QUARK MODEL WITH HIDDEN LOCAL SYMMETRY AND ITS APPLICATION TO THE MULTI QUARK SYSTEMS

Bing-Ran He, Masayasu Harada,
Bing-Song Zou

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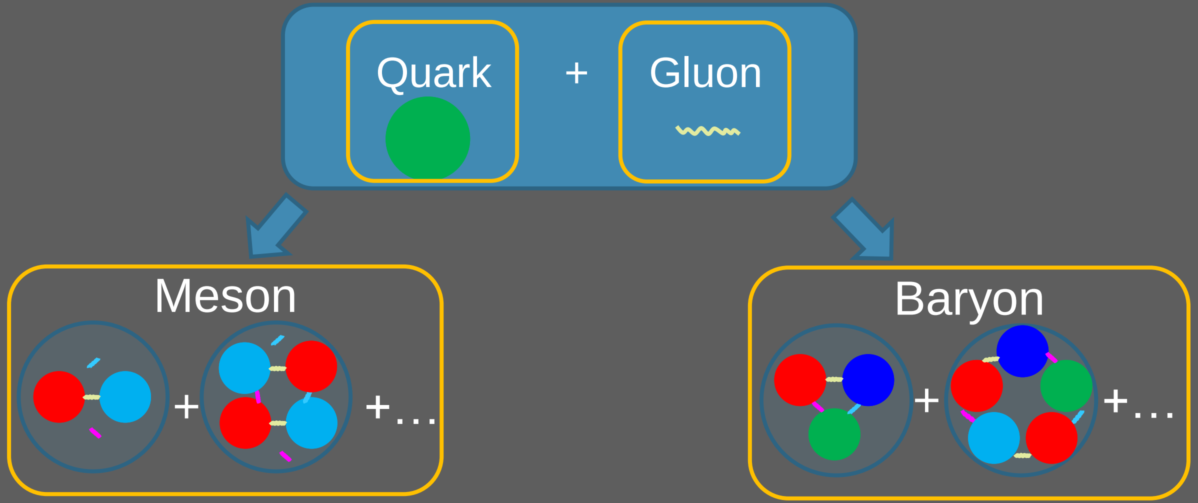
Bing-Ran HE
Nanjing Normal University

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 $q\overline{q}$ 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 ($S = C = B = 0$)

	$I^G(J^{PC})$
• $\pi^\pm$	$1^-(0^-)$
• π^0	$1^-(0^{-+})$
• η	$0^+(0^{-+})$
• $f_0(500)$	$0^+(0^{++})$
• $\rho(770)$	$1^+(1^{--})$
• $\omega(782)$	$0^-(1^{--})$
• $\eta'(958)$	$0^+(0^{-+})$
• $f_0(980)$	$0^+(0^{++})$
• $a_0(980)$	$1^-(0^{++})$
• $\phi(1020)$	$0^-(1^{--})$
• $h_1(1170)$	$0^-(1^{+-})$
• $b_1(1235)$	$1^+(1^{+-})$
• $a_1(1260)$	$1^-(1^{++})$
• $f_2(1270)$	$0^+(2^{++})$
• $f_1(1285)$	$0^+(1^{++})$
• $\eta(1295)$	$0^+(0^{-+})$
• $\pi(1300)$	$1^-(0^{-+})$
• $a_2(1320)$	$1^-(2^{++})$
• $f_0(1370)$	$0^+(0^{++})$
• $\pi_1(1400)$	$1^-(1^{-+})$
• $\eta(1405)$	$0^+(0^{-+})$
• $h_1(1415)$	$0^-(1^{+-})$
• $f_1(1420)$	$0^+(1^{++})$
• $\omega(1420)$	$0^-(1^{--})$
$f_2(1430)$	$0^+(2^{++})$
• $a_0(1450)$	$1^-(0^{++})$
• $\rho(1450)$	$1^+(1^{--})$
• $\eta(1475)$	$0^+(0^{-+})$
• $f_0(1500)$	$0^+(0^{++})$
$f_1(1510)$	$0^+(1^{++})$
• $f_2'(1525)$	$0^+(2^{++})$
$f_2(1565)$	$0^+(2^{++})$
$\rho(1570)$	$1^+(1^{--})$
$h_1(1595)$	$0^-(1^{+-})$
• $\pi_1(1600)$	$1^-(1^{-+})$
• $a_1(1640)$	$1^-(1^{++})$
$f_2(1640)$	$0^+(2^{++})$
• $\eta_2(1645)$	$0^+(2^{-+})$
• $\omega(1650)$	$0^-(1^{--})$
• $\omega_3(1670)$	$0^-(3^{--})$

	$I^G(J^{PC})$
• $\pi_2(1670)$	$1^-(2^{-+})$
• $\phi(1680)$	$0^-(1^{--})$
• $\rho_3(1690)$	$1^+(3^{--})$
• $\rho(1700)$	$1^+(1^{--})$
• $a_2(1700)$	$1^-(2^{++})$
• $f_0(1710)$	$0^+(0^{++})$
$X(1750)$	$?^-(1^{--})$
$\eta(1760)$	$0^+(0^{-+})$
• $\pi(1800)$	$1^-(0^{-+})$
$f_2(1810)$	$0^+(2^{++})$
$X(1835)$	$?^?(0^{-+})$
• $\phi_3(1850)$	$0^-(3^{--})$
• $\eta_2(1870)$	$0^+(2^{-+})$
• $\pi_2(1880)$	$1^-(2^{-+})$
$\rho(1900)$	$1^+(1^{--})$
$f_2(1910)$	$0^+(2^{++})$
$a_0(1950)$	$1^-(0^{++})$
• $f_2(1950)$	$0^+(2^{++})$
• $a_4(1970)$	$1^-(4^{++})$
$\rho_3(1990)$	$1^+(3^{--})$
$\pi_2(2005)$	$1^-(2^{-+})$
• $f_2(2010)$	$0^+(2^{++})$
$f_0(2020)$	$0^+(0^{++})$
• $f_4(2050)$	$0^+(4^{++})$
$\pi_2(2100)$	$1^-(2^{-+})$
$f_0(2100)$	$0^+(0^{++})$
$f_2(2150)$	$0^+(2^{++})$
$\rho(2150)$	$1^+(1^{--})$
• $\phi(2170)$	$0^-(1^{--})$
$f_0(2200)$	$0^+(0^{++})$
$f_J(2220)$	$0^+(2^{++}$ or $4^{++})$
$\eta(2225)$	$0^+(0^{-+})$
$\rho_3(2250)$	$1^+(3^{--})$
• $f_2(2300)$	$0^+(2^{++})$
$f_4(2300)$	$0^+(4^{++})$
$f_0(2330)$	$0^+(0^{++})$
• $f_2(2340)$	$0^+(2^{++})$
$\rho_5(2350)$	$1^+(5^{--})$
$X(2370)$	$?^?(?^{??})$
$f_6(2510)$	$0^+(6^{++})$

STRANGE ($S = \pm1$, $C = B = 0$)

	$I(J^P)$
• $K^\pm$	$1/2(0^-)$
• K^0	$1/2(0^-)$
• K^0_S	$1/2(0^-)$
• K^0_L	$1/2(0^-)$
• $K_0^*(700)$	$1/2(0^+)$
• $K^*(892)$	$1/2(1^-)$
• $K_1(1270)$	$1/2(1^+)$
• $K_1(1400)$	$1/2(1^+)$
• $K^*(1410)$	$1/2(1^-)$
• $K_0^*(1430)$	$1/2(0^+)$
• $K_2^*(1430)$	$1/2(2^+)$
• $K(1460)$	$1/2(0^-)$
$K_2(1580)$	$1/2(2^-)$
$K(1630)$	$1/2(?^?)$
• $K_1(1650)$	$1/2(1^+)$
• $K^*(1680)$	$1/2(1^-)$
• $K_2(1770)$	$1/2(2^-)$
• $K_3^*(1780)$	$1/2(3^-)$
• $K_2(1820)$	$1/2(2^-)$
$K(1830)$	$1/2(0^-)$
$K_0^*(1950)$	$1/2(0^+)$
• $K_2^*(1980)$	$1/2(2^+)$
• $K_4^*(2045)$	$1/2(4^+)$
$K_2(2250)$	$1/2(2^-)$
$K_3(2320)$	$1/2(3^+)$
$K_5^*(2380)$	$1/2(5^-)$
$K_4(2500)$	$1/2(4^-)$
$K(3100)$	$?^?(?^{??})$

CHARMED ($C = \pm1$)

	$I(J^P)$
• $D^\pm$	$1/2(0^-)$
• D^0	$1/2(0^-)$
• $D^*(2007)^0$	$1/2(1^-)$
• $D^*(2010)^\pm$	$1/2(1^-)$
• $D_0^*(2300)$	$1/2(0^+)$
• $D_1(2420)$	$1/2(1^+)$
• $D_1(2430)^0$	$1/2(1^+)$
• $D_2^*(2460)$	$1/2(2^+)$
$D_0(2550)^0$	$1/2(0^-)$
$D_1^*(2600)^0$	$1/2(1^-)$
$D^*(2640)^\pm$	$1/2(?^?)$
$D_2(2740)^0$	$1/2(2^-)$
• $D_3^*(2750)$	$1/2(3^-)$
$D_1^*(2760)^0$	$1/2(1^-)$
$D(3000)^0$	$1/2(?^?)$

CHARMED, STRANGE ($C = \pm1$, $S = \pm1$) (+ possibly non-$q\overline{q}$ states)

	$I(J^P)$
• $D_s^\pm$	$0(0^-)$
• $D_s^{*\pm}$	$0(?^?)$
• $D_{s0}^*(2317)^\pm$	$0(0^+)$
• $D_{s1}(2460)^\pm$	$0(1^+)$
• $D_{s1}(2536)^\pm$	$0(1^+)$
• $D_{s2}^*(2573)$	$0(2^+)$
$D_{s0}(2590)^+$	$0(0^-)$
• $D_{s1}^*(2700)^\pm$	$0(1^-)$
$D_{s1}^*(2860)^\pm$	$0(1^-)$
• $D_{s3}^*(2860)^\pm$	$0(3^-)$
$X_0(2900)$	$?(0^+)$
$X_1(2900)$	$?(1^-)$
$D_{sJ}(3040)^\pm$	$0(?^?)$

BOTTOM ($B = \pm1$)

• $B^\pm$	$1/2(0^-)$
• B^0	$1/2(0^-)$
• $B^\pm/B^0$ ADMIXTURE	
• $B^\pm/B^0/B^0_s/b$-baryon ADMIXTURE	
V_{cb} and V_{ub} CKM Matrix Elements	
• B^*	$1/2(1^-)$
• $B_1(5721)$	$1/2(1^+)$
$B_J^*(5732)$	$?(?^?)$
• $B_2^*(5747)$	$1/2(2^+)$
$B_J(5840)$	$1/2(?^?)$
• $B_J(5970)$	$1/2(?^?)$

BOTTOM, STRANGE ($B = \pm1$, $S = \mp1$)

• B^0_s	$0(0^-)$
• B^*_s	$0(1^-)$
$X(5568)^\pm$	$?(?^?)$
• $B_{s1}(5830)^0$	$0(1^+)$
• $B_{s2}^*(5840)^0$	$0(2^+)$
$B_{sJ}^*(5850)$	$?(?^?)$
$B_{sJ}(6063)^0$	$0(?^?)$
$B_{sJ}(6114)^0$	$0(?^?)$

BOTTOM, CHARMED ($B = C = \pm1$)

• B_c^+	$0(0^-)$
• $B_c(2S)^\pm$	$0(0^-)$

$c\overline{c}$ (+ possibly non-$q\overline{q}$ states)

	$I^G(J^{PC})$
• $\eta_c(1S)$	$0^+(0^{-+})$
• $J/\psi(1S)$	$0^-(1^{--})$
• $\chi_{c0}(1P)$	$0^+(0^{++})$
• $\chi_{c1}(1P)$	$0^+(1^{++})$
• $h_c(1P)$	$0^-(1^{+-})$
• $\chi_{c2}(1P)$	$0^+(2^{++})$
• $\eta_c(2S)$	$0^+(0^{-+})$
• $\psi(2S)$	$0^-(1^{--})$
• $\psi(3770)$	$0^-(1^{--})$

$c\overline{c}$ continued

	$I^G(J^{PC})$
• $\psi_2(3823)$	$0^-(2^{--})$
• $\psi_3(3842)$	$0^-(3^{--})$
$\chi_{c0}(3860)$	$0^+(0^{++})$
• $\chi_{c1}(3872)$	$0^+(1^{++})$
• $Z_c(3900)$	$1^+(1^{+-})$
• $\chi_{c0}(3915)$	$0^+(0^{++})$
• $\chi_{c2}(3930)$	$0^+(2^{++})$
$X(3940)$	$?^?(?^{??})$
• $X(4020)^\pm$	$1^+(?^{?-})$
• $\psi(4040)$	$0^-(1^{--})$
$X(4050)^\pm$	$1^-(?^{?+})$
$X(4055)^\pm$	$1^+(?^{?-})$
$X(4100)^\pm$	$1^-(?^{??})$
• $\chi_{c1}(4140)$	$0^+(1^{++})$
• $\psi(4160)$	$0^-(1^{--})$
$X(4160)$	$?^?(?^{??})$
$Z_c(4200)$	$1^+(1^{+-})$
• $\psi(4230)$	$0^-(1^{--})$
$R_{c0}(4240)$	$1^+(0^{--})$
$X(4250)^\pm$	$1^-(?^{?+})$
• $\chi_{c1}(4274)$	$0^+(1^{++})$
$X(4350)$	$0^+(?^{?+})$
• $\psi(4360)$	$0^-(1^{--})$
• $\psi(4415)$	$0^-(1^{--})$
• $Z_c(4430)$	$1^+(1^{+-})$
$\chi_{c0}(4500)$	$0^+(0^{++})$
$X(4630)$	$0^+(?^{?+})$
• $\psi(4660)$	$0^-(1^{--})$
$\chi_{c1}(4685)$	$0^+(1^{++})$
$\chi_{c0}(4700)$	$0^+(0^{++})$

$b\overline{b}$ (+ possibly non-$q\overline{q}$ states)

	$I^G(J^{PC})$
• $\eta_b(1S)$	$0^+(0^{-+})$
• $\Upsilon(1S)$	$0^-(1^{--})$
• $\chi_{b0}(1P)$	$0^+(0^{++})$
• $\chi_{b1}(1P)$	$0^+(1^{++})$
• $h_b(1P)$	$0^-(1^{+-})$
• $\chi_{b2}(1P)$	$0^+(2^{++})$
$\eta_b(2S)$	$0^+(0^{-+})$
• $\Upsilon(2S)$	$0^-(1^{--})$
• $\Upsilon_2(1D)$	$0^-(2^{--})$
• $\chi_{b0}(2P)$	$0^+(0^{++})$
• $\chi_{b1}(2P)$	$0^+(1^{++})$
• $h_b(2P)$	$0^-(1^{+-})$
• $\chi_{b2}(2P)$	$0^+(2^{++})$
• $\Upsilon(3S)$	$0^-(1^{--})$
• $\chi_{b1}(3P)$	$0^+(1^{++})$
• $\chi_{b2}(3P)$	$0^+(2^{++})$
• $\Upsilon(4S)$	$0^-(1^{--})$
• $Z_b(10610)$	$1^+(1^{+-})$
• $Z_b(10650)$	$1^+(1^{+-})$
$\Upsilon(10753)$	$?^?(1^{--})$
• $\Upsilon(10860)$	$0^-(1^{--})$
• $\Upsilon(11020)$	$0^-(1^{--})$

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	$1/2^+$	****
n	$1/2^+$	****
$N(1440)$	$1/2^+$	****
$N(1520)$	$3/2^-$	****
$N(1535)$	$1/2^-$	****
$N(1650)$	$1/2^-$	****
$N(1675)$	$5/2^-$	****
$N(1680)$	$5/2^+$	****
$N(1700)$	$3/2^-$	***
$N(1710)$	$1/2^+$	****
$N(1720)$	$3/2^+$	****
$N(1860)$	$5/2^+$	**
$N(1875)$	$3/2^-$	***
$N(1880)$	$1/2^+$	***
$N(1895)$	$1/2^-$	****
$N(1900)$	$3/2^+$	****
$N(1990)$	$7/2^+$	**
$N(2000)$	$5/2^+$	**
$N(2040)$	$3/2^+$	*
$N(2060)$	$5/2^-$	***
$N(2100)$	$1/2^+$	***
$N(2120)$	$3/2^-$	***
$N(2190)$	$7/2^-$	****
$N(2220)$	$9/2^+$	****
$N(2250)$	$9/2^-$	****
$N(2300)$	$1/2^+$	**
$N(2570)$	$5/2^-$	**
$N(2600)$	$11/2^-$	***
$N(2700)$	$13/2^+$	**

$\Delta(1232)$	$3/2^+$	****
$\Delta(1600)$	$3/2^+$	****
$\Delta(1620)$	$1/2^-$	****
$\Delta(1700)$	$3/2^-$	****
$\Delta(1750)$	$1/2^+$	*
$\Delta(1900)$	$1/2^-$	***
$\Delta(1905)$	$5/2^+$	****
$\Delta(1910)$	$1/2^+$	****
$\Delta(1920)$	$3/2^+$	***
$\Delta(1930)$	$5/2^-$	***
$\Delta(1940)$	$3/2^-$	**
$\Delta(1950)$	$7/2^+$	****
$\Delta(2000)$	$5/2^+$	**
$\Delta(2150)$	$1/2^-$	*
$\Delta(2200)$	$7/2^-$	***
$\Delta(2300)$	$9/2^+$	**
$\Delta(2350)$	$5/2^-$	*
$\Delta(2390)$	$7/2^+$	*
$\Delta(2400)$	$9/2^-$	**
$\Delta(2420)$	$11/2^+$	****
$\Delta(2750)$	$13/2^-$	**
$\Delta(2950)$	$15/2^+$	**
Λ	$1/2^+$	****
$\Lambda(1380)$	$1/2^-$	**
$\Lambda(1405)$	$1/2^-$	****
$\Lambda(1520)$	$3/2^-$	****
$\Lambda(1600)$	$1/2^+$	****
$\Lambda(1670)$	$1/2^-$	****
$\Lambda(1690)$	$3/2^-$	****
$\Lambda(1710)$	$1/2^+$	*
$\Lambda(1800)$	$1/2^-$	***
$\Lambda(1810)$	$1/2^+$	***
$\Lambda(1820)$	$5/2^+$	****
$\Lambda(1830)$	$5/2^-$	****
$\Lambda(1890)$	$3/2^+$	****
$\Lambda(2000)$	$1/2^-$	*
$\Lambda(2050)$	$3/2^-$	*
$\Lambda(2070)$	$3/2^+$	*
$\Lambda(2080)$	$5/2^-$	*
$\Lambda(2085)$	$7/2^+$	**
$\Lambda(2100)$	$7/2^-$	****
$\Lambda(2110)$	$5/2^+$	***
$\Lambda(2325)$	$3/2^-$	*
$\Lambda(2350)$	$9/2^+$	***
$\Lambda(2585)$		*

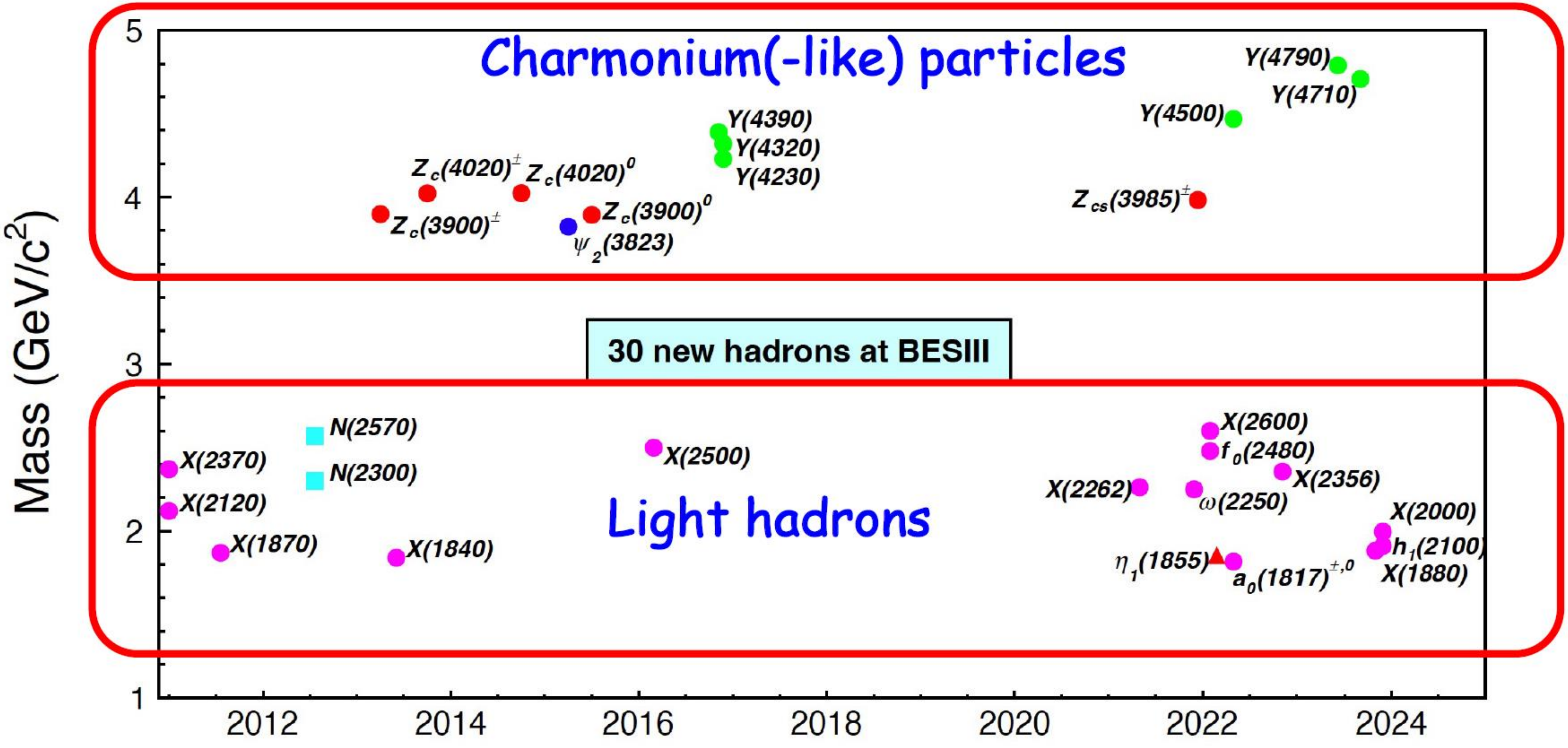
Σ^+	$1/2^+$	****
Σ^0	$1/2^+$	****
Σ^-	$1/2^+$	****
$\Sigma(1385)$	$3/2^+$	****
$\Sigma(1580)$	$3/2^-$	*
$\Sigma(1620)$	$1/2^-$	*
$\Sigma(1660)$	$1/2^+$	***
$\Sigma(1670)$	$3/2^-$	****
$\Sigma(1750)$	$1/2^-$	***
$\Sigma(1775)$	$5/2^-$	****
$\Sigma(1780)$	$3/2^+$	*
$\Sigma(1880)$	$1/2^+$	**
$\Sigma(1900)$	$1/2^-$	**
$\Sigma(1910)$	$3/2^-$	***
$\Sigma(1915)$	$5/2^+$	****
$\Sigma(1940)$	$3/2^+$	*
$\Sigma(2010)$	$3/2^-$	*
$\Sigma(2030)$	$7/2^+$	****
$\Sigma(2070)$	$5/2^+$	*
$\Sigma(2080)$	$3/2^+$	*
$\Sigma(2100)$	$7/2^-$	*
$\Sigma(2110)$	$1/2^-$	*
$\Sigma(2230)$	$3/2^+$	*
$\Sigma(2250)$		**
$\Sigma(2455)$		*
$\Sigma(2620)$		*
$\Sigma(3000)$		*
$\Sigma(3170)$		*
Ξ^0	$1/2^+$	****
Ξ^-	$1/2^+$	****
$\Xi(1530)$	$3/2^+$	****
$\Xi(1620)$		*
$\Xi(1690)$		***
$\Xi(1820)$	$3/2^-$	***
$\Xi(1950)$		***
$\Xi(2030)$	$\geq \frac{5}{2}?$	***
$\Xi(2120)$		*
$\Xi(2250)$		**
$\Xi(2370)$		**
$\Xi(2500)$		*
Ω^-	$3/2^+$	****
$\Omega(2012)^-$	$?^-$	***
$\Omega(2250)^-$		***
$\Omega(2380)^-$		**
$\Omega(2470)^-$		**

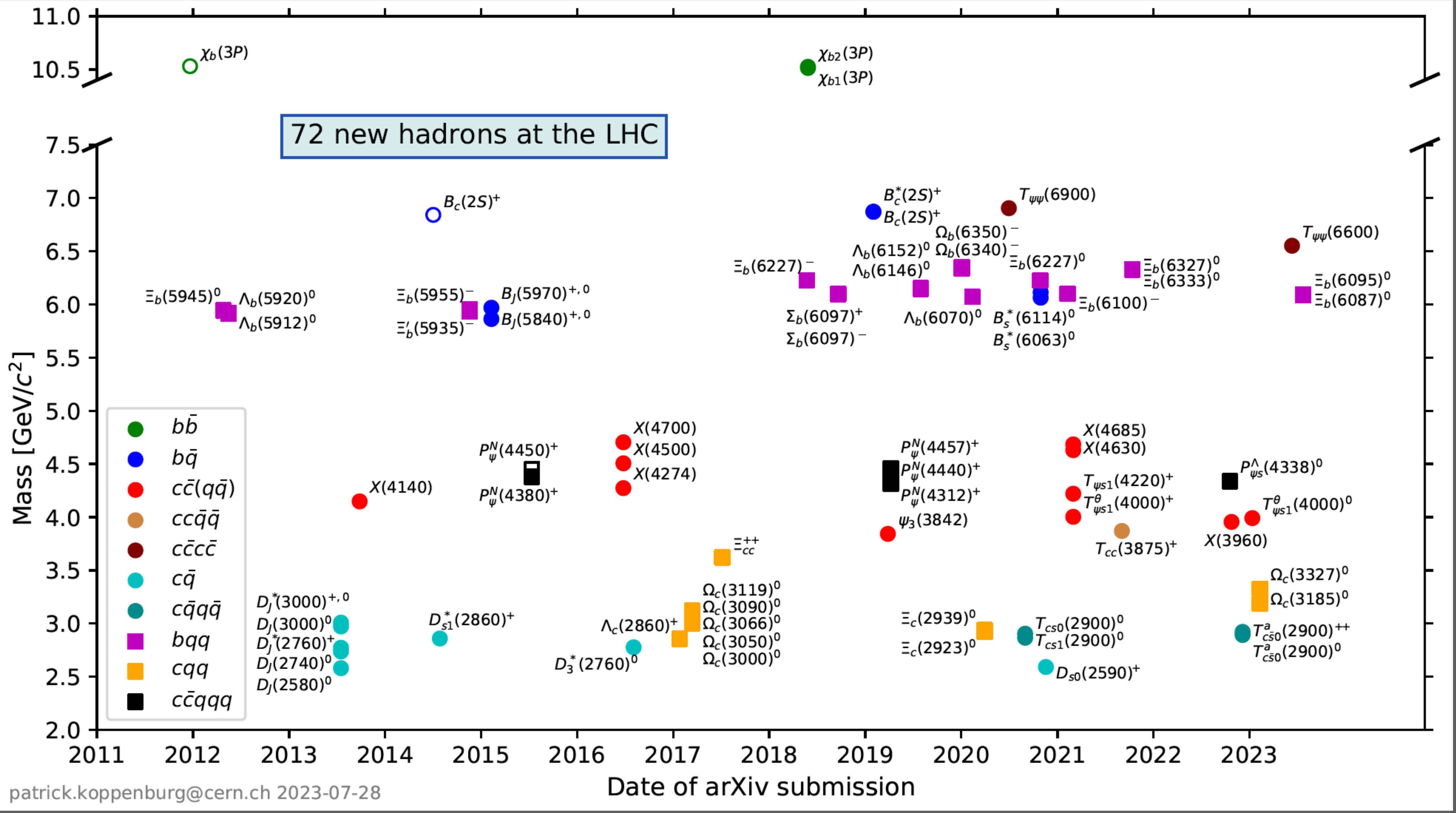
Λ_c^+	$1/2^+$	****
$\Lambda_c(2595)^+$	$1/2^-$	***
$\Lambda_c(2625)^+$	$3/2^-$	***
$\Lambda_c(2765)^+$		*
$\Lambda_c(2860)^+$	$3/2^+$	***
$\Lambda_c(2880)^+$	$5/2^+$	***
$\Lambda_c(2940)^+$	$3/2^-$	***
$\Sigma_c(2455)$	$1/2^+$	****
$\Sigma_c(2520)$	$3/2^+$	***
$\Sigma_c(2800)$		***
Ξ_c^+	$1/2^+$	***
Ξ_c^0	$1/2^+$	****
$\Xi_c'^+$	$1/2^+$	***
$\Xi_c'^0$	$1/2^+$	***
$\Xi_c(2645)$	$3/2^+$	***
$\Xi_c(2790)$	$1/2^-$	***
$\Xi_c(2815)$	$3/2^-$	***
$\Xi_c(2923)$		**
$\Xi_c(2930)$		**
$\Xi_c(2970)$	$1/2^+$	***
$\Xi_c(3055)$		***
$\Xi_c(3080)$		***
$\Xi_c(3123)$		*
Ω_c^0	$1/2^+$	***
$\Omega_c(2770)^0$	$3/2^+$	***
$\Omega_c(3000)^0$		***
$\Omega_c(3050)^0$		***
$\Omega_c(3065)^0$		***
$\Omega_c(3090)^0$		***
$\Omega_c(3120)^0$		***
Ξ_{cc}^+		*
Ξ_{cc}^{++}		***

Λ_b^0	$1/2^+$	***
$\Lambda_b(5912)^0$	$1/2^-$	***
$\Lambda_b(5920)^0$	$3/2^-$	***
$\Lambda_b(6070)^0$	$1/2^+$	***
$\Lambda_b(6146)^0$	$3/2^+$	***
$\Lambda_b(6152)^0$	$5/2^+$	***
Σ_b	$1/2^+$	***
Σ_b^*	$3/2^+$	***
$\Sigma_b(6097)^+$		***
$\Sigma_b(6097)^-$		***
Ξ_b^-	$1/2^+$	***
Ξ_b^0	$1/2^+$	***
$\Xi_b'(5935)^-$	$1/2^+$	***
$\Xi_b(5945)^0$	$3/2^+$	***
$\Xi_b(5955)^-$	$3/2^+$	***
$\Xi_b(6100)^-$	$3/2^-$	***
$\Xi_b(6227)^-$		***
$\Xi_b(6227)^0$		***
Ω_b^-	$1/2^+$	***
$\Omega_b(6316)^-$		*
$\Omega_b(6330)^-$		*
$\Omega_b(6340)^-$		*
$\Omega_b(6350)^-$		*
$P_c(4312)^+$		*
$P_c(4380)^+$		*
$P_c(4440)^+$		*
$P_c(4457)^+$		*

New resonant structures at BESIII

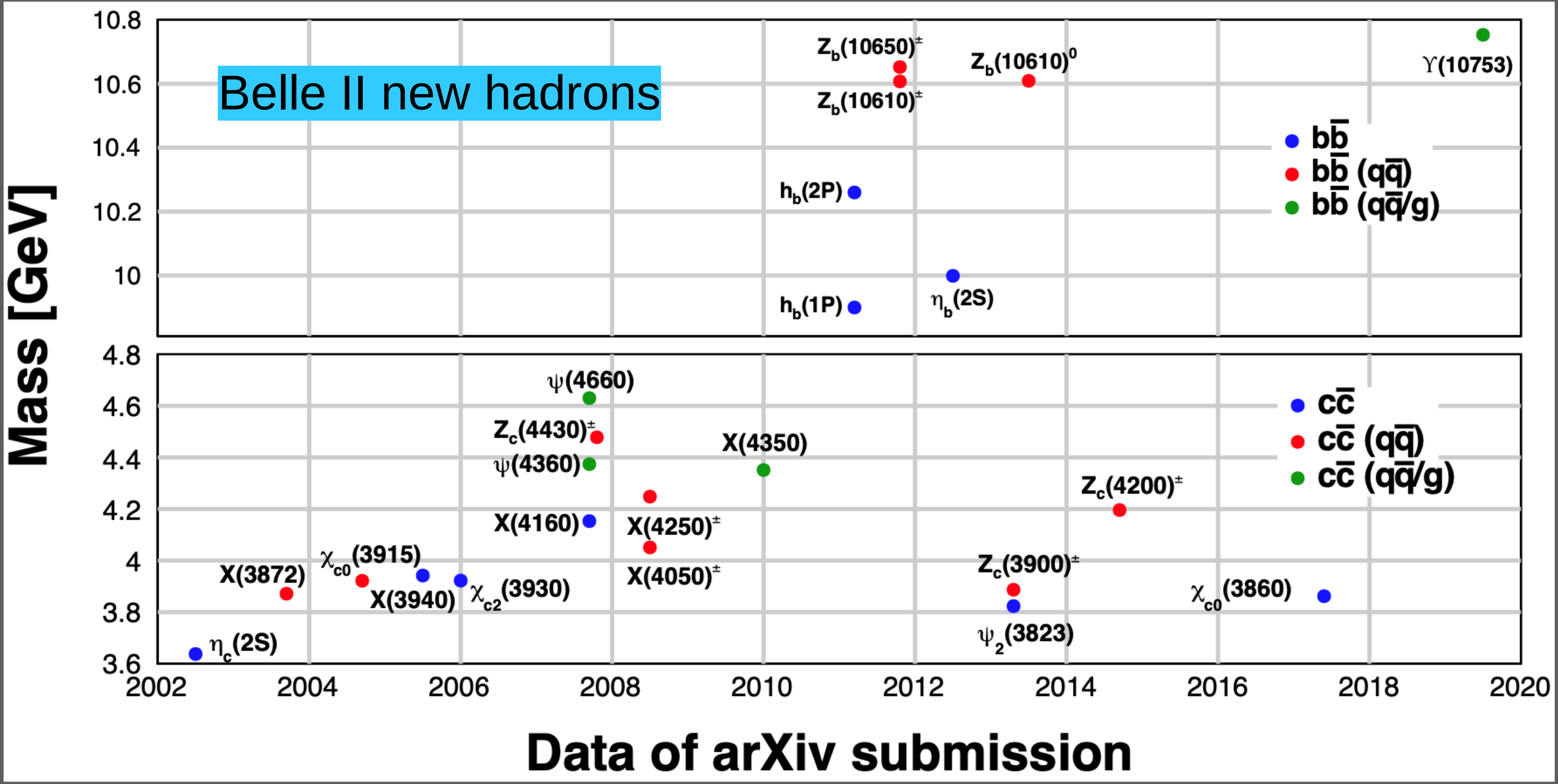
From Prof. Shuang-Shi Fang





72 new hadrons at the LHC
Mass [GeV/c^2]
Date of arXiv submission
2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023
2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5 10.5 11.0
$b\bar{b}$
$b\bar{q}$
$c\bar{c}(q\bar{q})$
$cc\bar{q}\bar{q}$
$c\bar{c}c\bar{c}$
$c\bar{q}$
$c\bar{q}q\bar{q}$
bqq
cqq
$c\bar{c}qqq$
$\chi_b(3P)$
$\chi_{b2}(3P)$
$\chi_{b1}(3P)$
$B_c(2S)^+$
$B_c^*(2S)^+$
$B_c(2S)^+$
$T_{\psi\psi}(6900)$
$T_{\psi\psi}(6600)$
$\Omega_b(6350)^-$
$\Omega_b(6340)^-$
$\Lambda_b(6152)^0$
$\Lambda_b(6146)^0$
$\Xi_b(6227)^-$
$\Xi_b(6227)^0$
$\Xi_b(6327)^0$
$\Xi_b(6333)^0$
$\Xi_b(6095)^0$
$\Xi_b(6087)^0$
$\Xi_b(5945)^0$
$\Lambda_b(5920)^0$
$\Lambda_b(5912)^0$
$\Xi_b(5955)^-$
$\Xi_b'(5935)^-$
$B_J(5970)^{+,0}$
$B_J(5840)^{+,0}$
$\Sigma_b(6097)^+$
$\Sigma_b(6097)^-$
$\Lambda_b(6070)^0$
$B_s^*(6114)^0$
$B_s^*(6063)^0$
$\Xi_b(6100)^-$
$X(4700)$
$X(4500)$
$X(4274)$
$X(4140)$
$P_\psi^N(4450)^+$
$P_\psi^N(4380)^+$
$P_\psi^N(4457)^+$
$P_\psi^N(4440)^+$
$P_\psi^N(4312)^+$
$\psi_3(3842)$
$X(4685)$
$X(4630)$
$T_{\psi s1}(4220)^+$
$T_{\psi s1}^\theta(4000)^+$
$T_{cc}(3875)^+$
$P_{\psi s}^\Lambda(4338)^0$
$T_{\psi s1}^\theta(4000)^0$
$X(3960)$
Ξ_{cc}^{++}
$\Omega_c(3119)^0$
$\Omega_c(3090)^0$
$\Omega_c(3066)^0$
$\Omega_c(3050)^0$
$\Omega_c(3000)^0$
$\Lambda_c(2860)^+$
$D_3^*(2760)^0$
$D_J^*(3000)^{+,0}$
$D_J(3000)^0$
$D_J^*(2760)^+$
$D_J(2740)^0$
$D_J(2580)^0$
$D_{s1}^*(2860)^+$
$\Xi_c(2939)^0$
$\Xi_c(2923)^0$
$T_{cs0}(2900)^0$
$T_{cs1}(2900)^0$
$D_{s0}(2590)^+$
$\Omega_c(3327)^0$
$\Omega_c(3185)^0$
$T_{c\bar{s}0}^a(2900)^{++}$
$T_{c\bar{s}0}^a(2900)^0$
patrick.koppenburg@cern.ch 2023-07-28

Belle II new hadrons



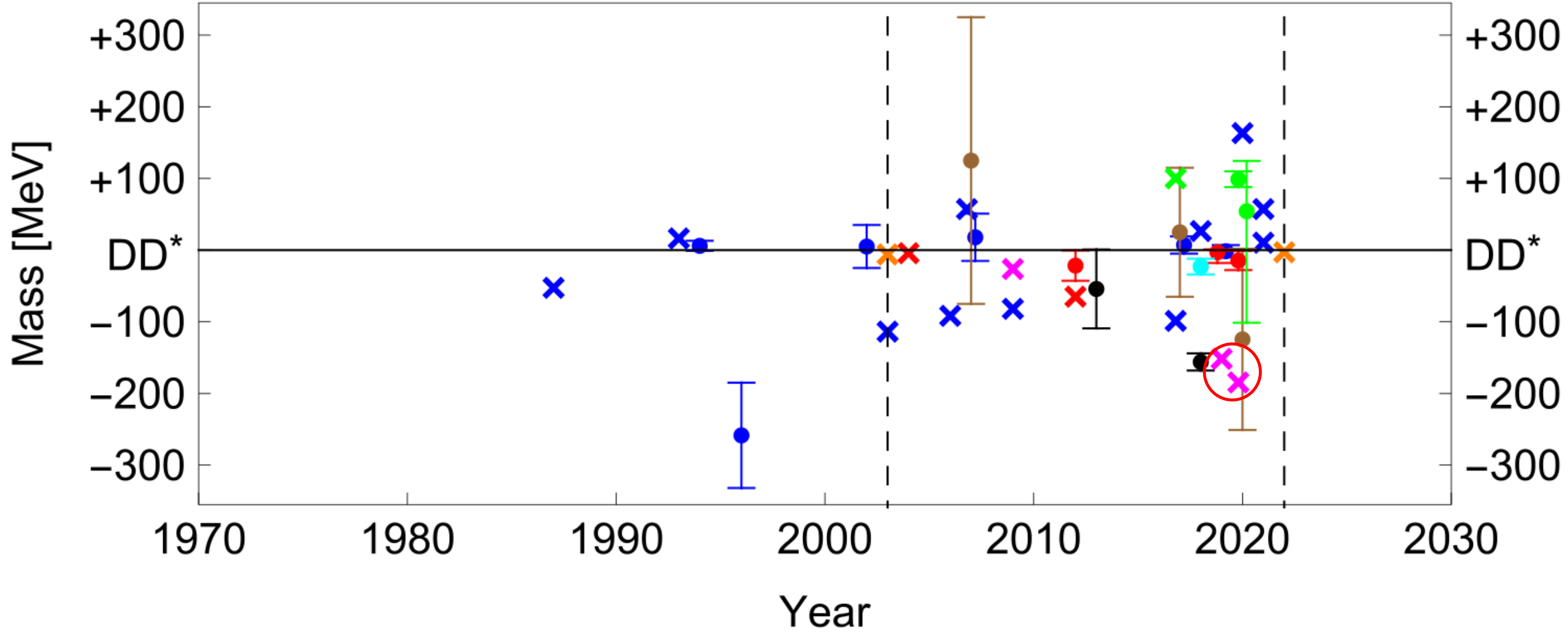


Figure 42. Theoretical predictions on the mass of the doubly charmed tetraquark state $cc\bar{u}\bar{d}$ with $(I)J^P = (0)1^+$, with uncertainties (error bars) and without uncertainties (crosses), calculated based on the compact tetraquark picture through various quark models [454, 500–515] (blue),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

- H. X. Chen, W. Chen, X. Liu, Y. R. Liu and S. L. Zhu, Rept. Prog. Phys. 86, no.2, 026201 (2023)

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

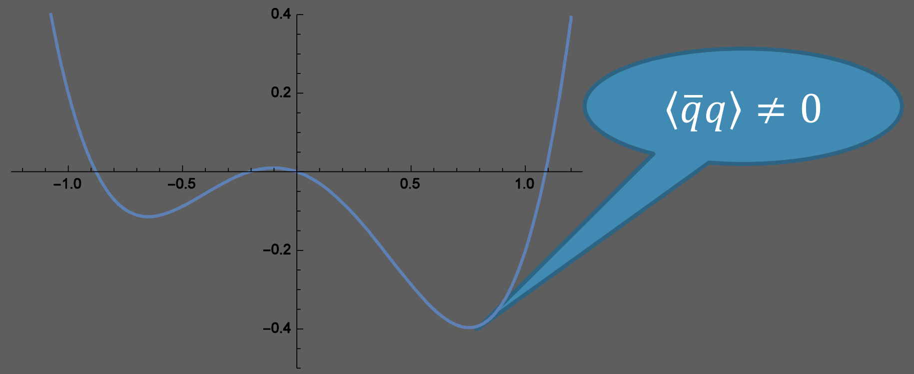
- Introduction
- ***Chiral quark model with HLS***
- $SU2$ ground states + excited states
- $SU3$ ground states
- Summary

The chiral symmetry

The chiral symmetry:

Spontaneously breaking of chiral symmetry:

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

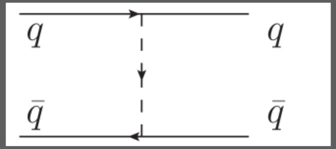


The effective theory based on chiral symmetry:

- Nonlinear sigma model
- Chiral perturbation theory

Chiral quark model

gluon exchange

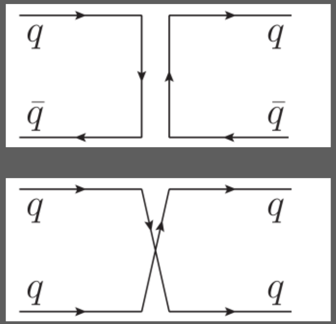


Naïve quark model:

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

- 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.

meson exchange



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

- 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:

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

$$U = \xi_L^\dagger \xi_R = e^{2i\frac{\pi(x)}{f_\pi}}$$

$$\xi_{L,R} \rightarrow h(x)\xi_{L,R} \cdot g_{L,R}^\dagger$$

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

$$\xi_{L,R} = e^{i\frac{V(x)}{f_V}} e^{\mp i\frac{\pi(x)}{f_\pi}}$$

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

- The transformation for U do not changes, which seems that the freedom of vector meson is "hidden"

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

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

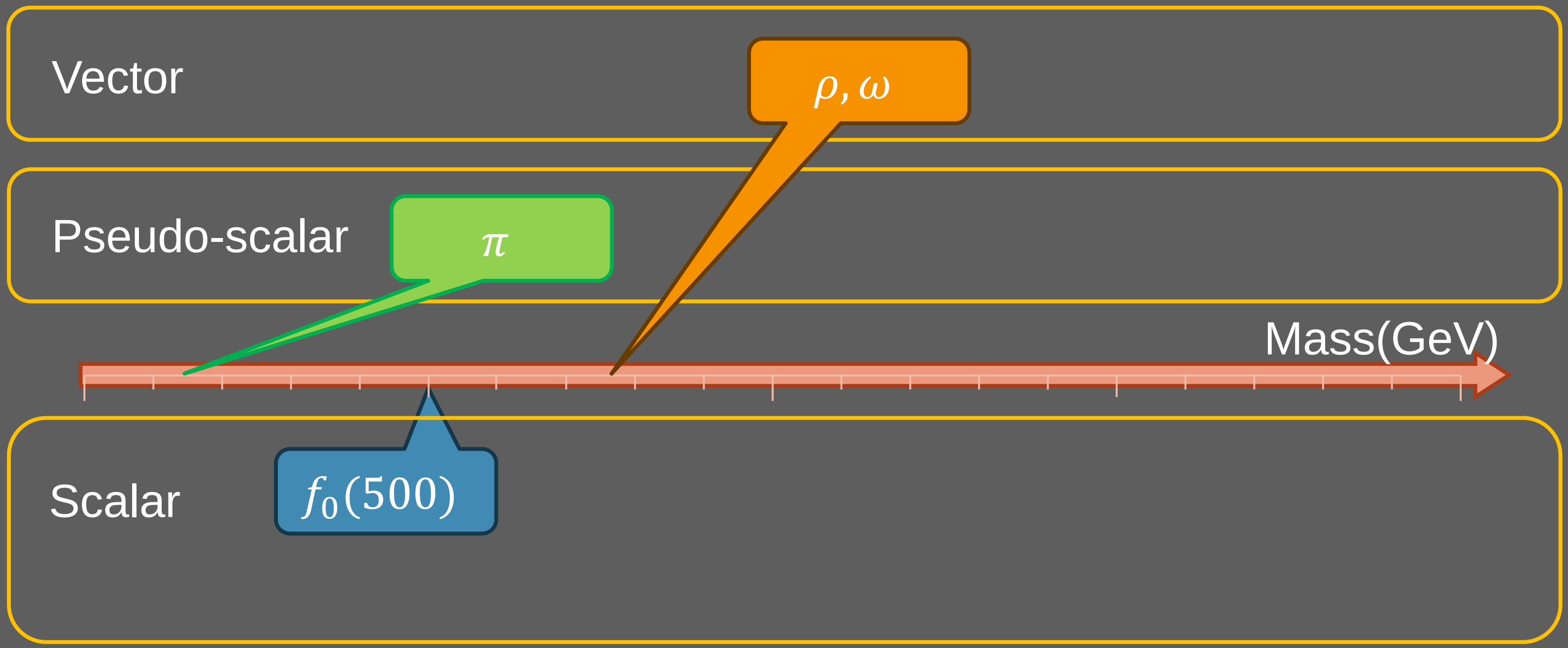
The Hamiltonian

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

Bing-Ran He, Masayasu Harada, Bing-Song Zou, 2306.03526

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

The exchanged mesons in $SU2$ model



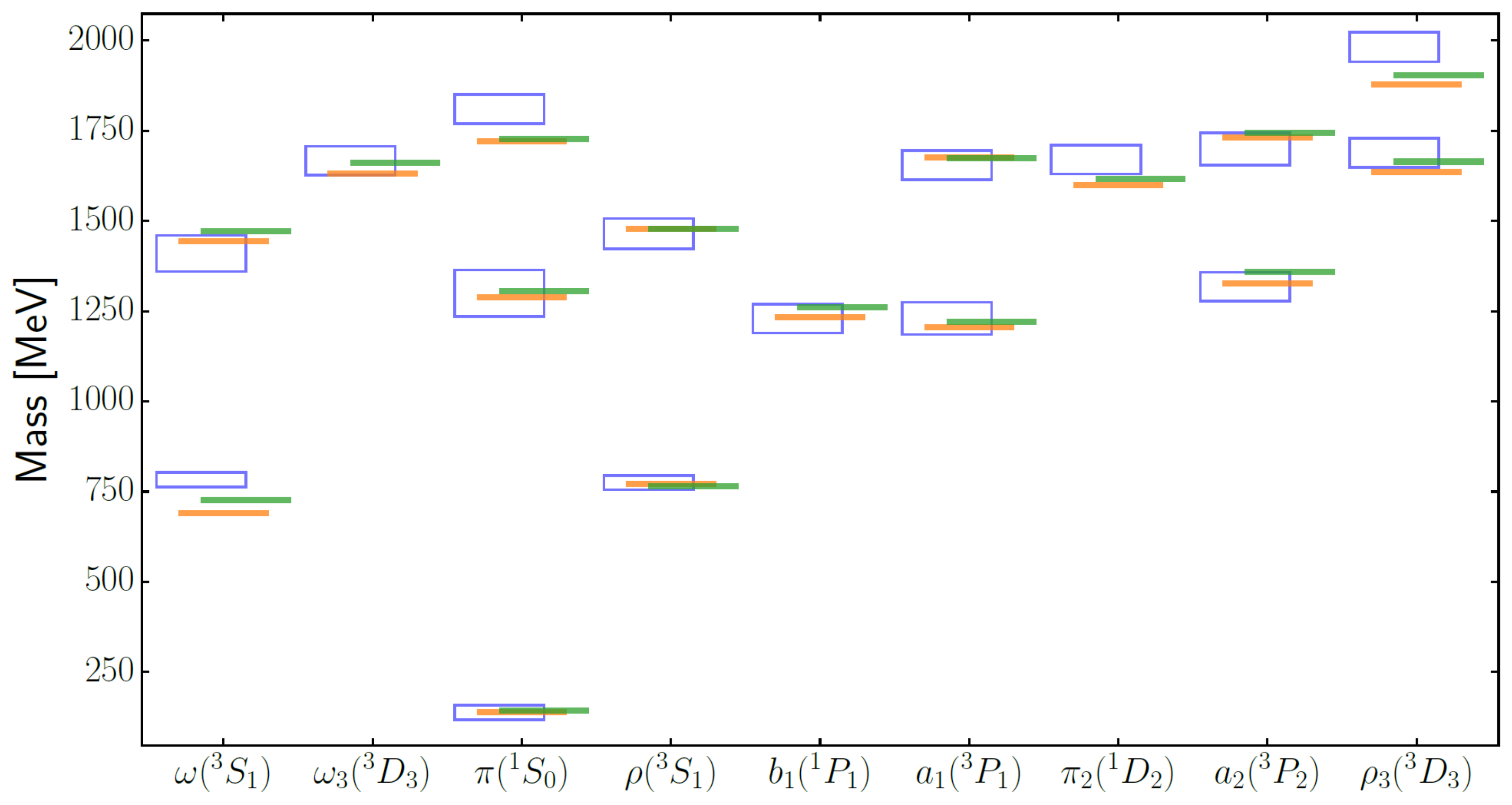
Symmetry of the model

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

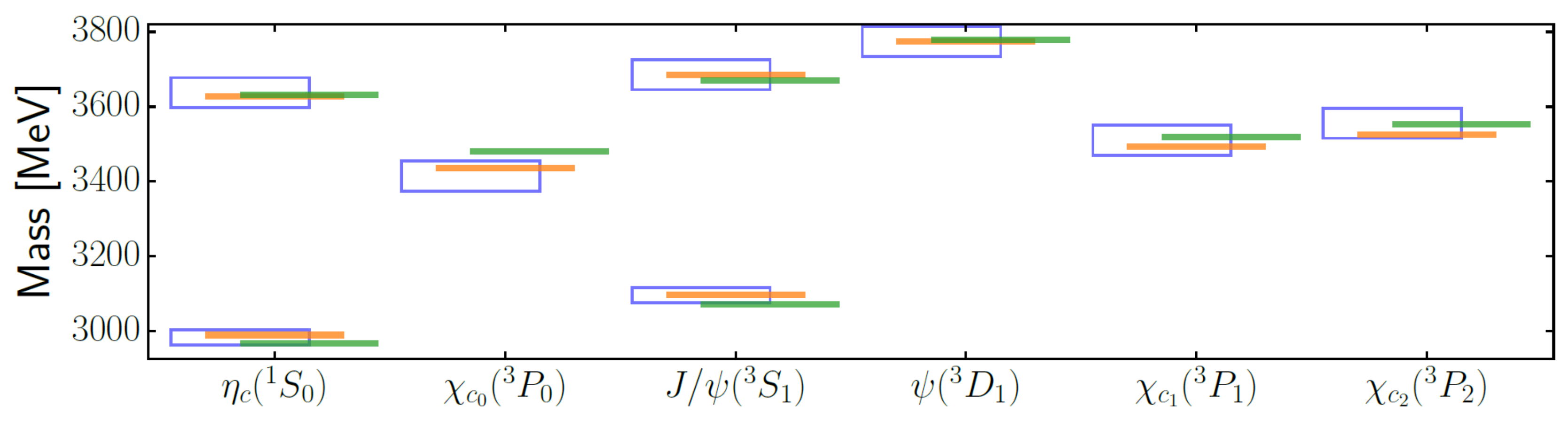
Wave functions

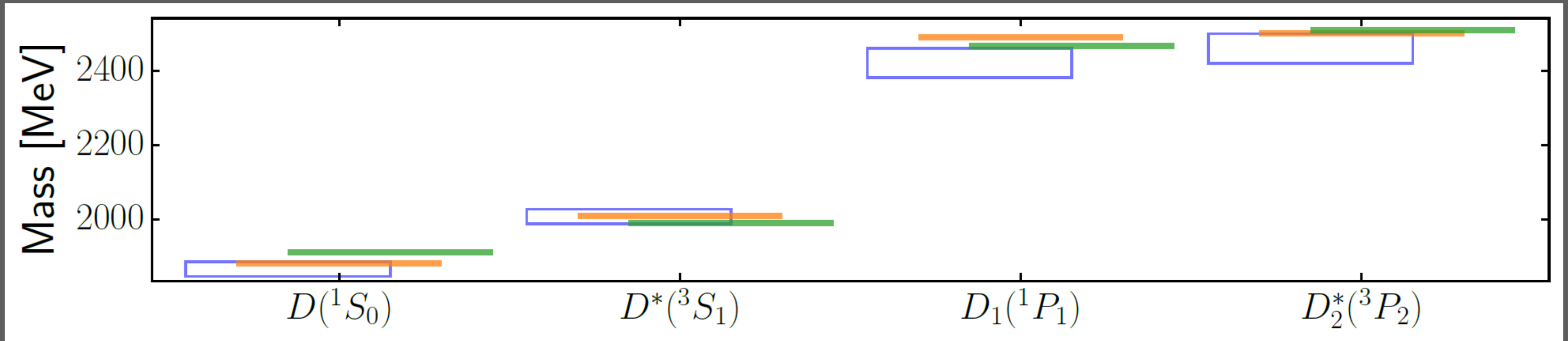
- Orbital (SO(3)): (ψ_L)
- Spin (SU(2)): (χ_S^σ)
- Flavor (SU(2)): (χ_I^f)
- Color (SU(3)): (χ^c)

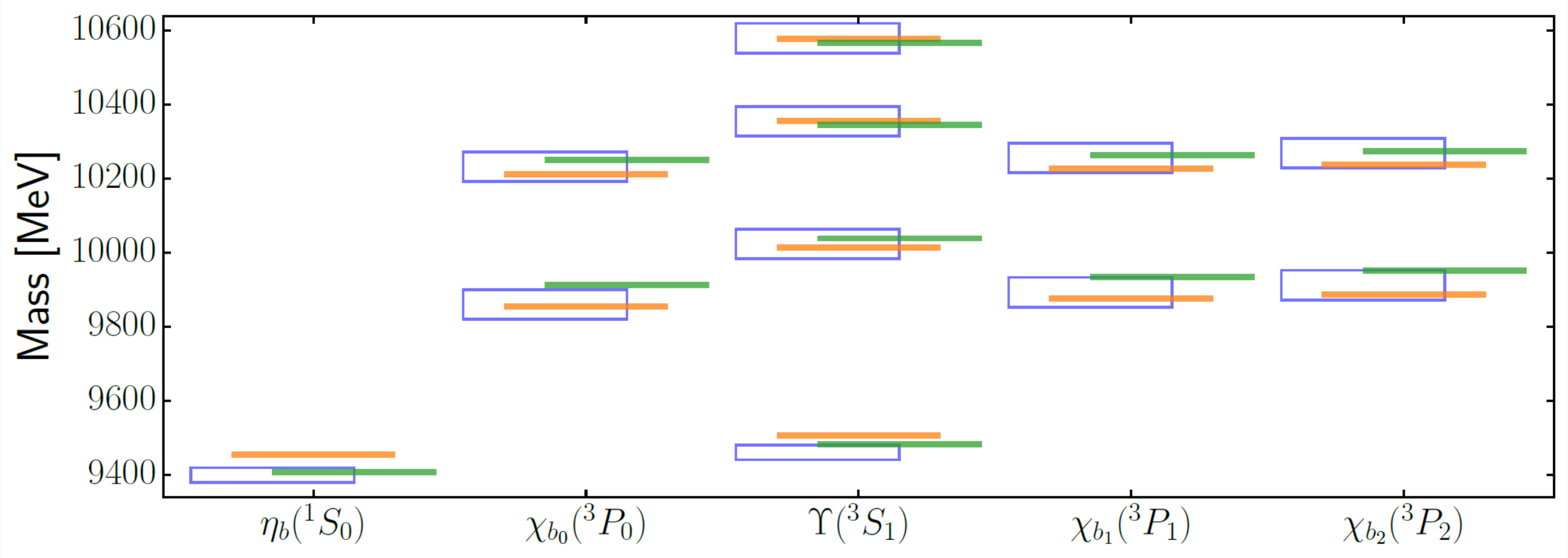
$$\Psi^{ijk}_{JM_J IM_I} = \mathcal{A}\left[\left[\psi_L \chi_S^{\sigma i}\right]_{JM_J} \chi_I^{fj} \chi_k^c \right]$$

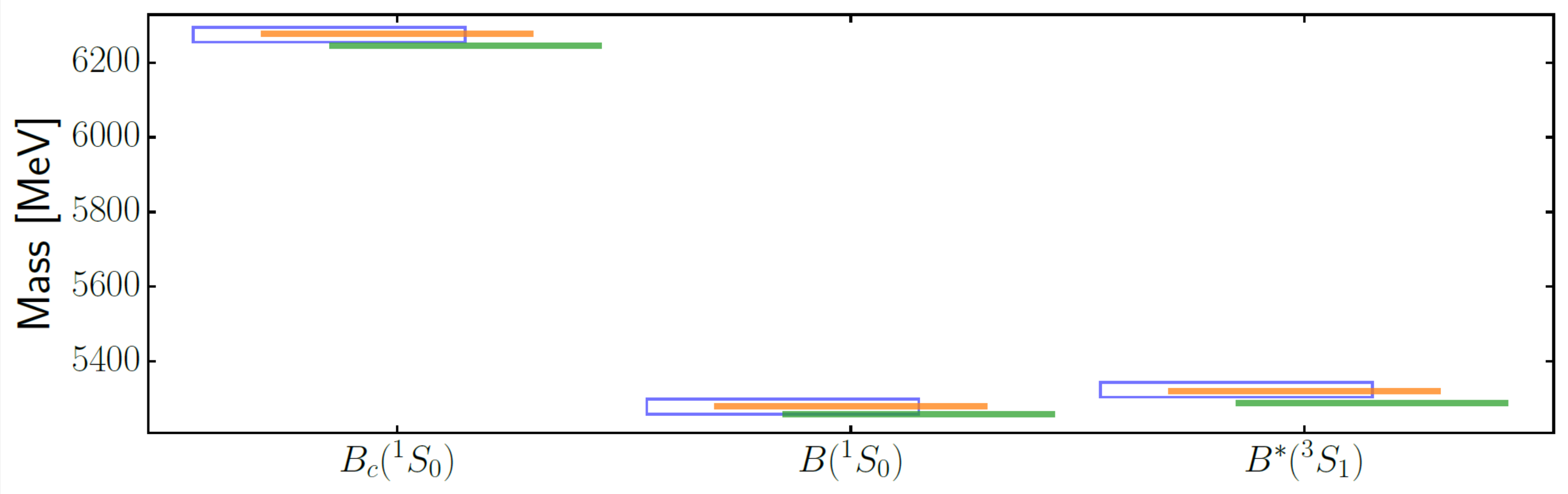


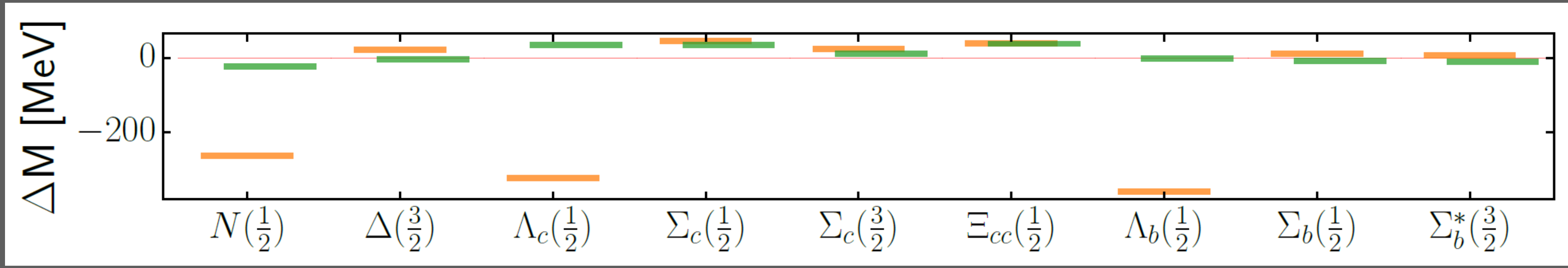
Mass [MeV]
2000
1750
1500
1250
1000
750
500
250
$\omega(^3S_1)$
$\omega_3(^3D_3)$
$\pi(^1S_0)$
$\rho(^3S_1)$
$b_1(^1P_1)$
$a_1(^3P_1)$
$\pi_2(^1D_2)$
$a_2(^3P_2)$
$\rho_3(^3D_3)$


Mass [MeV]
3800
3600
3400
3200
3000
$\eta_c(^1S_0)$
$\chi_{c_0}(^3P_0)$
$J/\psi(^3S_1)$
$\psi(^3D_1)$
$\chi_{c_1}(^3P_1)$
$\chi_{c_2}(^3P_2)$


Mass [MeV]
2400
2200
2000
$D(^1S_0)$
$D^*(^3S_1)$
$D_1(^1P_1)$
$D_2^*(^3P_2)$


Mass [MeV]
10600
10400
10200
10000
9800
9600
9400
$\eta_b(^1S_0)$
$\chi_{b_0}(^3P_0)$
$\Upsilon(^3S_1)$
$\chi_{b_1}(^3P_1)$
$\chi_{b_2}(^3P_2)$


Mass [MeV]
6200
6000
5800
5600
5400
$B_c(^1S_0)$
$B(^1S_0)$
$B^*(^3S_1)$



	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

Outline

- Introduction
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- ***$SU3$ ground states***
- Summary

The Hamiltonian

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

Bing-Ran He, Masayasu Harada, Bing-Song Zou, 2307.16280

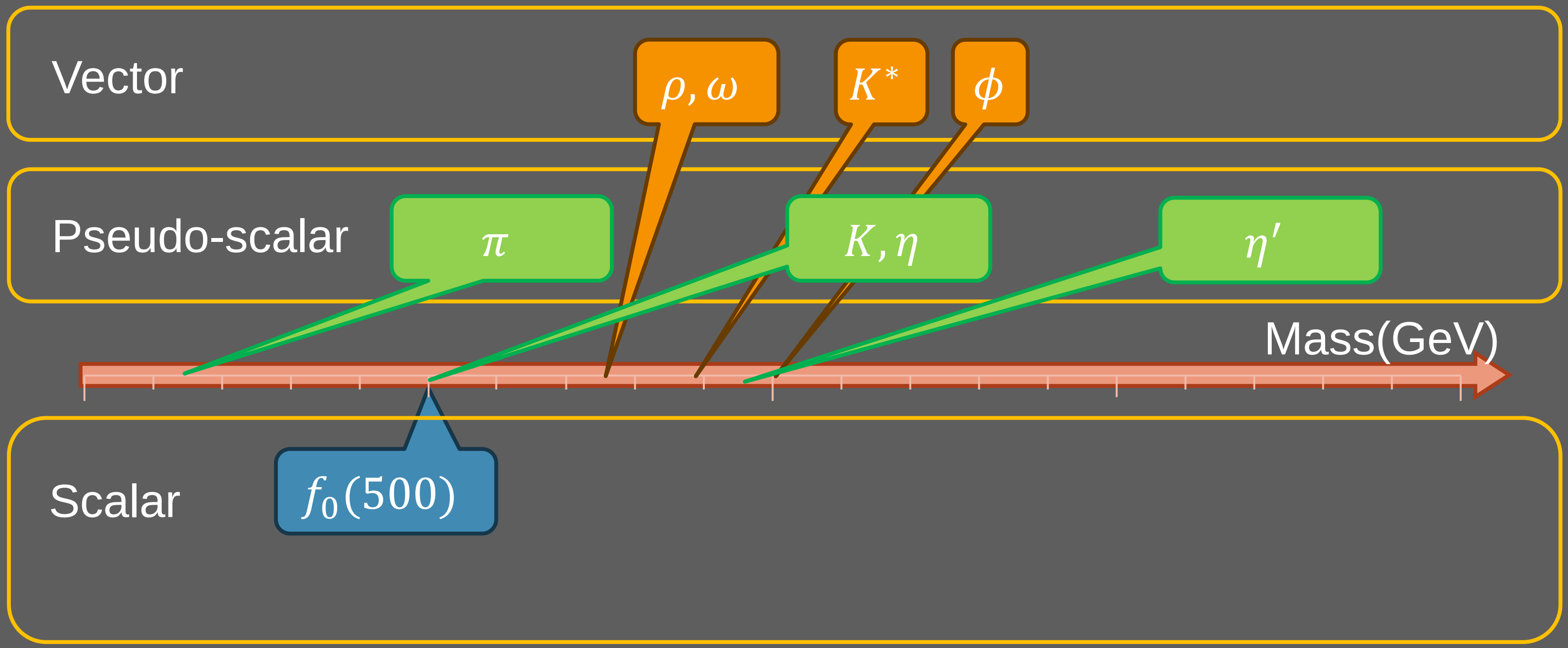
$$V_{ij}^{\bar\sigma}=V_{ij}^{s=\bar\sigma,g_s=g_{\bar\sigma q}}\lambda_i^q\lambda_j^q+V_{ij}^{s=\bar\sigma,g_s=g_{\bar\sigma s}}\lambda_i^s\lambda_j^s\,,$$
$$V_{ij}^{\eta}=V_{ij}^{p=\eta,g_p=g_{\eta q}}\lambda_i^q\lambda_j^q+V_{ij}^{p=\eta,g_p=g_{\eta s}}\lambda_i^s\lambda_j^s\,,$$
$$V_{ij}^{\eta'}=V_{ij}^{p=\eta',g_p=g_{\eta' q}}\lambda_i^q\lambda_j^q+V_{ij}^{p=\eta',g_p=g_{\eta' s}}\lambda_i^s\lambda_j^s\,,$$
$$V_{ij}^{\pi}=V_{ij}^{p=\pi,g_p=g_\pi}\sum_{a=1}^{3}\lambda_i^a\lambda_j^a\,,$$
$$V_{ij}^{K}=V_{ij}^{p=K,g_p=g_K}\sum_{a=4}^{7}\lambda_i^a\lambda_j^a\,,$$
$$V_{ij}^{\omega}=V_{ij}^{v=\omega,g_v=g_{\omega q}}\lambda_i^q\lambda_j^q+V_{ij}^{v=\omega,g_v=g_{\omega s}}\lambda_i^s\lambda_j^s\,,$$
$$V_{ij}^{\phi}=V_{ij}^{v=\phi,g_v=g_{\phi q}}\lambda_i^q\lambda_j^q+V_{ij}^{v=\phi,g_v=g_{\phi s}}\lambda_i^s\lambda_j^s\,,$$
$$V_{ij}^{\rho}=V_{ij}^{v=\rho,g_v=g_\rho}\sum_{a=1}^{3}\lambda_i^a\lambda_j^a\,,$$
$$V_{ij}^{K^*}=V_{ij}^{v=K^*,g_v=g_{K^*}}\sum_{a=4}^{7}\lambda_i^a\lambda_j^a$$

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

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

$$g_{\eta s}=g_{\eta q}-\sqrt{3}\cos\theta_p g_\pi$$
$$g_{\eta' q}=-\cot\theta_p g_{\eta q}+\frac{1}{\sqrt{3}\sin\theta_p}g_\pi$$
$$g_{\eta' s}=-\cot\theta_p g_{\eta q}+\frac{\cos\theta_p\cot\theta_p-2\sin\theta_p}{\sqrt{3}}g_\pi$$
$$g_\pi=g_K$$
$$g_{\omega s}=g_{\omega q}-g_\rho$$
$$g_{\phi q}=-\sqrt{\tfrac{1}{2}}(g_{\omega q}-g_\rho)$$
$$g_{\phi s}=-\sqrt{\tfrac{1}{2}}(g_{\omega q}+g_\rho)$$
$$g_\rho=g_{K^*}$$
$$f_{\omega s}=f_{\omega q}-f_\rho$$
$$f_{\phi q}=-\sqrt{\tfrac{1}{2}}(f_{\omega q}-f_\rho)$$
$$f_{\phi s}=-\sqrt{\tfrac{1}{2}}(f_{\omega q}+f_\rho)$$
$$f_\rho=f_{K^*}$$

The exchanged mesons in $SU3$ model



Symmetry of the model

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

Wave functions

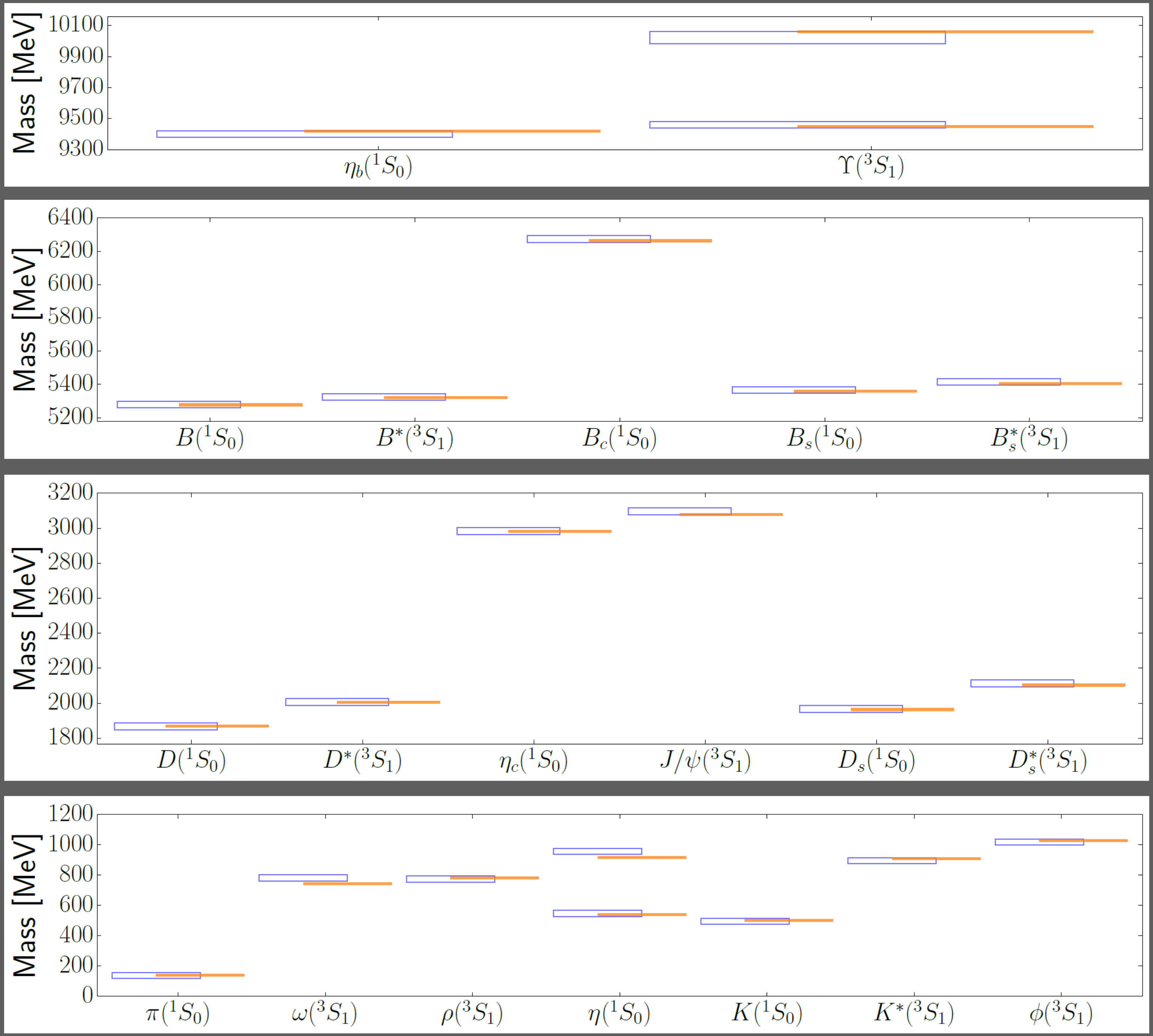
- Orbital (SO(3)): (ψ_L)
- Spin (SU(2)): (χ_S^σ)
- Flavor (SU(3)): (χ_I^f)
- Color (SU(3)): (χ^c)

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

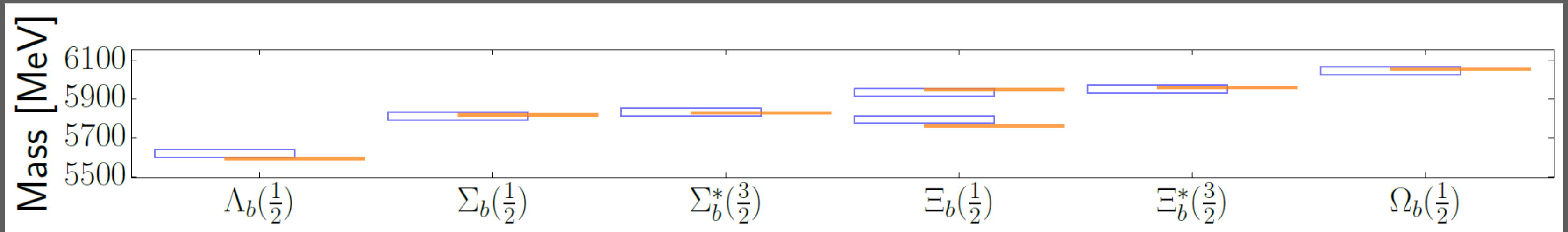
	1	$\lambda_i\lambda_j$	$\sigma_i\sigma_j$	$\sigma_i\sigma_j \cdot \lambda_i\lambda_j$
$\bar{\sigma}$	$-/-$			
η/η'			$+/+$	
π/K				$+/-$
ω/ϕ	$+/-$		$+/-$	
ρ/K^*		$+/+$		$+/+$
OGE	$-/-$		$+/+$	
CON	$+/+$			

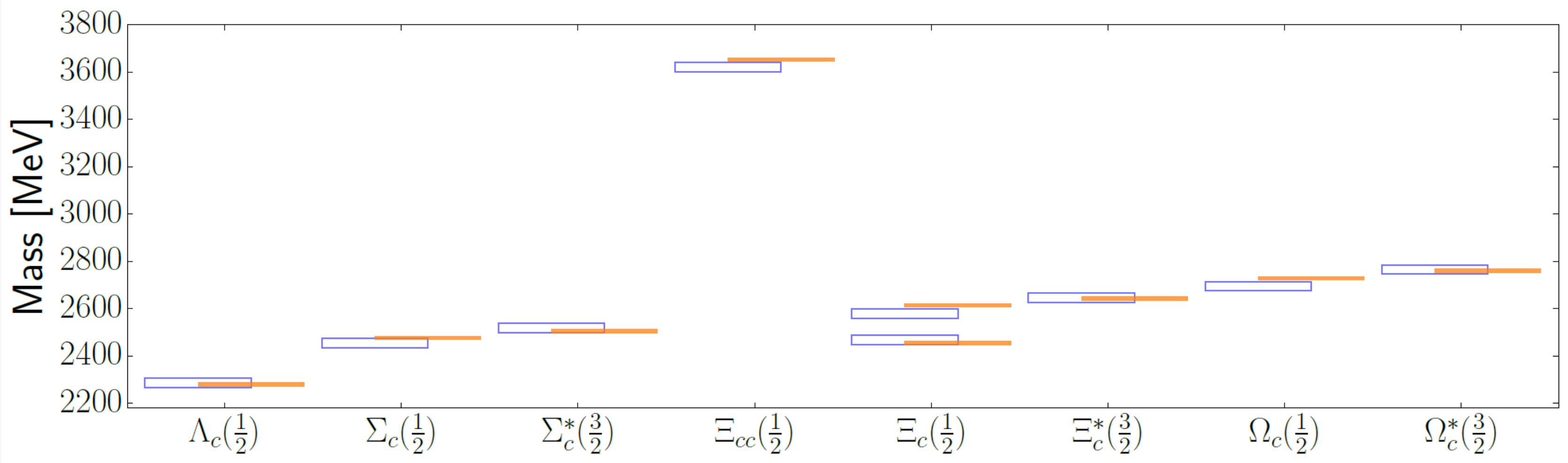
$qq/q\bar{q}$

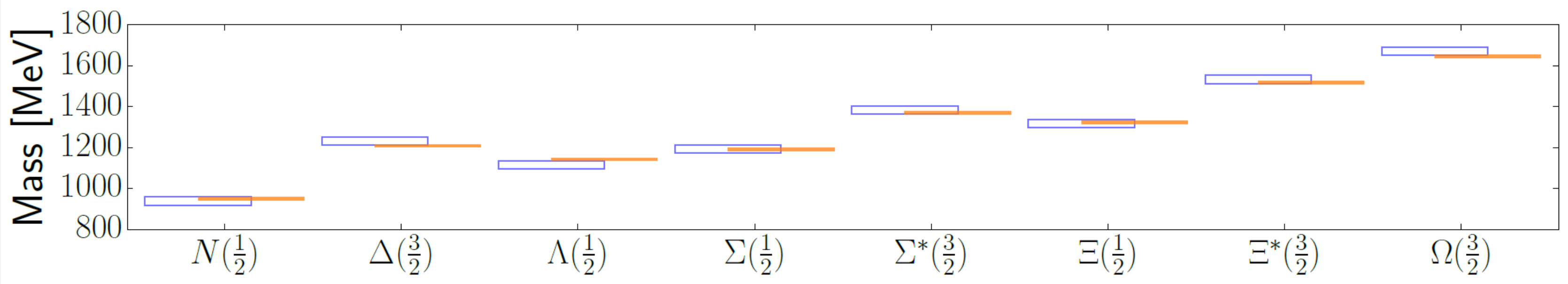
	No vector J. Phys. G 31, 481(2005)	$su2$ vector 2306.03526	$su3$ vector 2307.16280
$\alpha_s(qq)$	0.536	0.880	0.456
$\alpha_s(qs)$	0.479		0.426
$\alpha_s(qc)$	0.426	0.774	0.363
$\alpha_s(qb)$	0.409	0.749	0.339
$\alpha_s(ss)$	0.419		0.388
$\alpha_s(sc)$	0.360		0.308
$\alpha_s(sb)$	0.340		0.279
$\alpha_s(cc)$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



Mass [MeV]
10100
9900
9700
9500
9300
$\eta_b(^1S_0)$
$\Upsilon(^3S_1)$
Mass [MeV]
6400
6200
6000
5800
5600
5400
5200
$B(^1S_0)$
$B^*(^3S_1)$
$B_c(^1S_0)$
$B_s(^1S_0)$
$B_s^*(^3S_1)$
Mass [MeV]
3200
3000
2800
2600
2400
2200
2000
1800
$D(^1S_0)$
$D^*(^3S_1)$
$\eta_c(^1S_0)$
$J/\psi(^3S_1)$
$D_s(^1S_0)$
$D_s^*(^3S_1)$
Mass [MeV]
1200
1000
800
600
400
200
0
$\pi(^1S_0)$
$\omega(^3S_1)$
$\rho(^3S_1)$
$\eta(^1S_0)$
$K(^1S_0)$
$K^*(^3S_1)$
$\phi(^3S_1)$


Mass [MeV]
6100
5900
5700
5500
$\Lambda_b(\frac{1}{2})$
$\Sigma_b(\frac{1}{2})$
$\Sigma_b^*(\frac{3}{2})$
$\Xi_b(\frac{1}{2})$
$\Xi_b^*(\frac{3}{2})$
$\Omega_b(\frac{1}{2})$


Mass [MeV]
3800
3600
3400
3200
3000
2800
2600
2400
2200
$\Lambda_c(\frac{1}{2})$
$\Sigma_c(\frac{1}{2})$
$\Sigma_c^*(\frac{3}{2})$
$\Xi_{cc}(\frac{1}{2})$
$\Xi_c(\frac{1}{2})$
$\Xi_c^*(\frac{3}{2})$
$\Omega_c(\frac{1}{2})$
$\Omega_c^*(\frac{3}{2})$

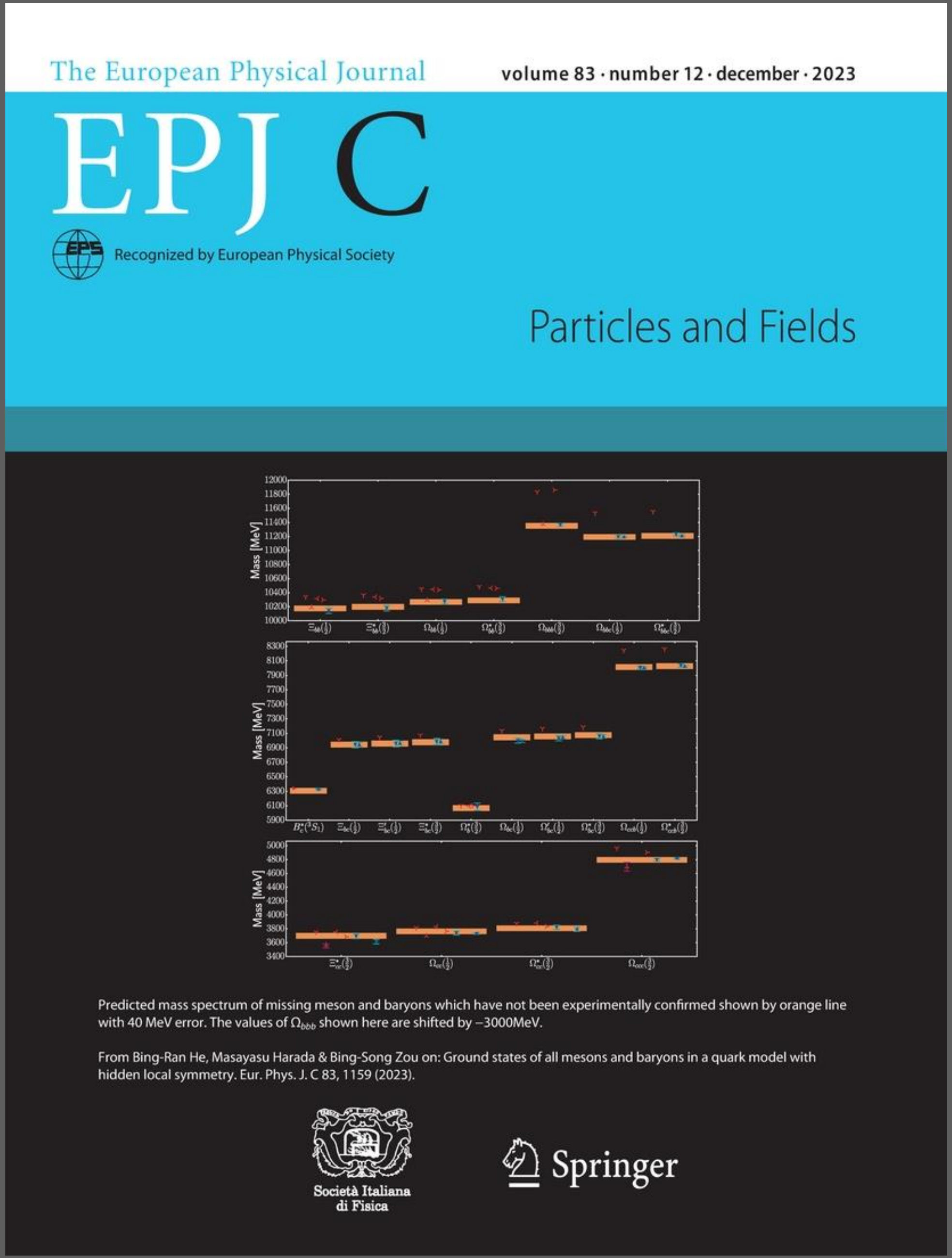

Mass [MeV]
1800
1600
1400
1200
1000
800
$N(\frac{1}{2})$
$\Delta(\frac{3}{2})$
$\Lambda(\frac{1}{2})$
$\Sigma(\frac{1}{2})$
$\Sigma^*(\frac{3}{2})$
$\Xi(\frac{1}{2})$
$\Xi^*(\frac{3}{2})$
$\Omega(\frac{3}{2})$

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)

$$\chi^2 = \sum_i \left(\frac{m_i(\mathrm{the}) - m_i(\mathrm{exp})}{\mathrm{Err_i(sys)}}\right)^2$$

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

Mass [MeV]
12000
11800
11600
11400
11200
11000
10800
10600
10400
10200
10000
$\Xi_{bb}(\frac{1}{2})$
$\Xi^*_{bb}(\frac{3}{2})$
$\Omega_{bb}(\frac{1}{2})$
$\Omega^*_{bb}(\frac{3}{2})$
$\Omega_{bbb}(\frac{3}{2})$
$\Omega_{bbc}(\frac{1}{2})$
$\Omega^*_{bbc}(\frac{3}{2})$
Mass [MeV]
8300
8100
7900
7700
7500
7300
7100
6900
6700
6500
6300
6100
5900
$B^*_c(^3S_1)$
$\Xi_{bc}(\frac{1}{2})$
$\Xi'_{bc}(\frac{1}{2})$
$\Xi^*_{bc}(\frac{3}{2})$
$\Omega^*_b(\frac{3}{2})$
$\Omega_{bc}(\frac{1}{2})$
$\Omega'_{bc}(\frac{1}{2})$
$\Omega^*_{bc}(\frac{3}{2})$
$\Omega_{ccb}(\frac{1}{2})$
$\Omega^*_{ccb}(\frac{3}{2})$
Mass [MeV]
5000
4800
4600
4400
4200
4000
3800
3600
3400
$\Xi^*_{cc}(\frac{3}{2})$
$\Omega_{cc}(\frac{1}{2})$
$\Omega^*_{cc}(\frac{3}{2})$
$\Omega_{ccc}(\frac{3}{2})$



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Particles and Fields
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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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!