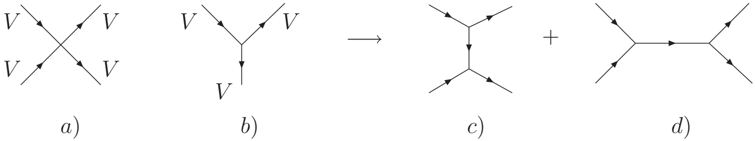
$$V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu - ig[V_\mu, V_\nu]$$

$$g = \frac{M_V}{2f}$$

V_μ

$$\begin{pmatrix} \frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & \rho^+ & K^{*+} & \bar{D}^{*0} \\ \rho^- & -\frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & K^{*0} & D^{*-} \\ K^{*-} & \bar{K}^{*0} & \phi & D_s^{*-} \\ D^{*0} & D^{*+} & D_s^{*+} & J/\psi \end{pmatrix}_\mu$$

The *VV* interaction



- The VV interaction comes from 1. a) and c)
- 1. d):
  - p-wave repulsive for equal masses (R. Molina, 2008)
  - minor component of s-wave for different masses (L. S. Geng, 2009)

Formalism: The *VV* interaction

Approximation

$$\epsilon_1^\mu = (0,1,0,0)$$
$$\epsilon_2^\mu = (0,0,1,0)$$
$$\epsilon_3^\mu = (|\vec{k}|,0,0,k^0)/m$$

$$k^\mu = (k^0,0,0,|\vec{k}|)$$

$$\vec{k}/m \simeq 0,$$
$$k_j^\mu \epsilon_\mu^{(l)} \simeq 0$$

$$\epsilon_1^\mu = (0,1,0,0)$$
$$\epsilon_2^\mu = (0,0,1,0)$$
$$\epsilon_3^\mu = (0,0,0,1)$$

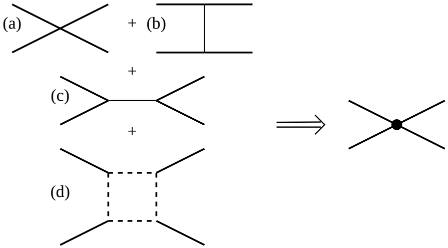
Spin projectors

$$\mathcal{P}^{(0)} = \frac{1}{3}\epsilon_\mu\epsilon^\mu\epsilon_\nu\epsilon^\nu$$

$$\mathcal{P}^{(1)} = \frac{1}{2}(\epsilon_\mu\epsilon_\nu\epsilon^\mu\epsilon^\nu - \epsilon_\mu\epsilon_\nu\epsilon^\nu\epsilon^\mu)$$

$$\mathcal{P}^{(2)} = \{\frac{1}{2}(\epsilon_\mu\epsilon_\nu\epsilon^\mu\epsilon^\nu + \epsilon_\mu\epsilon_\nu\epsilon^\nu\epsilon^\mu) - \frac{1}{3}\epsilon_\alpha\epsilon^\alpha\epsilon_\beta\epsilon^\beta\}$$

Formalism: The *VV* interaction



- (a) and (b)$\rightarrow$ Pole mass and width
- (c) $\rightarrow$ p-wave repulsive (not included)
- (d)$\rightarrow$ Pole width

Bethe equation

$$T = [I - VG]^{-1}V \qquad G = \int_0^{q_{max}} \frac{q^2 dq}{(2\pi)^2} \frac{\omega_1+\omega_2}{\omega_1\omega_2[(P^0)^2-(\omega_1+\omega_2)^2+i\epsilon]}$$

The VV interaction

1. $f_0(1370)$, $f_2(1270) \sim \rho\rho$
   R. Molina, D. Nicmorus and E. Oset, Phys. Rev. D **78**, 114018 (2008)
2. $f_0(1370)$, $f_0(1710)$, $f_2(1270)$, $f_2'(1525) \sim \rho\rho$, $K^*\bar{K}^*$...
   $K_2^*(1430) \sim \rho K^*$, ωK^*...
   L. S. Geng and E. Oset, Phys. Rev. D **79**, 074009 (2009)
3. $D^*(2640)$, $D_2^*(2460) \sim \rho(\omega)D^*$
   R. Molina, H. Nagahiro, A. Hosaka and E. Oset, Phys. Rev. D **80**, 014025 (2009)
4. Y(3940), Z(3930), X(4160) $\sim D^*\bar{D}^*$, $D_s^*\bar{D}_s^*$
   R. Molina and E. Oset, Phys. Rev. D **80**, 114013 (2009)

The *VV* interaction

- $C = 0; S = 1; I = 1/2$ (hidden charm):
  $$D_s^* \bar{D}^*,\ J/\psi K^*$$
- $C = 1; S = -1; I = 0, 1$:
  $$D^* \bar{K}^*$$
- $C = 1; S = 1; I = 0$:
  $$D^* K^*,\ D_s^* \omega,\ D_s^* \phi$$
- $C = 1; S = 1; I = 1$:
  $$D^* K^*,\ D_s^* \rho$$
- $C = 1; S = 2; I = 1/2$:
  $$D_s^* K^*$$
- $C = 2; S = 0; I = 0, 1$:
  $$D^* D^*$$
- $C = 2; S = 1; I = 1/2$:
  $$D_s^* D^*$$
- $C = 2; S = 2; I = 0$:
  $$D_s^* D_s^*$$

Convolution

Convolution due to the width of the ρ meson ($D_s^*\rho$ channel)

$$\tilde{G}(s) = \frac{1}{N}\int_{(m_\rho-2\Gamma_\rho)^2}^{(m_\rho+2\Gamma_\rho)^2} d\tilde{m}_1^2 \left(-\frac{1}{\pi}\right)\mathcal{I}m\frac{1}{\tilde{m}_1^2 - m_\rho^2 + i\Gamma\tilde{m}_1} G(s,\tilde{m}_1^2, m_{D_s^*}^2)$$

$$\Gamma(\tilde{m}) = \Gamma_\rho\left(\frac{\tilde{m}^2 - 4m_\pi^2}{m_\rho^2 - 4m_\pi^2}\right)^{3/2}\theta(\tilde{m} - 2m_\pi)$$

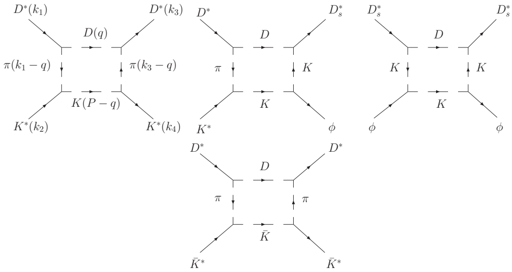
$\Gamma_{D^*} < 2.1$ MeV
$\Gamma_\rho = 146.2$ MeV
$\Gamma_{K^*} = 48$ MeV

- The ρ^*-mass convolution gives $\Gamma \simeq 8$ MeV ($D_s^*\pi\pi$)
- The K^*-mass convolution gives $\Gamma \simeq 3$ MeV (or less)($D^*\pi K$)

The *PP* decay mode

- The *PP* box diagram has only $J^P = 0^+$ and $J^P = 2^+$ quantum numbers
- We only find atractive interaction in the sectors:

- $C = 1; S = -1; I = 0$: $D^*\bar{K}^*$
- $C = 1; S = 1; I = 0$: D^*K^*, $D_s^*\phi$, $D_s^*\omega$
- $C = 1; S = 1; I = 1$: D^*K^*, $D_s^*\rho$
- $C = 2; S = 0; I = 0; J = 1$: D^*D^*
- $C = 2; S = 1; I = 1/2; J = 1$: $D_s^*D^*$



The *VV* interaction

- Model A:

$$F_1(q^2) = \frac{\Lambda_b^2 - m_1^2}{\Lambda_b^2 - (k_1^0 - q^0)^2 + |\vec{q}|^2},$$

$$F_3(q^2) = \frac{\Lambda_b^2 - m_3^2}{\Lambda_b^2 - (k_3^0 - q^0)^2 + |\vec{q}|^2},$$

with $q^0 = \frac{s+m_2^2-m_4^2}{2\sqrt{s}}$, $\vec{q}$ running variable, $\Lambda_b = 1.4, 1.5$ GeV and $g = M_\rho/2f_\pi$

- Model B:

$$F(q^2) = e^{((q^0)^2 - |\vec{q}|^2)/\Lambda^2} \; ,$$

with $\Lambda = 1, 1.2$ GeV, $q^0 = \frac{s+m_2^2-m_4^2}{2\sqrt{s}}$, $g = M_\rho/2f_\pi$, $g_{D_s} = M_{D_s^*}/2f_{D_s} = 5.47$ and $g_D = g_{D^*D\pi}^{\rm exp} = 8.95$ (experimental value)

Couplings (g_a) in units of MeV

$$T_{ab} = \frac{g_a g_b}{s - s_p}$$

$C = 1; S = -1; I = 0$

$I[J^P]$	$\sqrt{s}_{\rm pole}$	$g_{D^*\bar{K}^*}$
$0[0^+]$	2848	12227
$0[1^+]$	2839	13184
$0[2^+]$	2733	17379

$C = 1; S = 1; I = 0$

$I[J^P]$	$\sqrt{s}$	$g_{D^*K^*}$	$g_{D_s^*\omega}$	$g_{D_s^*\phi}$
$0[0^+]$	2683	15635	-4035	6074
$0[1^+]$	2707	14902	-5047	4788
$0[2^+]$	2572	18252	-7597	7257

$C = 1; S = 1; I = 1$

$I^G[J^{PC}]$	$\sqrt{s}_{\rm pole}$	$g_{D^*K^*}$	$g_{D_s^*\rho}$
$1[2^+]$	2786	11041	11092

$C = 2; S = 0; I = 0$

$I[J^P]$	$\sqrt{s}_{\rm pole}$	$g_{D^*D^*}$
$0[1^+]$	3969	16825

$C = 2; S = 1; I = 1/2$

$I[J^P]$	$\sqrt{s}_{\rm pole}$	$g_{D_s^*D^*}$
$1/2[1^+]$	4101	13429

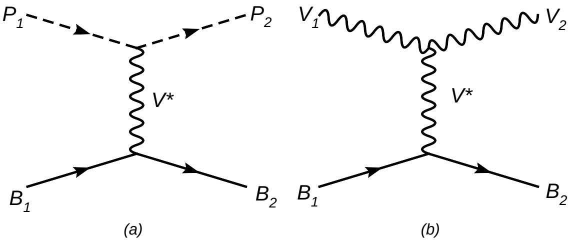
Summary

C, S	$I[J^P]$	$\sqrt{s}$	$\Gamma_A(\Lambda = 1400)$	$\Gamma_B(\Lambda = 1000)$	State	$\sqrt{s}_{exp}$	Γ_{exp}
$1, -1$	$0[0^+]$	2848	23	25			
	$0[1^+]$	2839	3	3			
	$0[2^+]$	2733	11	22			
$1, 1$	$0[0^+]$	2683	20	44			
	$0[1^+]$	2707	4×10^{-3}	4×10^{-3}			
	$0[2^+]$	2572	7	18	$D_{s2}(2573)$	2572.6 ± 0.9	20 ± 5
	$1[2^+]$	2786	8	9			
$2, 0,$	$0[1^+]$	3969	0	0			
$2, 1$	$1/2[1^+]$	4101	0	0			

Table: Summary of the nine states obtained. The width is given for the model A, Γ_A, and B, Γ_B. All the quantities here are in MeV. Two values of α are used: -1.6 and -1.4.

PB and *VB* resonances in the hidden charm sector

- $I = 1/2, S = 0$. Channels: $\bar{D}\Sigma_c$, $\bar{D}\Lambda_c^+$, $\eta_c N$, πN, ηN, $\eta' N$, $K\Sigma$, $K\Lambda$
- $I = 0, S = -1$. Channels: $\bar{D}_s\Lambda_c^+$, $\bar{D}\Xi_c$, $\bar{D}\Xi_c'$, $\eta_c\Lambda$, $\pi\Sigma$, $\eta\Lambda$, $\eta'\Lambda$, $\bar{K}N$, $K\Xi$



$$\mathcal{L}_{BBV} = g(\langle\bar{B}\gamma_\mu[V^\mu, B]\rangle + \langle\bar{B}\gamma_\mu B\rangle\langle V^\mu\rangle)$$

$$t_{B_1\bar{B}_2V} = \{g_{15_1} C_{15_1}(20' \otimes \bar{20}') + g_{15_2} C_{15_2}(20' \otimes \bar{20}') + g_1 C_1(20' \otimes \bar{20}')\}\bar{u}_{r'}(p_2)\gamma\cdot\epsilon\, u_r(p_1)$$

$$T = [I - VG]^{-1}V \qquad T_{ab} = \frac{g_a g_b}{\sqrt{s} - z_R}$$

PB resonances

(I, S)	z_R (MeV)	g_a		
$(1/2, 0)$		$\bar{D}\Sigma_c$	$\bar{D}\Lambda_c^+$	
	4269	2.85	0	
$(0, -1)$		$\bar{D}_s\Lambda_c^+$	$\bar{D}\Xi_c$	$\bar{D}\Xi'_c$
	4213	1.37	3.25	0
	4403	0	0	2.64

VB resonances

(I, S)	z_R (MeV)	g_a		
$(1/2, 0)$		$\bar{D}^*\Sigma_c$	$\bar{D}^*\Lambda_c^+$	
	4418	2.75	0	
$(0, -1)$		$\bar{D}_s^*\Lambda_c^+$	$\bar{D}^*\Xi_c$	$\bar{D}^*\Xi'_c$
	4370	1.23	3.14	0
	4550	0	0	2.53

Prediction of narrow N^* and Λ^* resonances above 4.2 GeV

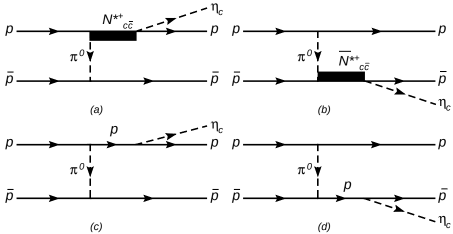
PB resonances (units in MeV)

(I,S)	M	Γ	Γ_i					
$(1/2,0)$			πN	ηN	$\eta' N$	$K\Sigma$		$\eta_c N$
	4261	56.9	3.8	8.1	3.9	17.0		23.4
$(0,-1)$			$\bar{K}N$	$\pi\Sigma$	$\eta\Lambda$	$\eta'\Lambda$	$K\Xi$	$\eta_c\Lambda$
	4209	32.4	15.8	2.9	3.2	1.7	2.4	5.8
	4394	43.3	0	10.6	7.1	3.3	5.8	16.3

VB resonances

(I,S)	M	Γ	Γ_i					
$(1/2,0)$			ρN	ωN	$K^*\Sigma$			$J/\psi N$
	4412	47.3	3.2	10.4	13.7			19.2
$(0,-1)$			$\bar{K}^*N$	$\rho\Sigma$	$\omega\Lambda$	$\phi\Lambda$	$K^*\Xi$	$J/\psi\Lambda$
	4368	28.0	13.9	3.1	0.3	4.0	1.8	5.4
	4544	36.6	0	8.8	9.1	0	5.0	13.8

Production cross section of the N^* resonances at FAIR



- $\bar{p}$ beam of 15 GeV/c, $\sqrt{s} = 5470$ MeV $\rightarrow M_X \simeq 4538$ MeV. $\frac{d\sigma_{p\bar{p}\rightarrow N^{*+}_{c\bar{c}}(4265)\bar{p}\rightarrow \eta_c p\bar{p}}}{dcos\theta dM_I^2} = 0.3\,\mu b/GeV^2$ at peak, $\sigma \simeq 0.07\,\mu b$.
- $\sigma(p\bar{p} \rightarrow N^{*+}_{c\bar{c}}(4418)\bar{p} \rightarrow \eta_c p\bar{p}) \simeq 0.002\mu b$.

This corresponds to an event production rate of 80000 **and** 1700 **events per day for the** $N^{*+}_{c\bar{c}}(4265)$ **and** $N^{*+}_{c\bar{c}}(4418)$ **respectively for a Luminosity of** $10^{31} cm^{-2} s^{-1}$**.**

Conclusions

- We studied dynamically generated resonances from vector-vector interaction in the charm-strange, hidden-charm and flavor exotic sectors and meson-baryon resonances with hidden charm
- In the present work we can assign one resonance to an experimental counterpart, which is the $D_2^*(2573)$
- We have found flavor exotic resonances with double charm, double charm-strangeness and new N^*, Λ^* states around 4.3 GeV that if observed cannot be accomodated in terms of $q\bar{q}$

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