

# QUARK MODEL WITH HIDDEN LOCAL SYMMETRY AND ITS APPLICATION TO THE HADRON SPECTRUM

具有隐藏定域对称性的夸克模型及其在强子谱  
中的应用

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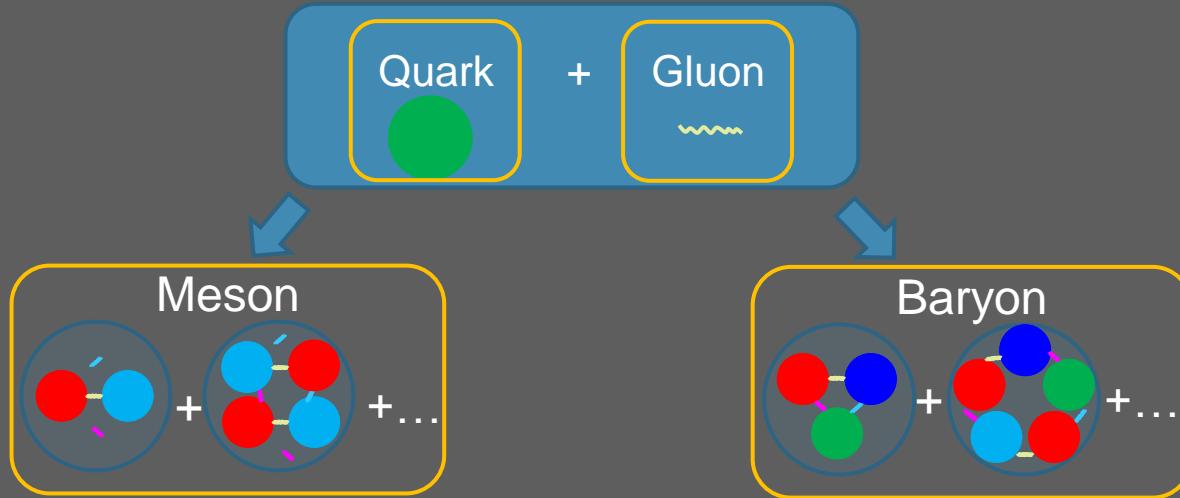
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# Outline

- ***Introduction***
- Chiral quark model with HLS
- $SU2$  ground states + excited states
- $SU3$  ground states
- Summary

# Introduction

Hadrons are made by quarks and gluons



The dynamics of quarks and gluons are described by Quantum chromodynamics (QCD)

- QCD have two important features:
  - ◆ Color confinement
  - ◆ Asymptotic freedom
- In low energy region the perturbative calculation for QCD is impossible, alternatively:
  - ◆ Lattice QCD (non-perturbative calculation)
  - ◆ Effective models (chiral perturbation theory, quark model, etc...)

## Meson Summary Table

See also the table of suggested  $q\bar{q}$  quark-model assignments in the Quark Model section.

icates particles that appear in the preceding Meson Summary Table. We do not regard the other entries as being established.

LIGHT UNFLAVORED ( $S = C = B = 0$ )		STRANGE ( $S = \pm 1, C = B = 0$ )		CHARMED, STRANGE ( $C = \pm 1, S = \pm 1$ ) (+ possibly non- $q\bar{q}$ states)		$c\bar{c}$ continued $f^0(J^{PC})$	
$f^0(J^{PC})$	$f^0(J^{PC})$	$f^0(J^{PC})$	$f^0(J^{PC})$	$f^0(J^{PC})$	$f^0(J^{PC})$		
$\bullet \pi^\pm$	$1^-(0^-)$	$\bullet \pi_2(1670)$	$1^-(2-+)$	$\bullet K^\pm$	$1/2(0^-)$	$\bullet \psi_{\text{2}}(3823)$	$0^-(2-+)$
$\bullet \pi^0$	$1^-(0-+)$	$\bullet \phi(1680)$	$0^-(1- -)$	$\bullet K^0$	$1/2(0^-)$	$\bullet \psi_{\text{3}}(3842)$	$0^-(3- -)$
$\bullet \eta$	$0^+(0-+)$	$\bullet \rho_3(1690)$	$1^+(3-+)$	$\bullet K_S^0$	$1/2(0^-)$	$\chi_{\text{CD}}(3860)$	$0^+(0++)$
$\bullet f_0(500)$	$0^+(0-+)$	$\bullet \rho(1700)$	$1^+(1- -)$	$\bullet K_L^0$	$1/2(0^-)$	$\times_{\text{C}}(3872)$	$0^+(1++)$
$\bullet \rho(770)$	$1^+(1- -)$	$\bullet a_2(1700)$	$1^-(2++)$	$\bullet K_0^*(700)$	$1/2(0^+)$	$Z_{\text{c}}(3900)$	$1^+(1-+)$
$\bullet \omega(782)$	$0^-(1- -)$	$\bullet f_0(1710)$	$0^+(0++)$	$\bullet K^*(892)$	$1/2(0^-)$	$\chi_{\text{CD}}(3915)$	$0^+(0++)$
$\bullet \eta'(958)$	$0^+(0-+)$	$X(1750)$	$?^-(1- -)$	$\bullet K_1(1270)$	$1/2(1^+)$	$\times_{\text{C}}(3930)$	$0^+(2++)$
$\bullet f_0(980)$	$0^+(0++)$	$\eta(1760)$	$0^+(0-+)$	$\bullet K_1(1400)$	$1/2(2^+)$	$X(3940)$	$?(^??)$
$\bullet a_0(980)$	$1^-(0-+)$	$\bullet \pi(1800)$	$1^-(0-+)$	$\bullet K^*(1410)$	$1/2(1^-)$	$\times(4020)$	$1^+(?^?)$
$\bullet d(1020)$	$0^-(1- -)$	$f_0(1810)$	$0^+(2++)$	$\bullet K_0^*(1430)$	$1/2(2^+)$	$\bullet \psi(4040)$	$0^-(1- -)$
$\bullet h_1(1170)$	$0^-(1- +)$	$X(1835)$	$?^-(0-+)$	$\bullet K_1^*(1430)$	$1/2(2^+)$	$X(4050)$	$1^-(?^?)$
$\bullet b_1(1235)$	$1^+(1- +)$	$\bullet \phi_3(1850)$	$0^-(3- -)$	$\bullet K(1460)$	$1/2(0^-)$	$X(4055)$	$1^+(?^?)$
$\bullet a_1(1260)$	$1^-(1- +)$	$\bullet \eta_2(1870)$	$0^+(2-+)$	$K_2(1580)$	$1/2(2^-)$	$X(4100)$	$1^+(?^?)$
$\bullet f_2(1270)$	$0^+(2-+)$	$\pi_2(1880)$	$1^-(2-+)$	$K(1630)$	$1/2(2^?)$	$\times_{\text{C}}(4140)$	$0^+(1++)$
$\bullet f_1(1285)$	$0^+(1-+)$	$\rho_1(1900)$	$1^+(1- -)$	$\bullet K_1(1650)$	$1/2(2^+)$	$\psi(4160)$	$0^-(1- -)$
$\bullet \eta(1295)$	$0^+(0-+)$	$f_2(1910)$	$0^+(2++)$	$\bullet K^*(1680)$	$1/2(2^+)$	$X(4160)$	$?(^??)$
$\pi(1300)$	$1^-(0-+)$	$a_0(1950)$	$1^-(0++)$	$\bullet K_2(1770)$	$1/2(2^-)$	$Z_{\text{c}}(4200)$	$1^+(1-+)$
$\bullet a_2(1320)$	$1^-(2-+)$	$\bullet f_2(1950)$	$0^+(2++)$	$\bullet K_3^*(1780)$	$1/2(3^-)$	$\psi_{\text{CD}}(4240)$	$1^+(0- -)$
$\bullet f_3(1370)$	$0^+(0++)$	$\bullet a_4(1970)$	$1^-(4++)$	$\bullet K_2(1820)$	$1/2(2^-)$	$X(4250)$	$1^-(?^?)$
$\bullet \pi_1(1400)$	$1^-(1- -)$	$\rho_2(1990)$	$1^+(3- -)$	$\bullet K(1830)$	$1/2(2^-)$	$\times_{\text{C}}(4274)$	$0^+(1++)$
$\bullet \eta(1405)$	$0^+(0-+)$	$\pi_2(2005)$	$1^-(2- -)$	$K_0^*(1950)$	$1/2(0^+)$	$X(4350)$	$0^+(?^?)$
$\bullet h_1(1415)$	$0^-(1- +)$	$\bullet f_2(2010)$	$0^+(2++)$	$\bullet K_2^*(1980)$	$1/2(2^+)$	$\psi(4360)$	$0^-(1- -)$
$\bullet f_1(1420)$	$0^+(1- +)$	$f_2(2020)$	$0^+(0++)$	$\bullet K_4^*(2045)$	$1/2(2^+)$	$\psi(4415)$	$0^-(1- -)$
$\bullet \omega(1420)$	$0^+(1- -)$	$\bullet f_4(2050)$	$0^+(4++)$	$\bullet K_2(2250)$	$1/2(2^-)$	$Z_{\text{c}}(4340)$	$1^+(1-+)$
$\bullet f_2(1430)$	$0^+(2-+)$	$\pi_2(2100)$	$1^-(2- -)$	$K_2(2320)$	$1/2(3^+)$	$\psi_{\text{CD}}(4572)$	$1/2(1^+)$
$\bullet a_0(1450)$	$1^-(0-+)$	$f_2(2100)$	$0^+(0++)$	$K_2(2380)$	$1/2(2^-)$	$\times_{\text{C}}(4573)$	$?(^?)$
$\bullet \rho_1(1450)$	$1^+(1- -)$	$f_2(2150)$	$0^+(2++)$	$K_4(2500)$	$1/2(2^-)$	$\bullet B_2^*(5747)$	$1/2(2^+)$
$\bullet \eta(1475)$	$0^+(0-+)$	$\rho(2150)$	$1^+(1- -)$	$K(23100)$	$?(^??)$	$B_J(5840)$	$1/2(?)$
$\bullet f_0(1500)$	$0^+(0-+)$	$\bullet \phi(2170)$	$0^-(1- -)$	$f_2(2200)$	$0^+(0++)$	$\times_{\text{C}}(5970)$	$1/2(?)$
$\bullet f_1(1510)$	$0^+(1- +)$						
$\bullet f_2(1525)$	$0^+(2-+)$						
$\bullet f_3(1565)$	$0^+(2-+)$						
$\rho(1570)$	$1^+(1- -)$						
$b_1(1595)$	$0^-(1- +)$						
$\bullet \pi_1(1600)$	$1^-(1- +)$						
$\bullet a_1(1640)$	$1^-(1- +)$						
$f_2(1640)$	$0^+(2-+)$						
$\bullet \eta_2(1645)$	$0^+(2- -)$						
$\bullet \omega(1650)$	$0^-(1- -)$						
$\bullet \omega_3(1670)$	$0^-(3- -)$						
CHARMED		BOTTOM, STRANGE ( $B = \pm 1, S = \mp 1$ )		$b\bar{b}$ (+ possibly non- $q\bar{q}$ states)			
$(C = \pm 1)$		$(B = \pm 1, S = \mp 1)$		$(+ \text{possibly non-}q\bar{q}\text{ states})$			
$\bullet D^\pm$	$1/2(0^-)$	$\bullet B_0^0$	$0(0^-)$	$\bullet \eta_{\text{b}}(1S)$	$0^+(0-+)$		
$\bullet D^0$	$1/2(0^-)$	$\bullet B_0^+$	$0(1^-)$	$\bullet \gamma_{\text{S}}(1S)$	$0^-(1- -)$		
$\bullet D^*(2007)^0$	$1/2(1^-)$	$\bullet D^*(2010)^{\pm}$	$1/2(1^-)$	$\times_{\text{C}}(1P)$	$0^+(\text{0}+)\text{+}$		
$\bullet D^*(2010)^{\pm}$	$1/2(1^-)$	$\bullet D_0^*(2300)$	$1/2(0^+)$	$\bullet \chi_{\text{b}}(1P)$	$0^+(1++)$		
$\bullet D_0^*(2300)$	$1/2(0^+)$	$\bullet D_1(2420)$	$1/2(0^+)$	$\bullet h_{\text{b}}(1P)$	$0^-(1- -)$		
$\bullet D_1(2420)$	$1/2(0^+)$	$\bullet D_1(2430)^0$	$1/2(2^+)$	$\bullet \chi_{\text{b}}(2P)$	$0^+(2++)$		
$\bullet D_1(2430)^0$	$1/2(2^+)$	$\bullet D_2(2600)^0$	$1/2(1^-)$	$\bullet \eta_{\text{b}}(2S)$	$0^+(0-+)$		
$\bullet D_2(2600)^0$	$1/2(1^-)$	$D_2(2740)^0$	$1/2(2^-)$	$\bullet \gamma_{\text{S}}(2S)$	$0^-(1- -)$		
$D^*(2640)^{\pm}$	$1/2(1^?)$	$D_2(2740)^0$	$1/2(2^-)$	$\bullet \chi_{\text{D}}(2D)$	$0^-(2- -)$		
$D_2(2740)^0$	$1/2(2^-)$	$\bullet D_3^*(2750)^0$	$1/2(3^-)$	$\bullet \chi_{\text{D}}(2P)$	$0^+(0++)$		
$D_3^*(2750)^0$	$1/2(3^-)$	$D_1^*(2760)^0$	$1/2(1^-)$	$\bullet \chi_{\text{D}}(1P)$	$0^+(1++)$		
$D_1^*(2760)^0$	$1/2(1^-)$	$D(3000)^0$	$1/2(2?)$	$\bullet h_{\text{b}}(2P)$	$0^-(1- -)$		
$c\bar{c}$		$c\bar{c}$		OTHER			
$(+ \text{possibly non-}q\bar{q}\text{ states})$		$(+ \text{possibly non-}q\bar{q}\text{ states})$		Further States			
$\bullet \eta_{\text{c}}(1S)$	$0^+(0-+)$	$\bullet J/\psi(1S)$	$0^-(1- -)$				
$\bullet J/\psi(1S)$	$0^-(1- -)$	$\times_{\text{C}}(1P)$	$0^+(0++)$				
$\times_{\text{C}}(1P)$	$0^+(0++)$	$\bullet \chi_{\text{c}}(1P)$	$0^+(1++)$				
$\bullet \chi_{\text{c}}(1P)$	$0^+(1++)$	$\bullet h_{\text{c}}(1P)$	$0^-(1- -)$				
$\bullet h_{\text{c}}(1P)$	$0^-(1- -)$	$\bullet \chi_{\text{c}}(2P)$	$0^+(2++)$				
$\bullet \chi_{\text{c}}(2P)$	$0^+(2++)$	$\bullet \eta_{\text{c}}(2S)$	$0^-(0-+)$				
$\bullet \eta_{\text{c}}(2S)$	$0^-(0-+)$	$\psi(2S)$	$0^-(1- -)$				
$\psi(2S)$	$0^-(1- -)$	$\psi(3770)$	$0^-(1- -)$				

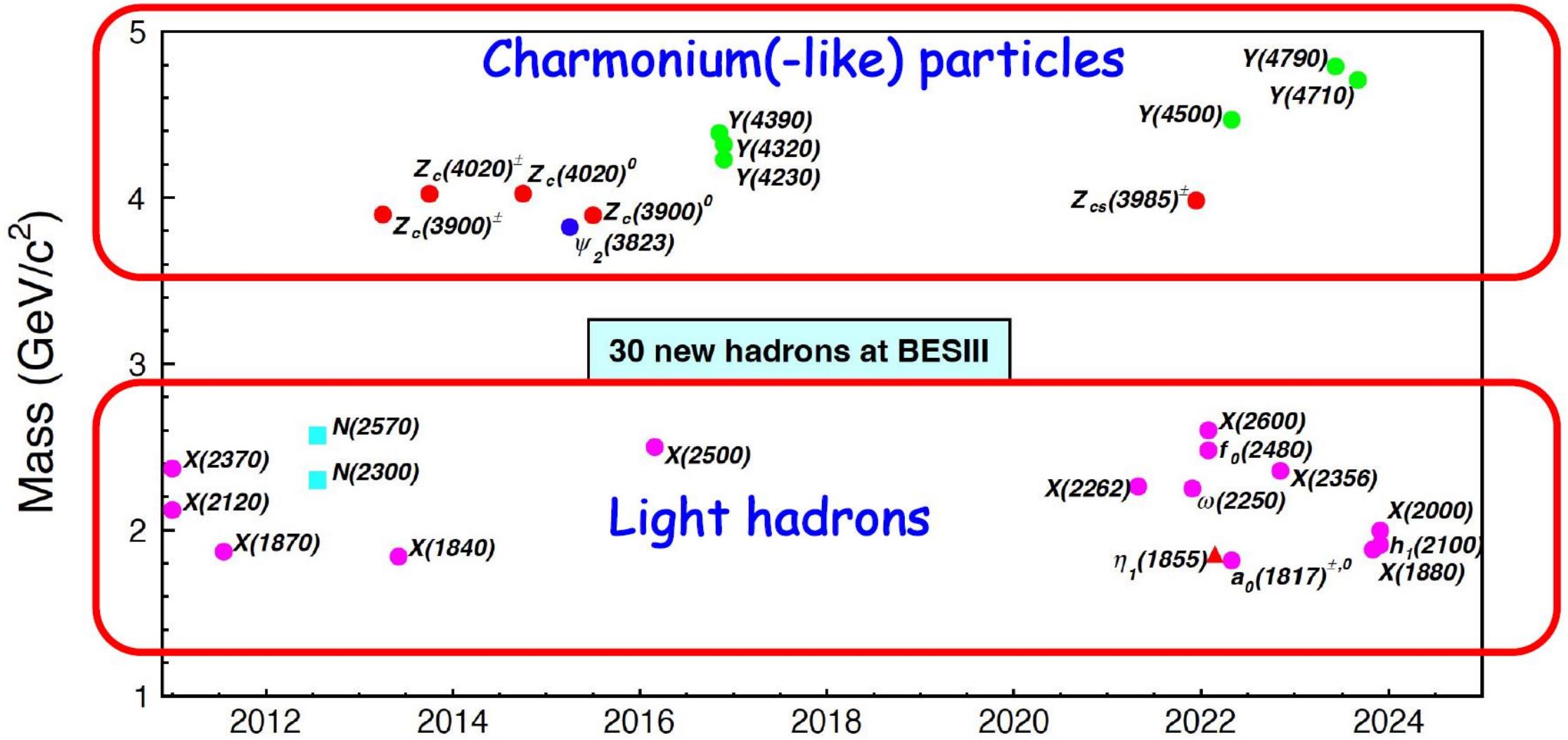
## Baryon Summary Table

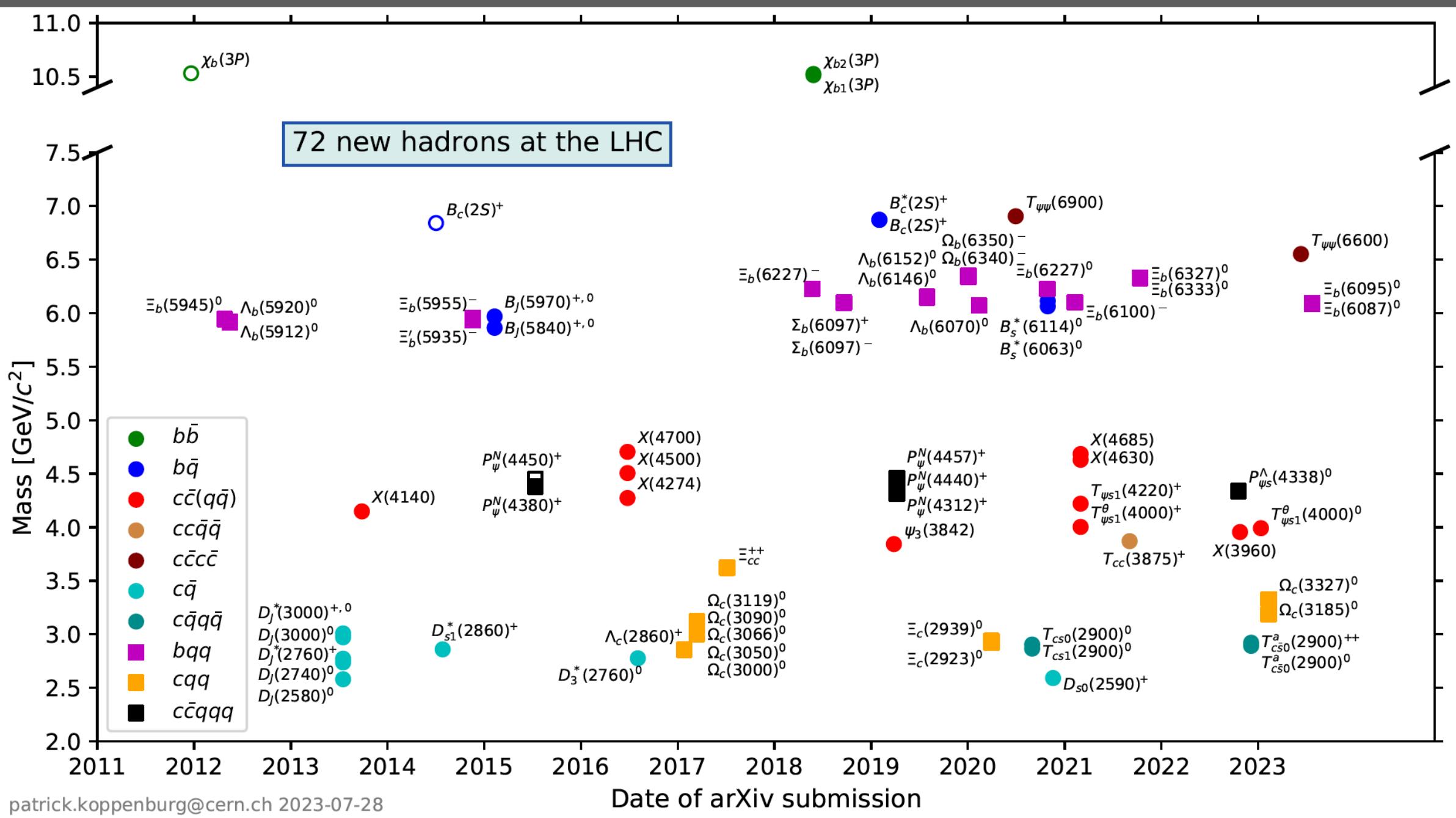
This short table gives the name, the quantum numbers (where known), and the status of baryons in the Review. Only the baryons with 3- or 4-star status are included in the Baryon Summary Table. Due to insufficient data or uncertain interpretation, the other entries in the table are not established baryons. The names with masses are of baryons that decay strongly. The spin parity  $J^P$  (when known) is given with each particle. For the strongly decaying particles, the  $J^P$  values are considered to be part of the names.

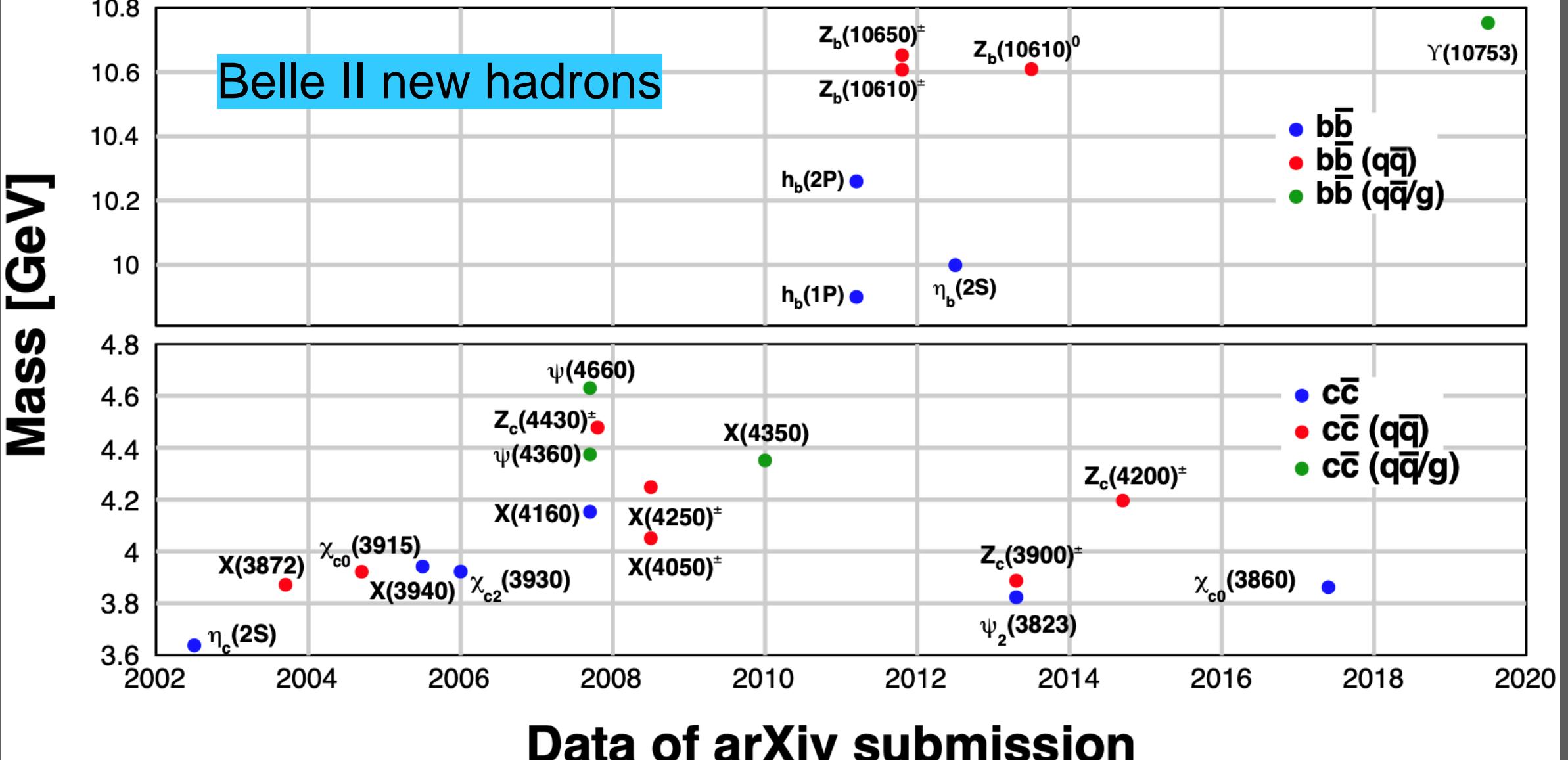
$p$	1/2 <sup>+</sup>	****	$\Delta(1232)$	3/2 <sup>+</sup>	****	$\Sigma^+$	1/2 <sup>+</sup>	****	$\Lambda_c^+$	1/2 <sup>+</sup>	****	$\Lambda_b^0$	1/2 <sup>+</sup>	***
$n$	1/2 <sup>+</sup>	****	$\Delta(1600)$	3/2 <sup>+</sup>	****	$\Sigma^0$	1/2 <sup>+</sup>	****	$\Lambda_c(2595)^+$	1/2 <sup>-</sup>	***	$\Lambda_b(5912)^0$	1/2 <sup>-</sup>	***
$N(1440)$	1/2 <sup>+</sup>	****	$\Delta(1620)$	1/2 <sup>-</sup>	****	$\Sigma^-$	1/2 <sup>+</sup>	****	$\Lambda_c(2625)^+$	3/2 <sup>-</sup>	***	$\Lambda_b(5920)^0$	3/2 <sup>-</sup>	***
$N(1520)$	3/2 <sup>-</sup>	****	$\Delta(1700)$	3/2 <sup>-</sup>	****	$\Sigma(1385)$	3/2 <sup>+</sup>	****	$\Lambda_c(2765)^+$	*		$\Lambda_b(6070)^0$	1/2 <sup>+</sup>	***
$N(1535)$	1/2 <sup>-</sup>	****	$\Delta(1750)$	1/2 <sup>+</sup>	*	$\Sigma(1580)$	3/2 <sup>-</sup>	*	$\Lambda_c(2860)^+$	3/2 <sup>+/-</sup>	***	$\Lambda_b(6146)^0$	3/2 <sup>/-</sup>	***
$N(1650)$	1/2 <sup>-</sup>	****	$\Delta(1900)$	1/2 <sup>-</sup>	*	$\Sigma(1620)$	1/2 <sup>-</sup>	*	$\Lambda_c(2880)^+$	5/2 <sup>+</sup>	***	$\Lambda_b(6152)^0$	5/2 <sup>+</sup>	***
$N(1675)$	5/2 <sup>+</sup>	****	$\Delta(1905)$	5/2 <sup>+</sup>	****	$\Sigma(1660)$	1/2 <sup>+</sup>	***	$\Lambda_c(2940)^+$	3/2 <sup>-</sup>	***	$\Sigma_b^-$	1/2 <sup>+</sup>	***
$N(1680)$	5/2 <sup>+</sup>	****	$\Delta(1910)$	1/2 <sup>+</sup>	****	$\Sigma(1670)$	3/2 <sup>-</sup>	****	$\Sigma_c(2455)$	1/2 <sup>+</sup>	****	$\Sigma_b^*$	3/2 <sup>+</sup>	***
$N(1700)$	3/2 <sup>-</sup>	***	$\Delta(1920)$	3/2 <sup>+</sup>	***	$\Sigma(1750)$	1/2 <sup>-</sup>	***	$\Sigma_c(2520)$	3/2 <sup>+</sup>	***	$\Sigma_b(6097)^+$		***
$N(1710)$	1/2 <sup>+</sup>	****	$\Delta(1930)$	5/2 <sup>-</sup>	***	$\Sigma(1775)$	5/2 <sup>-</sup>	***	$\Sigma_c(2800)$		***	$\Sigma_b(6097)^-$		***
$N(1720)$	3/2 <sup>+</sup>	****	$\Delta(1940)$	3/2 <sup>-</sup>	*	$\Sigma(1780)$	3/2 <sup>+</sup>	*	$\Xi_c^+$	1/2 <sup>+</sup>	***	$\Xi_b^-$	1/2 <sup>+</sup>	***
$N(1860)$	5/2 <sup>+</sup>	**	$\Delta(1950)$	7/2 <sup>+</sup>	****	$\Sigma(1880)$	1/2 <sup>+</sup>	**	$\Xi_c^0$	1/2 <sup>+</sup>	***	$\Xi_b^0$	1/2 <sup>+</sup>	***
$N(1875)$	3/2 <sup>-</sup>	***	$\Delta(2000)$	5/2 <sup>+</sup>	**	$\Sigma(1900)$	1/2 <sup>-</sup>	**	$\Xi_c^+$	1/2 <sup>+</sup>	***	$\Xi_b'(5935)^-$	1/2 <sup>+</sup>	***
$N(1880)$	1/2 <sup>+</sup>	***	$\Delta(2150)$	1/2 <sup>-</sup>	*	$\Sigma(1910)$	3/2 <sup>-</sup>	***	$\Xi_c^0$	1/2 <sup>+</sup>	***	$\Xi_b(5945)^0$	3/2 <sup>+</sup>	***
$N(1895)$	1/2 <sup>-</sup>	****	$\Delta(2200)$	7/2 <sup>-</sup>	***	$\Sigma(1915)$	5/2 <sup>+</sup>	****	$\Xi_c(2645)$	3/2 <sup>+</sup>	***	$\Xi_b(6955)^-$	3/2 <sup>+</sup>	***
$N(1900)$	3/2 <sup>+</sup>	****	$\Delta(2300)$	9/2 <sup>+</sup>	**	$\Sigma(1940)$	3/2 <sup>+</sup>	*	$\Xi_c(2790)$	1/2 <sup>-</sup>	***	$\Xi_b(6100)^-$	3/2 <sup>-</sup>	***
$N(1990)$	7/2 <sup>+</sup>	**	$\Delta(2350)$	5/2 <sup>-</sup>	*	$\Sigma(2010)$	3/2 <sup>-</sup>	*	$\Xi_c(2815)$	3/2 <sup>-</sup>	***	$\Xi_b(6227)^-$		***
$N(2000)$	5/2 <sup>+</sup>	**	$\Delta(2390)$	7/2 <sup>+</sup>	*	$\Sigma(2030)$	7/2 <sup>+</sup>	****	$\Xi_c(2923)$		**	$\Xi_b(6227)^0$		***
$N(2040)$	3/2 <sup>+</sup>	*	$\Delta(2400)$	9/2 <sup>-</sup>	*	$\Sigma(2070)$	5/2 <sup>+</sup>	*	$\Xi_c(2930)$		**	$\Omega_b^-$	1/2 <sup>+</sup>	***
$N(2060)$	5/2 <sup>-</sup>	***	$\Delta(2420)$	11/2 <sup>+</sup>	****	$\Sigma(2080)$	3/2 <sup>+</sup>	*	$\Xi_c(2970)$	1/2 <sup>+</sup>	***	$\Omega_b(6316)^-$		*
$N(2100)$	1/2 <sup>+</sup>	***	$\Delta(2750)$	13/2 <sup>-</sup>	**	$\Sigma(2110)$	7/2 <sup>-</sup>	*	$\Xi_c(3055)$		***	$\Omega_b(6330)^-$		*
$N(2120)$	3/2 <sup>-</sup>	***	$\Delta(2950)$	15/2 <sup>+</sup>	**	$\Sigma(2110)$	1/2 <sup>-</sup>	*	$\Xi_c(3080)$		***	$\Omega_b(6340)^-$		*
$N(2190)$	7/2 <sup>-</sup>	****				$\Sigma(2230)$	3/2 <sup>+</sup>	*	$\Xi_c(3123)$	*		$\Omega_b(6350)^-$	*	*
$N(2220)$	9/2 <sup>+</sup>	***	$\Lambda$	1/2 <sup>+</sup>	****	$\Sigma(2250)$		**	$\Omega_c^0$	1/2 <sup>+</sup>	***			*
$N(2250)$	9/2 <sup>-</sup>	****	$\Lambda(1380)$	1/2 <sup>-</sup>	**	$\Sigma(2455)$	*		$\Omega_c(2770)^0$	3/2 <sup>+</sup>	***	$P_c(4312)^+$		*
$N(2300)$	1/2 <sup>+</sup>	**	$\Lambda(1405)$	1/2 <sup>-</sup>	****	$\Sigma(2620)$	*		$\Omega_c(3000)^0$		***	$P_c(4380)^+$		*
$N(2570)$	5/2 <sup>-</sup>	**	$\Lambda(1520)$	3/2 <sup>-</sup>	****	$\Sigma(3000)$	*		$\Omega_c(3050)^0$		***	$P_c(4440)^+$		*
$N(2600)$	11/2 <sup>-</sup>	***	$\Lambda(1600)$	1/2 <sup>+</sup>	****	$\Sigma(3170)$	*		$\Omega_c(3065)^0$		***	$P_c(4457)^+$		*
$N(2700)$	13/2 <sup>+</sup>	**	$\Lambda(1670)$	1/2 <sup>-</sup>	***				$\Omega_c(3090)^0$		***			*
			$\Lambda(1690)$	3/2 <sup>-</sup>	****	$\Xi^0$	1/2 <sup>+</sup>	****	$\Omega_c(3120)^0$		***			*
			$\Lambda(1710)$	1/2 <sup>+</sup>	*	$\Xi^-$	1/2 <sup>+</sup>	****						*
			$\Lambda(1800)$	1/2 <sup>-</sup>	***	$\Xi(1530)$	3/2 <sup>+</sup>	****	$\Xi_{cc}^+$	*				*
			$\Lambda(1810)$	1/2 <sup>+</sup>	***	$\Xi(1620)$	*		$\Xi_{cc}^+$		***			*
			$\Lambda(1820)$	5/2 <sup>+</sup>	****	$\Xi(1690)$		***						*
			$\Lambda(1830)$	5/2 <sup>-</sup>	****	$\Xi(1820)$	3/2 <sup>-</sup>	***						*
			$\Lambda(1890)$	3/2 <sup>+</sup>	****	$\Xi(1950)$		***						*
			$\Lambda(2000)$	1/2 <sup>-</sup>	*	$\Xi(2030)$	$\geq \frac{5}{2}?$	***						*
			$\Lambda(2050)$	3/2 <sup>-</sup>	*	$\Xi(2120)$								*
			$\Lambda(2070)$	3/2 <sup>+</sup>	*	$\Xi(2250)$		**						*
			$\Lambda(2080)$	5/2 <sup>-</sup>	*	$\Xi(2370)$		**						*
			$\Lambda(2085)$	7/2 <sup>+</sup>	**	$\Xi(2500)$	*							*
			$\Lambda(2100)$	7/2 <sup>-</sup>	****									*
			$\Lambda(2110)$	5/2 <sup>+</sup>	***	$\Omega^-$	3/2 <sup>+</sup>	****						*
			$\Lambda(2325)$	3/2 <sup>-</sup>	*	$\Omega(2012)^-$	?-	***						*
			$\Lambda(2350)$	9/2 <sup>+</sup>	***	$\Omega(2250)^-$		***						*
			$\Lambda(2585)$	*		$\Omega(2380)^-$		**						*
						$\Omega(2470)^-$		**						*

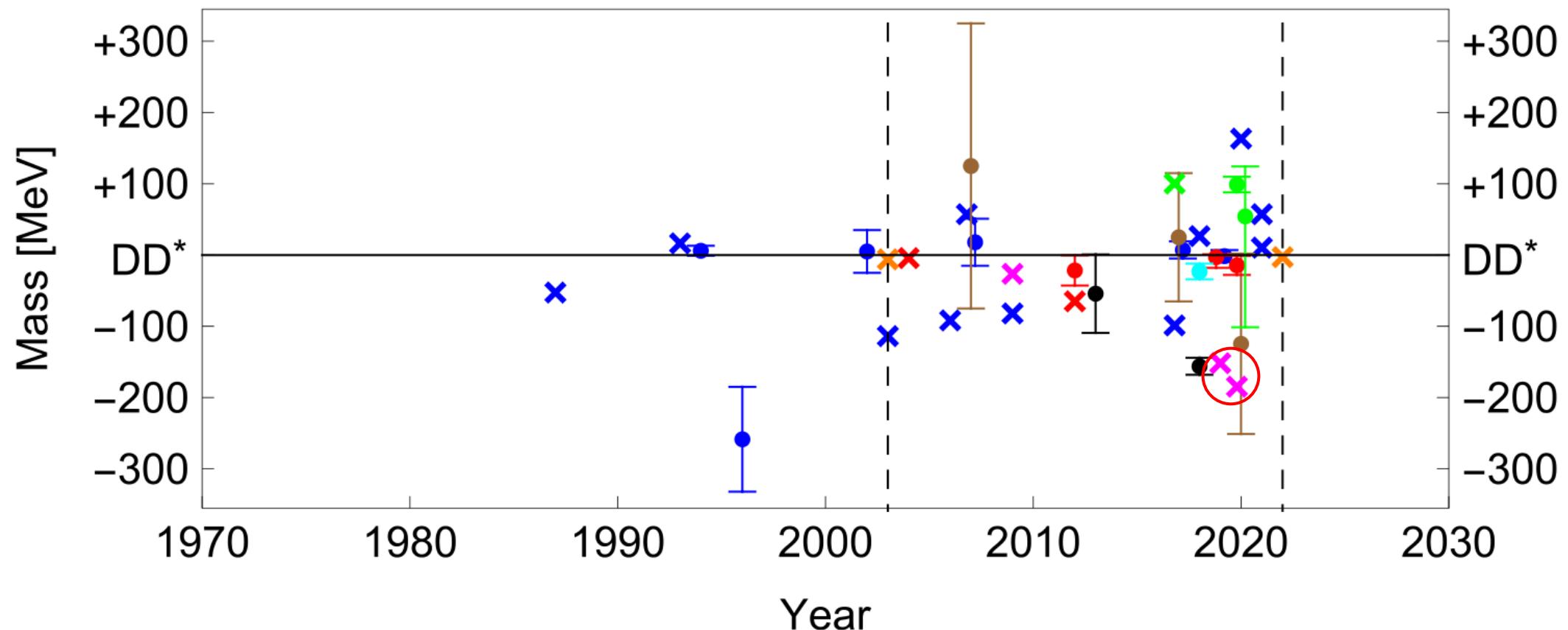
# New resonant structures at BESIII

From Prof. Shi-Shuang Fang









**Figure 42.** Theoretical predictions on the mass of the doubly charmed tetraquark state  $cc\bar{u}\bar{d}$  with  $(I)J^P = (0)1^+$ , with uncertainties (error bars) and without uncertainties (crosses), calculated based on the compact tetraquark picture through various quark models [454, 500–515] (blue), QCD sum rules [462, 516, 517] (brown), heavy quark symmetry [467–469] (green), and others [461, 466] (black), as well as those calculated through the hadronic molecular picture [477, 479, 518–520] (red), the quark model considering the mixture of the meson-meson and diquark-antidiquark structures [481–483] (magenta), and lattice QCD [499] (cyan). The two dashed lines with orange crosses denote the  $\chi_{c1}(3872)$  ( $X(3872)$ ) first observed by Belle in 2003 [30] and the  $T_{cc}^+$  recently observed by LHCb in 2021 [42, 43].

# Meson exchange in nuclear force:

- $\pi(138)$  **Long-ranged tensor force**
- $\sigma(500)$  **intermediate-ranged, attractive central force plus LS force**
- $\omega(782)$  **short-ranged, repulsive central force plus strong LS force**
- $\rho(770)$  **short-ranged tensor force, opposite to pion**

• R. Machleidt, Phys.Rev.C 63 (2001) 024001

# Outline

- Introduction
- **Chiral quark model with HLS**
- $SU2$  ground states + excited states
- $SU3$  ground states
- Summary

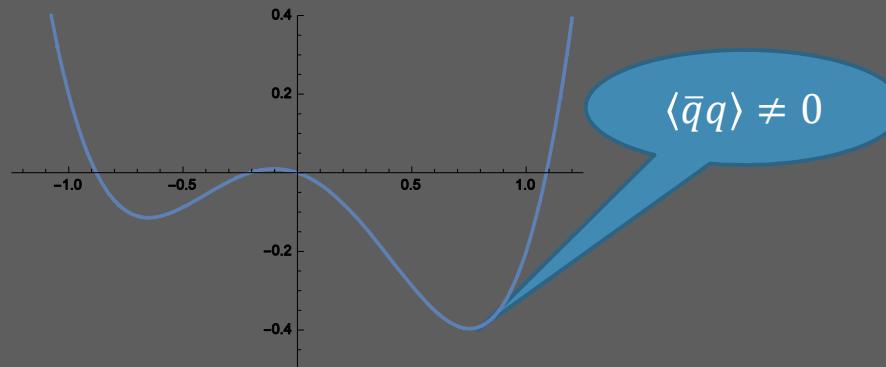
# The chiral symmetry

The chiral symmetry:



Spontaneously breaking of chiral symmetry:

$$\langle \bar{q}q \rangle = \langle \bar{q}_L q_R + \bar{q}_R q_L \rangle \neq 0$$



The effective theory based on chiral symmetry:

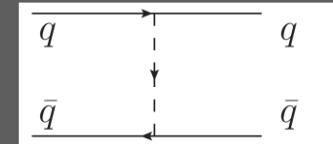
- Nonlinear sigma model
- Chiral perturbation theory

# Chiral quark model

## Naïve quark model:

- Quark mass term
- Kinetic term
- Color confinement potential (CON)
- One gluon exchange (OGE)

gluon exchange

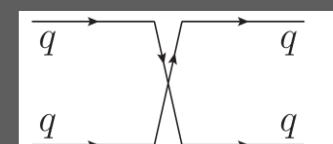
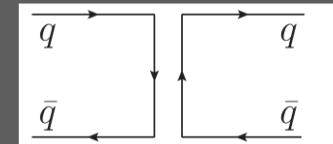


- Gell-Mann, M., 1964, Phys. Lett. 8, 214.
- Zweig, G., 1964, CERN Reports No. 8182/TH. 401 and No. 8419/TH. 412).
- N. Isgur, G. Karl, Phys.Lett.B 72 (1977) 109.

## The Nambu–Goldstone boson exchange:

- Chiral symmetry is spontaneously broken
- Pseudoscalars ( $\pi$ ,  $K$ ,  $\eta$ ) are the Nambu–Goldstone (NG) bosons of chiral symmetry breaking
- Scalar meson  $\sigma$  as the chiral partner of NG bosons

meson exchange



- K. Shimizu, Phys. Lett. B 148, 418-422 (1984)
- Z.Y. Zhang, Y.W. Yu, P.N. Shen, L.R. Dai, A. Faessler, U. Straub, Nucl. Phys. A 625 (1997) 59.
- J . Vijande, F . Fernandez, A . Valcarce, J. Phys. G 31, 481(2005)

# Chiral quark model

## pseudoscalar + vector meson exchange + CON

- Quark mass term
- Kinetic term
- Color confinement potential (CON)
- Pseudo-scalar + vector meson

- L. Y. Glozman and D. O. Riska, Phys. Rept. 268, 263-303 (1996).
- L. Y. Glozman, Nucl. Phys. A 663, 103-112 (2000).

## Scalar + pseudoscalar + vector meson exchange + CON + OGE

- Quark mass term
- Kinetic term
- Color confinement potential (CON)
- One gluon exchange (OGE)
- Scalar + pseudoscalar + vector meson

- L. R. Dai, Z. Y. Zhang, Y. W. Yu and P. Wang, Nucl. Phys. A 727, 321-332 (2003).
- Bing-Ran He, Masayasu Harada, Bing-Song Zou  
2306.03526, 2307.16280

# Incorporate the vector meson contribution

The hidden local symmetry:

$$\begin{aligned} U &= \xi_L^\dagger \xi_R = e^{2i\frac{\pi(x)}{f_\pi}} \\ \xi_{L,R} &\rightarrow h(x) \xi_{L,R} \cdot g_{L,R}^\dagger & h(x)^\dagger h(x) = 1 \\ \xi_{L,R} &= e^{i\frac{V(x)}{f_V}} e^{\mp i\frac{\pi(x)}{f_\pi}} \end{aligned}$$

$h(x) \in H_{\text{local}}$  ,     $g_{\text{L,R}} \in G_{\text{global}}$

M. Bando, T. Kugo, K. Yamawaki.  
Phys.Rept. 164 (1988) 217-314  
M. Harada, K. Yamawaki.  
Phys.Rept. 381 (2003) 1-233

- The transformation for  $U$  do not changes, which seems that the freedom of vector meson is “**hidden**”

$$[SU(N_f)_L \times SU(N_f)_R]_{\text{global}} \times [SU(N_f)_V]_{\text{local}} \rightarrow [SU(N_f)_V]_{\text{global}}$$

- Hidden local symmetry is an extension of chiral perturbation theory
- Hidden local symmetry is a systematic way to include pseudo-scalar mesons ( $\pi, K, \eta, \eta'$ ) and vector mesons ( $\rho, K^*, \omega, \phi$ )

# Outline

- Introduction
- Chiral quark model with HLS
- ***SU2 ground states + excited states***
- *SU3* ground states
- Summary

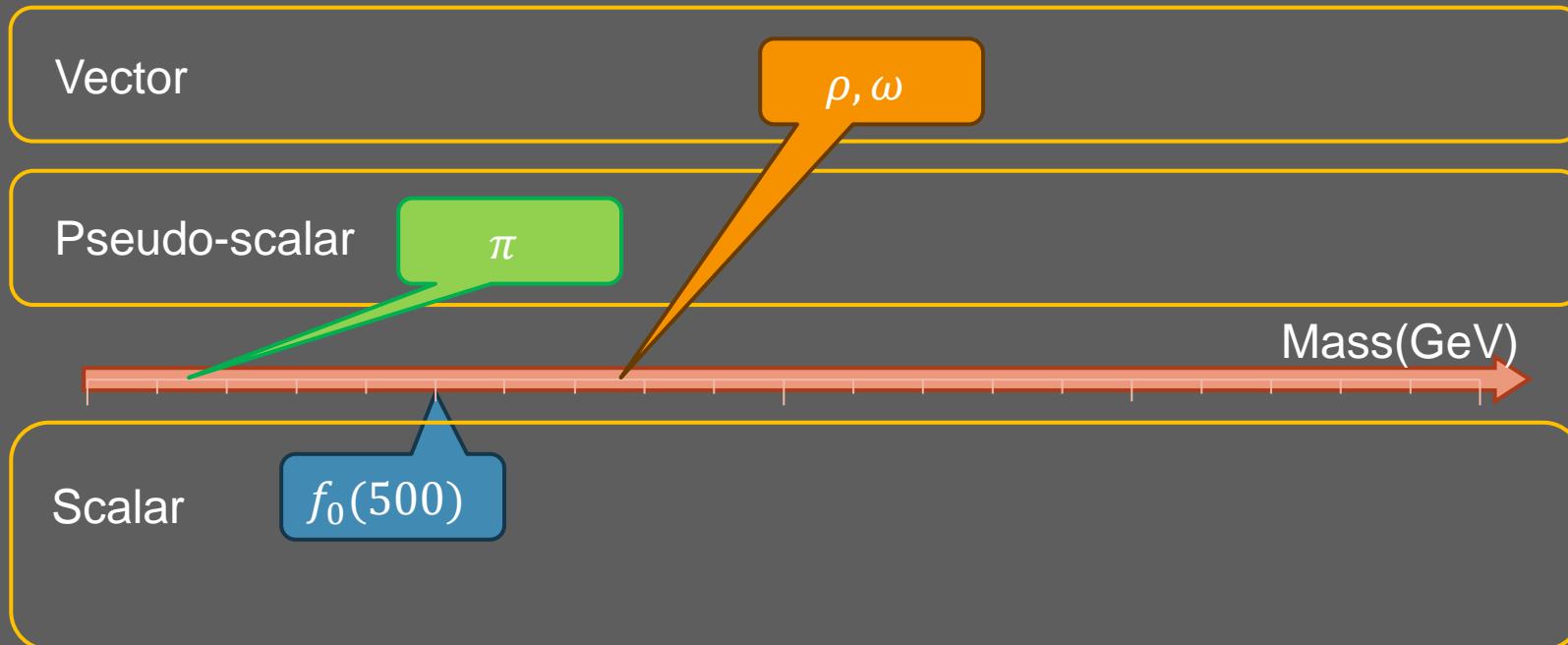
# The Hamiltonian

$$H = \sum_{i=1} \left( m_i + \frac{p_i^2}{2m_i} \right) - T_{CM} + \sum_{j>i=1} (V_{ij}^{\text{CON}} \\ + V_{ij}^{\text{OGE}} + V_{ij}^\sigma + V_{ij}^\pi + V_{ij}^\omega + V_{ij}^\rho)$$

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Bing-Song Zou, 2306.03526

$$V_{ij}^v = \frac{\Lambda_v^2}{\Lambda_v^2 - m_v^2} \left\{ \frac{g_v^2}{4\pi} m_v \left[ Y(m_v r) - \left( \frac{\Lambda_v}{m_v} \right) Y(\Lambda_v r) \right] \right. \\ + \frac{m_v^3}{m_i m_j} \left( \frac{g_v(2f_v + g_v)}{16\pi} + \frac{\boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j}{6} \frac{(f_v + g_v)^2}{4\pi} \right) \times \left[ Y(m_v r) - \left( \frac{\Lambda_v}{m_v} \right)^3 Y(\Lambda_v r) \right] \\ - \boldsymbol{S}_+ \cdot \boldsymbol{L} \frac{g_v(4f_v + 3g_v)}{8\pi} \frac{m_v^3}{m_i m_j} \times \left[ G(m_v r) - \left( \frac{\Lambda_v}{m_v} \right)^3 G(\Lambda_v r) \right] \\ \left. - \boldsymbol{S}_{ij} \frac{(f_v + g_v)^2}{4\pi} \frac{m_v^3}{12m_i m_j} \times \left[ H(m_v r) - \left( \frac{\Lambda_v}{m_v} \right)^3 H(\Lambda_v r) \right] \right\}$$

# The exchanged mesons in $SU(2)$ model



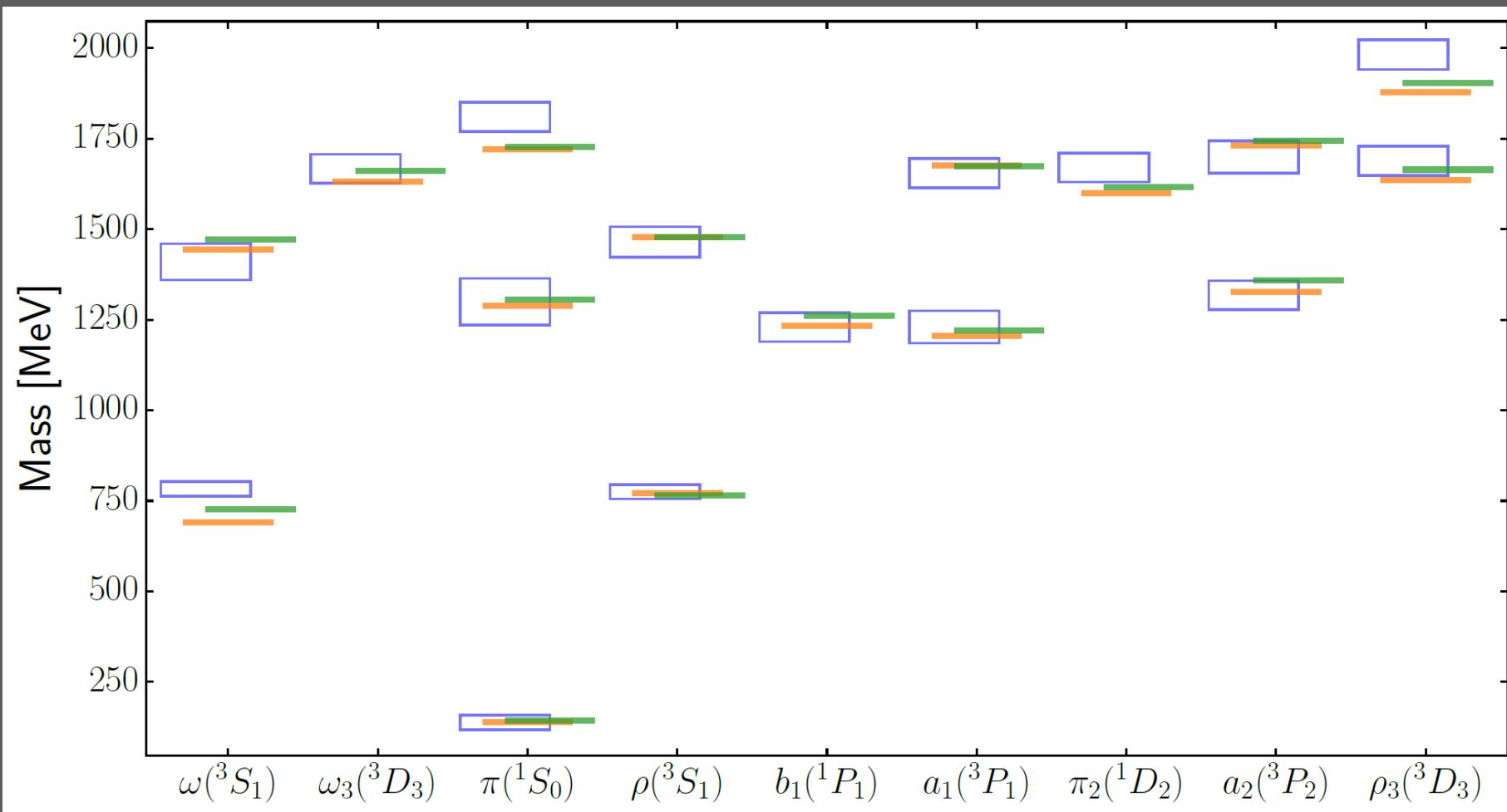
Symmetry of the model

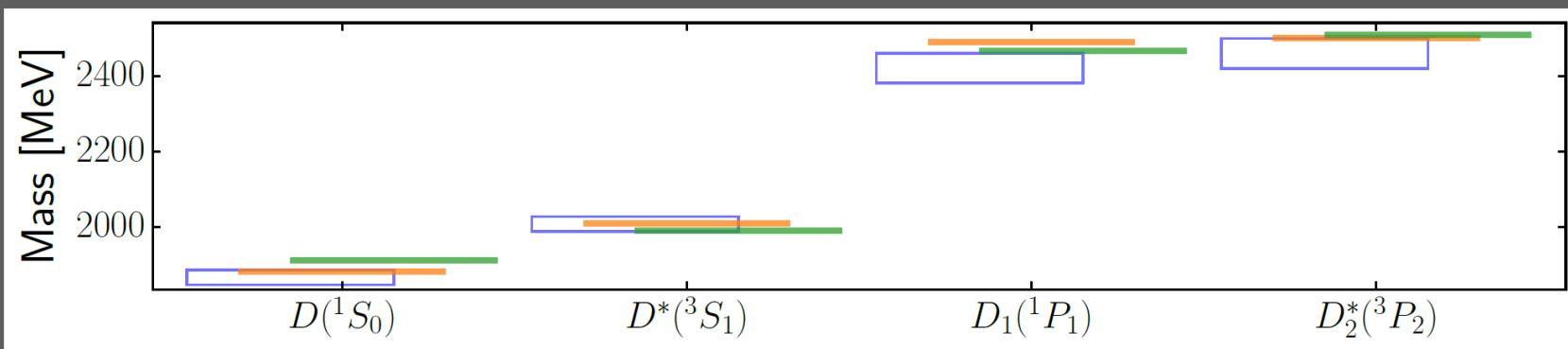
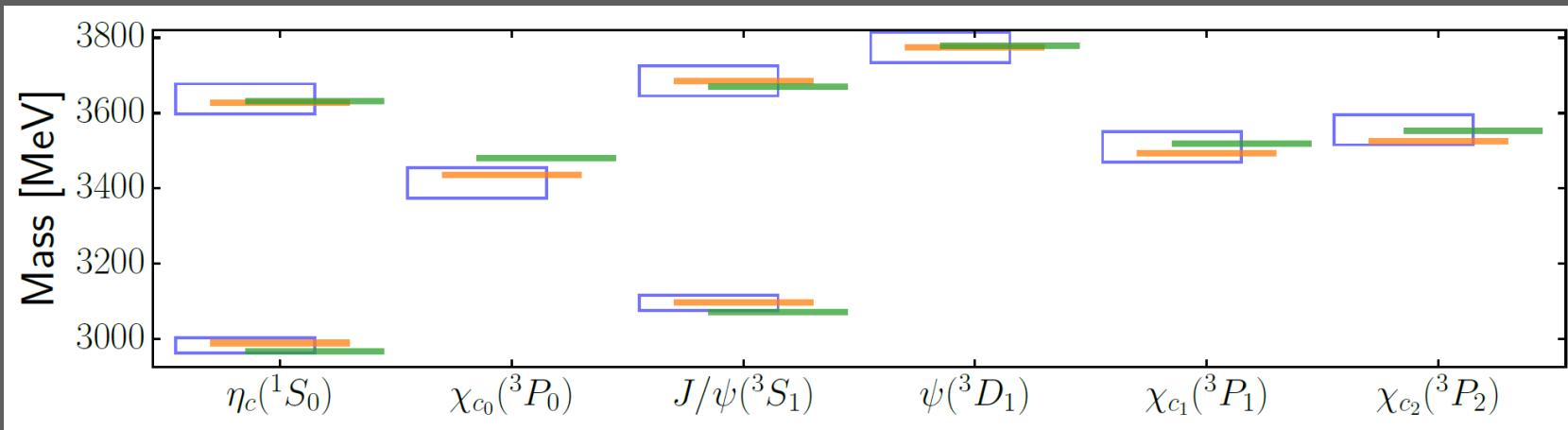
$$SU(2)_L \times SU(2)_R \times U(1)_V \longrightarrow SU(2)_V \times U(1)_V$$

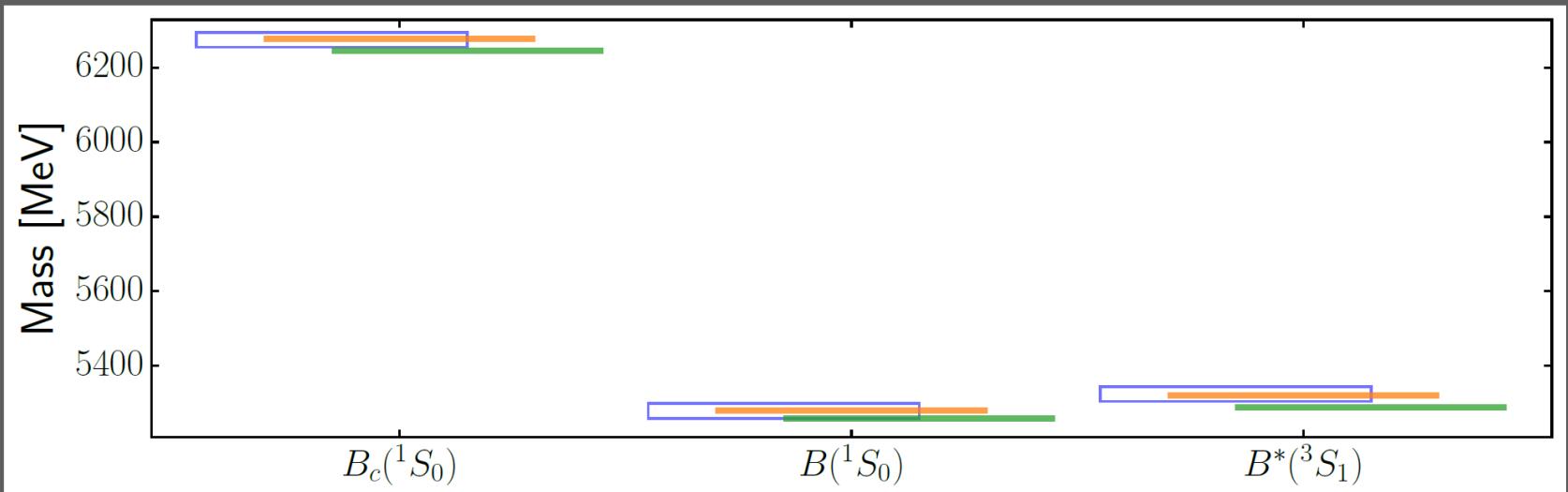
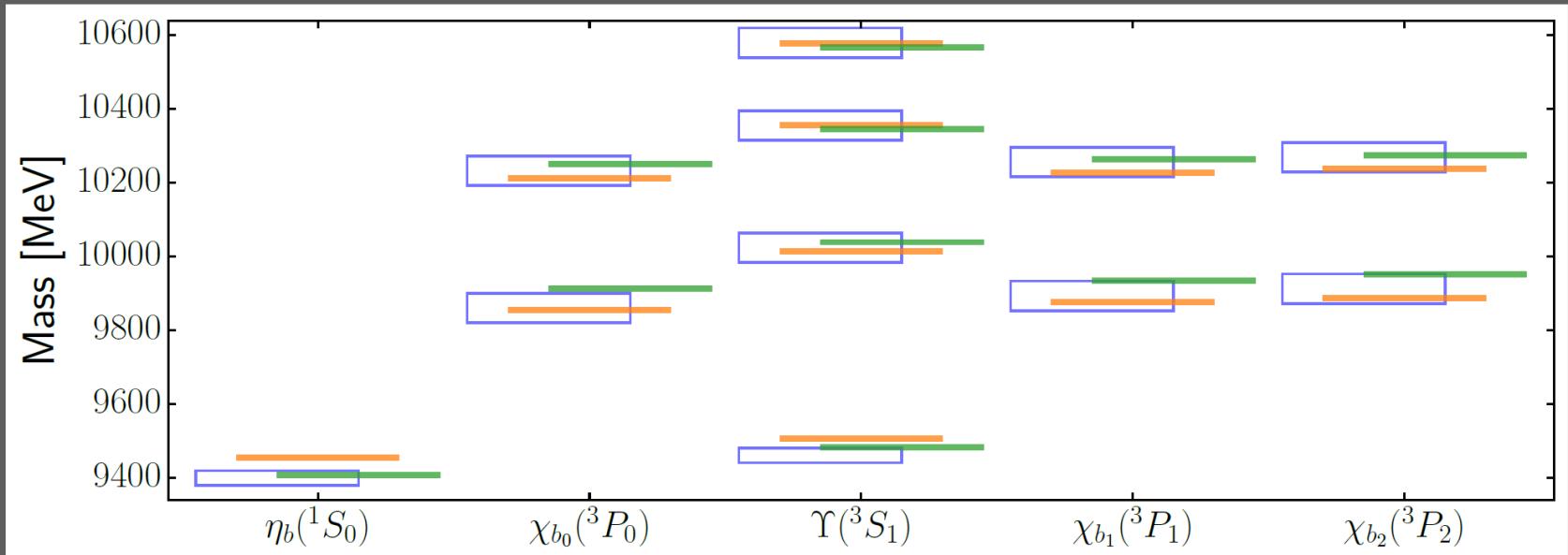
# Wave functions

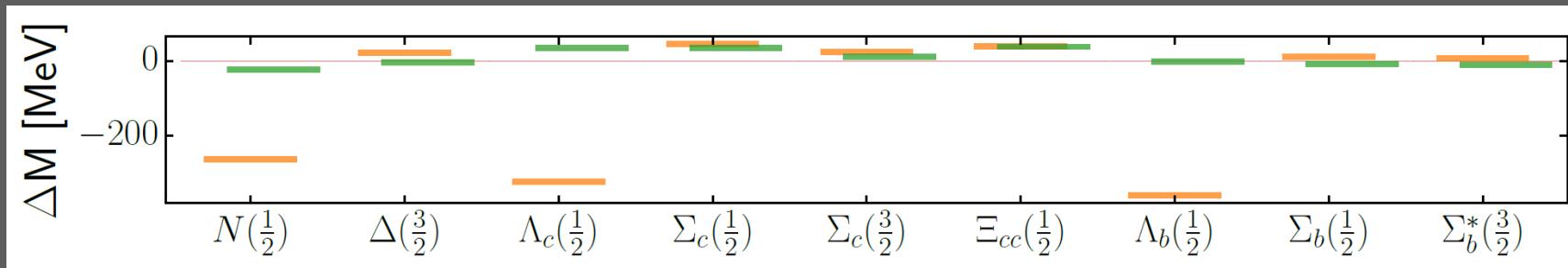
- Orbital ( $\text{SO}(3)$ ):  $(\psi_L)$
- Spin ( $\text{SU}(2)$ ):  $(\chi_S^\sigma)$
- Flavor ( $\text{SU}(2)$ ):  $(\chi_I^f)$
- Color ( $\text{SU}(3)$ ):  $(\chi^c)$

$$\Psi_{JM_J IM_I}^{ijk} = \mathcal{A} \left[ [\psi_L \chi_S^{\sigma i}]_{JM_J} \chi_I^{fj} \chi_k^c \right]$$









	1	$\tau_i \tau_j$	$\sigma_i \sigma_j$	$\sigma_i \sigma_j \cdot \tau_i \tau_j$
$\sigma$	$-/-$			
$\pi$				$+/-$
$a_0$		$-/+$		
OGE	$-/-$		$+/+$	
CON	$+/+$			
$\omega$ (This work)	$+/-$		$+/-$	
$\rho$ (This work)		$+/+$		$+/+$

$qq/q\bar{q}$

Channel	$E_B$		Channel	$E_B$	
$[DD^*]_{1\otimes 1}$	6.2	39%	$[BB^*]_{1\otimes 1}$	0.5	12%
$[D^*D]_{1\otimes 1}$	6.2	39%	$[B^*B]_{1\otimes 1}$	0.5	12%
$[D^*D^*]_{1\otimes 1}$	83.1	5%	$[B^*B^*]_{1\otimes 1}$	31	32%
$[DD^*]_{8\otimes 8}$	383.1	0%	$[BB^*]_{8\otimes 8}$	253.6	0%
$[D^*D]_{8\otimes 8}$	383.1	0%	$[B^*B]_{8\otimes 8}$	253.6	0%
$[D^*D^*]_{8\otimes 8}$	337.3	0%	$[B^*B^*]_{8\otimes 8}$	233.3	0%
$[(cc)(\bar{q}\bar{q})^*]_{6\otimes \bar{6}}$	337.5	0%	$[(bb)(\bar{q}\bar{q})^*]_{6\otimes \bar{6}}$	233.7	0%
$[(cc)^*(\bar{q}\bar{q})]_{\bar{3}\otimes 3}$	120.3	17%	$[(bb)^*(\bar{q}\bar{q})]_{\bar{3}\otimes 3}$	-37.8	44%
Mixed	-4.9		Mixed	-88.2	

	$r_{cc}$	$r_{\bar{q}c}$	$r_{\bar{q}\bar{q}}$	$r_{\bar{q}b}$	$r_{bb}$
$T_{cc}$	1.56	1.24	1.70		
$T_{bb}$			0.75	0.65	0.37

# Outline

- Introduction
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- $SU2$  ground states + excited states
- $SU3$  **ground states**
- Summary

# The Hamiltonian

$$H = \sum_{i=1} \left( m_i + \frac{p_i^2}{2m_i} \right) - T_{CM} + \sum_{j>i=1} (V_{ij}^{\text{CON}} + V_{ij}^{\text{OGE}} + V_{ij}^{\bar{\sigma}} + V_{ij}^{\eta} + V_{ij}^{\eta'} + V_{ij}^{\pi} + V_{ij}^K + V_{ij}^{\omega} + V_{ij}^{\phi} + V_{ij}^{\rho} + V_{ij}^{K^*})$$

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Bing-Song Zou, 2307.16280

$$V_{ij}^{\bar{\sigma}} = V_{ij}^{s=\bar{\sigma}, g_s=g_{\bar{\sigma}q}} \lambda_i^q \lambda_j^q + V_{ij}^{s=\bar{\sigma}, g_s=g_{\bar{\sigma}s}} \lambda_i^s \lambda_j^s,$$

$$V_{ij}^{\eta} = V_{ij}^{p=\eta, g_p=g_{\eta q}} \lambda_i^q \lambda_j^q + V_{ij}^{p=\eta, g_p=g_{\eta s}} \lambda_i^s \lambda_j^s,$$

$$V_{ij}^{\eta'} = V_{ij}^{p=\eta', g_p=g_{\eta'q}} \lambda_i^q \lambda_j^q + V_{ij}^{p=\eta', g_p=g_{\eta's}} \lambda_i^s \lambda_j^s,$$

$$V_{ij}^{\pi} = V_{ij}^{p=\pi, g_p=g_{\pi}} \sum_{a=1}^3 \lambda_i^a \lambda_j^a,$$

$$V_{ij}^K = V_{ij}^{p=K, g_p=g_K} \sum_{a=4}^7 \lambda_i^a \lambda_j^a,$$

$$V_{ij}^{\omega} = V_{ij}^{v=\omega, g_v=g_{\omega q}} \lambda_i^q \lambda_j^q + V_{ij}^{v=\omega, g_v=g_{\omega s}} \lambda_i^s \lambda_j^s,$$

$$V_{ij}^{\phi} = V_{ij}^{v=\phi, g_v=g_{\phi q}} \lambda_i^q \lambda_j^q + V_{ij}^{v=\phi, g_v=g_{\phi s}} \lambda_i^s \lambda_j^s,$$

$$V_{ij}^{\rho} = V_{ij}^{v=\rho, g_v=g_{\rho}} \sum_{a=1}^3 \lambda_i^a \lambda_j^a,$$

$$V_{ij}^{K^*} = V_{ij}^{v=K^*, g_v=g_{K^*}} \sum_{a=4}^7 \lambda_i^a \lambda_j^a$$

$$\lambda^q = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \lambda^s = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

The coupling have relations based on  $SU3$  flavor symmetry:

$$g_{\eta s} = g_{\eta q} - \sqrt{3} \cos \theta_p g_{\pi}$$

$$g_{\eta' q} = -\cot \theta_p g_{\eta q} + \frac{1}{\sqrt{3} \sin \theta_p} g_{\pi}$$

$$g_{\eta' s} = -\cot \theta_p g_{\eta q} + \frac{\cos \theta_p \cot \theta_p - 2 \sin \theta_p}{\sqrt{3}} g_{\pi}$$

$$g_{\pi} = g_K$$

$$g_{\omega s} = g_{\omega q} - g_{\rho}$$

$$g_{\phi q} = -\sqrt{\frac{1}{2}} (g_{\omega q} - g_{\rho})$$

$$g_{\phi s} = -\sqrt{\frac{1}{2}} (g_{\omega q} + g_{\rho})$$

$$g_{\rho} = g_{K^*}$$

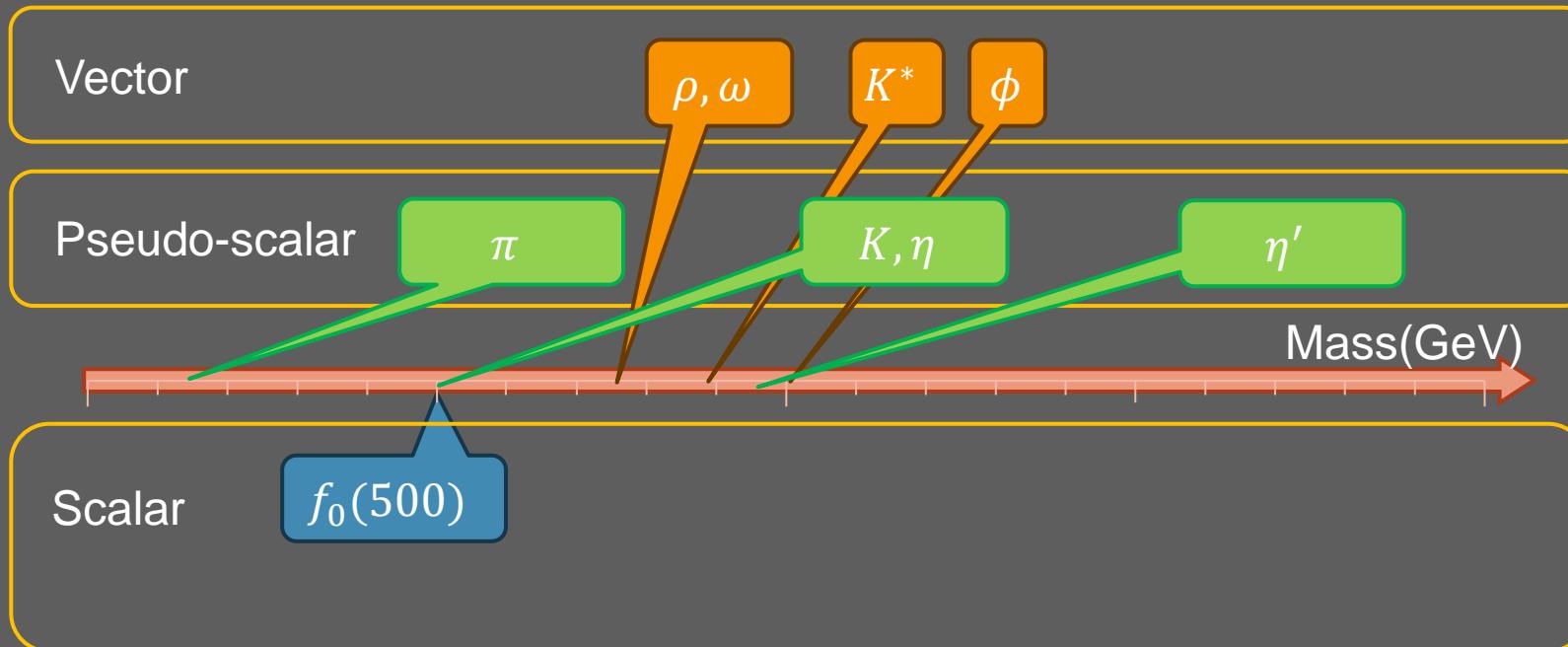
$$f_{\omega s} = f_{\omega q} - f_{\rho}$$

$$f_{\phi q} = -\sqrt{\frac{1}{2}} (f_{\omega q} - f_{\rho})$$

$$f_{\phi s} = -\sqrt{\frac{1}{2}} (f_{\omega q} + f_{\rho})$$

$$f_{\rho} = f_{K^*}$$

# The exchanged mesons in $SU3$ model



Symmetry of the model

$$SU(3)_L \times SU(3)_R \times U(1)_V \longrightarrow SU(3)_V \times U(1)_V$$

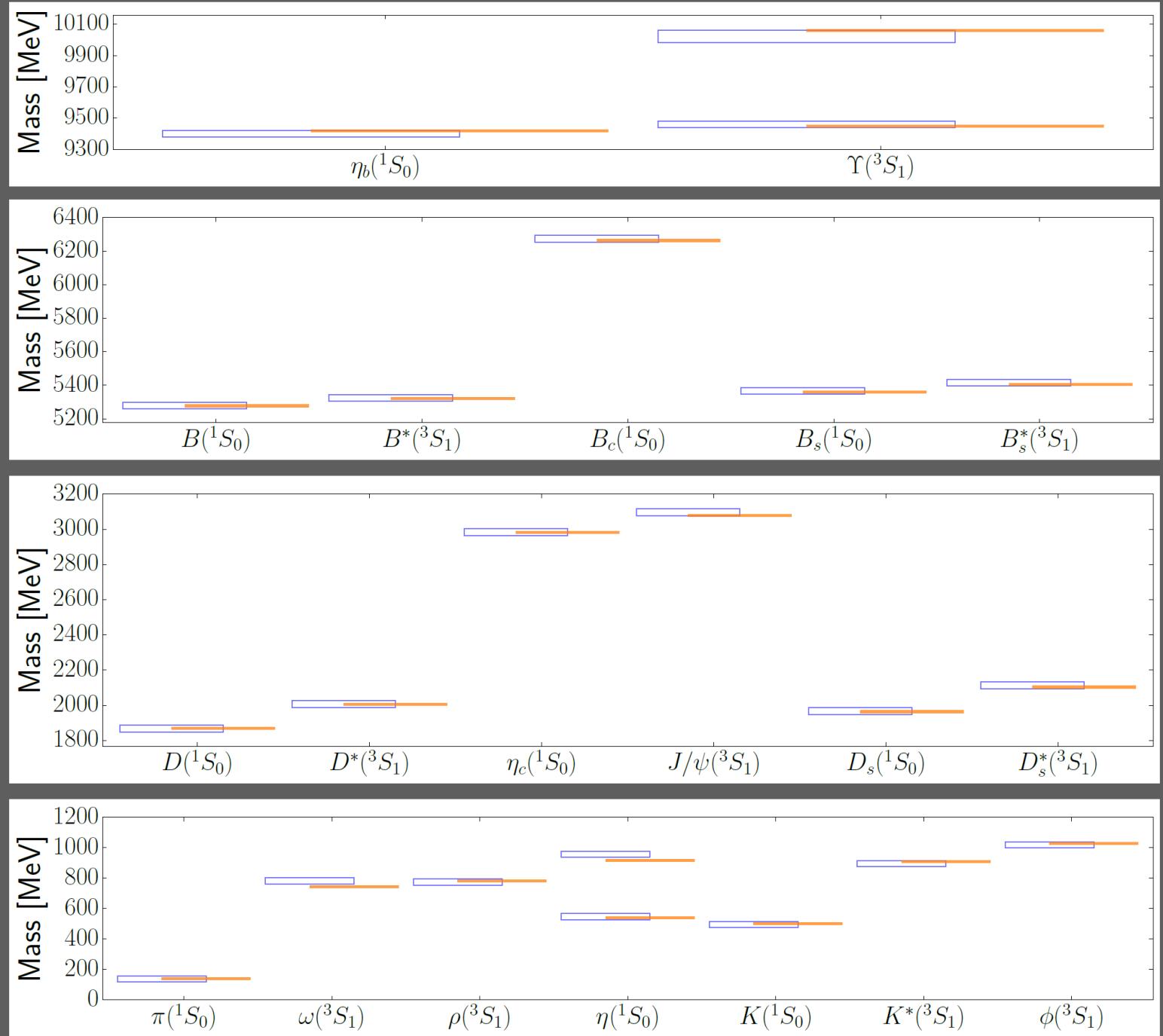
# Wave functions

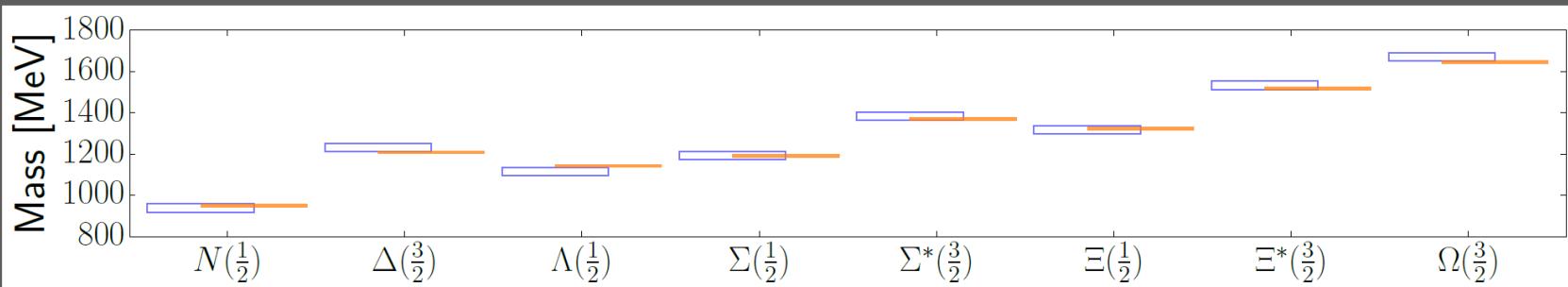
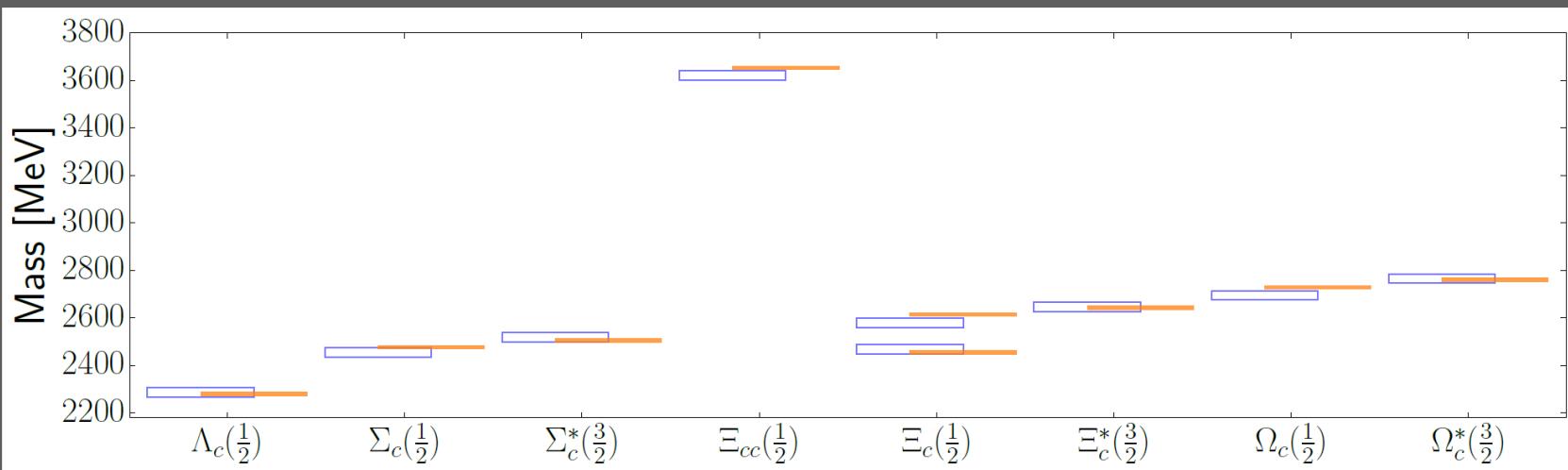
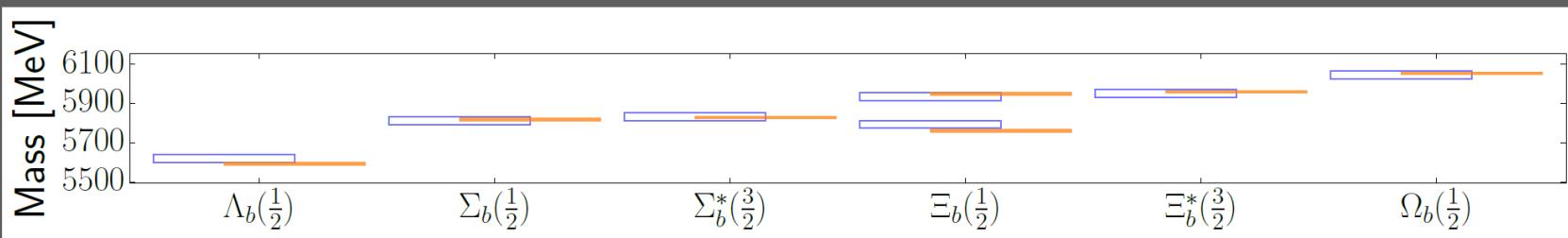
- Orbital ( $\text{SO}(3)$ ):  $(\psi_L)$
- Spin ( $\text{SU}(2)$ ):  $(\chi_S^\sigma)$
- Flavor ( $\text{SU}(3)$ ):  $(\chi_I^f)$
- Color ( $\text{SU}(3)$ ):  $(\chi^c)$

$$\Psi_{JM_J IM_I}^{ijk} = \mathcal{A} \left[ [\psi_L \chi_S^{\sigma i}]_{JM_J} \chi_I^{fj} \chi_k^c \right]$$

	1	$\lambda_i \lambda_j$	$\sigma_i \sigma_j$	$\sigma_i \sigma_j \cdot \lambda_i \lambda_j$
$\bar{\sigma}$	-/-			
$\eta/\eta'$			+/+	
$\pi/K$				+/-
$\omega/\phi$	+/-		+/-	
$\rho/K^*$		+/+		+/+
OGE	-/-		+/+	
CON	+/+			

	No vector J. Phys. G 31, 481(2005)	$su2$ vector 2306.03526	$su3$ vector 2307.16280	$qq/q\bar{q}$
$\alpha_s(qq)$	0.536	0.880	0.456	
$\alpha_s(qs)$	0.479		0.426	
$\alpha_s(qc)$	0.426	0.774	0.363	
$\alpha_s(qb)$	0.409	0.749	0.339	
$\alpha_s(ss)$	0.419		0.388	
$\alpha_s(sc)$	0.360		0.308	
$\alpha_s(sb)$	0.340		0.279	
$\alpha_s(cc)$	0.288	0.510	0.205	
$\alpha_s(cb)$	0.260	0.447	0.168	
$\alpha_s(bb)$	0.223	0.366	0.128	

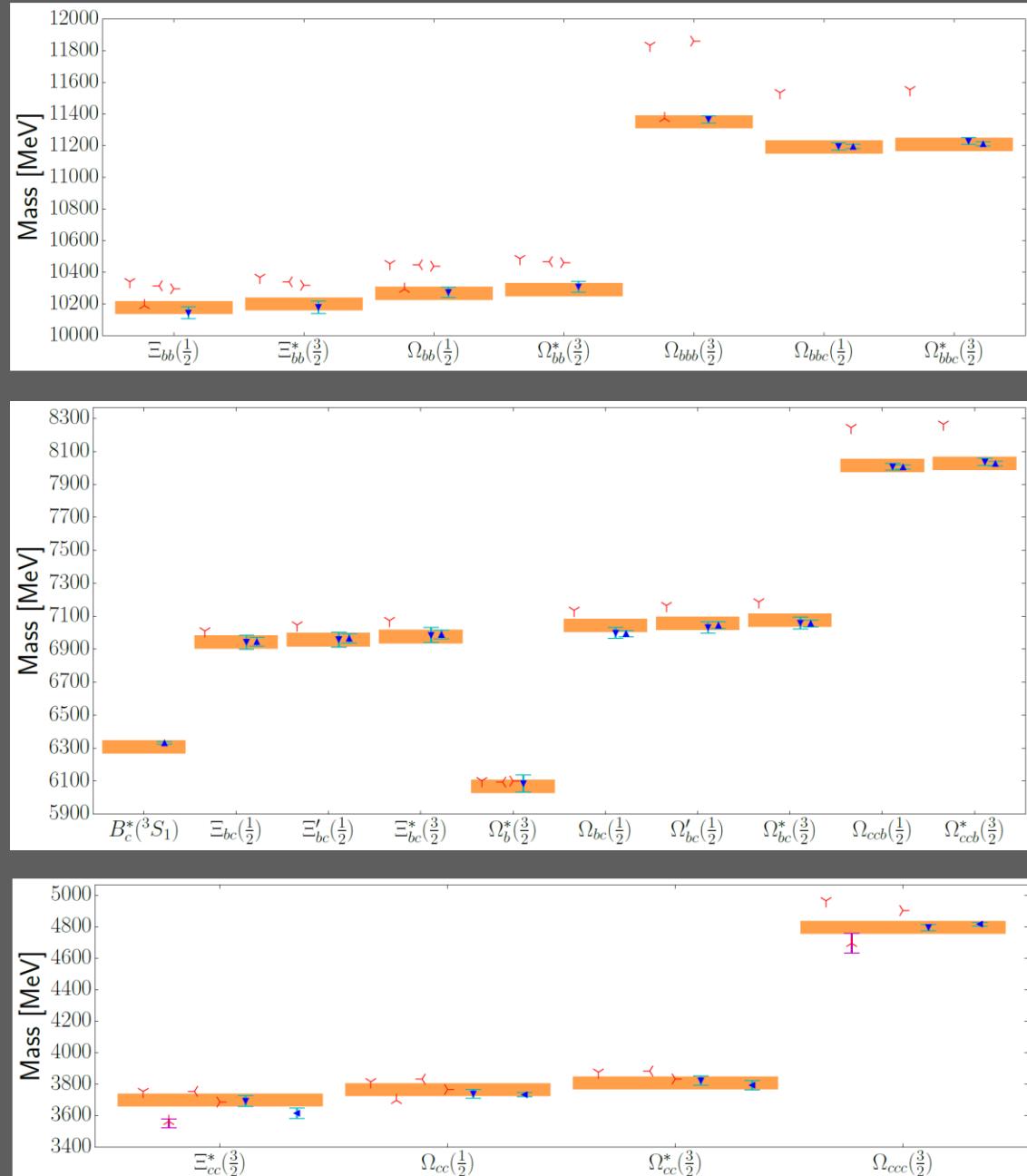




Models	Meson $\chi^2$ Err(the)=40MeV	Baryon $\chi^2$ Err(the)=40MeV
Godfrey & Isgur 1985	5.3 (21 meson)	
Capstick & Isgur 1986		3.78 (14 baryon)
J. Phys. G 31, 481(2005)	9.5 (21 meson)	305.8 (8 baryon, <i>unpublished</i> )
He & Harada & Zou 2307.16280	2.9 (21 meson)	5.7 (24 baryon)

$$\chi^2 = \sum_i \left( \frac{m_i(\text{the}) - m_i(\text{exp})}{\text{Err}_i(\text{sys})} \right)^2$$

$$\text{Err}(\text{sys}) = \sqrt{\text{Err}(\text{exp})^2 + \text{Err}(\text{the})^2}$$



# Outline

- Introduction
- Chiral quark model with HLS
- $SU2$  ground states + excited states
- $SU3$  ground states
- **Summary**

- Quark model with hidden local symmetry gives a systematic description from light meson/baryon to heavy meson/baryon
- Quark model with hidden local symmetry gives correct interaction between  $qq$  and  $q\bar{q}$ , thus its easy to extend the model to describe multiquark states, e.g., tetraquark, pentaquark, ...
- Quark model with hidden local symmetry gives size messages and percentage of components, which could help us to identify the particles observed from experiments

Thank you for your attention!