

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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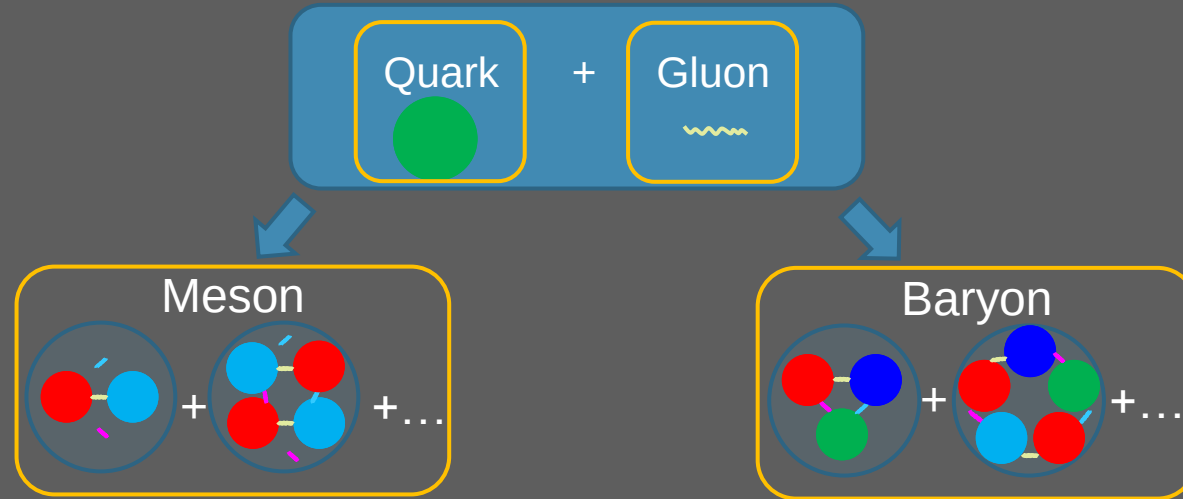
Outline

➤ Introduction

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

Introduction

Hadron 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.
 • Indicates 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 $f^C(J^{PC})$
$f^C(J^{PC})$	$f^C(J^{PC})$	$f^C(J^{PC})$	$f^C(J^{PC})$	$f^C(J^{PC})$	$f^C(J^{PC})$	$f^C(J^{PC})$
$\pi^\pm$ $1^-(0^-)$ π^0 $1^-(0^-)$ η $0^+(0^-)$ $\eta(500)$ $0^+(0^+)$ $\rho(770)$ $1^+(1^-)$ $\omega(782)$ $0^-(1^-)$ $\eta(958)$ $0^+(0^+)$ $f_0(980)$ $0^+(0^+)$ $a_0(980)$ $1^-(0^+)$ $\phi(1020)$ $0^-(1^-)$ $h_1(1170)$ $0^-(1^+)$ $\omega(1235)$ $1^+(1^-)$ $a_1(1260)$ $1^-(1^+)$ $f_2(1270)$ $0^+(2^+)$ $f_1(1285)$ $0^+(1^+)$ $\eta(1295)$ $0^+(0^-)$ $\pi(1300)$ $1^-(0^+)$ $a_2(1320)$ $1^-(2^+)$ $f_0(1370)$ $0^+(0^+)$ $\pi_1(1400)$ $1^-(1^+)$ $\eta(1405)$ $0^+(0^-)$ $h_1(1415)$ $0^-(1^+)$ $f_1(1420)$ $0^+(1^+)$ $\omega(1420)$ $0^-(1^-)$ $f_2(1430)$ $0^+(2^+)$ $a_0(1450)$ $1^-(0^+)$ $\rho(1450)$ $1^+(1^-)$ $\eta(1475)$ $0^+(0^-)$ $f_0(1500)$ $0^+(0^+)$ $f_1(1510)$ $0^+(1^+)$ $f_2'(1525)$ $0^+(2^+)$ $f_2(1565)$ $0^+(2^+)$ $\rho(1570)$ $1^+(1^-)$ $h_1(1595)$ $0^-(1^-)$ $\pi_1(1600)$ $1^-(1^+)$ $a_1(1640)$ $1^-(1^+)$ $f_2(1640)$ $0^+(2^+)$ $\eta_2(1645)$ $0^+(2^+)$ $\omega(1650)$ $0^-(1^-)$ $\omega_2(1670)$ $0^-(3^-)$	$\pi_2(1670)$ $1^-(2^+)$ $\phi(1680)$ $0^-(1^-)$ $\rho_2(1690)$ $1^+(3^-)$ $\rho(1700)$ $1^+(1^-)$ $a_2(1700)$ $1^-(2^+)$ $f_2(1710)$ $0^+(0^+)$ $X(1750)$ $?^-(1^-)$ $\eta(1760)$ $0^+(0^+)$ $\pi(1800)$ $1^-(0^+)$ $f_2(1810)$ $0^+(2^+)$ $X(1835)$ $?^2(0^-)$ $\phi_2(1850)$ $0^-(3^-)$ $\eta_2(1870)$ $0^+(2^+)$ $\pi_2(1880)$ $1^-(2^+)$ $\rho(1900)$ $1^+(1^-)$ $f_2(1910)$ $0^+(2^+)$ $a_0(1950)$ $1^-(0^+)$ $f_2(1950)$ $0^+(2^+)$ $a_4(1970)$ $1^-(4^+)$ $\pi_2(1990)$ $1^+(3^-)$ $\rho_2(1990)$ $1^-(2^+)$ $\pi_2(2005)$ $1^-(2^+)$ $f_2(2010)$ $0^+(2^+)$ $f_0(2020)$ $0^+(0^+)$ $f_4(2050)$ $0^+(4^+)$ $\pi_2(2100)$ $1^-(2^+)$ $f_2(2100)$ $0^+(0^+)$ $f_2(2150)$ $0^+(2^+)$ $\rho(2150)$ $1^+(1^-)$ $\phi(2170)$ $0^-(1^-)$ $f_2(2200)$ $0^+(0^+)$ $f_2(2220)$ $0^+(2^+)$ - or 4^+ $\eta(2225)$ $0^+(0^+)$ $\rho_2(2250)$ $1^+(3^-)$ $f_2(2300)$ $0^+(2^+)$ $f_4(2300)$ $0^+(4^+)$ $f_2(2330)$ $0^+(0^+)$ $f_2(2340)$ $0^+(2^+)$ $\rho_2(2350)$ $1^+(5^-)$ $X(2370)$ $?^2(??)$ $f_2(2510)$ $0^+(6^+)$	$K^\pm$ $1/2(0^-)$ K^0 $1/2(0^-)$ K_S^0 $1/2(0^-)$ K_L^0 $1/2(0^-)$ $K_S^*(700)$ $1/2(0^+)$ $K^*(892)$ $1/2(1^-)$ $K_1^*(1270)$ $1/2(1^+)$ $K_1(1400)$ $1/2(1^+)$ $K^*(1410)$ $1/2(1^-)$ $K_S^*(1430)$ $1/2(0^+)$ $K_S^*(1430)$ $1/2(2^+)$ $K(1460)$ $1/2(0^-)$ $K_2(1580)$ $1/2(2^-)$ $K(1630)$ $1/2(2^?)$ $K_1(1650)$ $1/2(1^+)$ $K^*(1680)$ $1/2(1^-)$ $K_2(1770)$ $1/2(2^-)$ $K_S^*(1780)$ $1/2(3^-)$ $K_2(1820)$ $1/2(2^-)$ $K(1830)$ $1/2(0^-)$ $K_S^*(1950)$ $1/2(0^+)$ $K_S^*(1980)$ $1/2(2^+)$ $K_S^*(2045)$ $1/2(4^+)$ $K_2(2250)$ $1/2(2^-)$ $K_2(2320)$ $1/2(3^+)$ $K_S^*(2380)$ $1/2(5^-)$ $K_2(2500)$ $1/2(4^-)$ $K(3100)$ $?^2(??)$	$D^\pm$ $1/2(0^-)$ D^0 $1/2(0^-)$ $D^*(2007)^0$ $1/2(1^-)$ $D^*(2010)^\pm$ $1/2(1^-)$ $D_S^*(2300)$ $1/2(0^+)$ $D_{S1}(2420)$ $1/2(1^+)$ $D_{S1}(2430)^0$ $1/2(1^+)$ $D_S^*(2460)$ $1/2(2^+)$ $D_{S1}(2550)^0$ $1/2(0^-)$ $D_S^*(2600)^0$ $1/2(1^-)$ $D^*(2640)^\pm$ $1/2(2^?)$ $D_2(2740)^0$ $1/2(2^-)$ $D_S^*(2750)$ $1/2(3^-)$ $D_S^*(2760)^0$ $1/2(1^-)$ $D(3000)^0$ $1/2(2^?)$	$D^\pm$ $1/2(0^-)$ D^0 $1/2(0^-)$ $D_S^*(2317)^\pm$ $0(0^?)$ $D_{S1}^*(2460)^\pm$ $0(1^?)$ $D_{S1}^*(2536)^\pm$ $0(1^?)$ $D_{S1}^*(2573)^\pm$ $0(1^?)$ $D_{S1}^*(2590)^\pm$ $0(0^-)$ $D_{S1}^*(2700)^\pm$ $0(1^-)$ $D_{S1}^*(2860)^\pm$ $0(1^-)$ $D_{S1}^*(2866)^\pm$ $0(3^-)$ $X_5(2900)$ $?^0(0^-)$ $X_3(2900)$ $?^1(1^-)$ $D_{sJ}(3040)^\pm$ $0(2^?)$	$\psi_2(3823)$ $0^-(2^-)$ $\psi_2(3842)$ $0^-(3^-)$ $\chi_{c0}(3860)$ $0^+(0^+)$ $\chi_{c1}(3872)$ $0^+(1^+)$ $Z_c(3900)$ $1^+(1^+)$ $\chi_{c0}(3915)$ $0^+(0^+)$ $\chi_{c2}(3930)$ $0^+(2^+)$ $X(3940)$ $?^2(??)$ $X(4020)^\pm$ $1^+(2^?)$ $\psi(4040)$ $0^-(1^-)$ $X(4050)^\pm$ $1^-(2^?)$ $X(4055)^\pm$ $1^+(2^?)$ $X(4100)^\pm$ $1^-(2^?)$ $\chi_{c1}(4140)$ $0^+(1^+)$ $\psi(4160)$ $0^-(1^-)$ $X(4160)$ $?^2(??)$ $Z_c(4200)$ $1^+(1^+)$ $\psi(4230)$ $0^-(1^-)$ $R_{c0}(4240)$ $1^+(0^-)$ $X(4250)^\pm$ $1^-(2^?)$ $\chi_{c1}(4274)$ $0^+(1^+)$ $X(4350)$ $0^+(2^?)$ $\psi(4360)$ $0^-(1^-)$ $\psi(4415)$ $0^-(1^-)$ $Z_c(4430)$ $1^+(1^+)$ $\chi_{c0}(4500)$ $0^+(0^+)$ $X(4630)$ $0^+(2^?)$ $\psi(4660)$ $0^-(1^-)$ $\chi_{c1}(4685)$ $0^+(1^+)$ $\chi_{c0}(4700)$ $0^+(0^+)$	
				BOTTOM ($B = \pm 1$)		
				$B^\pm$ $1/2(0^-)$ B^0 $1/2(0^-)$ $B^\pm/B^0$ ADMIXTURE $B^\pm/B^0/B_S^\pm/B$ baryon ADMIXTURE V_{cb} and V_{ub} CKM Matrix Elements B^* $1/2(1^-)$ $B_1(5721)$ $1/2(1^+)$ $B_J^*(5732)$ $?^2(1^+)$ $B_J^*(5747)$ $1/2(2^+)$ $B_J(5840)$ $1/2(2^?)$ $B_J(5970)$ $1/2(2^?)$		
				BOTTOM, STRANGE ($B = \pm 1, S = \mp 1$)		$b\bar{b}$ (+ possibly non- $q\bar{q}$ states)
				$B_c^\pm$ $0(0^-)$ B_c^0 $0(1^-)$ $X(5568)^\pm$ $?^2(1^+)$ $B_{c1}(5830)^0$ $0(1^+)$ $B_{c2}^*(5840)^0$ $0(2^+)$ $B_{c2}^*(5850)$ $?^2(2^+)$ $B_{cJ}(6063)^0$ $0(2^?)$ $B_{cJ}(6114)^0$ $0(2^?)$	$\eta_b(1S)$ $0^+(0^-)$ $\Upsilon(1S)$ $0^-(1^-)$ $\chi_{b0}(1P)$ $0^+(0^+)$ $\chi_{b1}(1P)$ $0^+(1^+)$ $h_b(1P)$ $0^-(1^+)$ $\chi_{b2}(1P)$ $0^+(2^+)$ $\eta_b(2S)$ $0^+(0^-)$ $\Upsilon(2S)$ $0^-(1^-)$ $\Upsilon_2(1D)$ $0^-(2^-)$ $\chi_{b0}(2P)$ $0^+(0^+)$ $\chi_{b1}(2P)$ $0^+(1^+)$ $h_b(2P)$ $0^-(1^+)$ $\chi_{b2}(2P)$ $0^+(2^+)$ $\Upsilon(3S)$ $0^-(1^-)$ $\chi_{b1}(3P)$ $0^+(1^+)$ $\chi_{b2}(3P)$ $0^+(2^+)$ $\Upsilon(4S)$ $0^-(1^-)$ $Z_b(10610)$ $1^+(1^+)$ $Z_b(10650)$ $1^+(1^+)$ $\Upsilon(10753)$ $?^2(1^-)$ $\Upsilon(10860)$ $0^-(1^-)$ $\Upsilon(11020)$ $0^-(1^-)$	
				BOTTOM, CHARMED ($B = C = \pm 1$)		
				$B_c^\pm$ $0(0^-)$ $B_c(2S)^\pm$ $0(0^-)$	$c\bar{c}$ (+ possibly non- $q\bar{q}$ states)	
				$\eta_c(1S)$ $0^+(0^-)$ $J/\psi(1S)$ $0^-(1^-)$ $\chi_{c0}(1P)$ $0^+(0^+)$ $\chi_{c1}(1P)$ $0^+(1^+)$ $h_c(1P)$ $0^-(1^+)$ $\chi_{c2}(1P)$ $0^+(2^+)$ $\eta_c(2S)$ $0^+(0^-)$ $\psi(2S)$ $0^-(1^-)$ $\psi(3770)$ $0^-(1^-)$		
				OTHER		
				Further States		

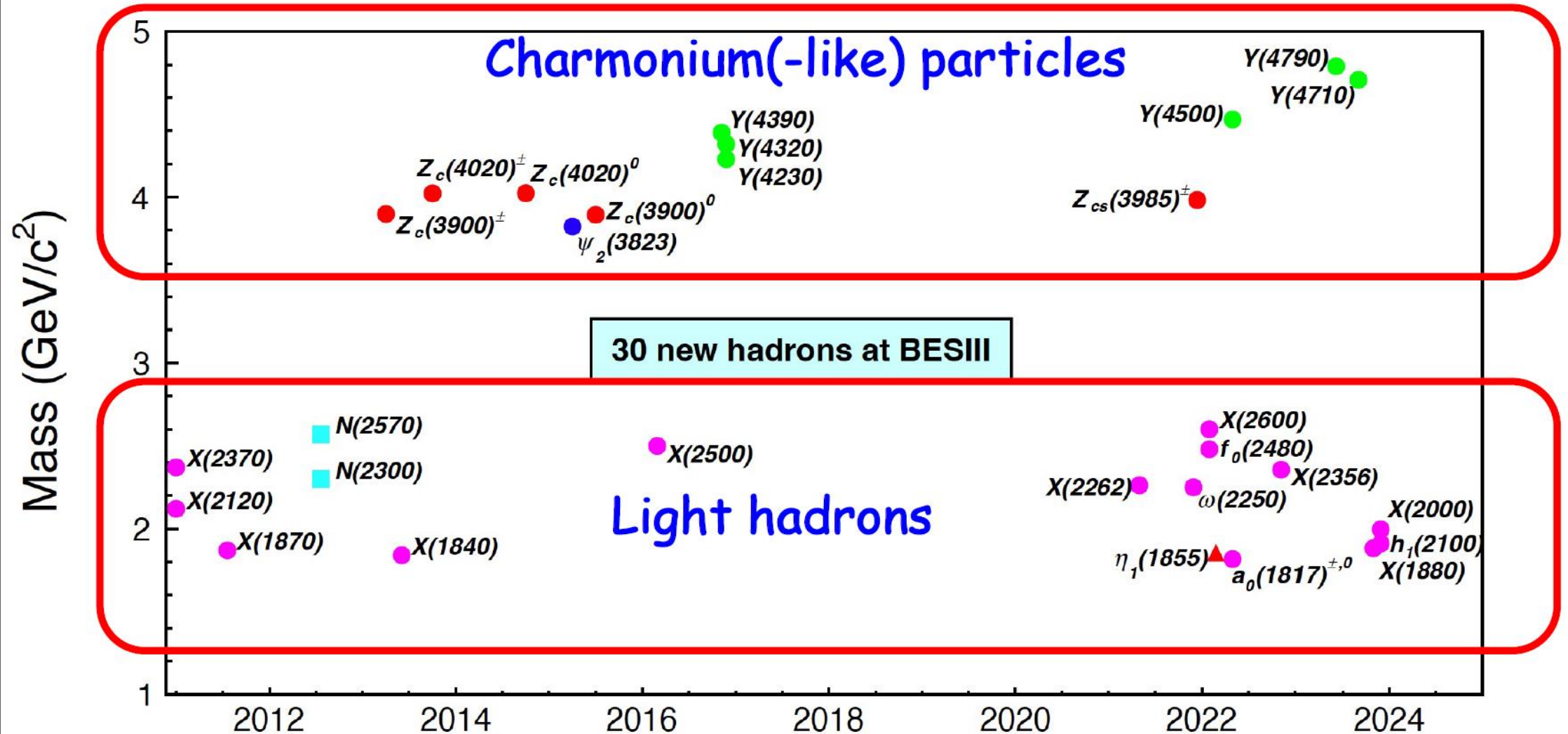
Baryon Summary Table

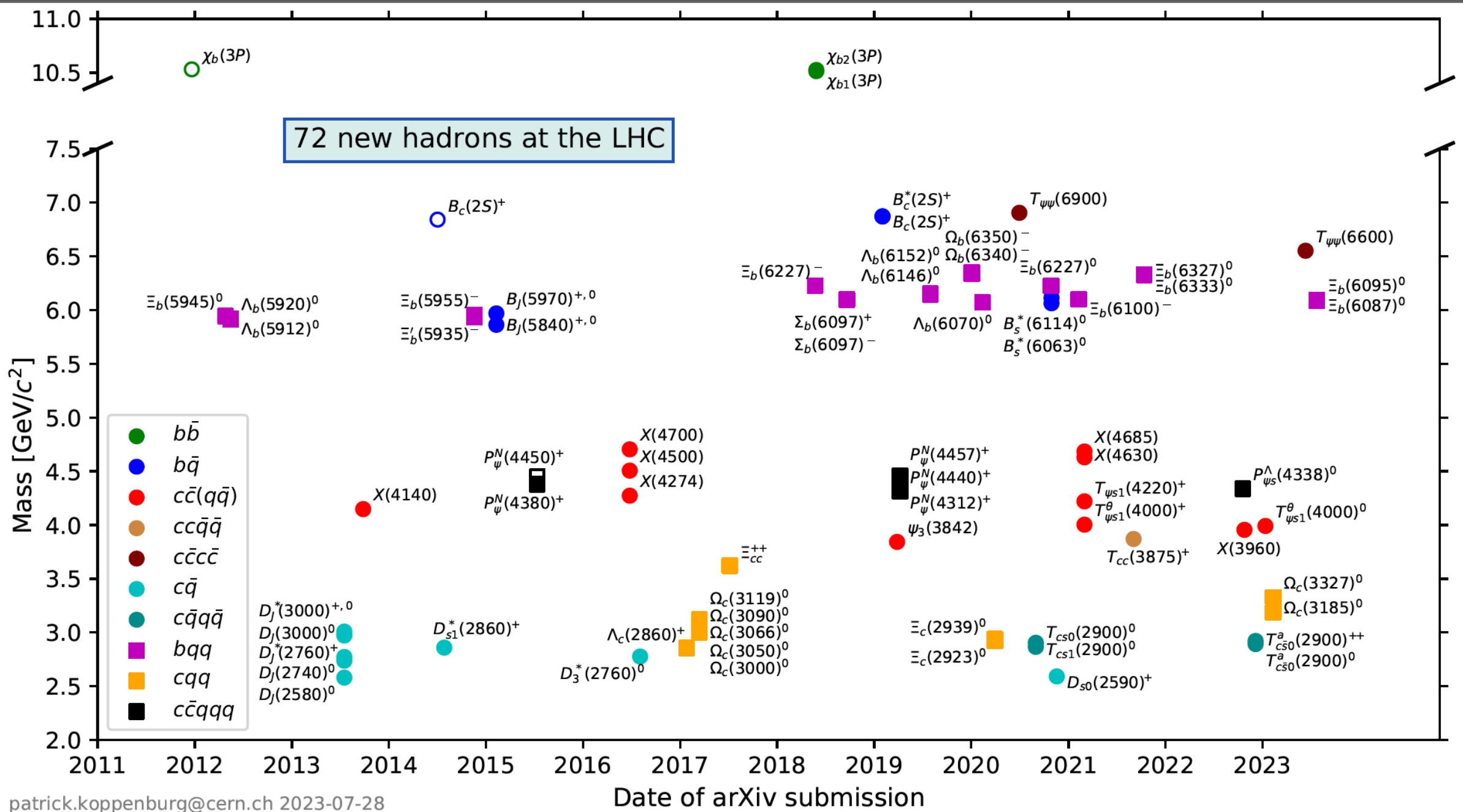
This short table gives the name, the quantum numbers (where known), and the status of baryons in the Review. Only the baryons with 3- or 4- star status are included in the Baryon Summary Table. Due to insufficient data or uncertain interpretation, the other entries in the table are not established baryons. 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	$1/2^+$ ****	$\Delta(1232)$	$3/2^+$ ****	Σ^+	$1/2^+$ ****	Λ_c^+	$1/2^+$ ****	Λ_b^0	$1/2^+$ ****
n	$1/2^+$ ****	$\Delta(1600)$	$3/2^+$ ****	Σ^0	$1/2^+$ ****	$\Lambda_c(2595)^+$	$1/2^-$ ***	$\Lambda_b(5912)^0$	$1/2^-$ ***
$N(1440)$	$1/2^+$ ****	$\Delta(1620)$	$1/2^-$ ****	Σ^-	$1/2^+$ ****	$\Lambda_c(2625)^+$	$3/2^-$ ***	$\Lambda_b(5920)^0$	$3/2^-$ ***
$N(1520)$	$3/2^-$ ****	$\Delta(1700)$	$3/2^-$ ****	$\Sigma(1385)$	$3/2^+$ ****	$\Lambda_c(2765)^+$	*	$\Lambda_b(6070)^0$	$1/2^+$ ***
$N(1535)$	$1/2^-$ ****	$\Delta(1750)$	$1/2^+$ *	$\Sigma(1580)$	$3/2^-$ *	$\Lambda_c(2860)^+$	$3/2^+$ ***	$\Lambda_b(6146)^0$	$3/2^+$ ***
$N(1650)$	$1/2^-$ ****	$\Delta(1900)$	$1/2^-$ ***	$\Sigma(1620)$	$1/2^-$ *	$\Lambda_c(2880)^+$	$5/2^+$ ***	$\Lambda_b(6152)^0$	$5/2^+$ ***
$N(1675)$	$5/2^-$ ****	$\Delta(1905)$	$5/2^+$ ****	$\Sigma(1660)$	$1/2^+$ ***	$\Lambda_c(2940)^+$	$3/2^-$ ***	Σ_b	$1/2^+$ ***
$N(1680)$	$5/2^+$ ****	$\Delta(1910)$	$1/2^+$ ****	$\Sigma(1670)$	$3/2^-$ ****	$\Sigma_c(2455)$	$1/2^+$ ****	Σ_b^*	$3/2^+$ ****
$N(1700)$	$3/2^-$ ***	$\Delta(1920)$	$3/2^+$ ***	$\Sigma(1750)$	$1/2^-$ ***	$\Sigma_c(2520)$	$3/2^+$ ***	$\Sigma_b(6097)^+$	***
$N(1710)$	$1/2^+$ ****	$\Delta(1930)$	$5/2^-$ ***	$\Sigma(1775)$	$5/2^-$ ****	$\Sigma_c(2800)$	***	$\Sigma_b(6097)^-$	***
$N(1720)$	$3/2^+$ ****	$\Delta(1940)$	$3/2^-$ ***	$\Sigma(1780)$	$3/2^+$ *	Ξ_c^+	$1/2^+$ ***	Ξ_b^-	$1/2^+$ ***
$N(1860)$	$5/2^+$ **	$\Delta(1950)$	$7/2^+$ ****	$\Sigma(1880)$	$1/2^+$ **	Ξ_c^0	$1/2^+$ ****	Ξ_b^0	$1/2^+$ ***
$N(1875)$	$3/2^-$ ***	$\Delta(2000)$	$5/2^+$ **	$\Sigma(1900)$	$1/2^-$ **	Ξ_c^+	$1/2^+$ ****	$\Xi_b^0(5935)^-$	$1/2^+$ ***
$N(1880)$	$1/2^+$ ***	$\Delta(2150)$	$1/2^-$ **	$\Sigma(1910)$	$3/2^-$ ****	Ξ_c^0	$1/2^+$ ****	$\Xi_b(5945)^0$	$3/2^+$ ***
$N(1895)$	$1/2^-$ ****	$\Delta(2200)$	$7/2^-$ ***	$\Sigma(1915)$	$5/2^+$ ****	$\Xi_c(2645)$	$3/2^+$ ****	$\Xi_b(5955)^-$	$3/2^+$ ****
$N(1900)$	$3/2^+$ ****	$\Delta(2300)$	$9/2^+$ **	$\Sigma(1940)$	$3/2^+$ *	$\Xi_c(2790)$	$1/2^-$ ****	$\Xi_b(6100)^-$	$3/2^-$ ****
$N(1990)$	$7/2^+$ **	$\Delta(2350)$	$5/2^-$ *	$\Sigma(2010)$	$3/2^-$ *	$\Xi_c(2815)$	$3/2^-$ ****	$\Xi_b(6227)^-$	***
$N(2000)$	$5/2^+$ **	$\Delta(2390)$	$7/2^+$ *	$\Sigma(2030)$	$7/2^+$ ****	$\Xi_c(2923)$	**	$\Xi_b(6227)^0$	***
$N(2040)$	$3/2^+$ *	$\Delta(2400)$	$9/2^-$ **	$\Sigma(2070)$	$5/2^+$ *	$\Xi_c(2930)$	**	Ω_b^-	$1/2^+$ ****
$N(2060)$	$5/2^-$ ***	$\Delta(2420)$	$11/2^+$ ****	$\Sigma(2080)$	$3/2^+$ *	$\Xi_c(2970)$	$1/2^+$ ****	$\Omega_b(6316)^-$	*
$N(2100)$	$1/2^+$ ***	$\Delta(2750)$	$13/2^-$ **	$\Sigma(2100)$	$7/2^-$ *	$\Xi_c(3055)$	***	$\Omega_b(6330)^-$	*
$N(2120)$	$3/2^-$ ***	$\Delta(2950)$	$15/2^+$ **	$\Sigma(2110)$	$1/2^-$ *	$\Xi_c(3080)$	***	$\Omega_b(6340)^-$	*
$N(2190)$	$7/2^-$ ****			$\Sigma(2230)$	$3/2^+$ *	$\Xi_c(3123)$	*	$\Omega_b(6350)^-$	*
$N(2220)$	$9/2^+$ ****	Λ	$1/2^+$ ****	$\Sigma(2250)$	**	Ω_c^0	$1/2^+$ ****		
$N(2250)$	$9/2^-$ ****	$\Lambda(1380)$	$1/2^-$ **	$\Sigma(2455)$	*	$\Omega_c(2770)^0$	$3/2^+$ ****	$P_c(4312)^+$	*
$N(2300)$	$1/2^+$ **	$\Lambda(1405)$	$1/2^-$ ****	$\Sigma(2620)$	*	$\Omega_c(3000)^0$	***	$P_c(4380)^+$	*
$N(2570)$	$5/2^-$ **	$\Lambda(1520)$	$3/2^-$ ****	$\Sigma(3000)$	*	$\Omega_c(3050)^0$	***	$P_c(4440)^+$	*
$N(2600)$	$11/2^-$ ***	$\Lambda(1600)$	$1/2^+$ ****	$\Sigma(3170)$	*	$\Omega_c(3065)^0$	***	$P_c(4457)^+$	*
$N(2700)$	$13/2^+$ **	$\Lambda(1670)$	$1/2^-$ ****			$\Omega_c(3090)^0$	***		
		$\Lambda(1690)$	$3/2^-$ ****	Ξ^0	$1/2^+$ ****	$\Omega_c(3120)^0$	***		
		$\Lambda(1710)$	$1/2^+$ *	Ξ^-	$1/2^+$ ****				
		$\Lambda(1800)$	$1/2^-$ ***	$\Xi(1530)$	$3/2^+$ ****	Ξ_c^+	*		
		$\Lambda(1810)$	$1/2^+$ ***	$\Xi(1620)$	*	Ξ_c^0	***		
		$\Lambda(1820)$	$5/2^+$ ****	$\Xi(1690)$	***	Ξ_c^+	***		
		$\Lambda(1830)$	$5/2^-$ ****	$\Xi(1820)$	$3/2^-$ ***				
		$\Lambda(1890)$	$3/2^+$ ****	$\Xi(1950)$					
		$\Lambda(2000)$	$1/2^-$ *	$\Xi(2030)$	$\geq \frac{3}{2}^?$ ***				
		$\Lambda(2050)$	$3/2^-$ *	$\Xi(2120)$	*				
		$\Lambda(2070)$	$3/2^+$ *	$\Xi(2250)$	**				
		$\Lambda(2080)$	$5/2^-$ *	$\Xi(2370)$	**				
		$\Lambda(2085)$	$7/2^+$ **	$\Xi(2500)$	*				
		$\Lambda(2100)$	$7/2^-$ ****						
		$\Lambda(2110)$	$5/2^+$ ***	Ω^-	$3/2^+$ ****				
		$\Lambda(2325)$	$3/2^-$ *	$\Omega(2012)^-$	$?^-$ ***				
		$\Lambda(2350)$	$9/2^+$ ***	$\Omega(2250)^-$	***				
		$\Lambda(2585)$	*	$\Omega(2380)^-$	**				
				$\Omega(2470)^-$	**				

New resonant structures at BESIII

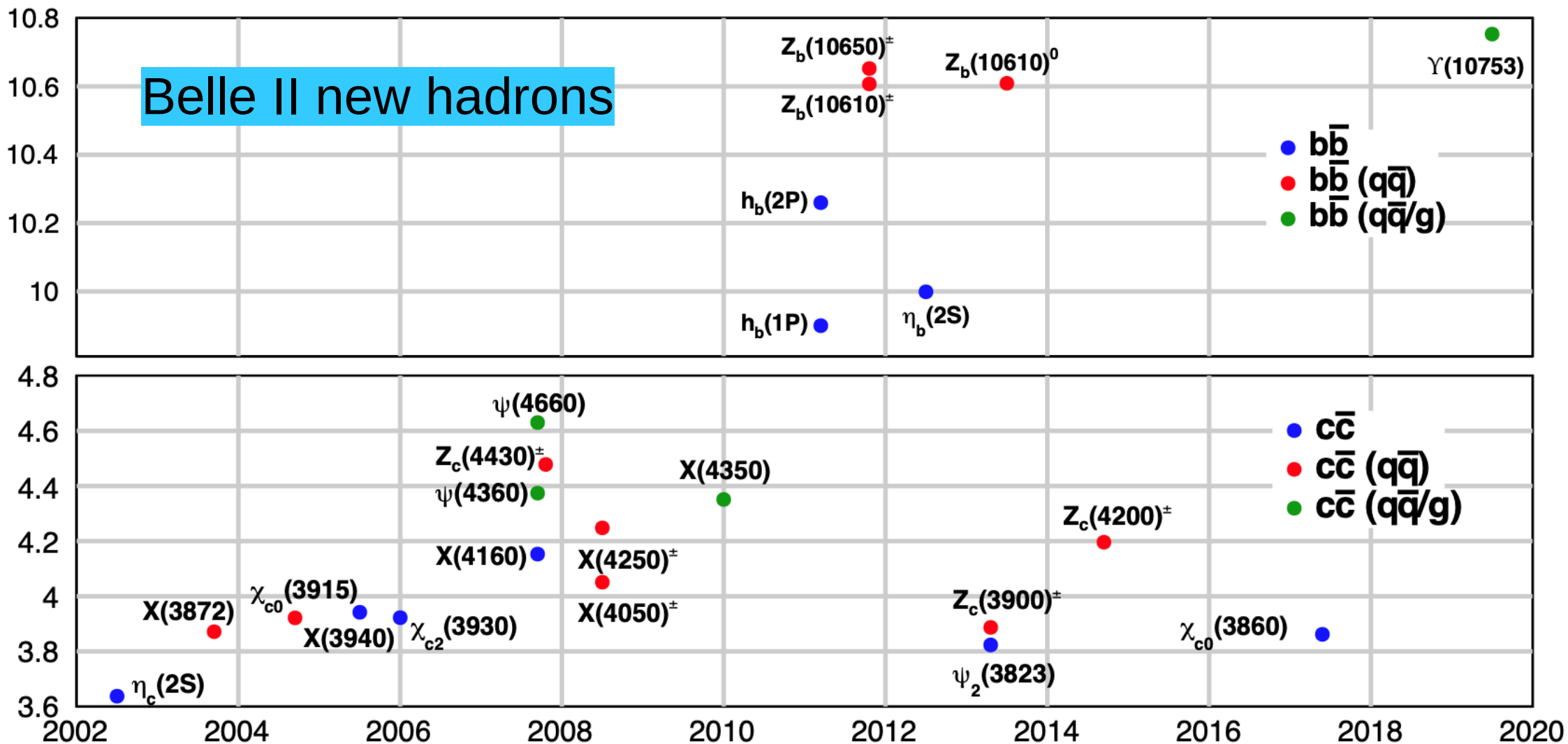
From Prof. Shuang-Shi Fang





Mass [GeV]

Belle II new hadrons



Data of arXiv submission

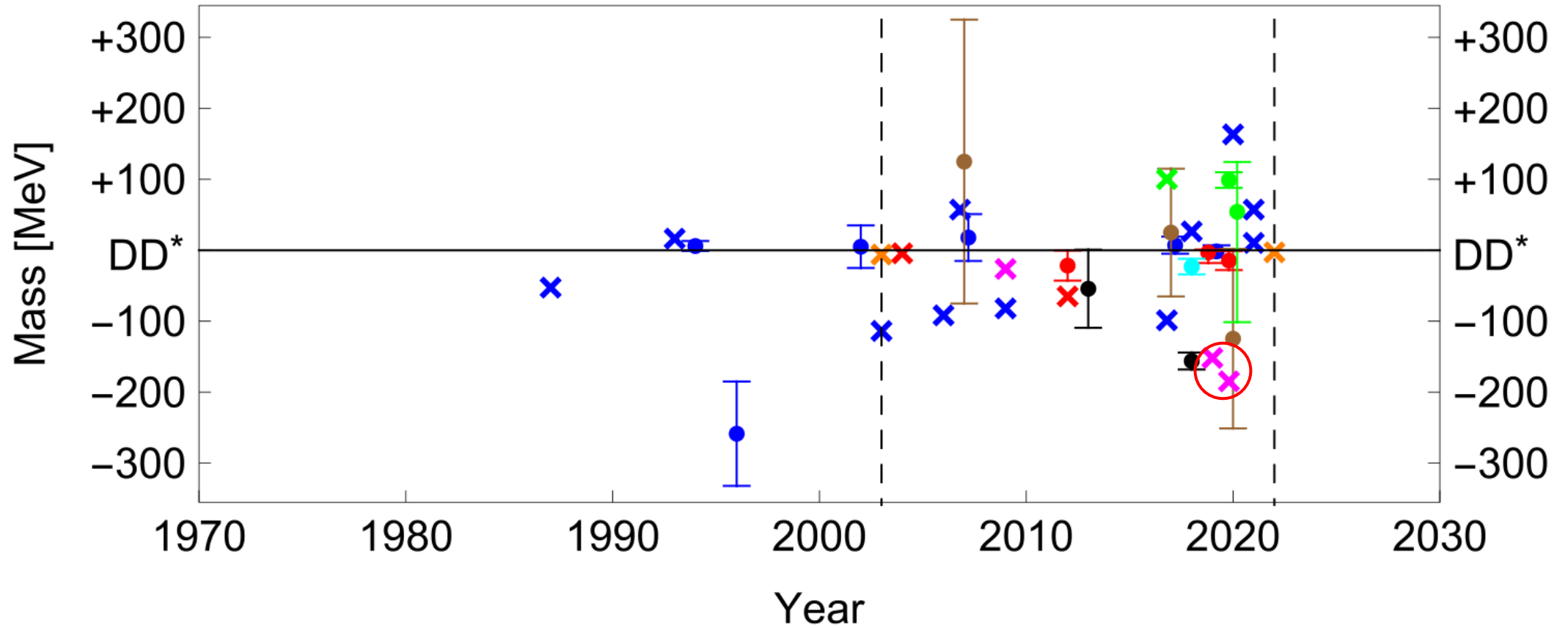


Figure 42. Theoretical predictions on the mass of the doubly charmed tetraquark state $cc\bar{u}\bar{d}$ with $(I)J^P = (0)1^+$, with uncertainties (error bars) and without uncertainties (crosses), calculated based on the compact tetraquark picture through various quark models [454, 500–515] (blue), 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

Outline

- Introduction

- *Chiral quark model with HLS*

- ⊙ $SU2$ ground states + excited states
- ⊙ $SU3$ ground states
- ⊙ Summary

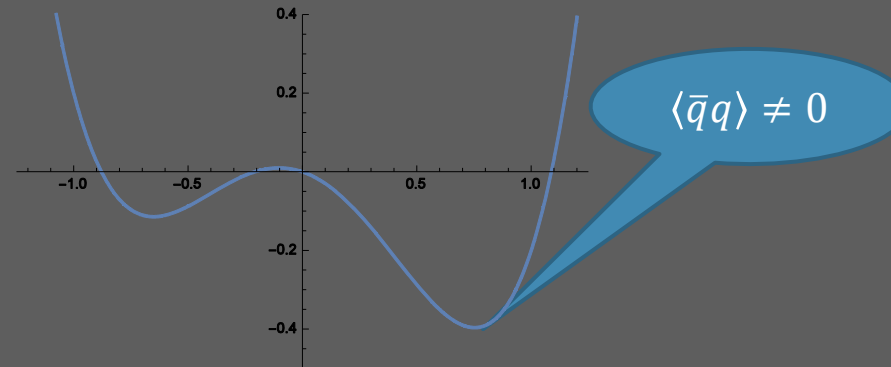
The chiral symmetry

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:

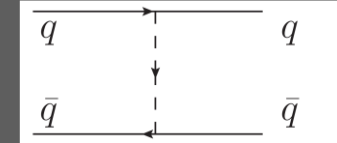
- Nonlinear sigma model
- Chiral perturbation theory

Chiral quark model

Naïve quark model:

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

gluon exchange

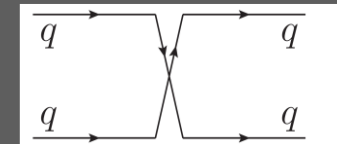
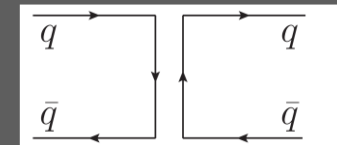


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- Zweig, G., 1964, CERN Reports No. 8182/TH. 401 and No. 8419/TH. 412).
- N. Isgur, G. Karl, Phys.Lett.B 72 (1977) 109.

The Nambu–Goldstone boson exchange:

- Chiral symmetry is spontaneously broken
- Pseudoscalars (π , K , η) are the Nambu–Goldstone (NG) bosons of chiral symmetry breaking
- Scalar meson σ as the chiral partner of NG bosons

meson exchange



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- 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:

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

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

$$h(x)^\dagger h(x) = 1$$

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

- 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 (π, K, η, η') and vector mesons (ρ, K^*, ω, ϕ)

Outline

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

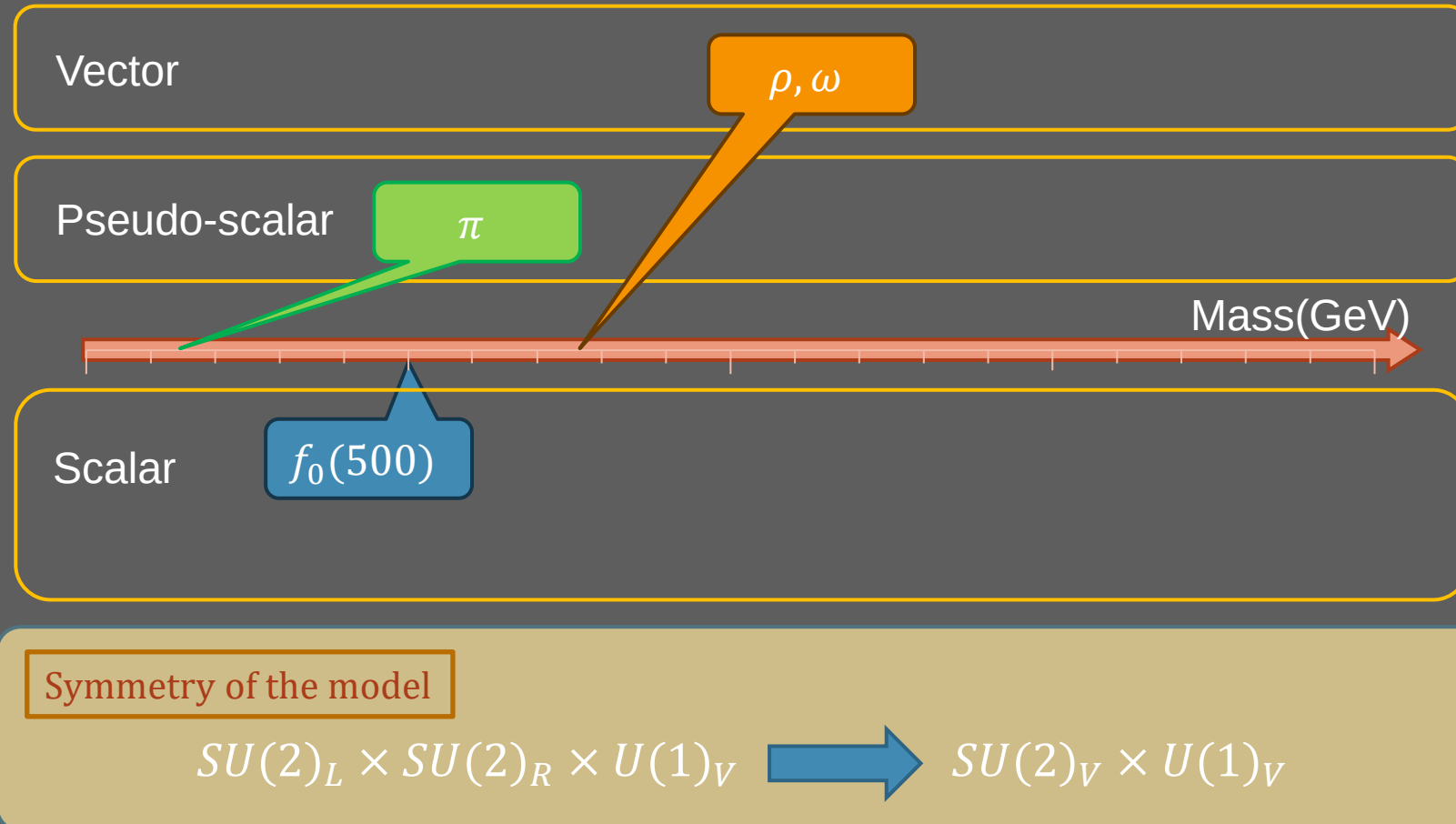
The Hamiltonian

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

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Bing-Song Zou, 2306.03526

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

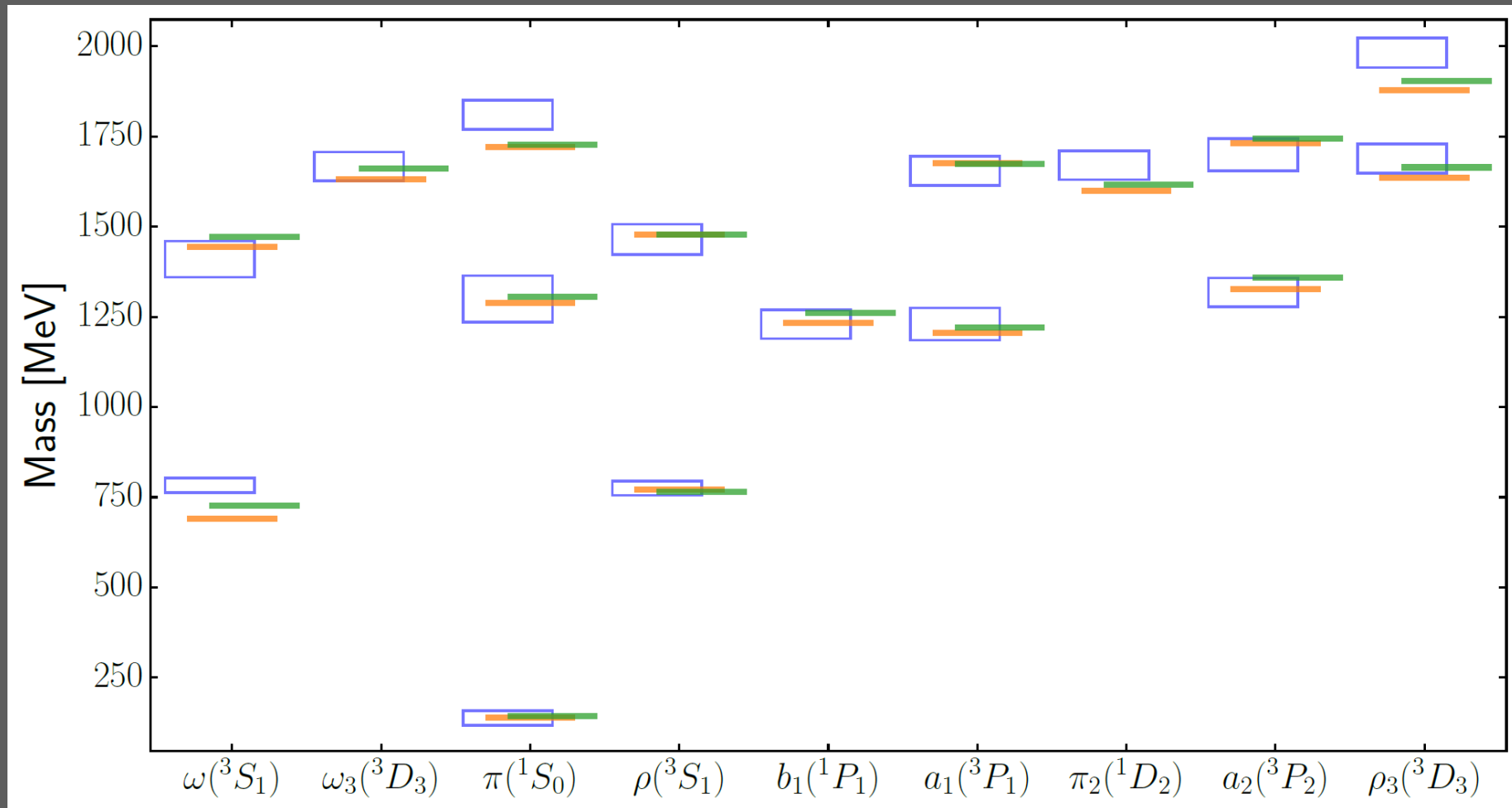
The exchanged mesons in $SU2$ model

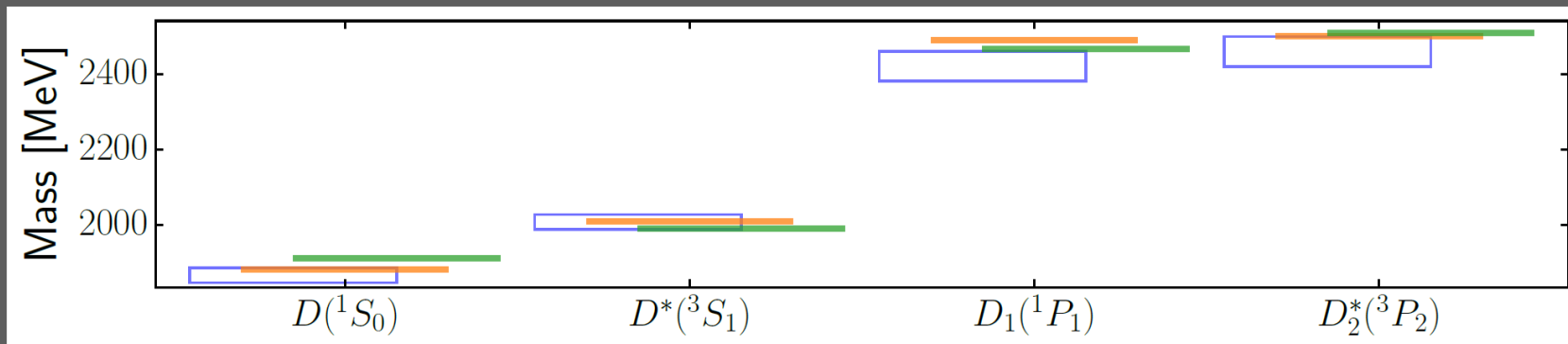
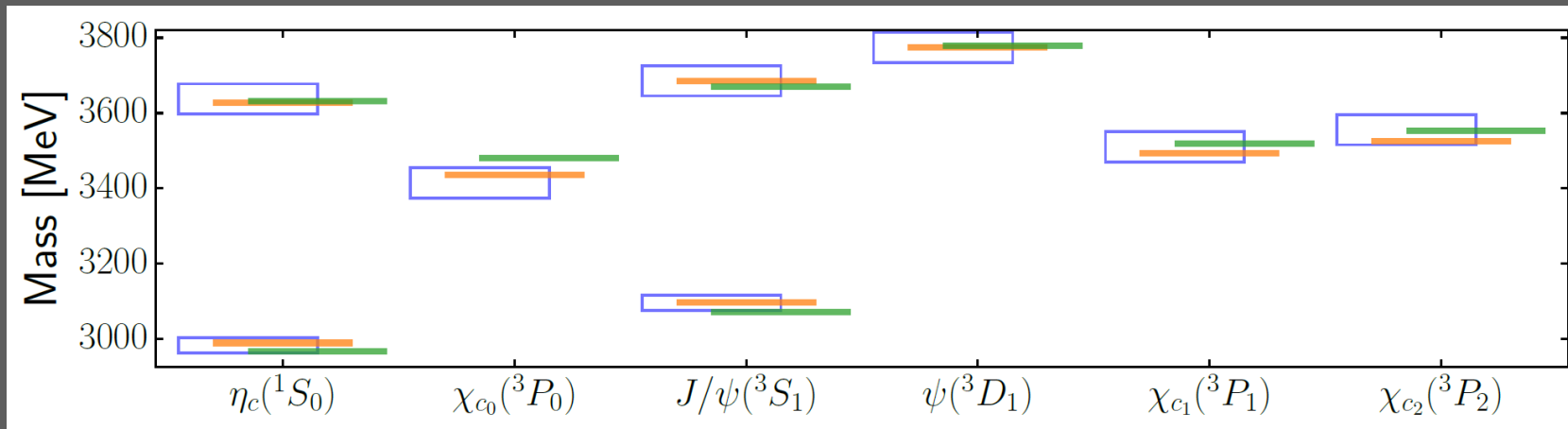


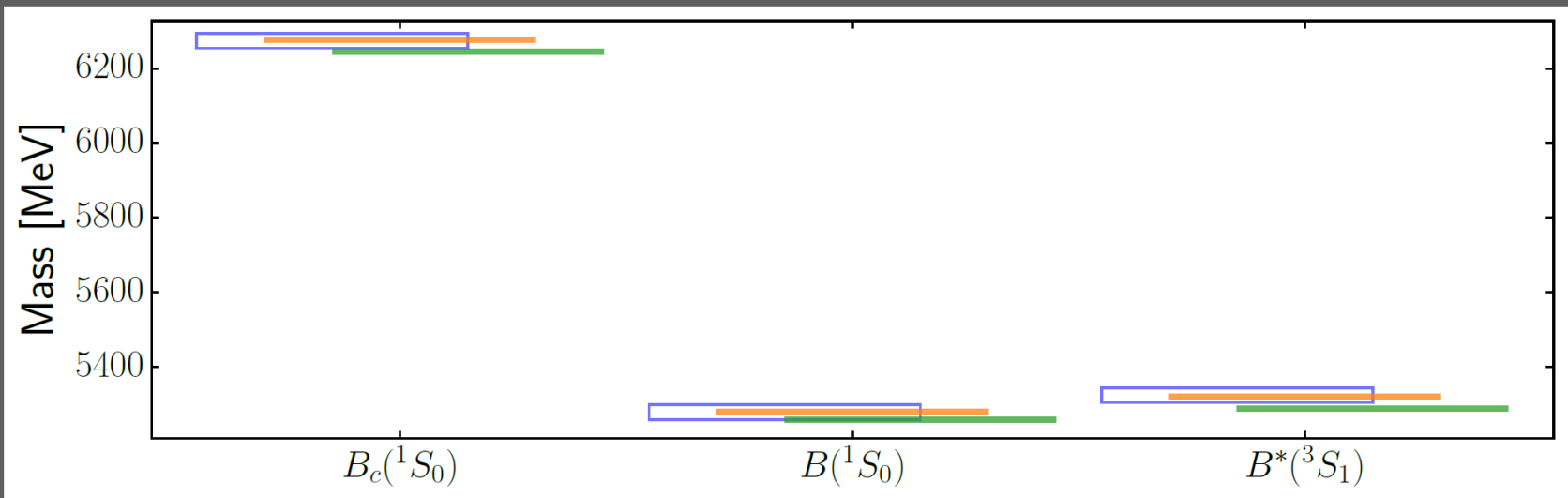
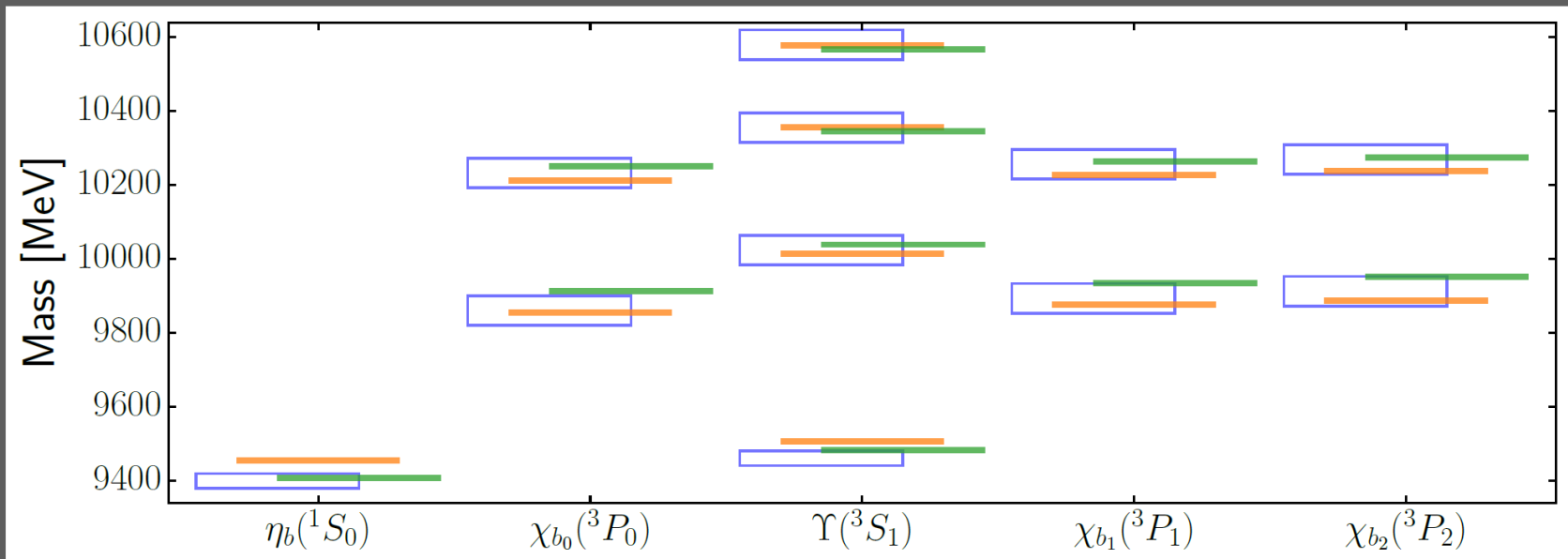
Wave functions

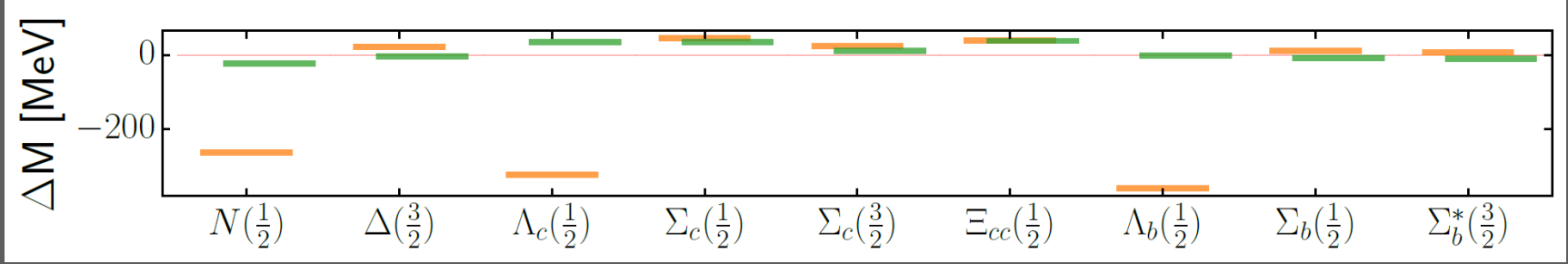
- Orbital (SO(3)): (ψ_L)
- Spin (SU(2)): (χ_S^σ)
- Flavor (SU(2)): (χ_I^f)
- Color (SU(3)): (χ^c)

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









	1	$\tau_i \tau_j$	$\sigma_i \sigma_j$	$\sigma_i \sigma_j \cdot \tau_i \tau_j$
σ	-/-			
π				+/-
a_0		-/+		
OGE	-/-		+/+	
CON	+/+			
ω (This work)	+/-		+/-	
ρ (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

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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 SU_3 flavor symmetry:

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

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

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

$$g_{\pi} = g_K$$

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

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

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

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

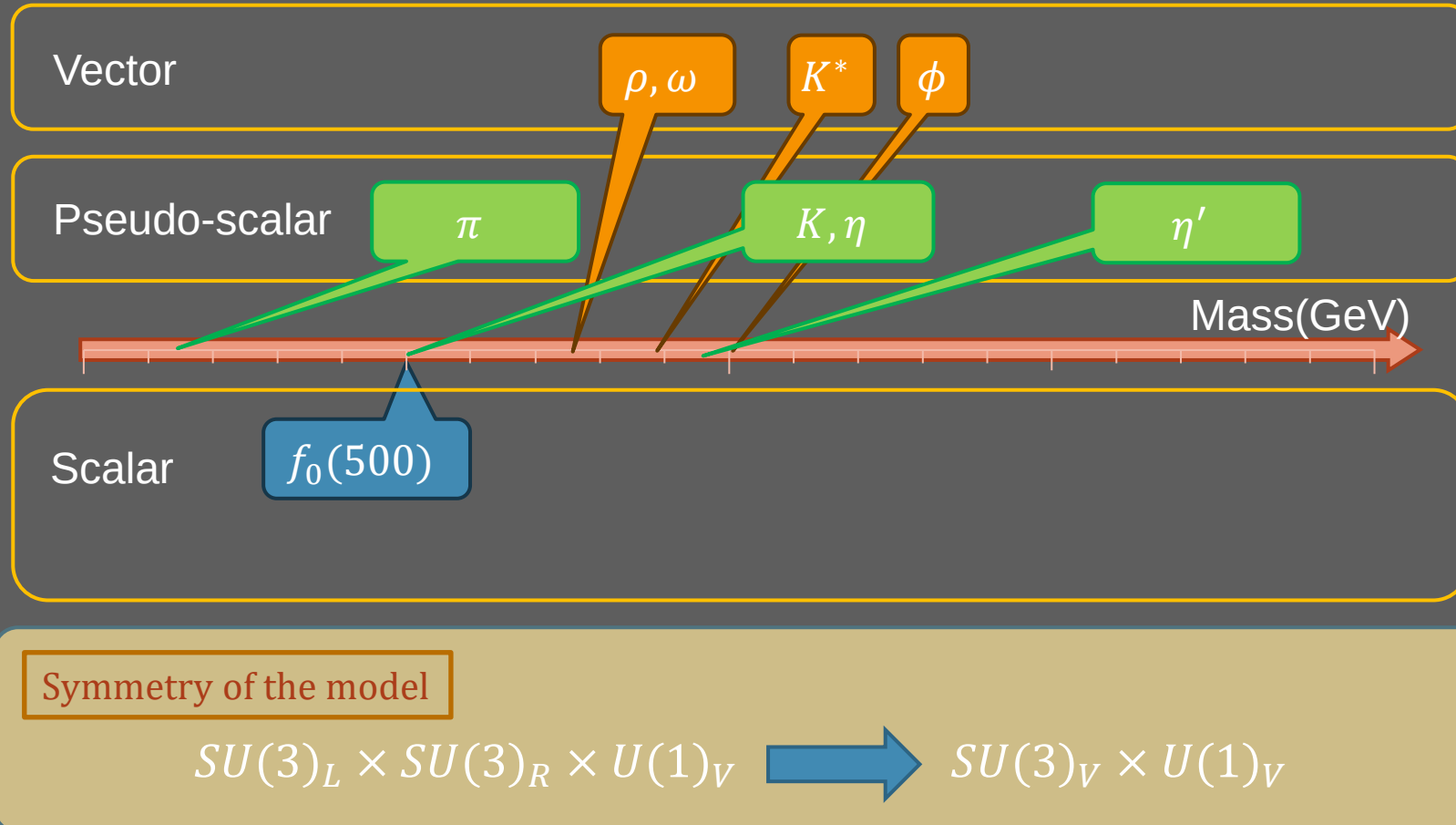
$$f_{\omega s} = f_{\omega q} - f_{\rho}$$

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

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

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

The exchanged mesons in $SU3$ model



Wave functions

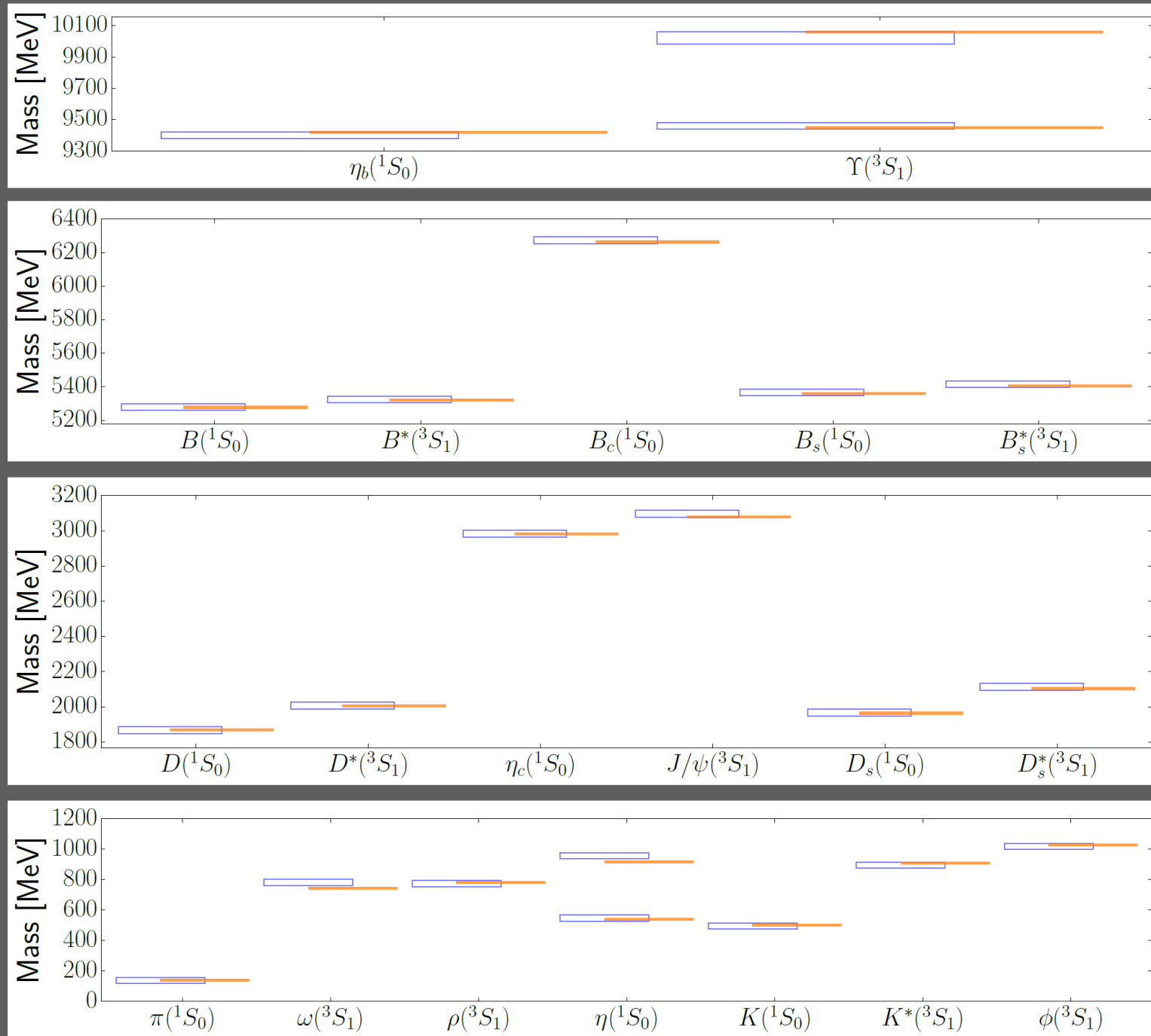
- Orbital (SO(3)): (ψ_L)
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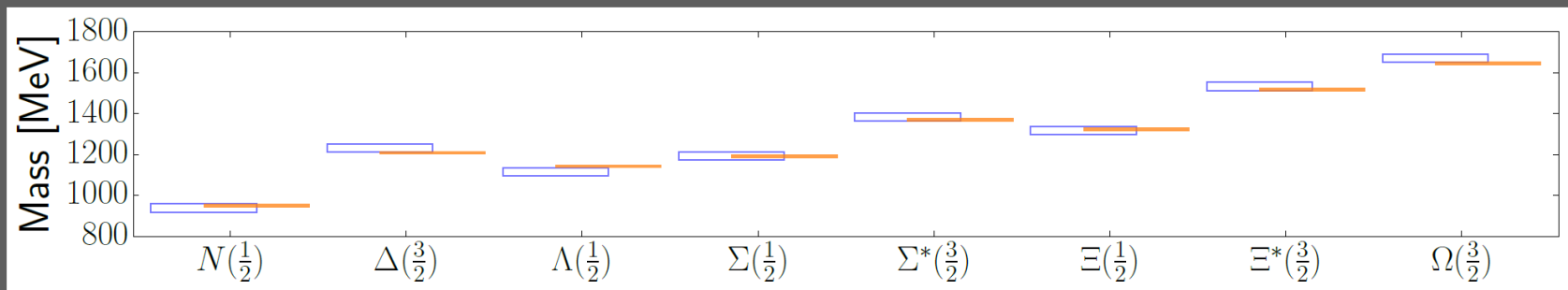
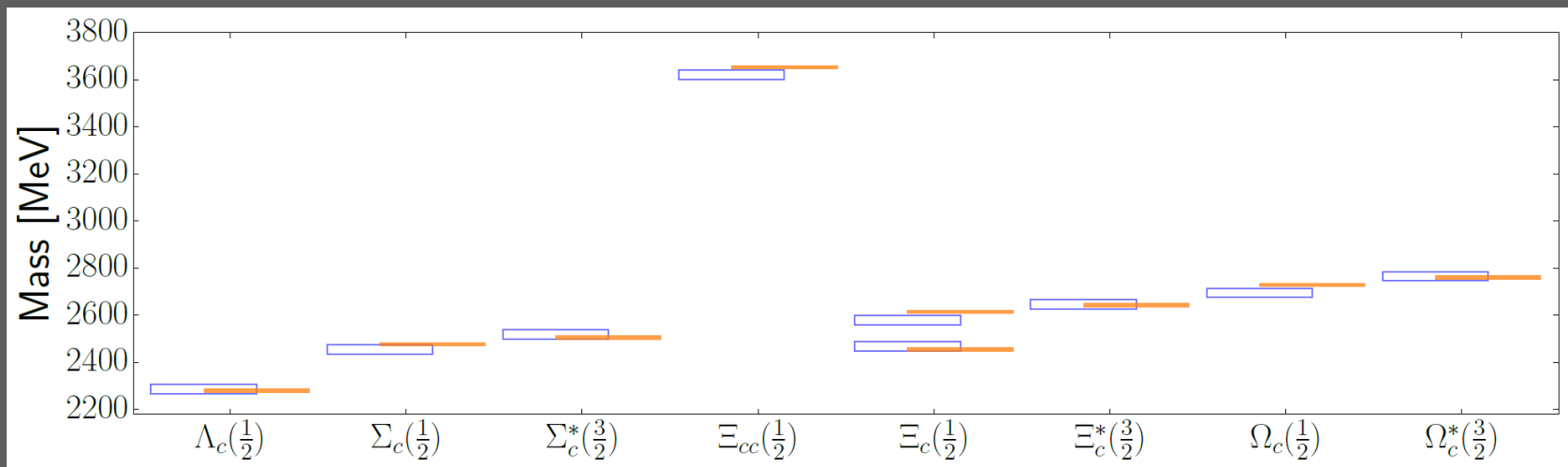
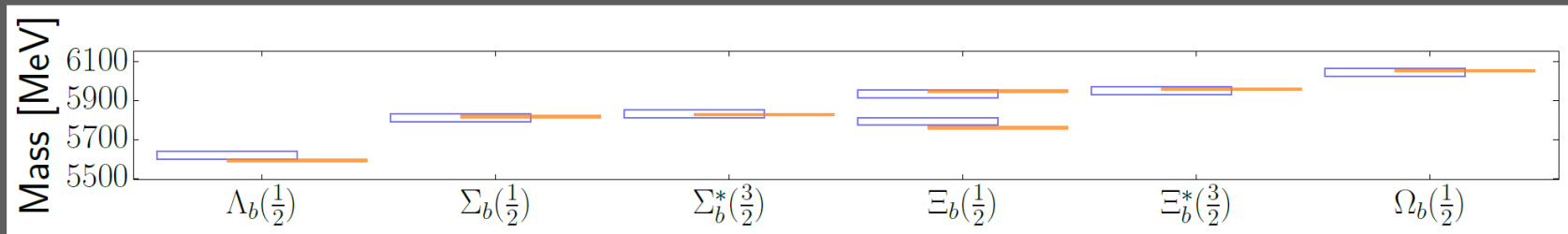
$$\Psi_{JM_J IM_I}^{ijk} = \mathcal{A} \left[[\psi_L \chi_S^{\sigma i}]_{JM_J} \chi_I^{fj} \chi_k^c \right]$$

	1	$\lambda_i \lambda_j$	$\sigma_i \sigma_j$	$\sigma_i \sigma_j \cdot \lambda_i \lambda_j$
$\bar{\sigma}$	$-/-$			
η/η'			$+/+$	
π/K				$+/-$
ω/ϕ	$+/-$		$+/-$	
ρ/K^*		$+/+$		$+/+$
OGE	$-/-$		$+/+$	
CON	$+/+$			

	No vector J. Phys. G 31, 481(2005)	su2 vector 2306.03526	su3 vector 2307.16280
$\alpha_s(qq)$	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

$qq/q\bar{q}$

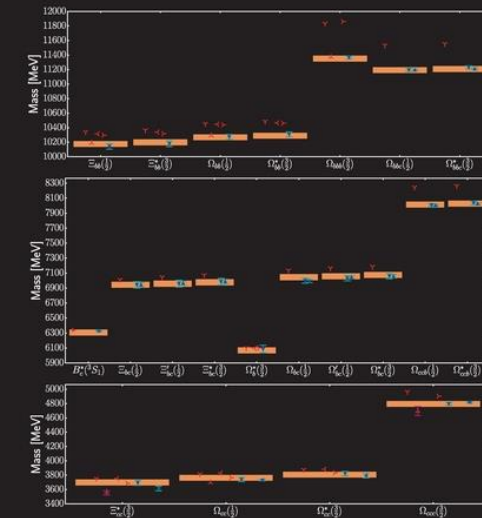
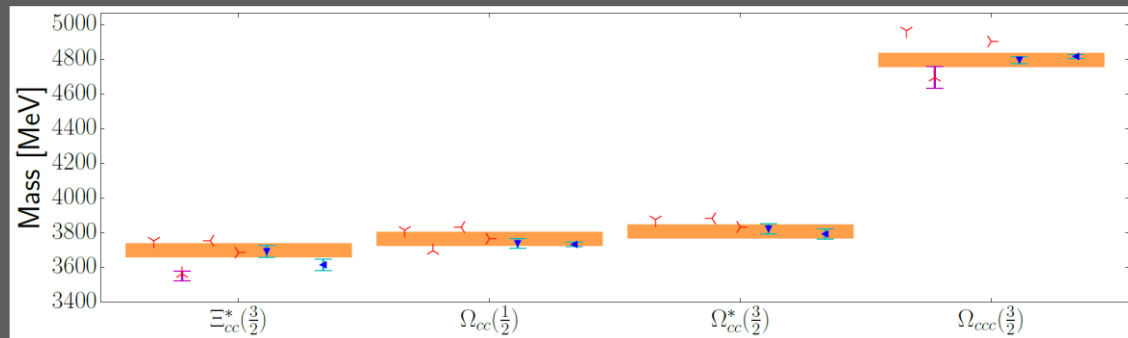
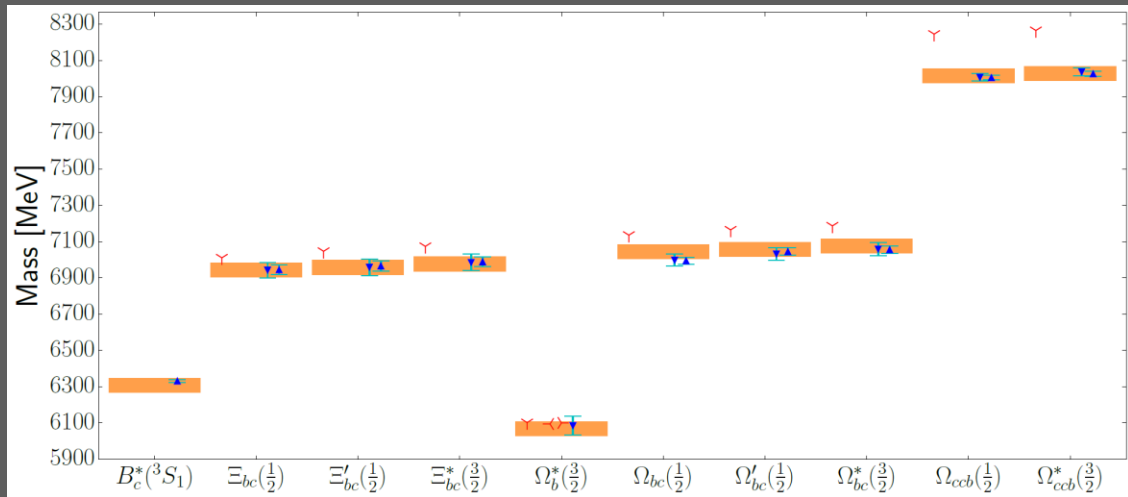
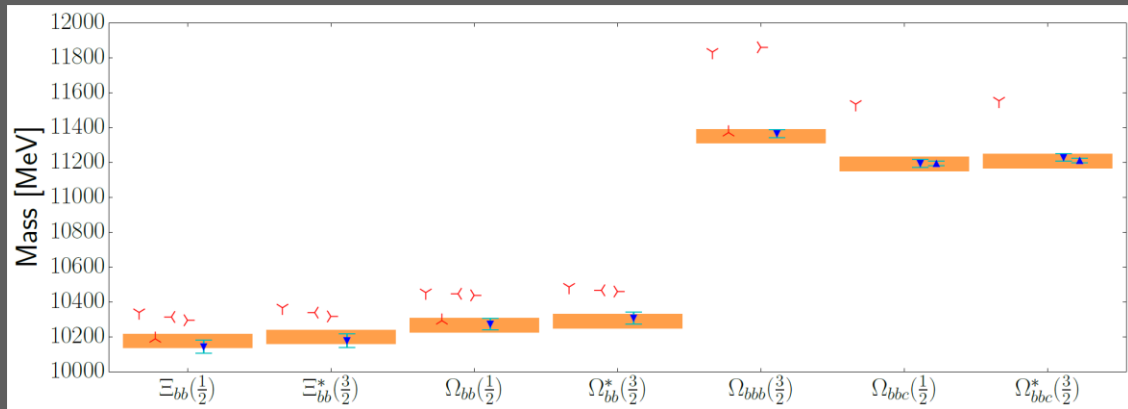




Models	Meson χ^2 Err(the)=40MeV	Baryon χ^2 Err(the)=40MeV
Godfrey & Isgur (1985)	5.3 (21 meson)	
Capstick & Isgur (1986)		3.78 (14 baryon)
Vijande & Fernandez & Valcarce (2005)	9.5 (21 meson)	305.8 (8 baryon, unpublished)
He & Harada & Zou 2307.16280	2.9 (21 meson)	5.7 (24 baryon)

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

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



Predicted mass spectrum of missing meson and baryons which have not been experimentally confirmed shown by orange line with 40 MeV error. The values of Ω_{bbb} shown here are shifted by -3000MeV .

From Bing-Ran He, Masayasu Harada & Bing-Song Zou on: Ground states of all mesons and baryons in a quark model with hidden local symmetry. Eur. Phys. J. C 83, 1159 (2023).



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- **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!