Frontiers in Nuclear and Hadronic Physics 2025

The Galileo Galilei Institute
For Theoretical Physics
Centro Nazionale di Studi Avanzati dell'Istituto Nazionale di Fisica Nucleare
Arcetri, Firenze

Hadron Spectroscopy

Feb 24, 2025 - Feb 28, 2025

J. Nieves

IFIC
INSTITUT DE FÍSICA CORPUSCULAR

CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

VNIVERSITAT DE VALÈNCIA

EXCELENCIA SEVERO OCHOA

- Lowest lying odd parity resonances in the charm sector: $SU(6)_{lsf} \times$ HQSS model
  - ✓ $\Lambda_c(2595)$ and $\Lambda_c(2625)$
  - ✓ Ω_c (LHCb) and Ξ_c excited states
  - ✓ Extension to the bottom sector
- Lowest lying $\left(\frac{1}{2}\right)^-$ and $\left(\frac{3}{2}\right)^-$ Λ_Q resonances: from the strange to the bottom sectors
  - ✓ Interplay between chiral meson-baryon and CQM degrees of freedom and the role played by the renormalization scheme
  - ✓ Molecular content, HQSS and thresholds: $\Lambda_b(5912)$ /$\Lambda_c(5920)$, $\Lambda_c(2595)/\Lambda_c(2625)$ and $\Lambda(1405)/\Lambda(1520)$
  - ✓ Higher resonances: $\Lambda_b(6070)$ and $\Lambda_c(2765)$; molecules versus CQM 2S states

Lowest lying odd parity resonances in the charm sector: $\mathrm{SU(6)_{lsf}} \times \mathrm{HQSS}$ model

$\Lambda_c(2625)^+$ $\quad I(J^P) = 0(3/2^-)$

The spin-parity has not been measured but is expected to be $3/2^-$: this is presumably the charm counterpart of the strange $\Lambda(1520)$.

charm sector

$\Lambda_c(2625)^+$ MASS	2628.11 ± 0.19 MeV (S = 1.1)
$\Lambda_c(2625)^+ - \Lambda_c^+$ MASS DIFFERENCE	341.65 ± 0.13 MeV (S = 1.1)
$\Lambda_c(2625)^+$ WIDTH	< 0.97 MeV CL=90.0%

$\Lambda_c(2625)^+$ Decay Modes

$\Lambda_c^+\pi\pi$ and its submode $\Sigma(2455)\pi$ are the only strong decays allowed to an excited Λ_c^+ having this mass.

	Mode		*Fraction* (Γ_i/Γ)	*Scale Factor/ Conf. Level*
Γ_1	$\Lambda_c^+\pi^+\pi^-$		$\approx 67\%$	
Γ_2	$\Sigma_c(2455)^{++}\pi^-$		< 5	CL=90
Γ_3	$\Sigma_c(2455)^{0}\pi^+$		< 5	CL=90
Γ_4	$\Lambda_c^+\pi^+\pi^-$ 3-body		*large*	
Γ_5	$\Lambda_c^+\pi^0$	[1]	not seen	
Γ_6	$\Lambda_c^+\gamma$		not seen	

$\Lambda_c(2595)^+$ $\quad I(J^P) = 0(1/2^-)$

The $\Lambda_c^+\pi^+\pi^-$ mode is largely, and perhaps entirely, $\Sigma_c\pi$, which is just at threshold; since the Σ_c has $J^P = 1/2^+$, the J^P here is almost certainly $1/2^-$. This result is in accord with the theoretical expectation that this is the charm counterpart of the strange $\Lambda(1405)$.

$\Lambda_c(2595)^+$ MASS	2592.25 ± 0.28 MeV
$\Lambda_c(2595)^+ - \Lambda_c^+$ MASS DIFFERENCE	305.79 ± 0.24 MeV
$\Lambda_c(2595)^+$ WIDTH	2.6 ± 0.6 MeV

$\Lambda_c(2595)^+$ Decay Modes

$\Lambda_c^+\pi\pi$ and its submode $\Sigma_c(2455)\pi$ — the latter just barely — are the only strong decays allowed to an excited Λ_c^+ having this mass; and the submode seems to dominate.

	Mode		*Fraction* (Γ_i/Γ)	*Scale Factor/ Conf. Level*	*P(MeV/c)*
Γ_1	$\Lambda_c^+\pi^+\pi^-$	[1]			117
Γ_2	$\Sigma_c(2455)^{++}\pi^-$		$24 \pm 7\%$		3
Γ_3	$\Sigma_c(2455)^{0}\pi^+$		$24 \pm 7\%$		3
Γ_4	$\Lambda_c^+\pi^+\pi^-$ 3-body		$18 \pm 10\%$		117
Γ_5	$\Lambda_c^+\pi^0$	[2]	not seen		258
Γ_6	$\Lambda_c^+\gamma$		not seen		288

$\Lambda_b(5920)^0$

Quantum numbers are based on quark model expectations.

$I(J^P) = 0(3/2^-)$

$\Lambda_b(5920)^0$ MASS	5920.09 ± 0.17 MeV
$\Lambda_b(5920)^0$ WIDTH	< 0.19 MeV CL=90.0%

$\Lambda_b(5920)^0$ Decay Modes

	Mode	Fraction (Γ_i/Γ)	Scale Factor/ Conf. Level	P(MeV/c)
Γ_1	$\Lambda_b^0\pi^+\pi^-$	seen		108

bottom sector

$\Lambda_b(5912)^0$

Quantum numbers are based on quark model expectations.

$I(J^P) = 0(1/2^-)$

$\Lambda_b(5912)^0$ MASS	5912.19 ± 0.17 MeV
$\Lambda_b(5912)^0$ WIDTH	< 0.25 MeV CL=90.0%

$\Lambda_b(5912)^0$ Decay Modes

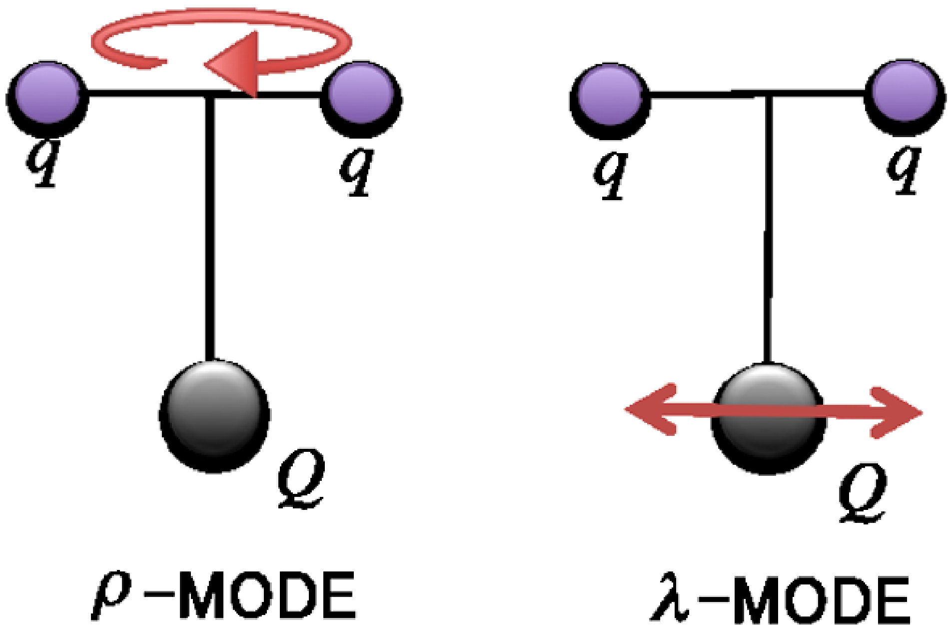
	Mode	Fraction (Γ_i/Γ)	Scale Factor/ Conf. Level	P(MeV/c)
Γ_1	$\Lambda_b^0\pi^+\pi^-$	seen		86

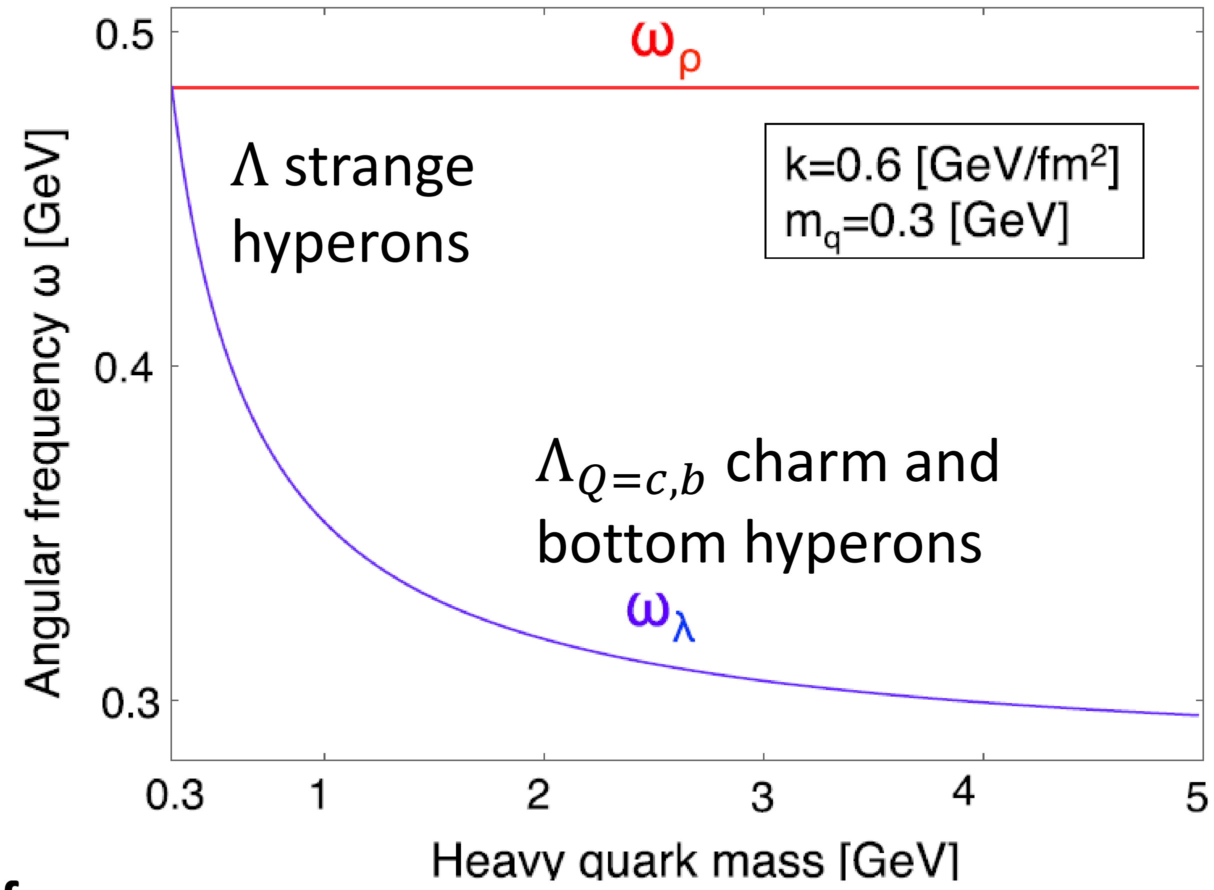
PHYSICAL REVIEW D **92**, 114029 (2015)

Spectrum of heavy baryons in the quark model

T. Yoshida,[1,*] E. Hiyama,[2,1,3] A. Hosaka,[4,3] M. Oka,[1,3] and K. Sadato[4,†]

Constituent Quark Model (CQM)





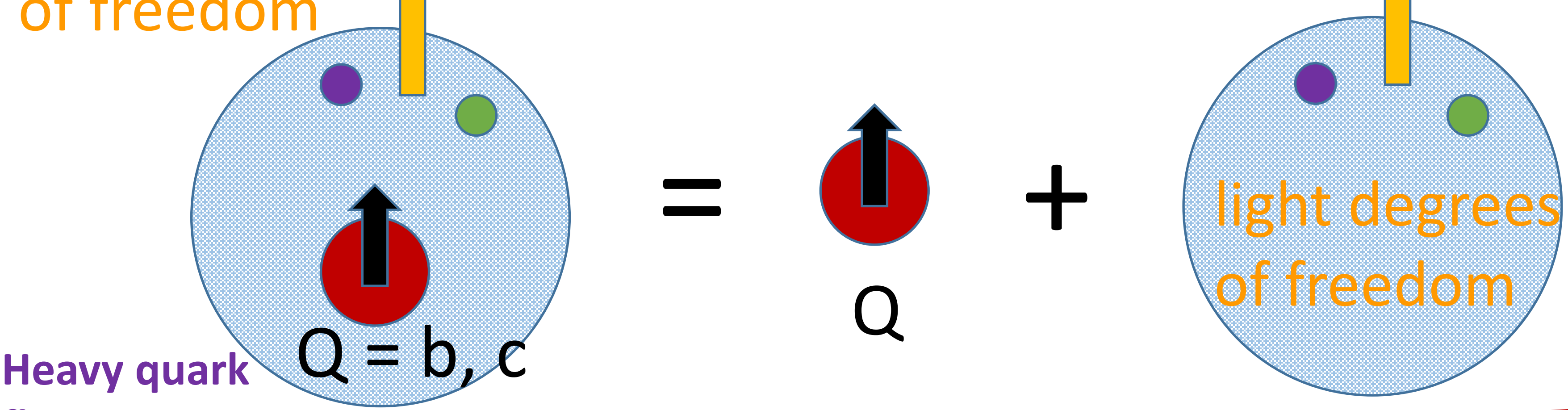
ρ- and λ-mode excitations of a **single-heavy baryon**

λ mode: excitations between the Q and the ldof

ρ mode.: excitations in the inner structure of the ldof

Heavy quark spin-flavor symmetry

The light degrees of freedom in the hadron orbit around the heavy quark, which acts as a source of color moving with the hadrons's velocity. On average, this is also the velocity of the "brown muck".



$$\vec{J} = \vec{S}_Q + \vec{J}_{ldof}$$

$\vec{J}^{\,2}_{ldof}$ is conserved!

HQSS

$SU(2N_h)$ symmetry in the $m_Q \to \infty$ limit

Heavy quark flavor symmetry HQFS

$$\mathcal{L}_{\rm eff} = \bar{h}_v i v \cdot D h_v + \frac{1}{2m_Q}\bar{h}_v (iD_\perp)^2 h_v + \frac{g_s}{4m_Q}\bar{h}_v \sigma_{\alpha\beta} G^{\alpha\beta} h_v + \mathcal{O}(1/m_Q^2)$$

$$D^\mu_{\alpha\beta} \equiv \delta_{\alpha\beta}\partial^\mu - i g_s T^a_{\alpha\beta} G^\mu_a$$

HQSS predicts that all types of spin interactions vanish for infinitely massive quarks: the dynamics is unchanged under arbitrary transformations in the spin of the heavy quark Q. The spin-dependent interactions are proportional to the chromomagnetic moment of the heavy quark, hence are of the order of $1/m_Q$.

The total angular momentum $\vec{j}_{ldof}$ of the brown muck, which is the subsystem of the hadron apart from the heavy quark, is conserved and hadrons with $J = j_{ldof} \pm 1/2$ form a degenerate doublet. For instance, $m_{\bar{B}^*}(J^P = 1^-) - m_{\bar{B}}(J^P = 0^-) = 45.22 \pm 0.21$ MeV $\sim \Lambda_{QCD}, m_d, m_u$ **doublet** for $j^P_{ldof} = 1/2^-$

S_Q

HQFS predicts that, besides de mass of the heavy quark, the single-heavy hadron mass is independent of the flavor of the heavy quark Q. The flavor-dependent interactions are proportional to $1/m_Q$, $\boldsymbol{M_H/m_Q \sim \left(1 + \frac{O(\Lambda_{QCD})}{M_Q}\right)}$

$$[m_{\bar{B}^*}(J^P = 1^-) - m_{\bar{B}}(J^P = 0^-)] \sim [m_{D^*}(J^P = 1^-) - m_D(J^P = 0^-)] \sim \Lambda_{QCD}, m_d, m_u$$

HQSFS $SU(2N_h)$ approximate symmetry seen in the hadron spectrum

PHYSICAL REVIEW D VOLUME 45, NUMBER 7 1 APRIL 1992

Chiral perturbation theory for hadrons containing a heavy quark

consistent with the $1/m_Q$ expansion: HMChPT

Mark B. Wise
California Institute of Technology, Pasadena, California 91125
(Received 10 January 1992)

An effective Lagrangian that describes the low-momentum interactions of mesons containing a heavy quark with the pseudo Goldstone bosons π, K, and η is constructed. It is invariant under both heavy-quark spin symmetry and chiral $SU(3)_L \times SU(3)_R$ symmetry. Implications for semileptonic B and D decays are discussed.

PACS number(s): 14.40.Jz, 11.30.Rd, 13.20.Fc, 13.20.Jf

hadron velocity

$$\mathcal{L} = -i\,\mathrm{Tr}\bar{H}_a v_\mu \partial^\mu H_a + \tfrac{1}{2} i\,\mathrm{Tr}\bar{H}_a H_b v^\mu (\xi^\dagger \partial_\mu \xi + \xi \partial_\mu \xi^\dagger)_{ba} + \tfrac{1}{2} ig\,\mathrm{Tr}\bar{H}_a H_b \gamma_\nu \gamma_5 (\xi^\dagger \partial^\nu \xi - \xi \partial^\nu \xi^\dagger)_{ba} + \cdots, \quad (12)$$

For instance, for heavy mesons: super-field including the $j^P_{ldof} = 1/2^-$ doublet

Goldstone bosons

$$H_a = \frac{1+\not{v}}{2}(P^*_{a\mu}\gamma^\mu - P_a \gamma_5)$$

1^- 0^-

HQSFS: ground states

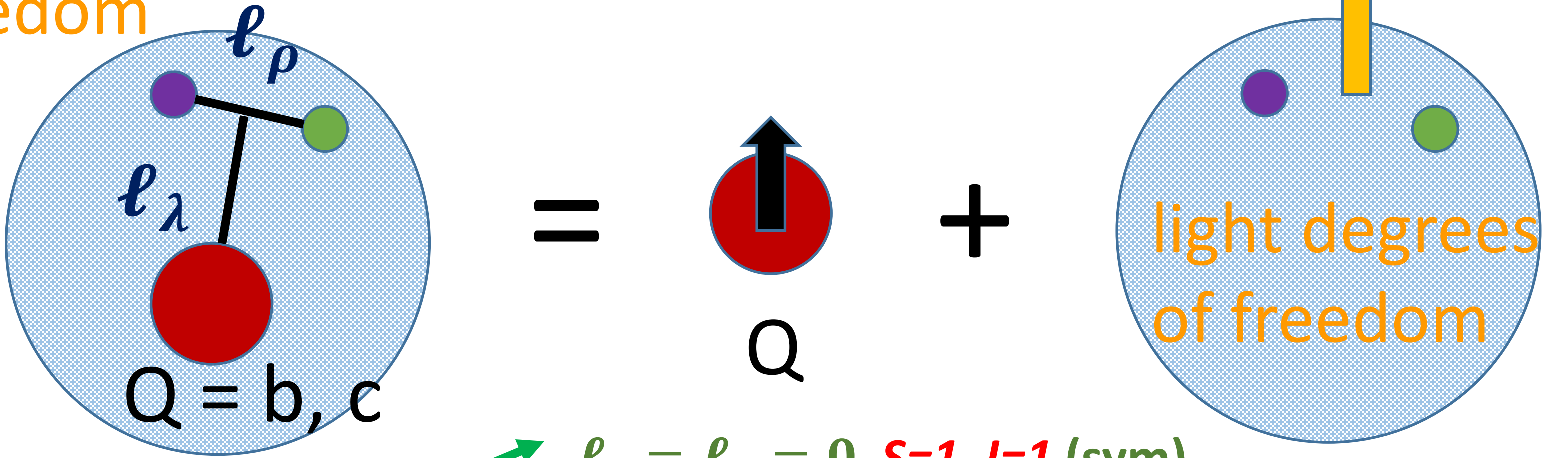
The light degrees of freedom in the hadron orbit around the heavy quark, which acts as a source of color moving with the hadrons's velocity. On average, this is also the velocity of the "brown muck".

$$\vec{J} = \vec{S}_Q + \vec{j}_{ldof}$$

$\vec{j}^{\,2}_{ldof}$ **is conserved!**

HQSS

light degrees of freedom



$SU(2N_h)$ symmetry in the $m_Q \to \infty$ limit

$\ell_\lambda = \ell_\rho = 0$, **S=0, I=0** (sym)

$\ell_\lambda = \ell_\rho = 0$, **S=1, I=1** (sym)

$$\underbrace{1/2^+}_{s_Q^P} \otimes \underbrace{1^+}_{j_{ldof}^P} = \underbrace{1/2^+}_{\Sigma_c(2455)}, \underbrace{3/2^+}_{\Sigma_c^*(2520)}$$

HQSS doublet

$$\underbrace{1/2^+}_{s_Q^P} \otimes \underbrace{0^+}_{j_{ldof}^P} = \underbrace{1/2^+}_{\Lambda_c(2286)}$$

HQSFS: odd parity excited states

CQM: T. Yoshida, E. Hiyama, A. Hosaka, M. Oka, and K. Sadato, PRD92 (2015) 114029

The light degrees of freedom in the hadron orbit around the heavy quark, which acts as a source of color moving with the hadrons's velocity. On average, this is also the velocity of the "brown muck".

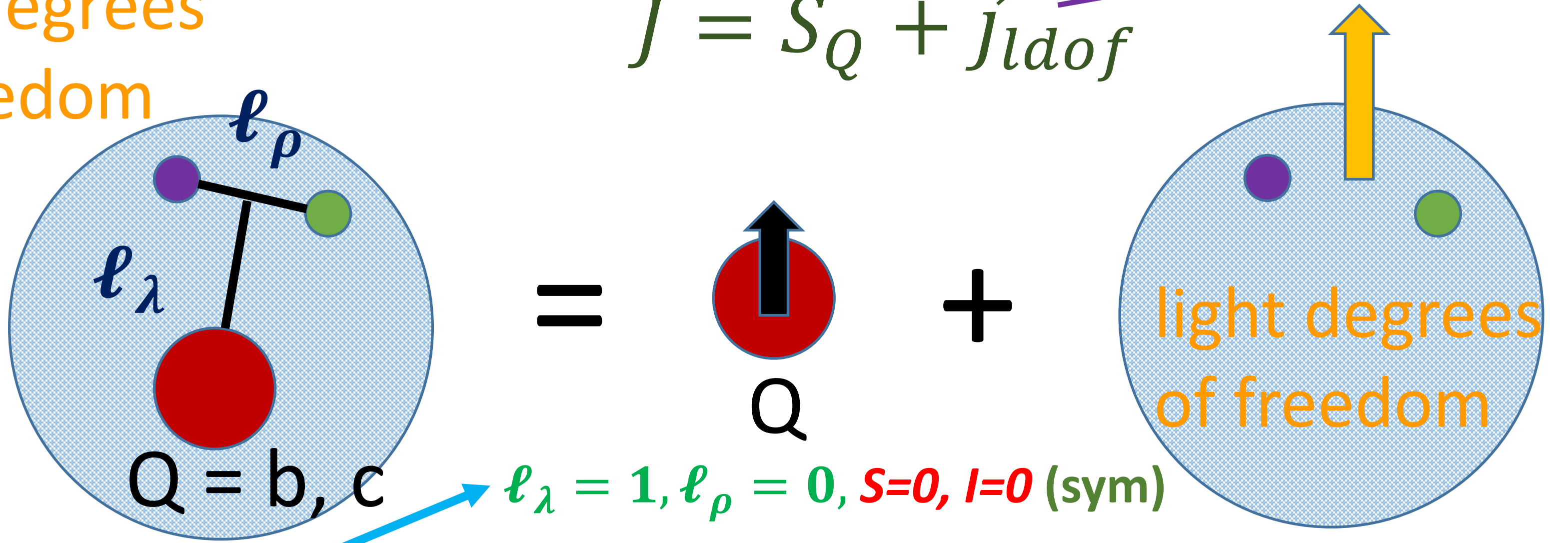
light degrees of freedom

$$\vec{J} = \vec{S}_Q + \vec{j}_{ldof}$$

$\vec{j}^{\,2}_{ldof}$ **is conserved!**

HQSS

$\boldsymbol{SU(2N_h)}$ **symmetry in the $\boldsymbol{m_Q \to \infty}$ limit**



$\ell_\lambda = 0, \ell_\rho = 1$, *S=1, I=0* (sym)

$\ell_\lambda = 1, \ell_\rho = 0$, *S=0, I=0* (sym)

$$\underbrace{1/2^+}_{S_Q^P} \otimes \underbrace{1^-}_{j^P_{ldof}} = \underbrace{1/2^-}_{\Lambda_c(2595)}, \underbrace{3/2^-}_{\Lambda_c(2625)}$$

CQM states

$$\underbrace{1/2^+}_{S_Q^P} \otimes \underbrace{0^-, 1^-, 2^-}_{j^P_{ldof}} = \underbrace{1/2^-, \ldots}_{\Lambda_c^*}$$

λ **−mode excitations**

ρ **−mode excitations**

HQSFS: odd parity excited states

chiral molecules

$$\underbrace{\Sigma_c^{(*)}\pi}_{ldof:\ 1^+ \otimes 0^- = 1^-} \Rightarrow J^P = 1/2^-, 3/2^-$$

NLO SU(3) ChPT: J.-X. Lu, Y. Zhou, H.-X. Chen, J.-J. Xie, and L.-S. Geng, PRD92 (2015) 014036

obtains the $\Lambda_c(2625)$ [$J^P = \frac{3}{2}^-$] using a **moderately large UV cutoff** $\sim$ 2.1 GeV

existence of some relevant degrees of freedom (CQM states and/or $ND^{(*)}$ components) that are not properly accounted for ?

F.-K. Guo, U.-G. Meissner, and B.-S. Zou, Commun. Theor. Phys. 65 (2016) 593
M. Albaladejo, JN, E. Oset, Z.-F. Sun, and X. Liu, PLB757 (2016) 515

- ✓ CQM degrees of freedom
- ✓ Analogy $\Lambda(1520)$, $\boldsymbol{\Lambda(1405)}$

$\Sigma^{(*)} \leftrightarrow \Sigma_c^{(*)}$, $\bar{K}^{(*)} \leftrightarrow D^{(*)}$

L. Tolos, J. Schaner-Bielich, and A. Mishra, PRC70 (2004) 025203 ; J. Hofmann and M. Lutz, NPA763 (2005) 90; 766 (2006) 7 ; T. Mizutani and A. Ramos, PRC74 (2006) 065201

HQSFS: odd parity excited states hadron molecules

$$\underbrace{\Sigma_c^{(*)}\pi}_{ldof:\ 1^+ \otimes 0^- = 1^-} \Rightarrow J^P = 1/2^-, 3/2^-$$

$$\underbrace{ND^{(*)}}_{ldof:\ 1/2^+ \otimes 1/2^- = 0^-, 1^-} \Rightarrow J^P = 1/2^-, 3/2^-$$

$\bar{\ell}$

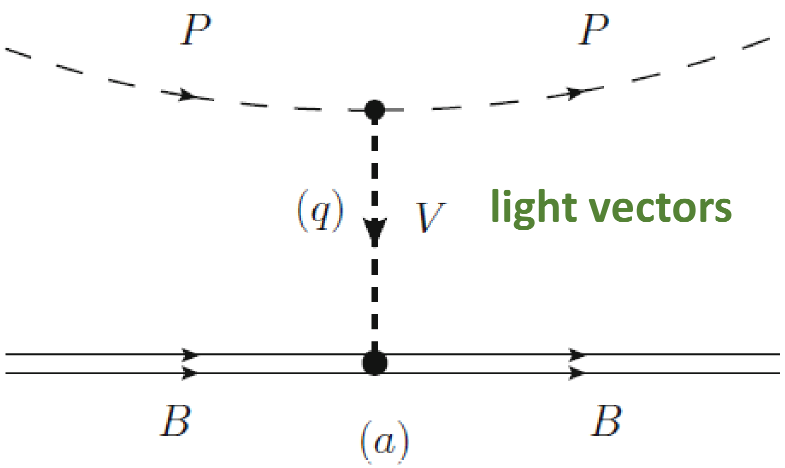
new configuration !

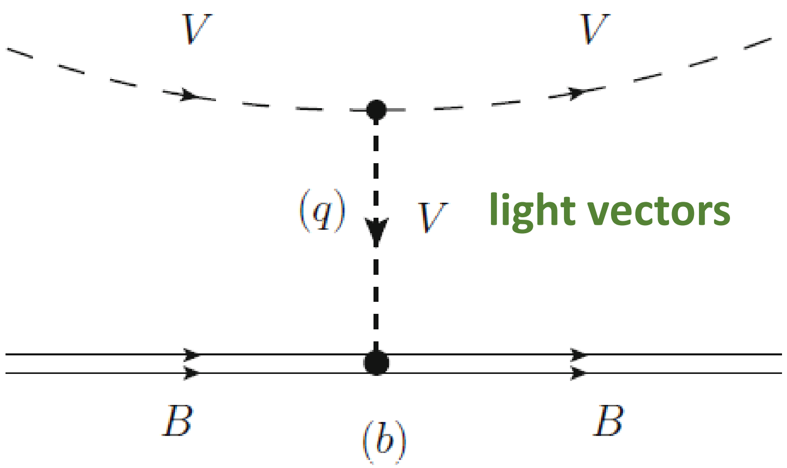
key issue: $ND^{(*)} \longrightarrow ND^{(*)}, \Sigma_c^{(*)}\pi$ coupled-channels interaction consistent with HQSS and its breaking pattern. In addition renormalization of BSE amplitudes & short distance (UV) physics

Σ_c and Σ_c^* or D and D^* are related by a charm quark spin rotation, which commutes with H_{QCD}, up to Λ_{QCD}/m_c corrections.

<u>LO HQSS does not fix</u> $ND^{(*)} \longrightarrow ND^{(*)}, \Sigma_c^{(*)}\pi$ coupled-channels interaction; There exist several models in the literature consistent with LO HQSS constraints. Moreover, <u>renormalization parameters can be fine tuned</u> to reproduce the position of the $\Lambda_c(2595)$ and $\Lambda_c(2625)$ resonances….

Extended local hidden gauge (ELHG) model W. Liang, T. Uchino, C. Xiao, E. Oset, EPJ A**51** (2015) 16





+

A different approach: $\mathrm{SU}(6)_{\mathrm{lsf}} \times \mathrm{SU}(2)_{\mathrm{HQSS}}$ extension of the Weinberg-Tomozawa $N\pi$ interaction

- ✓ $\boldsymbol{\pi}$ **–octet,** $\boldsymbol{\rho}$ **–nonet,** $\boldsymbol{D_{(s)}^{(*)}, \bar{D}_{(s)}^{(*)}}$
- ✓ $\boldsymbol{N}$ **–octet,** $\boldsymbol{\Delta}$ **–decuplet,** $\boldsymbol{\Lambda_c, \Sigma_c^{(*)}, \Xi_c^{(*,\prime)}, \Omega_c^{(*)}}$

light spin-flavor (mesons and baryons)

- ✓ consistent with HQSS and chiral symmetry
- ✓ dependence of renormalization scheme

- $C = 1$, C. Garcia-Recio, V.K. Magas, T. Mizutani, JN, A. Ramos, L.L. Salcedo, L. Tolos, PRD79 (2009), 054004; O. Romanets, L. Tolos, C. Garcia-Recio, JN, L.L. Salcedo and R.G.E. Timmermans, PRD85 (2012) 114032.
- $C = -1$, D. Gamermann, C. Garcia-Recio, JN, L.L. Salcedo and L. Tolos, PRD81 (2010) 094016.
- beauty $\Lambda_b(5912)$ and $\Lambda_b(5920)$, C. Garcia-Recio, JN, O. Romanets, L.L. Salcedo and L. Tolos, PRD 87 (2013) 034032.
- LHCb Ω_c^* states, JN, R. Pavao and L. Tolos, EPJC78 (2018) 114.
- Ξ_c^* and Ξ_b^* states, JN, R. Pavao and L. Tolos, EPJC80 (2020) 22.

CHARMED BARYONS ($C = +1$)

$\Lambda_c^+ = udc$, $\Sigma_c^{++} = uuc$, $\Sigma_c^+ = udc$, $\Sigma_c^0 = ddc$,
$\Xi_c^+ = usc$, $\Xi_c^0 = dsc$, $\Omega_c^0 = ssc$

See related review:
Charmed Baryons

Λ_c^+	$1/2^+$	****
$\Lambda_c(2595)^+$	$1/2^-$	***
$\Lambda_c(2625)^+$	$3/2^-$	***
$\Lambda_c(2765)^+$ or $\Sigma_c(2765)$		*
$\Lambda_c(2860)^+$	$3/2^+$	***
$\Lambda_c(2880)^+$	$5/2^+$	***
$\Lambda_c(2940)^+$	$3/2^-$	***
$\Sigma_c(2455)$	$1/2^+$	****
$\Sigma_c(2520)$	$3/2^+$	***
$\Sigma_c(2800)$		***
Ξ_c^+	$1/2^+$	***
Ξ_c^0	$1/2^+$	****
$\Xi_c'^+$	$1/2^+$	***
$\Xi_c'^0$	$1/2^+$	***
$\Xi_c(2645)$	$3/2^+$	***
$\Xi_c(2790)$	$1/2^-$	***
$\Xi_c(2815)$	$3/2^-$	***
$\Xi_c(2930)$		**
$\Xi_c(2970)$ was $\Xi_c(2980)$		***
$\Xi_c(3055)$		***
$\Xi_c(3080)$		***
$\Xi_c(3123)$		*
Ω_c^0	$1/2^+$	***
$\Omega_c(2770)^0$	$3/2^+$	***
$\Omega_c(3000)^0$		***
$\Omega_c(3050)^0$		***
$\Omega_c(3065)^0$		***
$\Omega_c(3090)^0$		***
$\Omega_c(3120)^0$		***

Belle

LHCb

**** Existence is certain, and properties are at least fairly explored.
*** Existence ranges from very likely to certain, but further confirmation is desirable and/or quantum numbers, branching fractions, etc. are not well determined.
** Evidence of existence is only fair.
* Evidence of existence is poor.

BOTTOM BARYONS ($B = -1$)

$\Lambda_b^0 = udb$, $\Xi_b^0 = usb$, $\Xi_b^- = dsb$, $\Omega_b^- = ssb$

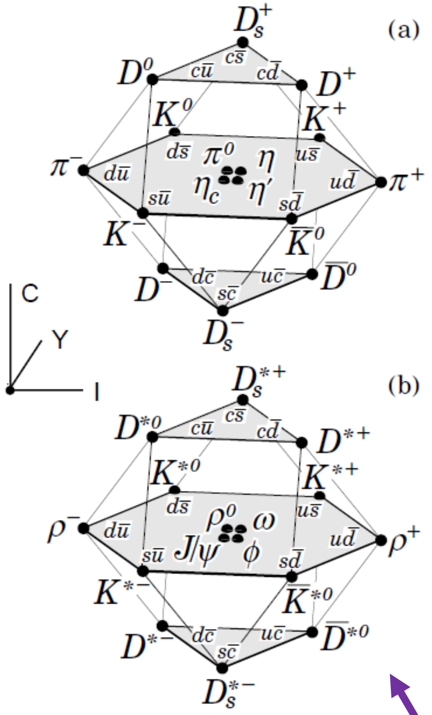
Λ_b^0	$1/2^+$	***
$\Lambda_b(5912)^0$	$1/2^-$	***
$\Lambda_b(5920)^0$	$3/2^-$	***
Σ_b	$1/2^+$	***
Σ_b^*	$3/2^+$	***
$\Sigma_b(6097)^+$		***
$\Sigma_b(6097)^-$		***
Ξ_b^0, Ξ_b^-	$1/2^+$	***
$\Xi_b'(5935)^-$	$1/2^+$	***
$\Xi_b(5945)^0$	$3/2^+$	***
$\Xi_b(5955)^-$	$3/2^+$	***
$\Xi_b(6227)$		***
Ω_b^-	$1/2^+$	***
b-baryon ADMIXTURE (Λ_b, Ξ_b, Σ_b, Ω_b)		

LHCb

*** Existence ranges from very likely to certain, but further confirmation is desirable and/or quantum numbers, branching fractions, etc. are not well determined.

Odd parity open heavy-flavor baryons

$\mathrm{SU}(6)_{lsf} \times$ HQSS
Extension of the WT Lagrangian



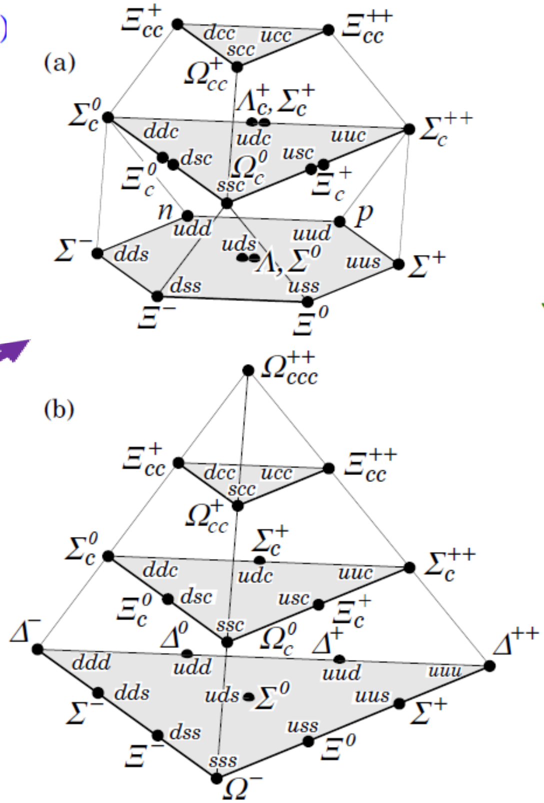
With four flavors and the inclusion of spin, there are **64 quark–antiquark ($q\bar{q}$) states,**

$$8 \otimes 8^* = 63 \oplus 1 = \underbrace{(15_1 \oplus 15_3 \oplus 1_3)}_{63} \oplus 1_1 .$$

Assuming that the lowest bound state is a s-state and since the relative parity of a fermion–antifermion pair is odd, the **SU(4) 15-plet of pseudoscalar $(D_s, D, K, \pi, \eta, \eta_c, \bar{K}, \bar{D}, \bar{D}_s)$ and the 16-plet of vector $(D_s^*, D^*, K^*, \rho, \omega, J/\Psi, \bar{K}^*, \bar{D}^*, \bar{D}_s^*, \phi)$ mesons are placed in the 63 representation.**

MESONS

BARYONS



With four flavors and the inclusion of spin, there are **512 three quark states,**

$$8 \otimes 8 \otimes 8 = 120 \oplus 56 \oplus 168 \oplus 168 =$$
$$\underbrace{(20_2 \oplus 20'_4)}_{120} \oplus \underbrace{(4_4 \oplus 20_2)}_{56} \oplus 2 \times \underbrace{(20'_2 \oplus 20_4 \oplus 20_2 \oplus 4_2)}_{168} .$$

with ⊞ and ▭▭▭, the **20** and **20′** SU(4) representations, respectively. Lowest–lying baryons are placed in the **120 of SU(8)**, since it can accommodate in the light sector an octet of spin–1/2 baryons and a decuplet of spin–3/2 baryons, which are precisely the SU(3)–spin combinations of the low–lying baryon states $(N, \Sigma, \Lambda, \Xi$ and $\Delta, \Sigma^*, \Xi^*, \Omega)$. The remaining states in the $\mathbf{20_2}$ and $\mathbf{20'_4}$ are completed with the charmed baryons: $\Xi_{cc}, \Omega_{cc}, \Lambda_c, \Sigma_c, \Xi_c, \Xi'_c, \Omega_c$ and $\Omega^*_{ccc}, \Xi^*_{cc}, \Omega^*_{cc}, \Sigma^*_c, \Xi^*_c$, respectively.

$SU(6)_{lsf} \times$ HQSS
Extension of the WT Lagrangian

$$\mathbf{63} \otimes \mathbf{120} = \mathbf{120} \oplus \mathbf{168} \oplus \mathbf{2520} \oplus \mathbf{4752}$$

SU(8) symmetry → 4 WEIME's. Equivalently,

$$\mathbf{63} \otimes \mathbf{63} = \mathbf{1} \oplus \mathbf{63}_s \oplus \mathbf{63}_a \oplus \mathbf{720} \oplus \mathbf{945} \oplus \mathbf{945}^* \oplus \mathbf{1232}$$
$$\mathbf{120} \otimes \mathbf{120}^* = \mathbf{1} \oplus \mathbf{63} \oplus \mathbf{1232} \oplus \mathbf{13104}$$

lead[a] to a total of **4 different $t-$channel SU(8) couplings**

$$\left((M^\dagger \otimes M)_{\mathbf{1}} \otimes (B^\dagger \otimes B)_{\mathbf{1}}\right)_{\mathbf{1}}, \quad \left((M^\dagger \otimes M)_{\mathbf{63}_a} \otimes (B^\dagger \otimes B)_{\mathbf{63}}\right)_{\mathbf{1}},$$
$$\left((M^\dagger \otimes M)_{\mathbf{63}_s} \otimes (B^\dagger \otimes B)_{\mathbf{63}}\right)_{\mathbf{1}}, \quad \left((M^\dagger \otimes M)_{\mathbf{1232}} \otimes (B^\dagger \otimes B)_{\mathbf{1232}}\right)_{\mathbf{1}}$$

[a] The singlet representation **1** only appears in the reduction of the product of one representation by its complex-conjugate. **1**, **63** and **1232** are self-complex conjugate representations.

TABLE II: $I = 0$, $J = 1/2$, $S = 0$, $C = 1$. Meson-Baryon states with more than one c quark have not been included.

	ND	ΛD_s	$\Lambda_c\eta$	$\Lambda_c\eta'$	$\Sigma_c\pi$	Ξ'_cK	Ξ_cK	ND^*	ΛD^*_s	$\Lambda_c\omega$	$\Lambda_c\phi$	$\Sigma_c\rho$	Ξ'_cK^*	Ξ_cK^*	$\Sigma^*_c\rho$	$\Xi^*_cK^*$
ND	-3	$-\sqrt{3}$	$\sqrt{\frac{1}{2}}$	1	$\sqrt{\frac{3}{2}}$	0	0	$-\sqrt{27}$	-3	$\sqrt{\frac{9}{2}}$	0	$-\sqrt{\frac{1}{2}}$	0	0	2	0
ΛD_s	$-\sqrt{3}$	-1	$-\sqrt{\frac{2}{3}}$	$\sqrt{\frac{1}{3}}$	0	$\sqrt{\frac{3}{2}}$	$\sqrt{\frac{1}{2}}$	-3	$-\sqrt{3}$	0	$-\sqrt{3}$	0	$-\sqrt{\frac{1}{2}}$	$\sqrt{\frac{3}{2}}$	0	2
$\Lambda_c\eta$	$\sqrt{\frac{1}{2}}$	$-\sqrt{\frac{2}{3}}$	0	0	0	0	$-\sqrt{3}$	$\sqrt{\frac{3}{2}}$	$-\sqrt{2}$	0	0	0	$-\sqrt{3}$	0	0	$-\sqrt{6}$
$\Lambda_c\eta'$	1	$\sqrt{\frac{1}{3}}$	0	0	0	0	0	$\sqrt{3}$	1	0	0	0	0	0	0	0
$\Sigma_c\pi$	$\sqrt{\frac{3}{2}}$	0	0	0	-4	$-\sqrt{3}$	0	$-\sqrt{\frac{1}{2}}$	0	0	0	$-\sqrt{\frac{64}{3}}$	-2	$-\sqrt{3}$	$\sqrt{\frac{32}{3}}$	$\sqrt{2}$
Ξ'_cK	0	$\sqrt{\frac{3}{2}}$	0	0	$-\sqrt{3}$	-2	0	0	$-\sqrt{\frac{1}{2}}$	-1	$-\sqrt{2}$	-2	$-\sqrt{\frac{16}{3}}$	0	$\sqrt{2}$	$\sqrt{\frac{8}{3}}$
Ξ_cK	0	$\sqrt{\frac{1}{2}}$	$-\sqrt{3}$	0	0	0	-2	0	$\sqrt{\frac{3}{2}}$	0	0	$-\sqrt{3}$	0	0	$-\sqrt{6}$	0
ND^*	$-\sqrt{27}$	-3	$\sqrt{\frac{3}{2}}$	$\sqrt{3}$	$-\sqrt{\frac{1}{2}}$	0	0	-9	$-\sqrt{27}$	$-\sqrt{\frac{3}{2}}$	0	$\sqrt{\frac{25}{6}}$	0	0	$\sqrt{\frac{4}{3}}$	0
ΛD^*_s	-3	$-\sqrt{3}$	$-\sqrt{2}$	1	0	$-\sqrt{\frac{1}{2}}$	$\sqrt{\frac{3}{2}}$	$-\sqrt{27}$	-3	0	1	0	$\sqrt{\frac{25}{6}}$	$-\sqrt{\frac{1}{2}}$	0	$\sqrt{\frac{4}{3}}$
$\Lambda_c\omega$	$\sqrt{\frac{9}{2}}$	0	0	0	0	-1	0	$-\sqrt{\frac{3}{2}}$	0	0	0	-4	$-\sqrt{\frac{4}{3}}$	-1	$\sqrt{8}$	$\sqrt{\frac{2}{3}}$
$\Lambda_c\phi$	0	$-\sqrt{3}$	0	0	0	$-\sqrt{2}$	0	0	1	0	0	0	$\sqrt{\frac{8}{3}}$	$-\sqrt{2}$	0	$-\sqrt{\frac{4}{3}}$
$\Sigma_c\rho$	$-\sqrt{\frac{1}{2}}$	0	0	0	$-\sqrt{\frac{64}{3}}$	-2	$-\sqrt{3}$	$\sqrt{\frac{25}{6}}$	0	-4	0	$-\frac{20}{3}$	$-\sqrt{\frac{49}{3}}$	-2	$-\sqrt{\frac{8}{9}}$	$-\sqrt{\frac{2}{3}}$
Ξ'_cK^*	0	$-\sqrt{\frac{1}{2}}$	$-\sqrt{3}$	0	-2	$-\sqrt{\frac{16}{3}}$	0	0	$\sqrt{\frac{25}{6}}$	$-\sqrt{\frac{4}{3}}$	$\sqrt{\frac{8}{3}}$	$-\sqrt{\frac{49}{3}}$	-2	$-\sqrt{\frac{16}{3}}$	$-\sqrt{\frac{2}{3}}$	0
Ξ_cK^*	0	$\sqrt{\frac{3}{2}}$	0	0	$-\sqrt{3}$	0	0	0	$-\sqrt{\frac{1}{2}}$	-1	$-\sqrt{2}$	-2	$-\sqrt{\frac{16}{3}}$	-2	$\sqrt{2}$	$\sqrt{\frac{8}{3}}$
$\Sigma^*_c\rho$	2	0	0	0	$\sqrt{\frac{32}{3}}$	$\sqrt{2}$	$-\sqrt{6}$	$\sqrt{\frac{4}{3}}$	0	$\sqrt{8}$	0	$-\sqrt{\frac{8}{9}}$	$-\sqrt{\frac{2}{3}}$	$\sqrt{2}$	$-\frac{22}{3}$	$-\sqrt{\frac{64}{3}}$
$\Xi^*_cK^*$	0	2	$-\sqrt{6}$	0	$\sqrt{2}$	$\sqrt{\frac{8}{3}}$	0	0	$\sqrt{\frac{4}{3}}$	$\sqrt{\frac{2}{3}}$	$-\sqrt{\frac{4}{3}}$	$-\sqrt{\frac{2}{3}}$	0	$\sqrt{\frac{8}{3}}$	$-\sqrt{\frac{64}{3}}$	-2

and D **a matrix in the coupled channel space. f.i., $I = 0, J = 1/2, S = 0, C = 1$:** ND, ΛD_s, $\Lambda_c\eta$, $\Lambda_c\eta'$, $\Sigma_c\pi$, Ξ'_cK, Ξ_cK, , ND^*, ΛD^*_s, $\Lambda_c\omega$, $\Lambda_c\phi$, $\Sigma_c\rho$, Ξ'_cK^*, Ξ_cK^*, $\Sigma^*_c\rho$, $\Xi^*_cK^*$.

$DN - D^*N$ might **play an important role ⇐ necessary to accommodate spin symmetry in the charm sector.**

+ symmetry breaking: masses and decay constants

To guaranty that the SU(8) amplitudes will reduce to those deduced from the SU(3) WT Lagrangian (**63⇒ adjoint representation**)

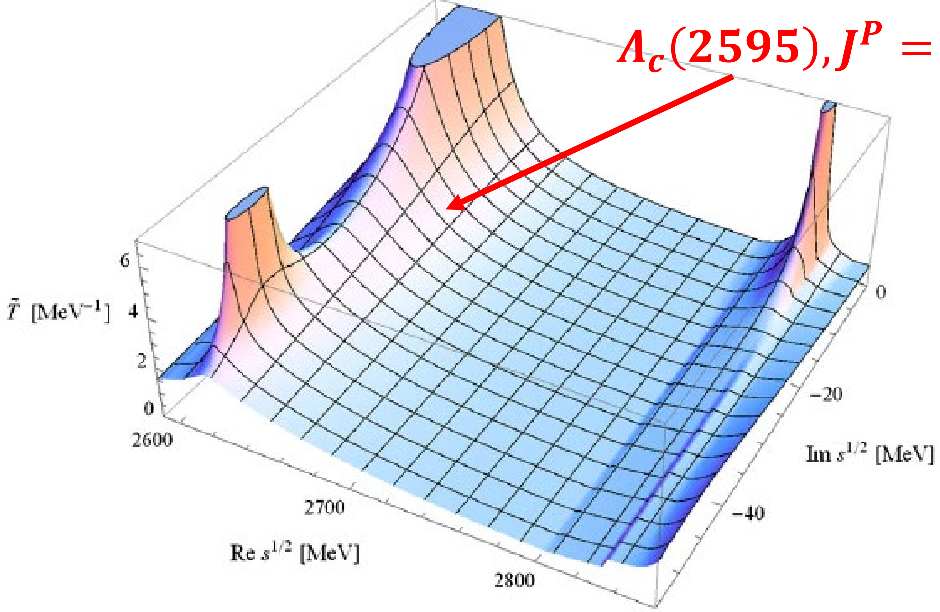
$$\mathcal{L}_{\rm WT}^{\rm SU(8)} = \left((M^\dagger \otimes M)_{\mathbf{63}_a} \otimes (B^\dagger \otimes B)_{\mathbf{63}}\right)_{\mathbf{1}}$$

$$\mathcal{L}_{\rm WT}^{\rm SU(3)} = \left((M^\dagger \otimes M)_{8_a} \otimes (B^\dagger \otimes B)_{8}\right)_{1} \quad \mathcal{L}_{\rm WT}^{\rm SU(6)} = \left((M^\dagger \otimes M)_{35_a} \otimes (B^\dagger \otimes B)_{35}\right)_{1}$$

which is the natural and unique SU(8) extension of the usual SU(3) WT Lagrangian. The reduction of this lagrangian to the SU(6) sector reproduces $\mathcal{L}_{\rm WT}^{\rm SU(6)}$. **Tree level amplitudes in a $JISC$ sector,**

$$V_{ab}^{JISC}(\sqrt{s}) = D_{ab}^{JISC}\frac{\sqrt{s}-M}{4\,f^2}$$

M the common mass of the baryons of the SU(8) 120.



Dynamics of $\Lambda_c(2595)$: PHYSICAL REVIEW D **85**, 114032 (2012)

- Two pole structure: Narrow (wide) $\Rightarrow$ small (large) coupling to the open channel $\Sigma_c\pi$. Similar to $\Lambda(1405)$.
- Narrow $\Lambda_c(2595)$: Reminiscent of a D^*N bound state

Hofmann+Lutz, NPA763 (2005) 90 $\Rightarrow$ DN bound state,

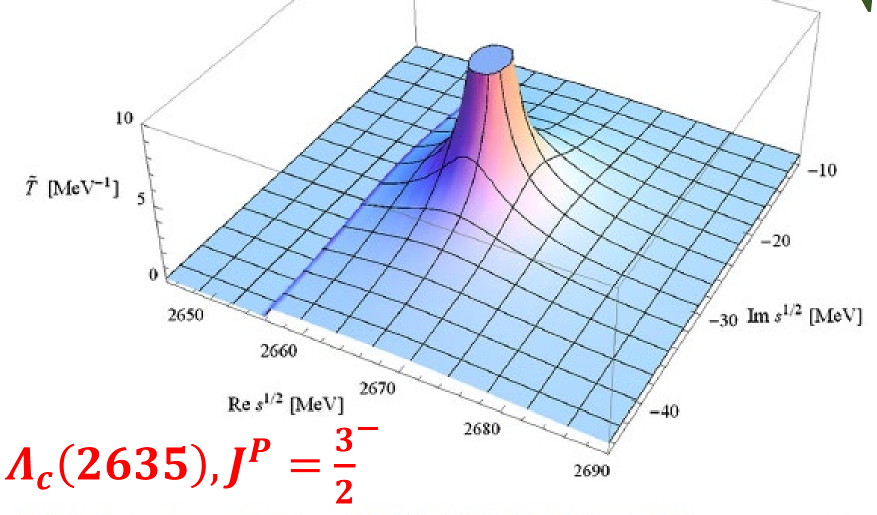
$$V = -3\frac{\sqrt{s} - M_N}{4\boxed{f_\pi^2}}$$

HQSS $\Rightarrow$ DN, D^*N coupled channels,

$$V = D\frac{\sqrt{s} - M_N}{4\boxed{f_D^2}}, \quad D = \begin{pmatrix} -3 & -\sqrt{27} \\ -\sqrt{27} & -9 \end{pmatrix} \begin{matrix} DN \\ D^*N \end{matrix}$$

J. Hofmann and M. Lutz, NPA763 (2005) 90

subtraction at a common scale $\mu \sim \sqrt{m_\pi^2 + M_{\Sigma_c}^2}$



light degrees of freedom coupled to spin-parity 0^-

Eigenvalues and eigenvectors,

$$\lambda_1 = -12 \quad \Rightarrow \quad |1\rangle = \frac{1}{2}|DN\rangle + \frac{\sqrt{3}}{2}|D^*N\rangle, \quad \overbrace{\mathbf{-12/f_D^2}}^{\text{HQSS}} \sim \underbrace{\mathbf{-3/f_\pi^2}}_{\mathbf{SU(4)}}$$

$$\lambda_1 = 0 \quad \Rightarrow \quad |2\rangle = \frac{1}{2}|D^*N\rangle - \frac{\sqrt{3}}{2}|DN\rangle, \quad \textbf{(sterile)}$$

dependence of renormalization scheme

$$T^J(s) = \frac{1}{1 - V^J(s)G^J(s)} V^J(s),$$

$$G_i(s) = i2M_i \int \frac{d^4q}{(2\pi)^4} \frac{1}{q^2 - m_i^2 + i\epsilon} \frac{1}{(P-q)^2 - M_i^2 + i\epsilon}$$

$$= \overline{G}_i(s) + G_i(s_{i+}) \qquad s_{i+} = (M_i + m_i)^2$$

finite UV divergent

different UV cutoffs for each meson-baryon channel

subtraction at a common scale $\mu \sim \sqrt{m_\pi^2 + M_{\Sigma_c}^2}$:

J. Hofmann and M. Lutz, NPA763 (2005) 90

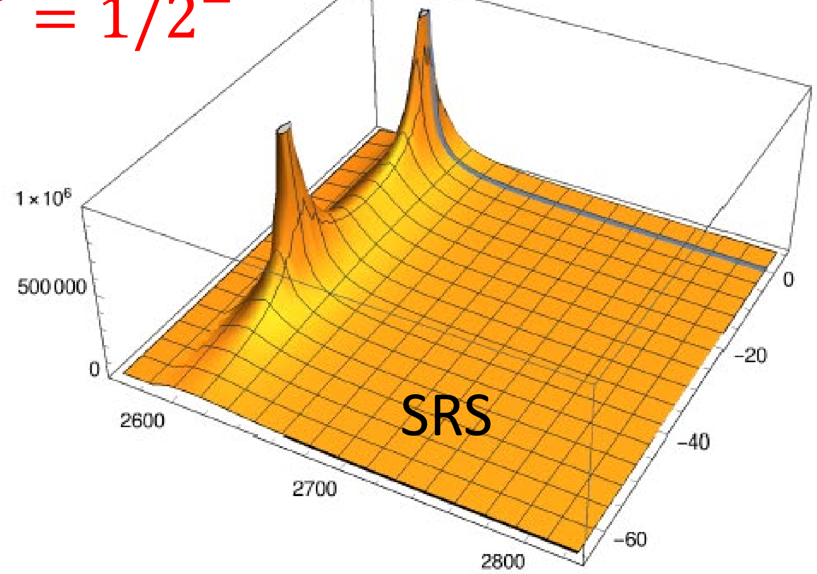
$$G_i^\mu(s_{i+}) = -\overline{G}_i(\mu^2)$$

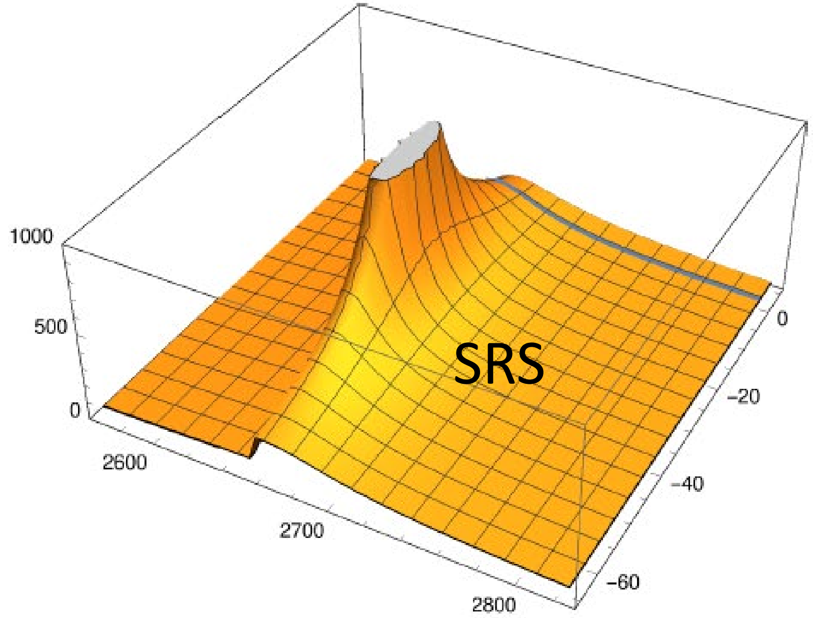
common UV cutoff
Λ =650 MeV

$$G_i^\Lambda(s_{i+}) = \frac{1}{4\pi^2} \frac{M_i}{m_i + M_i} \left(m_i \ln \frac{m_i}{\Lambda + \sqrt{\Lambda^2 + m_i^2}} + M_i \ln \frac{M_i}{\Lambda + \sqrt{\Lambda^2 + M_i^2}} \right)$$

Absolute value of the determinant of the T −matrix

$J^P = 1/2^-$

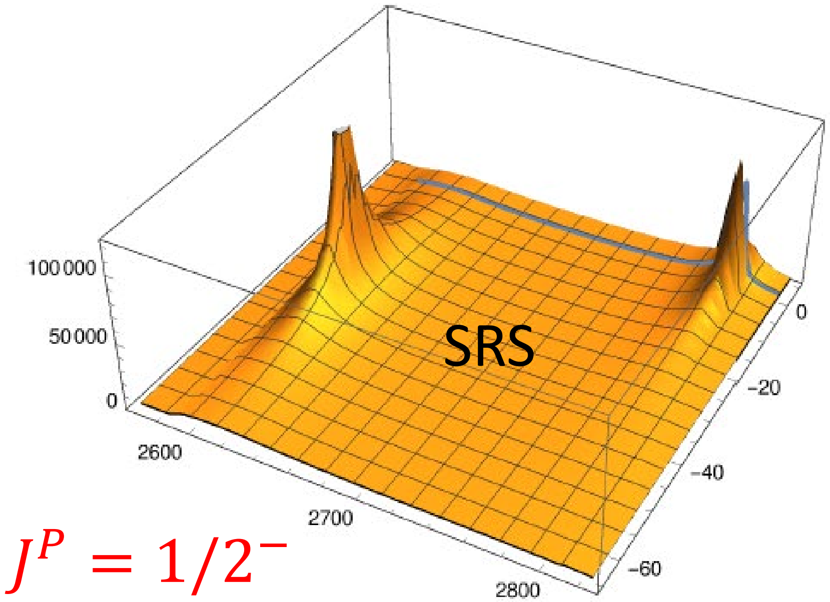


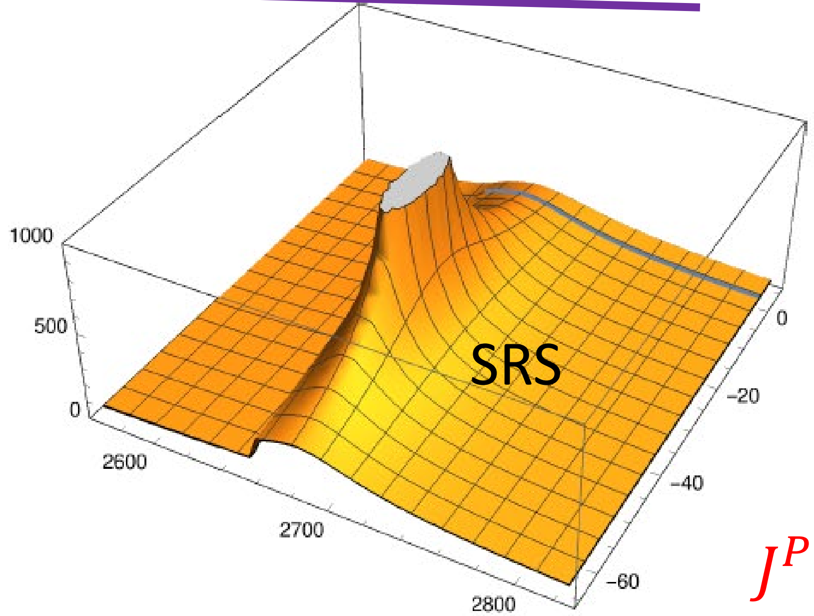


$J^P = 3/2^-$

subtraction at a common scale **(no fit!)**

- ✓ main features of $3/2^-$ pole do not depend much on the RS: $M = 2660 - 2680$ MeV and $\Gamma = 55 - 65$ MeV: **difficult to assign it to the narrow $\Lambda_c(2625)$.**
- ✓ **spectrum in the $1/2^-$ sector depends strongly on the adopted RS**





common UV cutoff 650 MeV

(no fit!)

$J^P = 1/2^-$

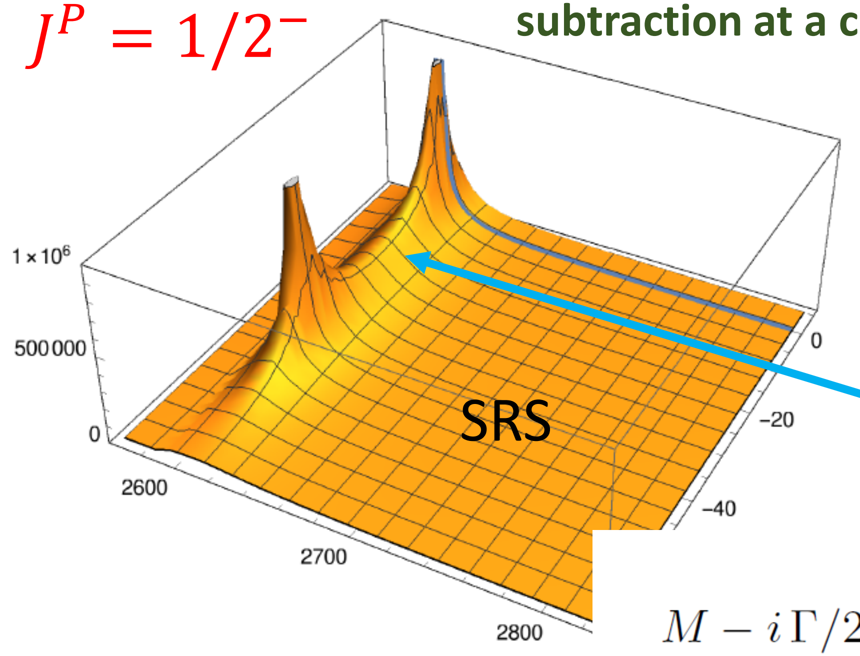
$J^P = 3/2^-$

$C = 1,\ ND^{(*)}, \Sigma_c^{(*)}\pi$ coupled-channels

Absolute value of the determinant of the T −matrix

$J^P = 1/2^-$

subtraction at a common scale **(no fit!)**

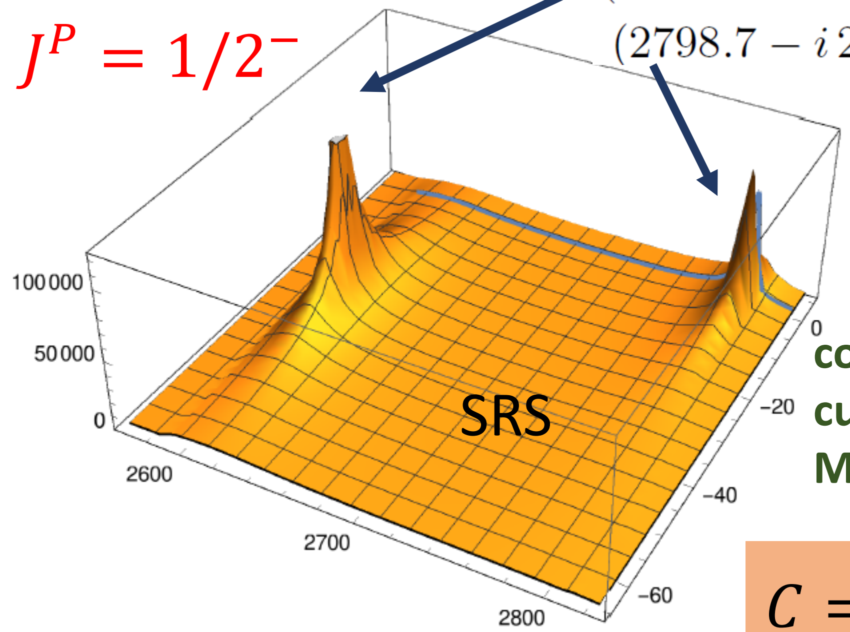


Two pole pattern , but

- ✓ **narrow resonance** has a small coupling to $\Sigma_c\pi$, since it has **dominant 0^- configuration** for the light degrees of freedom. Moreover **its position depends strongly on the RS**, since it might appear close to the ND or $\Sigma_c\pi$ thresholds (∼200 MeV of difference!). In the latter case (subtraction at a common scale), it could be identified with the $\Lambda_c(2595)$. In both RS's the narrow resonance has large ND and ND^* components.

$\Lambda = 650$ MeV					SCμ ($\alpha = 0.95$)				
$M - i\Gamma/2$	Type	$\lvert g_{\Sigma_c\pi}\rvert$	$\lvert g_{ND}\rvert$	$\lvert g_{ND^*}\rvert$	$M - i\Gamma/2$	Type	$\lvert g_{\Sigma_c\pi}\rvert$	$\lvert g_{ND}\rvert$	$\lvert g_{ND^*}\rvert$
$(2609.9 - i\,28.8)$	1^-	2.0	2.3	0.7	$(2608.9 - i\,38.6)$	1^-	2.3	2.0	1.9
$(2798.7 - i\,2.0)$	0^-	0.3	1.8	4.1	$(2610.2 - i\,1.2)$	0^-	0.5	3.9	6.2

$J^P = 1/2^-$



(no fit!)

common UV cutoff 650 MeV

- ✓ **broad resonance** has a large coupling to $\Sigma_c\pi$, and hence has a **dominant 1^- configuration** for the light degrees of freedom. It is located around 2610 MeV and with a width of 60-80 MeV. In the subtraction at a common scale RS, this state will be completely shadowed by the narrow $\Lambda_c(2595)$ state. When a common UV cutoff is used, it is difficult to assign this pole to the $\Lambda_c(2595)$.

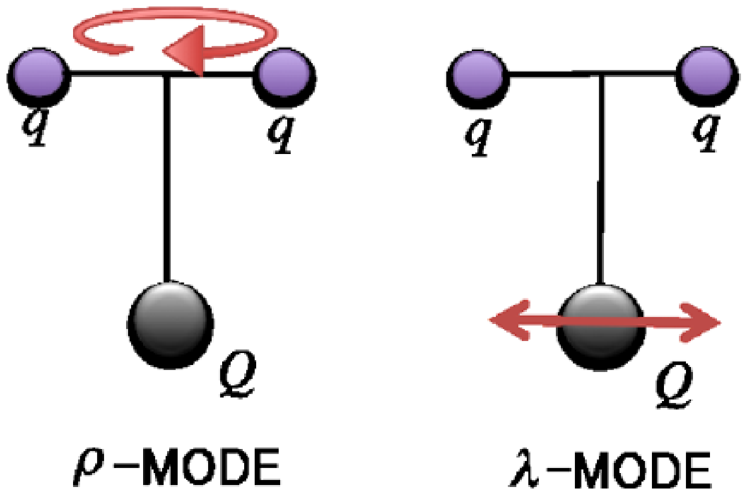
$C = 1,\ ND^{(*)}, \Sigma_c^{(*)}\pi$ coupled-channels

...and CQM predictions:

$\ell_\lambda = 1, \ell_\rho = 0$, **S=0, I=0** (sym)

λ −mode excitations

$$\underbrace{1/2^+}_{s_Q^P} \otimes \underbrace{1^-}_{j^P_{ldof}} = \underbrace{1/2^-}_{\Lambda_c(2595)} \; , \; \underbrace{3/2^-}_{\Lambda_c(2625)}$$



PHYSICAL REVIEW D **92**, 114029 (2015)

Spectrum of heavy baryons in the quark model

T. Yoshida,[1,*] E. Hiyama,[2,1,3] A. Hosaka,[4,3] M. Oka,[1,3] and K. Sadato[4,†]

	Λ_c	
J^P	Theory (MeV)	Experiment (MeV)
$\frac{1}{2}^+$	2285	2285
	2857	
	3123	
$\frac{3}{2}^+$	2920	
	3175	
	3191	
$\frac{5}{2}^+$	2922	2881
	3202	
	3230	
$\frac{1}{2}^-$	2628	2595
	2890	
	2933	

	Λ_c	
J^P	Theory (MeV)	Experiment (MeV)
$\frac{3}{2}^-$	2630	2628
	2917	
	2956	
$\frac{5}{2}^-$	2960	
	3444	
	3491	

bare CQM state should be explicitly taken into account in the dynamics, in particular for the $\Lambda_c(2625)$ resonance: for these energies it produces a rapidly changing energy dependent interaction

Lowest lying $\left(\frac{1}{2}\right)^{-}$ and $\left(\frac{3}{2}\right)^{-}$ Λ_Q resonances: from the strange to the bottom sectors

CHARMED BARYONS ($C = +1$)

$\Lambda_c^+ = udc$, $\Sigma_c^{++} = uuc$, $\Sigma_c^+ = udc$, $\Sigma_c^0 = ddc$,
$\Xi_c^+ = usc$, $\Xi_c^0 = dsc$, $\Omega_c^0 = ssc$

Λ_c^+	$1/2^+$	****
$\Lambda_c(2595)^+$	$1/2^-$	***
$\Lambda_c(2625)^+$	$3/2^-$	***
$\Lambda_c(2765)^+$ or $\Sigma_c(2765)$		*
$\Lambda_c(2860)^+$	$3/2^+$	***
$\Lambda_c(2880)^+$	$5/2^+$	***
$\Lambda_c(2940)^+$	$3/2^-$	***
$\Sigma_c(2455)$	$1/2^+$	****
$\Sigma_c(2520)$	$3/2^+$	***

BOTTOM BARYONS ($B = -1$)

$\Lambda_b^0 = udb$, $\Xi_b^0 = usb$, $\Xi_b^- = dsb$, $\Omega_b^- = ssb$

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^*	$3/2^+$	***

Lowest-lying open heavy-flavor baryons

HQSFS: odd parity excited states

CQM: T. Yoshida, E. Hiyama, A. Hosaka, M. Oka, and K. Sadato, PRD92 (2015) 114029

The light degrees of freedom in the hadron orbit around the heavy quark, which acts as a source of color moving with the hadrons's velocity. On average, this is also the velocity of the "brown muck".

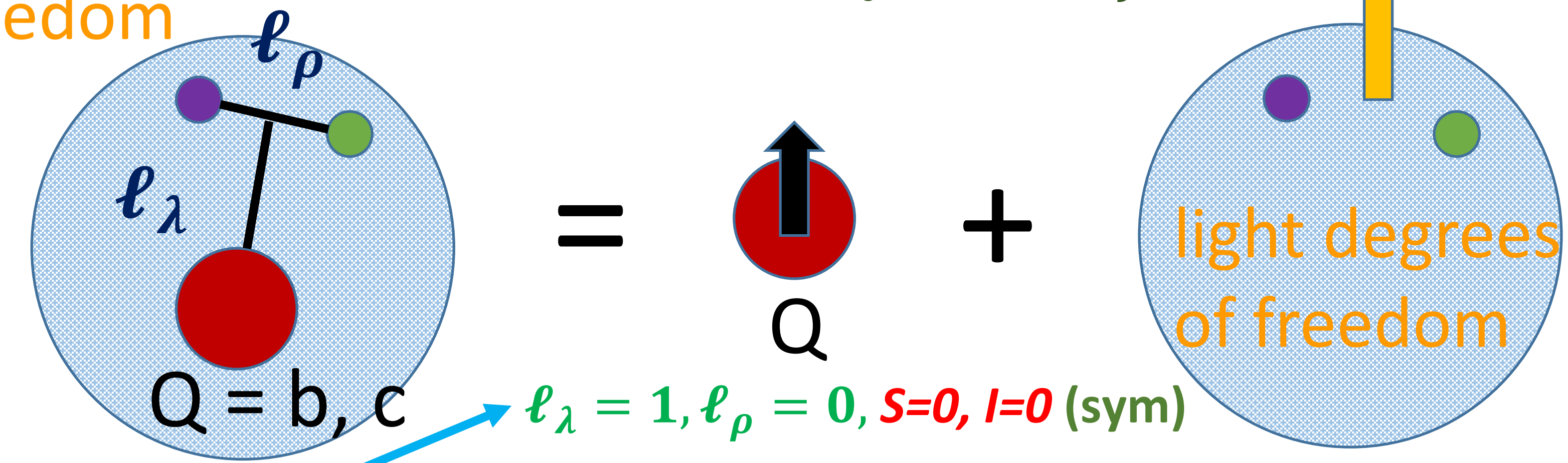
$$\vec{J} = \vec{S}_Q + \vec{j}_{ldof}$$

$\vec{j}^{\,2}_{ldof}$ is conserved!

HQSS

$SU(2N_h)$ symmetry in the $m_Q \to \infty$ limit

light degrees of freedom



$\ell_\lambda = 0, \ell_\rho = 1$, S=1, I=0 (sym)

$\ell_\lambda = 1, \ell_\rho = 0$, S=0, I=0 (sym)

$$\underbrace{1/2^+}_{S_Q^P} \otimes \underbrace{1^-}_{j_{ldof}^P} = \underbrace{1/2^-}_{\Lambda_c(2595)}, \underbrace{3/2^-}_{\Lambda_c(2625)}$$

CQM states

$$\underbrace{1/2^+}_{S_Q^P} \otimes \underbrace{0^-, 1^-, 2^-}_{j_{ldof}^P} = \underbrace{1/2^-, \ldots}_{\Lambda_c^*}$$

λ –mode excitations

ρ –mode excitations

HQSFS: odd parity excited states

chiral molecules

$$\underbrace{\Sigma_c^{(*)}\pi}_{ldof:\ 1^+\otimes 0^-=1^-} \Rightarrow J^P = 1/2^-, 3/2^-$$

NLO SU(3) ChPT: J.-X. Lu, Y. Zhou, H.-X. Chen, J.-J. Xie, and L.-S. Geng, PRD92 (2015) 014036

obtains the $\Lambda_c(2625)$ [$J^P = \frac{3}{2}^-$] using a **moderately large UV cutoff** $\sim$ 2.1 GeV

- ✓ CQM degrees of freedom
- ✓ Analogy $\Lambda(1520)$, $\boldsymbol{\Lambda(1405)}$

$\Sigma^{(*)} \leftrightarrow \Sigma_c^{(*)}$, $\bar{K}^{(*)} \leftrightarrow D^{(*)}$

L. Tolos, J. Schaner-Bielich, and A. Mishra, PRC70 (2004) 025203 ; J. Hofmann and M. Lutz, NPA763 (2005) 90; 766 (2006) 7 ; T. Mizutani and A. Ramos, PRC74 (2006) 065201

existence of some relevant degrees of freedom (CQM states and/or $ND^{(*)}$ components) that are not properly accounted for ?

F.-K. Guo, U.-G. Meissner, and B.-S. Zou, Commun. Theor. Phys. 65 (2016) 593

M. Albaladejo, JN, E. Oset, Z.-F. Sun, and X. Liu, PLB757 (2016) 515

HQSFS: odd parity excited states hadron molecules

$\underbrace{\Sigma_c^{(*)}\pi}_{ldof:\,1^+\otimes\,0^-=1^-} \Rightarrow J^P = 1/2^-, 3/2^-$

$\underbrace{ND^{(*)}}_{ldof:\,1/2^+\otimes\,1/2^-=0^-,1^-} \Rightarrow J^P = 1/2^-, 3/2^-$

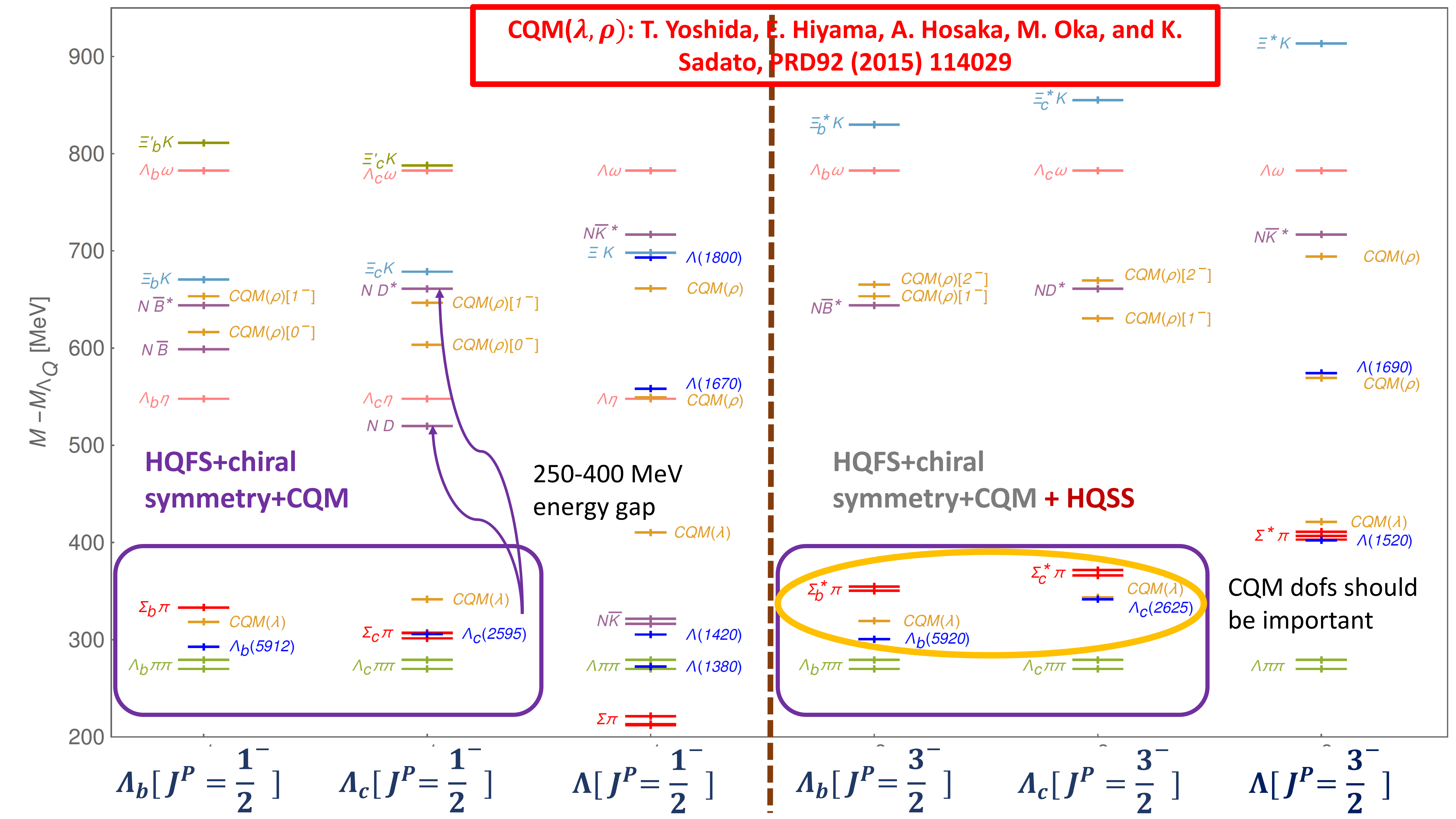
$\bar{\ell}$

new configuration !

but....

key issue: $ND^{(*)} \longrightarrow ND^{(*)}, \Sigma_c^{(*)}\pi$ coupled-channels interaction consistent with HQSS and its breaking pattern. In addition renormalization of BSE amplitudes & short distance (UV) physics

Σ_c and Σ_c^* or D and D^* are related by a charm quark spin rotation, which commutes with H_{QCD}, up to Λ_{QCD}/m_c corrections.



CQM(λ, ρ): T. Yoshida, E. Hiyama, A. Hosaka, M. Oka, and K. Sadato, PRD92 (2015) 114029
M − M_ΛQ [MeV]
900
800
700
600
500
400
300
200
Ξ'_b K
Λ_b ω
Ξ_b K
CQM(ρ)[1⁻]
N B̄*
CQM(ρ)[0⁻]
N B̄
Λ_b η
Ξ'_c K
Λ_c ω
Ξ_c K
N D*
CQM(ρ)[1⁻]
CQM(ρ)[0⁻]
Λ_c η
N D
Λω
NK̄*
Ξ K
Λ(1800)
CQM(ρ)
Λ(1670)
Λη
CQM(ρ)
HQFS+chiral symmetry+CQM
250-400 MeV energy gap
CQM(λ)
Σ_b π
CQM(λ)
Λ_b(5912)
Λ_b ππ
CQM(λ)
Σ_c π
Λ_c(2595)
Λ_c ππ
NK̄
Λ(1420)
Λππ
Λ(1380)
Σπ
Ξ*_b K
Λ_b ω
CQM(ρ)[2⁻]
CQM(ρ)[1⁻]
NB̄*
Ξ*_c K
Λ_c ω
CQM(ρ)[2⁻]
ND*
CQM(ρ)[1⁻]
Ξ* K
Λω
NK̄*
CQM(ρ)
Λ(1690)
CQM(ρ)
HQFS+chiral symmetry+CQM + HQSS
CQM(λ)
Σ* π
Λ(1520)
Σ*_b π
CQM(λ)
Λ_b(5920)
Λ_b ππ
Σ*_c π
CQM(λ)
Λ_c(2625)
Λ_c ππ
CQM dofs should be important
Λππ
Λ_b[J^P = 1⁻/2]
Λ_c[J^P = 1⁻/2]
Λ[J^P = 1⁻/2]
Λ_b[J^P = 3⁻/2]
Λ_c[J^P = 3⁻/2]
Λ[J^P = 3⁻/2]

$$T^J(s) = \frac{1}{1 - V^J(s)G^J(s)} V^J(s),$$

$$V^J = V^J_\chi + V^J_{ex}$$

$$V_\chi^{J=1/2} \sim V_\chi^{J=3/2} \sim -4\frac{\sqrt{s}-M}{2f^2}$$

$$G_i(s) = i2M_i \int \frac{d^4q}{(2\pi)^4} \frac{1}{q^2 - m_i^2 + i\epsilon} \frac{1}{(P-q)^2 - M_i^2 + i\epsilon}$$

$$= \overline{G}_i(s) + G_i(s_{i+})$$

finite — UV divergent

$$s_{i+} = (M_i + m_i)^2$$

different UV cutoffs for each meson-baryon channel

subtraction at a common scale $\mu \sim \sqrt{m_\pi^2 + M_{\Sigma_c}^2}$:

J. Hofmann and M. Lutz, NPA763 (2005) 90

$$G_i^\mu(s_{i+}) = -\overline{G}_i(\mu^2)$$

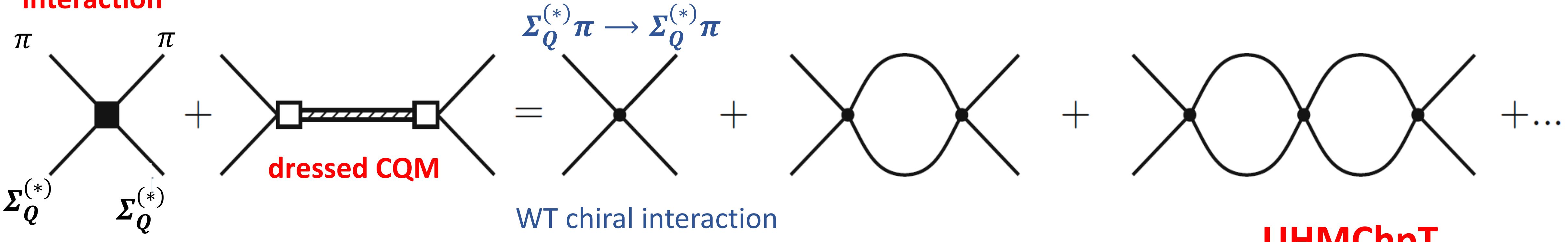
common UV cutoff $\Lambda \sim 0.5 - 1$ GeV

$$G_i^\Lambda(s_{i+}) = \frac{1}{4\pi^2}\frac{M_i}{m_i + M_i}\left(m_i \ln\frac{m_i}{\Lambda + \sqrt{\Lambda^2 + m_i^2}} + M_i \ln\frac{M_i}{\Lambda + \sqrt{\Lambda^2 + M_i^2}}\right)$$

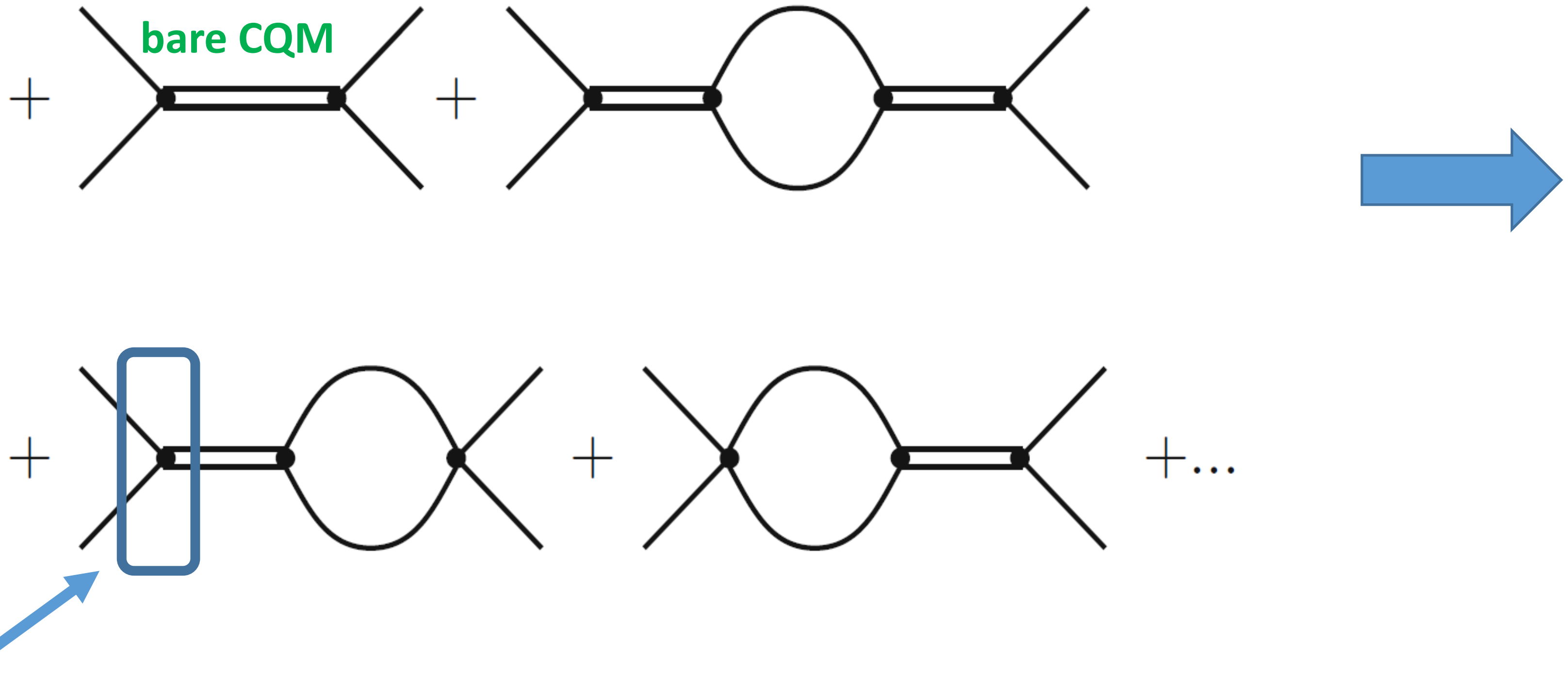
renormalization scheme consistent with HQS

J.-X. Lu et al., PRD92 (2015) 014036

UHMChpT interaction

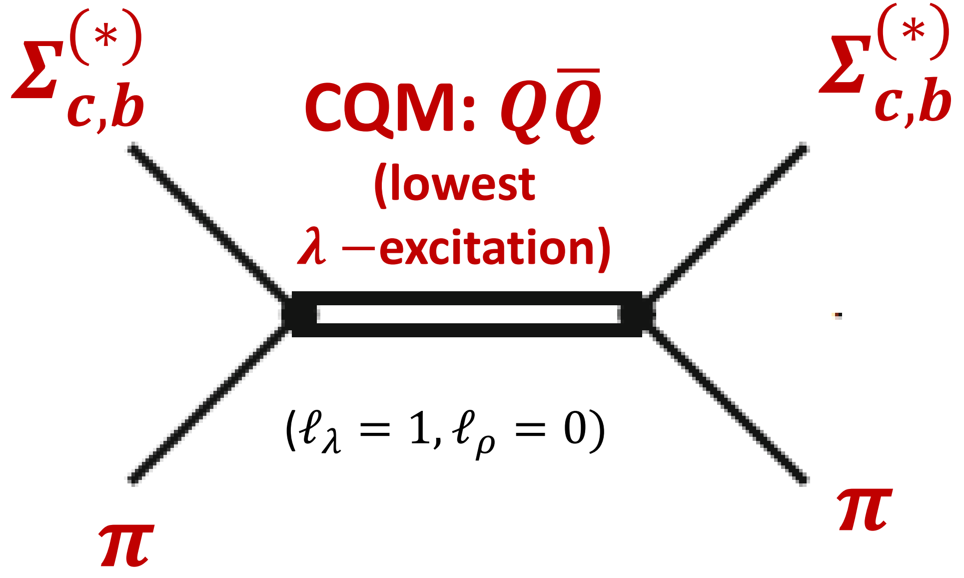


UHMChpT interaction



… coupling **chiral $\Sigma_Q^{(*)}\pi$ and λ −mode CQM** degrees of freedom, taking into account HQSS constraints…

CQM: T. Yoshida, E. Hiyama, A. Hosaka, M. Oka, and K. Sadato, PRD92 (2015) 114029



$$V_{ex}^{J=1/2} \sim V_{ex}^{J=3/2} = 2M_{\mathrm{CQM}} \frac{d_Q^2}{s - M_{\mathrm{CQM}}^2}$$

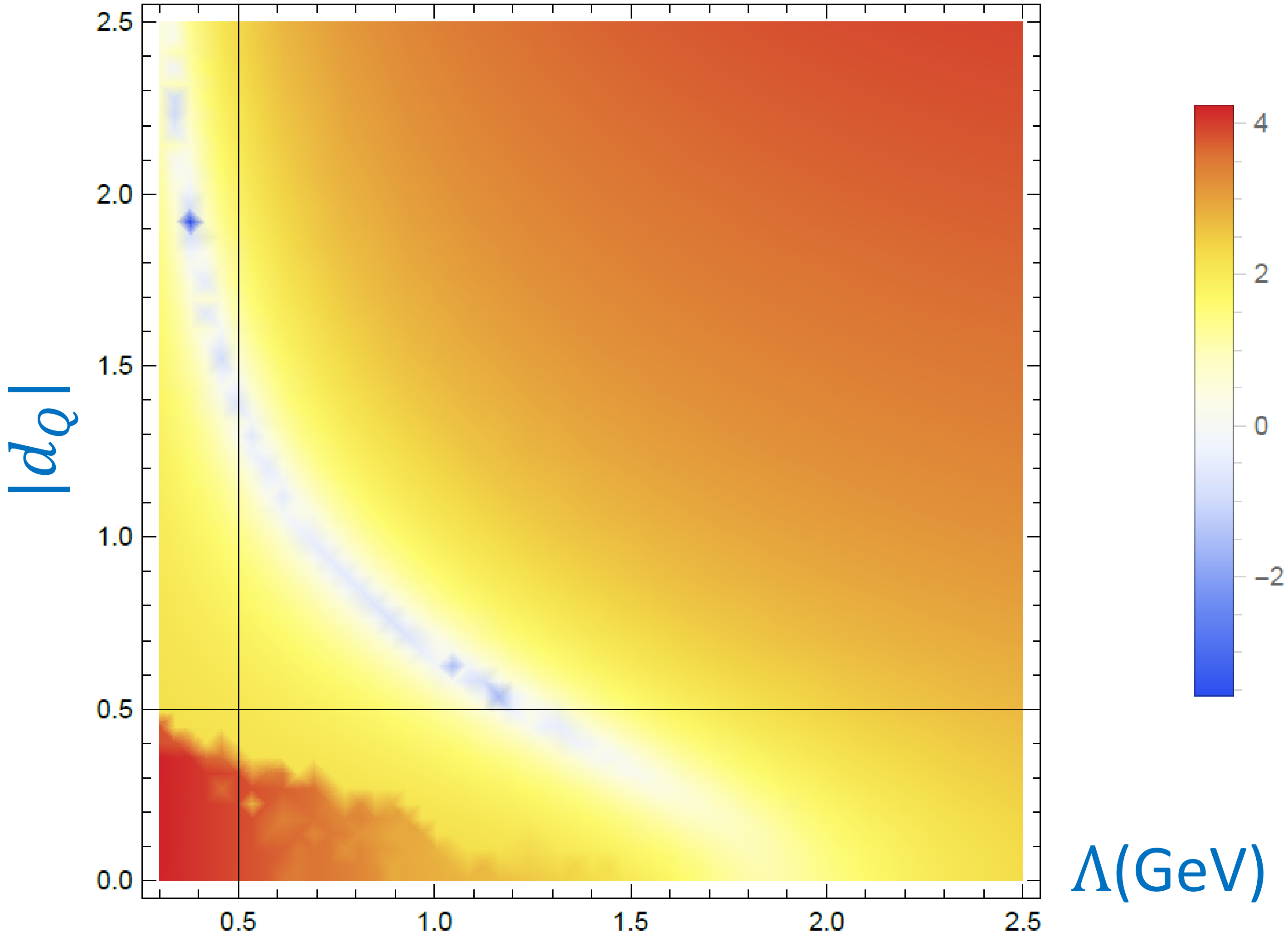
$$\underbrace{1/2^+}_{S_Q^P} \otimes \underbrace{1^-}_{j_{ldof}^P} = \underbrace{1/2^-}_{\substack{\Lambda_b(5912) \\ \Lambda_c(2595)}} , \underbrace{3/2^-}_{\substack{\Lambda_b(5920) \\ \Lambda_c(2625)}}$$

LEC d_Q^2 (up to $\Lambda_{\mathrm{QCD}}/m_Q$ corrections):

- **HQSS: independent of heavy quark spin (J=1/2 or J=3/2)**
- **HQFS: independent of heavy quark flavor (bottom or charm)**

$$\chi^2(|d_Q|,\Lambda) = \left[\frac{M_{\Lambda_b(5912)} - M_{R-\mathrm{BSE}}^{J^P=1/2^-}(|d_Q|,\Lambda)}{\sigma(\Sigma_b)}\right]^2 + \left[\frac{M_{\Lambda_b(5920)} - M_{R-\mathrm{BSE}}^{J^P=3/2^-}(|d_Q|,\Lambda)}{\sigma(\Sigma_b^*)}\right]^2$$

$\mathrm{Log}[\chi^2(|d_Q|,\Lambda)]$



we determine $|d_Q|$ for different UV cutoffs Λ from the pole position of the $\Lambda_b(5912)$ $[J^P = (1/2)^-]$ and $\Lambda_b(5920)$ $[J^P = (3/2)^-]$

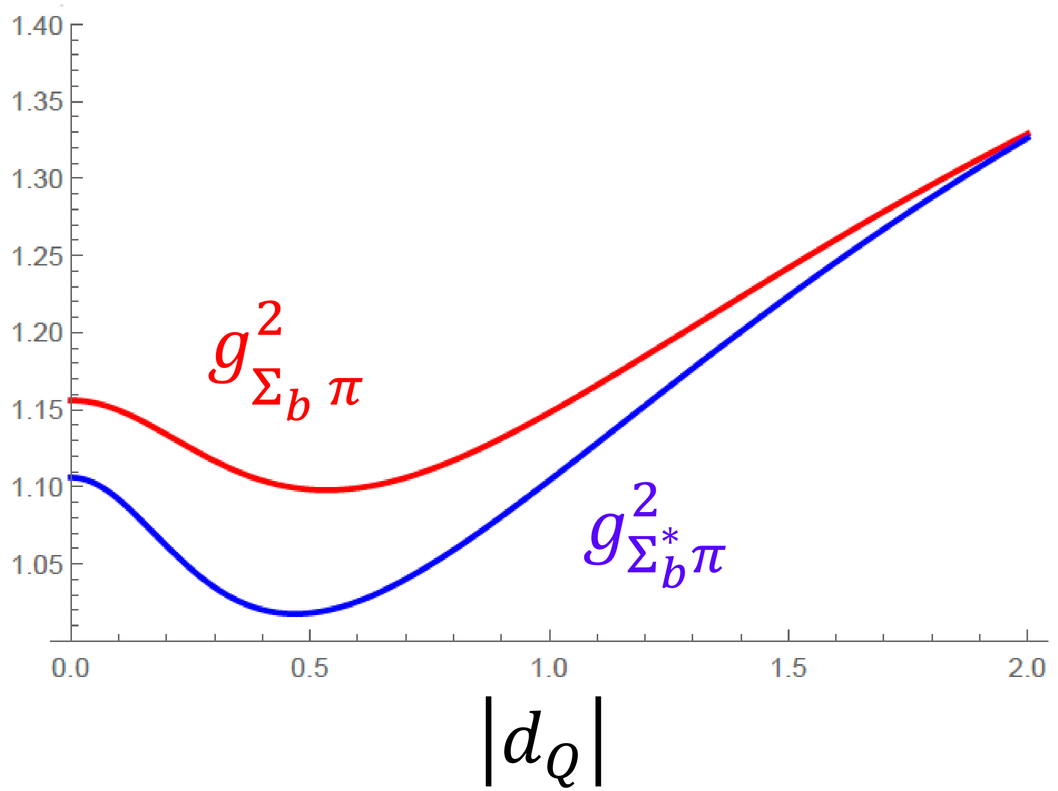
			$\Lambda_b(5912)$				$\Lambda_b(5920)$			
			$\Sigma_b\pi\ J^P=\frac{1}{2}^-$				$\Sigma_b^*\pi\ J^P=\frac{3}{2}^-$			
Λ [GeV]	χ^2	$\lvert d_Q\rvert$	M [MeV]	$\lvert g_{\Sigma_b\pi}\rvert$	$P_{\Sigma_b\pi}$	$\Gamma^R_{\Lambda_b\pi\pi}$ [keV]	M [MeV]	$\lvert g_{\Sigma_b^*\pi}\rvert$	$P_{\Sigma_b^*\pi}$	$\Gamma^R_{\Lambda_b\pi\pi}$ [keV]
0.4	0.02	1.79 ± 0.11	5912.4 ± 2.0	1.67 ± 0.06	0.35 ± 0.02	18 ± 5	5919.8 ± 1.6	1.66 ± 0.07	0.31 ± 0.03	37 ± 5
0.65	0.32	1.06 ± 0.06	5913.1 ± 2.0	1.34 ± 0.04	0.23 ± 0.01	13 ± 4	5919.1 ± 1.7	1.26 ± 0.05	0.18 ± 0.01	19 ± 3
0.9	0.16	0.75 ± 0.04	5912.9 ± 1.7	1.23 ± 0.03	0.19 ± 0.01	10 ± 3	5919.5 ± 1.6	1.11 ± 0.04	0.14 ± 0.01	16 ± 3
1.15	0.00	0.55 ± 0.04	5912.1 ± 2.0	1.21 ± 0.02	0.18 ± 0.01	9 ± 3	5920.2 ± 1.9	1.04 ± 0.03	0.12 ± 0.01	15 ± 3
1.85 ± 0.04	12	0	5905.5 ± 1.7	1.27 ± 0.02	0.19 ± 0.01	2.5 ± 1.2	5924.9 ± 1.7	1.27 ± 0.02	0.19 ± 0.01	39 ± 8

D. Gamermann, J.N., E. Oset, and E. Ruiz Arriola, PRD81 (2010) 014029

~ -0.1

molecular probability

$$P_{\Sigma_Q^{(*)}\pi} = -g^2_{\Sigma_Q^{(*)}\pi}\ \frac{\partial \overline{G}_{\Sigma_Q^{(*)}\pi}(\sqrt{s})}{\partial\sqrt{s}}\Bigg|_{\sqrt{s}=\sqrt{s_R}}$$



$\sim 0.15 - 0.35$

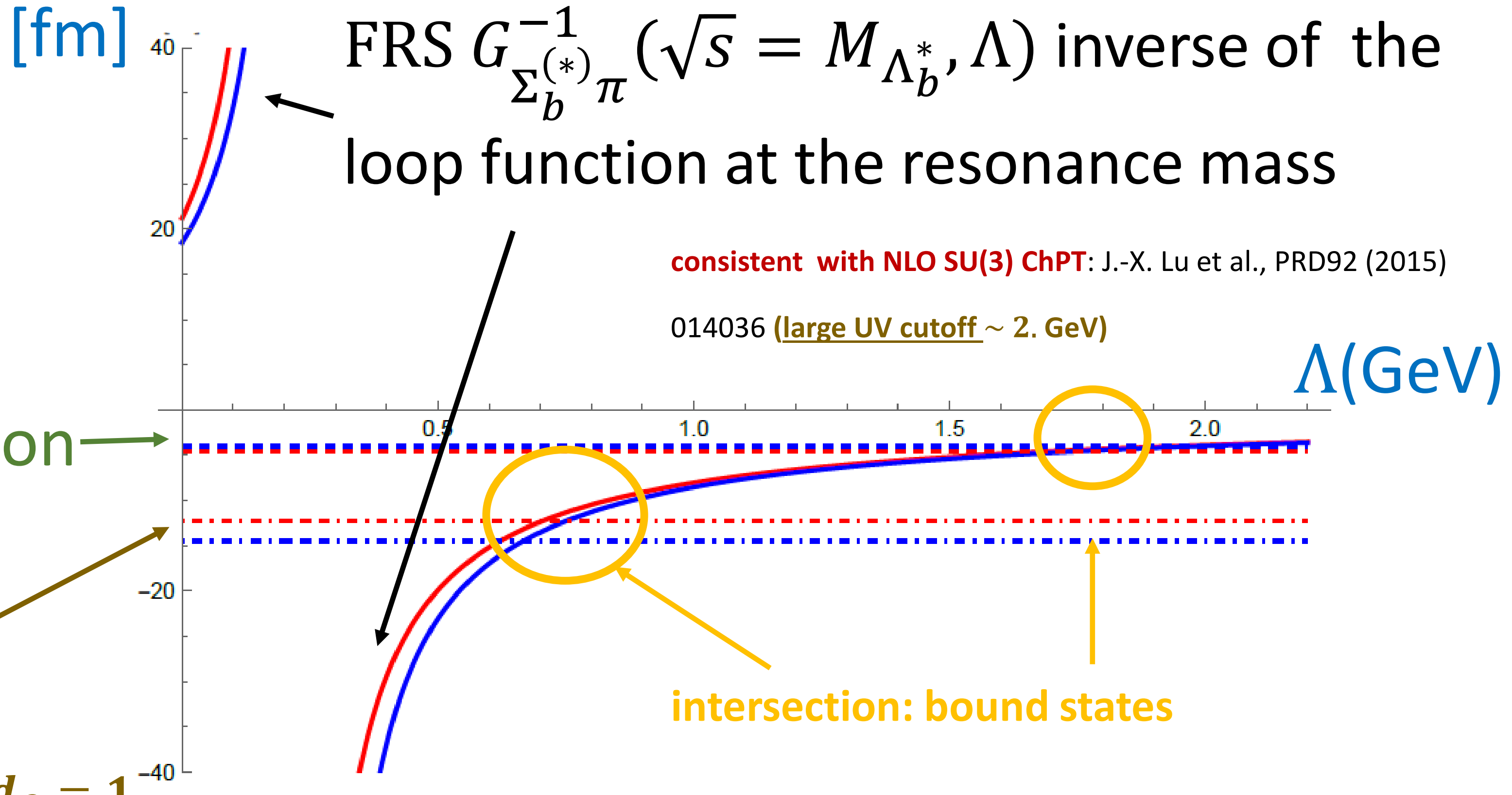
$\Lambda_b(5912)$ and $\Lambda_b(5920)$ are:

- largely CQM states
- HQSS partners

	$\Lambda_b(5912)$						$\Lambda_b(5920)$			
			$\Sigma_b\pi\ J^P = \frac{1}{2}^-$				$\Sigma_b^*\pi\ J^P = \frac{3}{2}^-$			
Λ [GeV]	χ^2	$\lvert d_Q \rvert$	M [MeV]	$\lvert g_{\Sigma_b\pi} \rvert$	$P_{\Sigma_b\pi}$	$\Gamma^R_{\Lambda_b\pi\pi}$ [keV]	M [MeV]	$\lvert g_{\Sigma_b^*\pi} \rvert$	$P_{\Sigma_b^*\pi}$	$\Gamma^R_{\Lambda_b\pi\pi}$ [keV]
0.4	0.02	1.79 ± 0.11	5912.4 ± 2.0	1.67 ± 0.06	0.35 ± 0.02	18 ± 5	5919.8 ± 1.6	1.66 ± 0.07	0.31 ± 0.03	37 ± 5
0.65	0.32	1.06 ± 0.06	5913.1 ± 2.0	1.34 ± 0.04	0.23 ± 0.01	13 ± 4	5919.1 ± 1.7	1.26 ± 0.05	0.18 ± 0.01	19 ± 3
0.9	0.16	0.75 ± 0.04	5912.9 ± 1.7	1.23 ± 0.03	0.19 ± 0.01	10 ± 3	5919.5 ± 1.6	1.11 ± 0.04	0.14 ± 0.01	16 ± 3
1.15	0.00	0.55 ± 0.04	5912.1 ± 2.0	1.21 ± 0.02	0.18 ± 0.01	9 ± 3	5920.2 ± 1.9	1.04 ± 0.03	0.12 ± 0.01	15 ± 3
1.85 ± 0.04	12	0	5905.5 ± 1.7	1.27 ± 0.02	0.19 ± 0.01	2.5 ± 1.2	5924.9 ± 1.7	1.27 ± 0.02	0.19 ± 0.01	39 ± 8

neglecting the interaction driven by the CQM bare state

FRS $G^{-1}_{\Sigma_b^{(*)}\pi}(\sqrt{s} = M_{\Lambda_b^*}, \Lambda)$ inverse of the loop function at the resonance mass



consistent with NLO SU(3) ChPT: J.-X. Lu et al., PRD92 (2015) 014036 (large UV cutoff ~ 2. GeV)

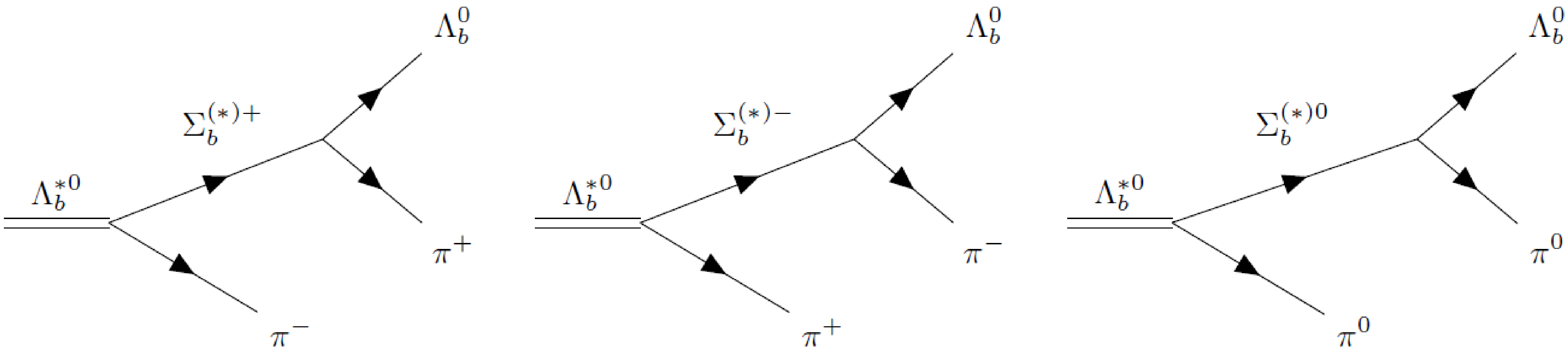
$V^J_\chi(\sqrt{s} = M_{\Lambda_b^*})$ chiral interaction

$V^J_\chi(\sqrt{s} = M_{\Lambda_b^*}) + \dfrac{2M_{\text{CQM}}}{M^2_{\Lambda_b^*} - M^2_{\text{CQM}}}$

CQM exchange potential for $d_Q = 1$

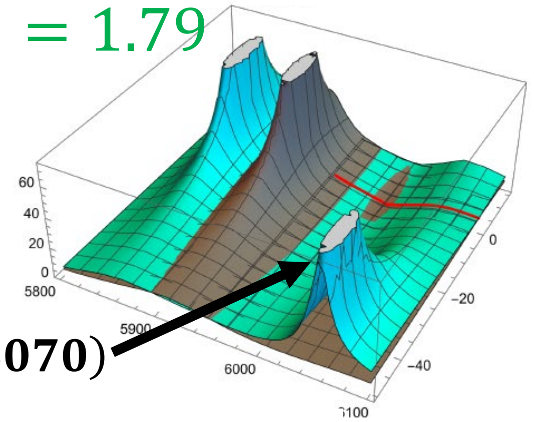
intersection: bound states

			$\Lambda_b(5912)$				$\Lambda_b(5920)$			
			$\Sigma_b\pi$ $J^P=\frac{1}{2}^-$				$\Sigma_b^*\pi$ $J^P=\frac{3}{2}^-$			
Λ [GeV]	χ^2	$\lvert d_Q\rvert$	M [MeV]	$\lvert g_{\Sigma_b\pi}\rvert$	$P_{\Sigma_b\pi}$	$\Gamma^R_{\Lambda_b\pi\pi}$ [keV]	M [MeV]	$\lvert g_{\Sigma_b^*\pi}\rvert$	$P_{\Sigma_b^*\pi}$	$\Gamma^R_{\Lambda_b\pi\pi}$ [keV]
0.4	0.02	1.79 ± 0.11	5912.4 ± 2.0	1.67 ± 0.06	0.35 ± 0.02	18 ± 5	5919.8 ± 1.6	1.66 ± 0.07	0.31 ± 0.03	37 ± 5
0.65	0.32	1.06 ± 0.06	5913.1 ± 2.0	1.34 ± 0.04	0.23 ± 0.01	13 ± 4	5919.1 ± 1.7	1.26 ± 0.05	0.18 ± 0.01	19 ± 3
0.9	0.16	0.75 ± 0.04	5912.9 ± 1.7	1.23 ± 0.03	0.19 ± 0.01	10 ± 3	5919.5 ± 1.6	1.11 ± 0.04	0.14 ± 0.01	16 ± 3
1.15	0.00	0.55 ± 0.04	5912.1 ± 2.0	1.21 ± 0.02	0.18 ± 0.01	9 ± 3	5920.2 ± 1.9	1.04 ± 0.03	0.12 ± 0.01	15 ± 3
1.85 ± 0.04	12	0	5905.5 ± 1.7	1.27 ± 0.02	0.19 ± 0.01	2.5 ± 1.2	5924.9 ± 1.7	1.27 ± 0.02	0.19 ± 0.01	39 ± 8



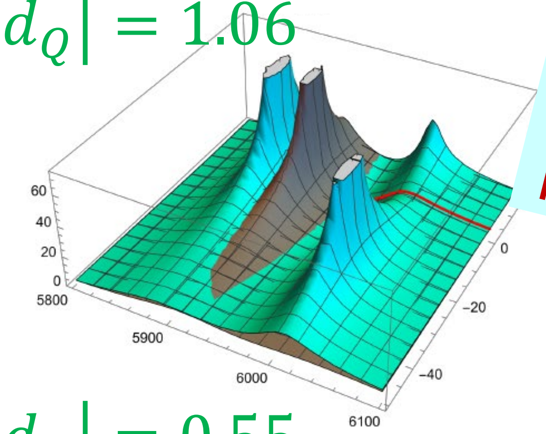
small 3-body decay widths (tens of keV)

$|d_Q| = 1.79$



$\boldsymbol{\Lambda_b(6070)}$

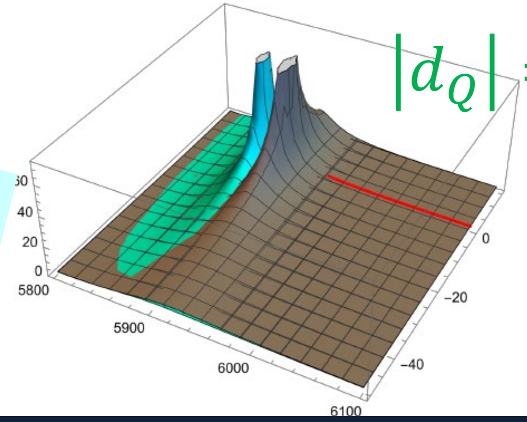
$|d_Q| = 1.06$



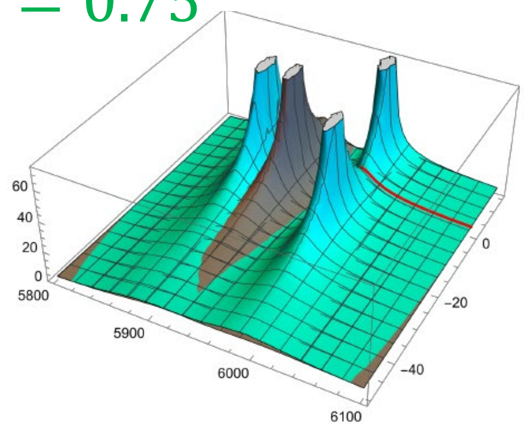
FRS & SRS

$|T_{\Sigma_b\pi}(\sqrt{s} = x + iy)|$

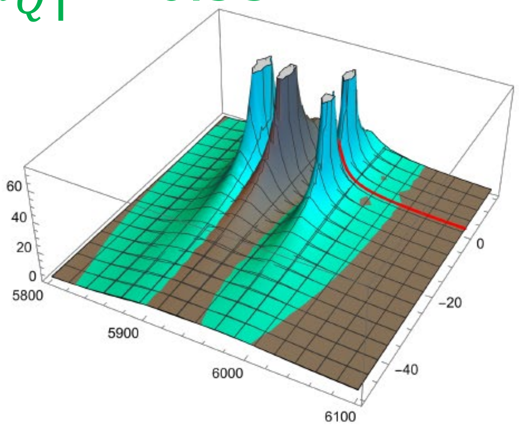
$|d_Q| = 0$

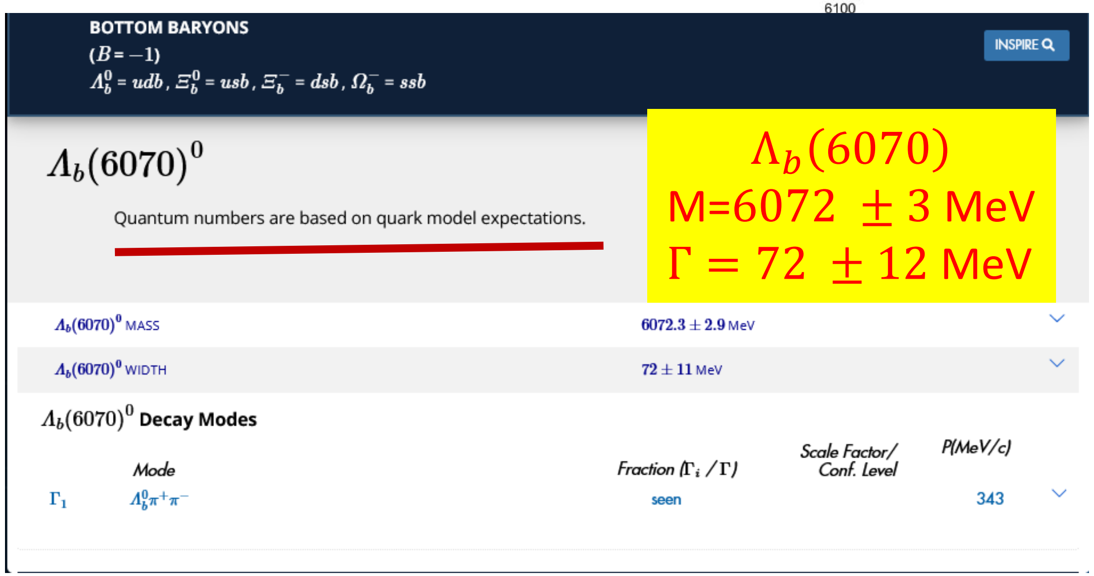


$|d_Q| = 0.75$



$|d_Q| = 0.55$




BOTTOM BARYONS

$(B = -1)$

$\Lambda_b^0 = udb$, $\Xi_b^0 = usb$, $\Xi_b^- = dsb$, $\Omega_b^- = ssb$

INSPIRE

$\Lambda_b(6070)^0$

Quantum numbers are based on quark model expectations.

$\Lambda_b(6070)^0$ MASS	6072.3 ± 2.9 MeV
$\Lambda_b(6070)^0$ WIDTH	72 ± 11 MeV

$\Lambda_b(6070)^0$ Decay Modes

	Mode	Fraction (Γ_i/Γ)	Scale Factor/ Conf. Level	P(MeV/c)
Γ_1	$\Lambda_b^0\pi^+\pi^-$	seen		343

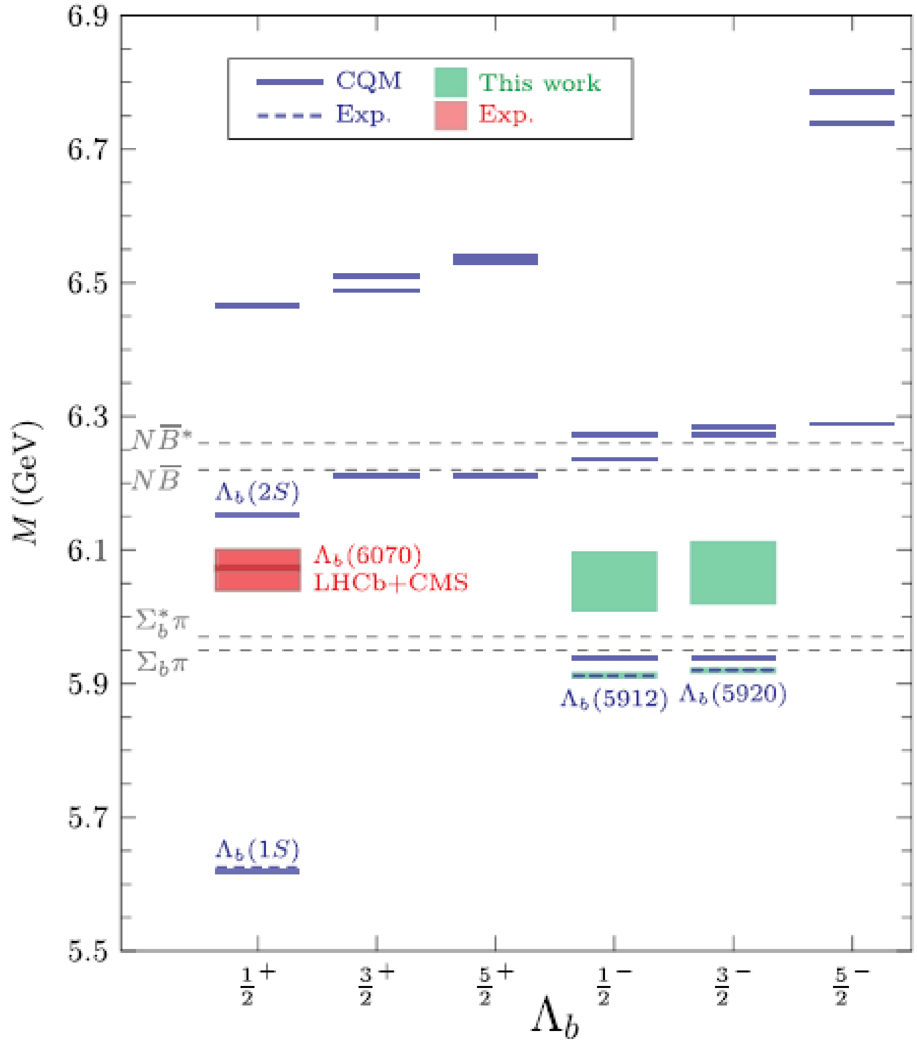
$\Lambda_b(6070)$

M=6072 $\pm$ 3 MeV

Γ = 72 $\pm$ 12 MeV

poles in the SRS

		$\Sigma_b\pi$ $[J^P = 1/2^-]$				$\Sigma_b^*\pi$ $[J^P = 3/2^-]$			
Λ [GeV]	$\lvert d_Q\rvert$	M [MeV]	Γ [MeV]	$\lvert g_{\Sigma_b\pi}\rvert$	$\phi_{\Sigma_b\pi}$	M [MeV]	Γ [MeV]	$\lvert g_{\Sigma_b^*\pi}\rvert$	$\phi_{\Sigma_b^*\pi}$
0.4	1.79 ± 0.11	6053 ± 6	85.2 ± 0.4	1.60 ± 0.03	-0.70 ± 0.01	6066 ± 6	90.0 ± 0.5	1.65 ± 0.03	-0.67 ± 0.01
0.65	1.06 ± 0.06	6008 ± 3	49.6 ± 0.5	1.46 ± 0.02	-0.53 ± 0.01	6021 ± 3	52.9 ± 0.4	1.54 ± 0.02	-0.50 ± 0.01
0.9	0.75 ± 0.04	5983 ± 3	24.5 ± 0.7	1.23 ± 0.01	-0.41 ± 0.01	5995 ± 2	25.9 ± 0.8	1.35 ± 0.01	-0.38 ± 0.01
1.15	0.55 ± 0.04	5966 ± 3	9.5 ± 1.1	0.97 ± 0.01	-0.30 ± 0.01	5976 ± 3	7 ± 2	$1.15^{+0.06}_{-0.02}$	$-0.30^{+0.01}_{-0.05}$



- LHCb reported a broad excess of events in the $\Lambda_b\pi^+\pi^-$ spectrum in region of 6040 - 6100 MeV.
- The spin and parity quantum-numbers of the $\Lambda_b(6070)$ were not established by LHCb.
- In the RPP, it is assumed to be the radial excitation $\Lambda_b(2S)$, which would have $J^P = (^1/_2)^+$
- We naturally find **for UV cutoffs around 500 MeV** two resonances ($J^P = (^1/_2)^-$ and $J^P = (^3/_2)^-$) which should be observed in the $\Lambda_b\pi^+\pi^-$ in the region of 6050 MeV

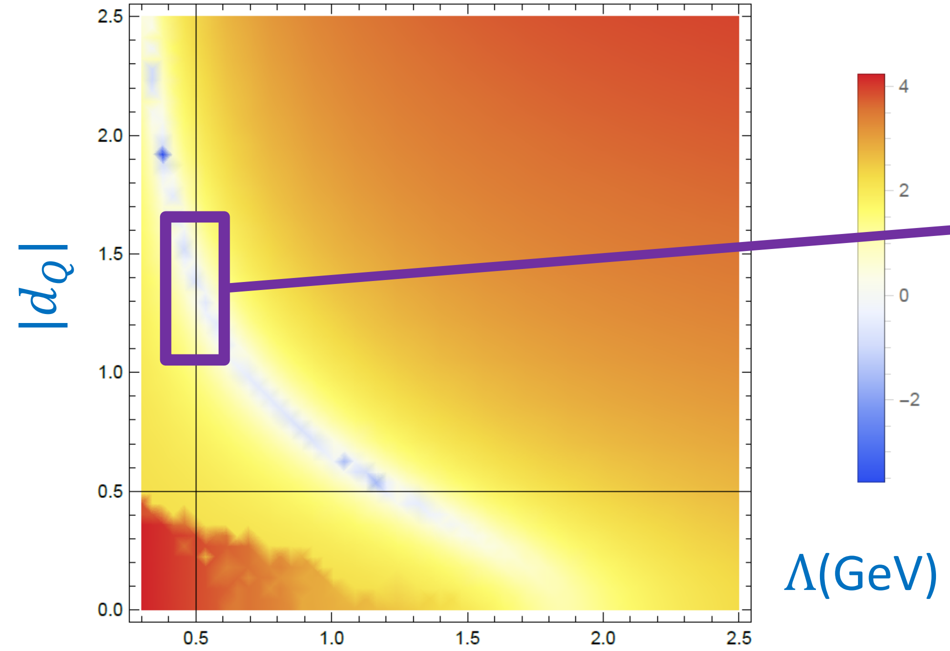
the vertical range shows masses $\pm$ widths of our predicted resonances. The horizontal range does not have any meaning since the resonances have $(^1/_2)^-$ and $(^3/_2)^-$ spin-parities

		$\Sigma_b\pi$ $[J^P = 1/2^-]$				$\Sigma_b^*\pi$ $[J^P = 3/2^-]$			
Λ [GeV]	$\|d_Q\|$	M [MeV]	Γ [MeV]	$\|g_{\Sigma_b\pi}\|$	$\phi_{\Sigma_b\pi}$	M [MeV]	Γ [MeV]	$\|g_{\Sigma_b^*\pi}\|$	$\phi_{\Sigma_b^*\pi}$
0.4	1.79 ± 0.11	6053 ± 6	85.2 ± 0.4	1.60 ± 0.03	-0.70 ± 0.01	6066 ± 6	90.0 ± 0.5	1.65 ± 0.03	-0.67 ± 0.01
0.65	1.06 ± 0.06	6008 ± 3	49.6 ± 0.5	1.46 ± 0.02	-0.53 ± 0.01	6021 ± 3	52.9 ± 0.4	1.54 ± 0.02	-0.50 ± 0.01
0.9	0.75 ± 0.04	5983 ± 3	24.5 ± 0.7	1.23 ± 0.01	-0.41 ± 0.01	5995 ± 2	25.9 ± 0.8	1.35 ± 0.01	-0.38 ± 0.01
1.15	0.55 ± 0.04	5966 ± 3	9.5 ± 1.1	0.97 ± 0.01	-0.30 ± 0.01	5976 ± 3	7 ± 2	$1.15^{+0.06}_{-0.02}$	$-0.30^{+0.01}_{-0.05}$

CQM(λ, ρ): T. Yoshida, E. Hiyama, A. Hosaka, M. Oka, and K. Sadato, PRD92 (2015) 114029

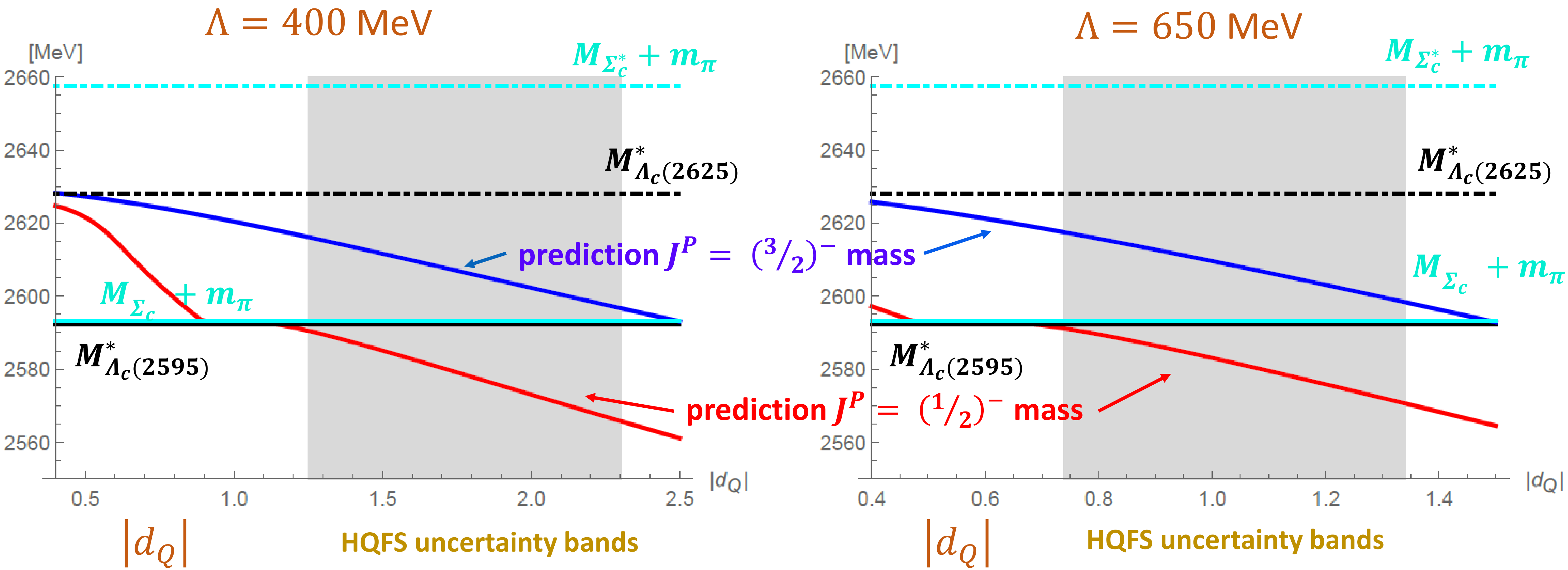
- LHCb reported a broad excess of events in the $\Lambda_b\pi^+\pi^-$ spectrum in region of 6040 - 6100 MeV.
- The spin and parity quantum-numbers of the $\Lambda_b(6070)$ were not established by LHCb.
- In the RPP, it is assumed to be the radial excitation $\Lambda_b(2S)$, which would have $J^P = (^1/_2)^+$
- We naturally find **<u>for UV cutoffs around 500 MeV</u>** two resonances ($J^P = (^1/_2)^-$ and $J^P = (^3/_2)^-$) which should be observed in the $\Lambda_b\pi^+\pi^-$ in the region of 6050 MeV
- Hence, we can fix the UV cutoffs and the strength d_Q of the coupling of the $\Sigma_c^{(*)}\pi$ pair to the CQM lowest-lying λ−mode excitation, which are now fully determined by the pole position of the $\Lambda_b(5912)$ and $\Lambda_b(5920)$ resonances
- Now using **<u>Heavy Quark Flavor Symmetry</u>** we can make predictions in the **<u>charm sector</u>**

$\text{Log}[\chi^2(|d_Q|,\Lambda)]$



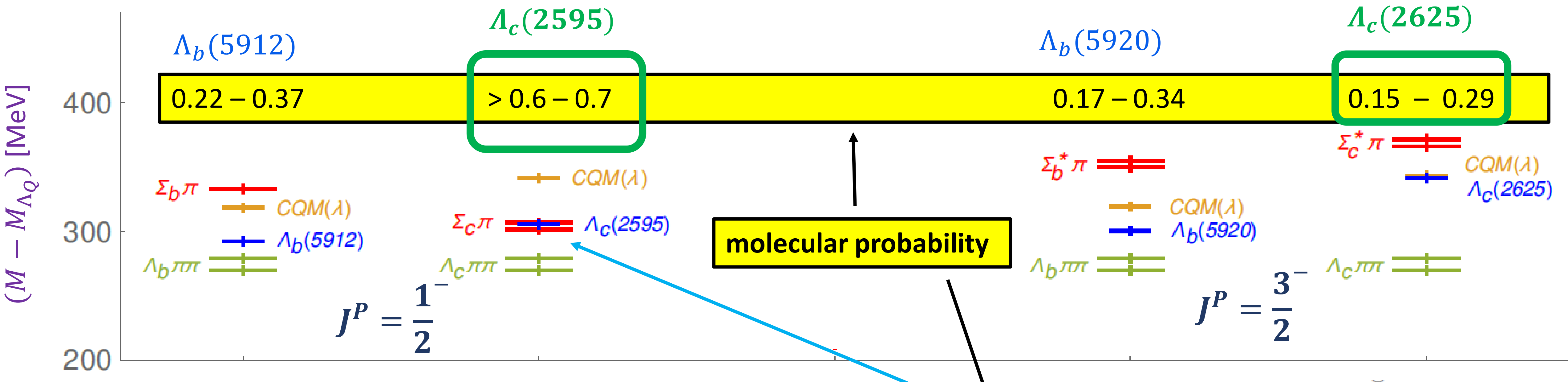
favored <u>natural size</u> UV cutoffs
$\Lambda \sim 650 - 400$ MeV
and $|d_Q(\Lambda)| \sim$ 1-1.8

charm sector



For each UV cutoff, the **grey band shows the range of values for $|d_Q|$** obtained in the bottom sector, enhanced by HQFS breaking corrections

Reasonable simultaneous description of the $\Lambda_c(2595)$ and $\Lambda_c(2625)$ resonances considering chiral $\Sigma_c^{(*)}\pi$ pairs and their coupling to lowest-lying $\boldsymbol{\lambda}$–mode CQM states fixed in the bottom sector from $\Lambda_b(5912)$, $\Lambda_b(5920)$ and $\Lambda_b(6070)$



$$\partial \overline{G}_{\Sigma_c\pi}/\partial\sqrt{s}\Big|_{\sqrt{s}=M_{\Lambda_c(2595)}} \sim -(0.7^{+2.4}_{-0.2})$$

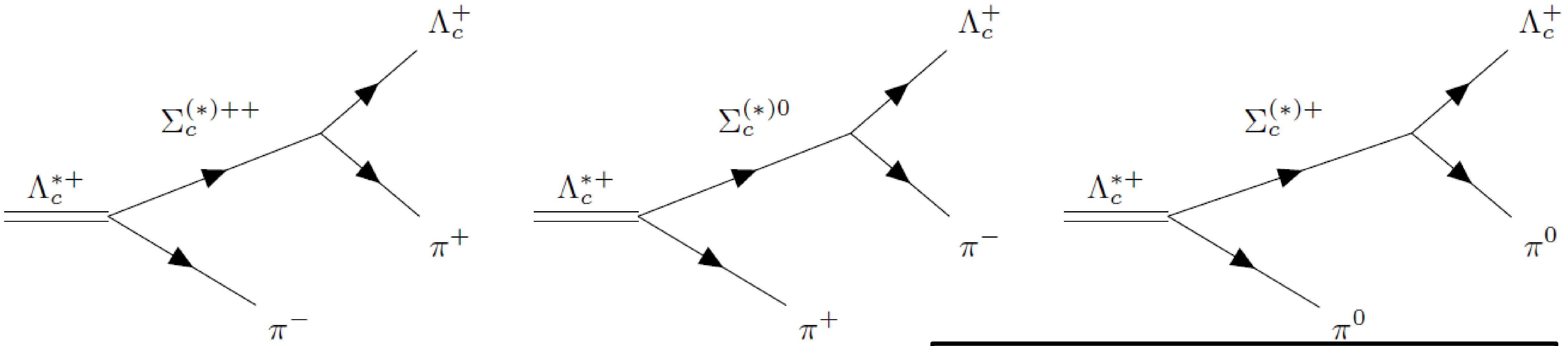
diverges at threshold!

$$P_{\Sigma_Q^{(*)}\pi} = -g^2_{\Sigma_Q^{(*)}\pi}\,\frac{\partial \overline{G}_{\Sigma_Q^{(*)}\pi}(\sqrt{s})}{\partial\sqrt{s}}\Bigg|_{\sqrt{s}=\sqrt{s_R}}$$

$g^2_{\Lambda_c(2595)\Sigma_c\pi} = 1.37 \pm 0.35$

- ✓ The $\Lambda_c(2595)$ and the $\Lambda_c(2625)$ might not be HQSS partners **(Λ_c^* –puzzle)**
- ✓ The $J^P = 3/2^-$ resonance should be viewed mostly as a quark-model state naturally predicted to lie very close to its nominal mass
- ✓ The $\Lambda_c(2595)$ is predicted to have a predominant chiral $\Sigma_c\pi$ molecular structure, which threshold is located much more closer than the mass of the bare three-quark state

Three body $\Lambda_c\pi\pi$ decay width and the $g_{\Lambda_c^*\Sigma_c^{(*)}\pi}$ coupling



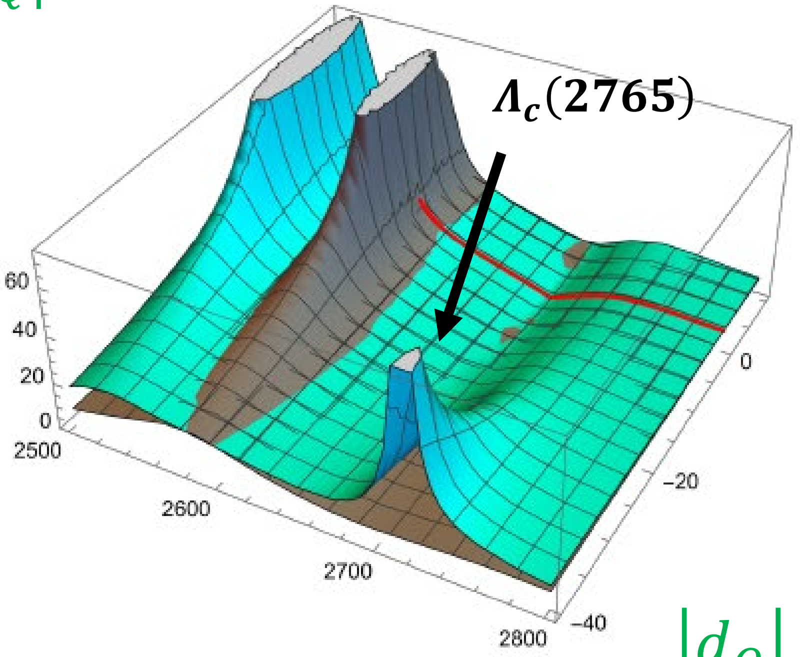
$$\Gamma^{R\dagger}[\Lambda_c(2595) \to \Lambda_c\pi\pi] = (1.9 \pm 0.2) \times g^2_{\Lambda_c(2595)\Sigma_c\pi} \text{ [MeV]},$$
$$\Gamma^{R\dagger}[\Lambda_c(2625) \to \Lambda_c\pi\pi] = (0.27 \pm 0.01) \times g^2_{\Lambda_c(2625)\Sigma_c^*\pi} \text{ [MeV]}$$

$\Gamma[\Lambda_c(2595)] = 2.6 \pm 0.6$ **MeV**

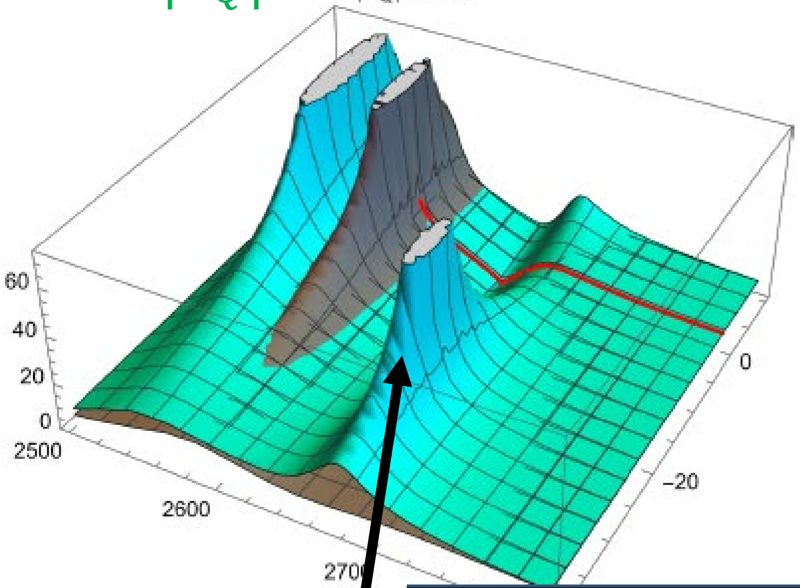
$g^2_{\Lambda_c(2595)\Sigma_c\pi} = 1.37 \pm 0.35$

In the charm sector, these resonant contributions to the $\Lambda_c\pi\pi$ three-body decay channel are much larger than in the bottom sector because **the intermediate Σ_c and Σ_c^* states are closer to be on the mass shell**, especially for the $\Lambda_c(2595)$

$|d_Q| = 1.79$ & $\Lambda = 0.4$ GeV



$|d_Q| = 1.06$ & $\Lambda = 0.65$ GeV



$\Lambda_c(2765)$

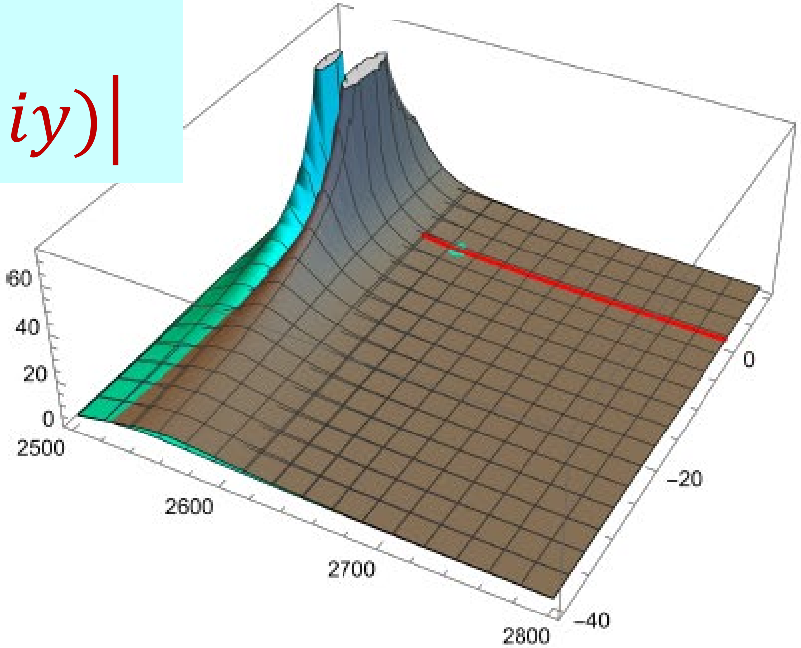
$I(J^P) = ?(?^?)$

$\Lambda_c(2765)$ or $\Sigma_c(2765)$
or
M=2766 $\pm$ 3 MeV
$\Gamma \simeq 50$ MeV

$|d_Q| = 0$

FRS & SRS

$|T_{\Sigma_c\pi}(\sqrt{s} = x + iy)|$



if $d_Q = 0$, the second resonance is not generated

CHARMED BARYONS
$(C = +1)$
$\Lambda_c^+ = udc$, $\Sigma_c^{++} = uuc$, $\Sigma_c^+ = udc$, $\Sigma_c^0 = ddc$,
$\Xi_c^+ = usc$, $\Xi_c^0 = dsc$, $\Omega_c^0 = ssc$

INSPIRE

$\Lambda_c(2765)^+$ or $\Sigma_c(2765)$ $\quad I(J^P) = ?(?^?)$

A broad, statistically significant peak (997^{+141}_{-129} events) seen in $\Lambda_c^+\pi^+\pi^-$. However, nothing at all is known about its quantum numbers, including whether it is a Λ_c^+ or a Σ_c, or whether the width might be due to overlapping states.

$\Lambda_c(2765)^+$ MASS	2766.6 ± 2.4 MeV
$\Lambda_c(2765)^+ - \Lambda_c^+$ MASS DIFFERENCE	480.1 ± 2.4 MeV
$\Lambda_c(2765)^+$ WIDTH	50 MeV

$\Lambda_c(2765)^+$ or $\Sigma_c(2765)$ **Decay Modes**

	Mode	Fraction (Γ_i/Γ)	Scale Factor/ Conf. Level	P(MeV/c)
Γ_1	$\Lambda_c^+\pi^+\pi^-$	seen		356

poles in the SRS

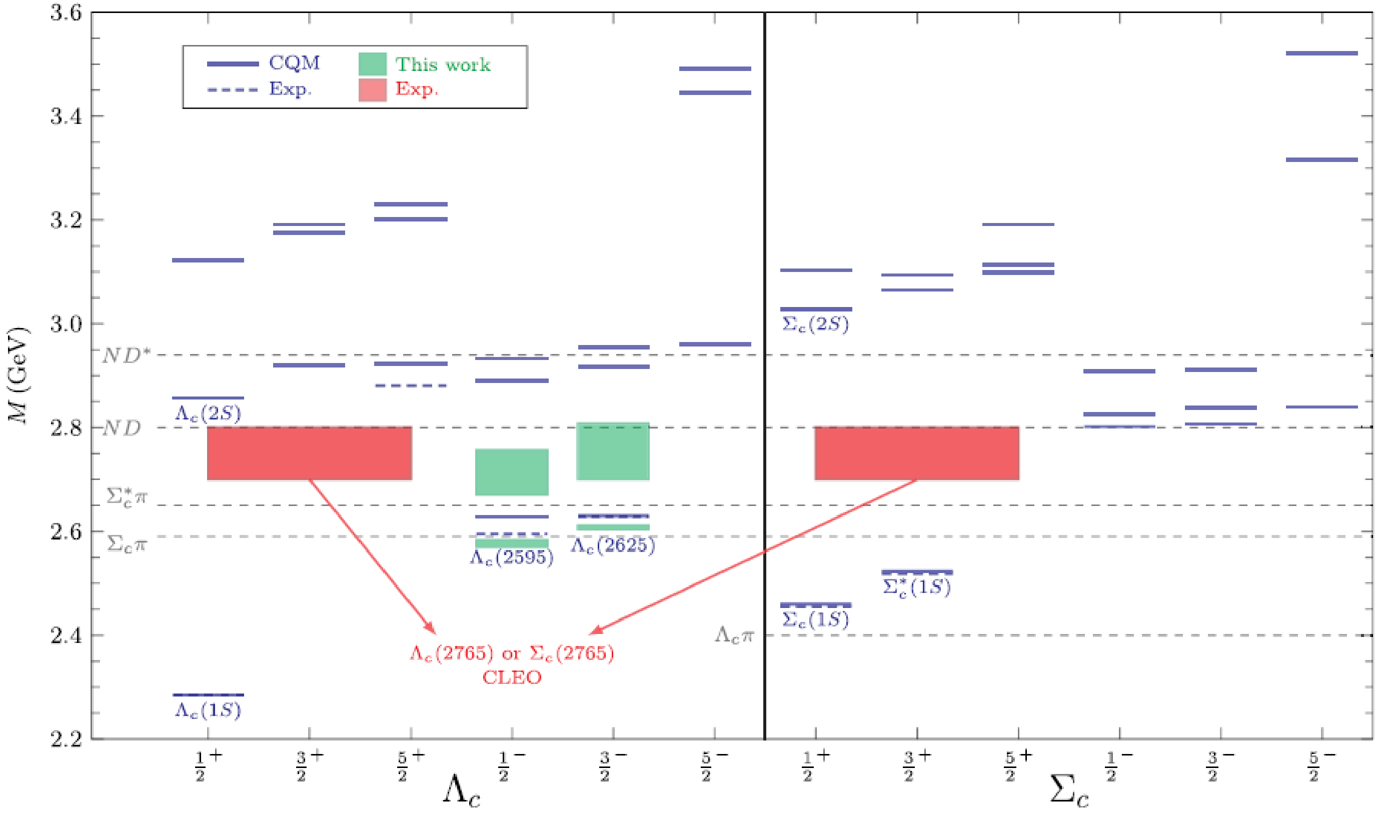
		$\Sigma_c\pi$ $[J^P=1/2^-]$				$\Sigma_c^*\pi$ $[J^P=3/2^-]$			
Λ [GeV]	$\lvert d_Q \rvert$	M [MeV]	Γ [MeV]	$\lvert g_{\Sigma_c\pi} \rvert$	$\phi_{\Sigma_c\pi}$	M [MeV]	Γ [MeV]	$\lvert g_{\Sigma_c^*\pi} \rvert$	$\phi_{\Sigma_c^*\pi}$
0.4	1.79 ± 0.11	2714 ± 6	85.7 ± 0.6	1.60 ± 0.02	-0.92 ± 0.01	2754 ± 6	107.7 ± 0.3	1.80 ± 0.03	-0.77 ± 0.01
0.65	1.06 ± 0.06	2674 ± 4	45.2 ± 1.1	1.33 ± 0.01	-0.75 ± 0.01	2711 ± 3	62.5 ± 0.5	1.66 ± 0.02	-0.57 ± 0.01

- The CLEO collaboration investigated the spectrum of charmed baryons which decay into $\Lambda_c\pi^+\pi^-$ spectrum and found a evidence of a broad state ($\Gamma \approx 50$ MeV) which would have an invariant mass roughly 480 MeV above that of the Λ_c ground state baryon
- This is collected in the RPP as the $\Lambda_c(2765)$ or $\Sigma_c(2765)$ and it is explicitly stated that nothing at all is known about its quantum numbers, including whether it is a Λ_c, or a Σ_c, or whether the width might be due to overlapping states

- For UV cutoffs in the range 400-650 MeV, we obtain broad resonances around 2675-2755 MeV in both the $J^P = (^1/_2)^-$ and $J^P = (^3/_2)^-$ sectors, which will provide a natural explanation for the excess of events in the $\Lambda_c\pi^+\pi^-$ spectrum reported by CLEO.
- These resonances will be heavy quark flavor siblings of those related to the $\Lambda_b(6070)$ in the bottom sector.

poles in the SRS

		$\Sigma_c\pi$ $[J^P = 1/2^-]$				$\Sigma_c^*\pi$ $[J^P = 3/2^-]$			
Λ [GeV]	$\lvert d_Q \rvert$	M [MeV]	Γ [MeV]	$\lvert g_{\Sigma_c\pi} \rvert$	$\phi_{\Sigma_c\pi}$	M [MeV]	Γ [MeV]	$\lvert g_{\Sigma_c^*\pi} \rvert$	$\phi_{\Sigma_c^*\pi}$
0.4	1.79 ± 0.11	2714 ± 6	85.7 ± 0.6	1.60 ± 0.02	-0.92 ± 0.01	2754 ± 6	107.7 ± 0.3	1.80 ± 0.03	-0.77 ± 0.01
0.65	1.06 ± 0.06	2674 ± 4	45.2 ± 1.1	1.33 ± 0.01	-0.75 ± 0.01	2711 ± 3	62.5 ± 0.5	1.66 ± 0.02	-0.57 ± 0.01

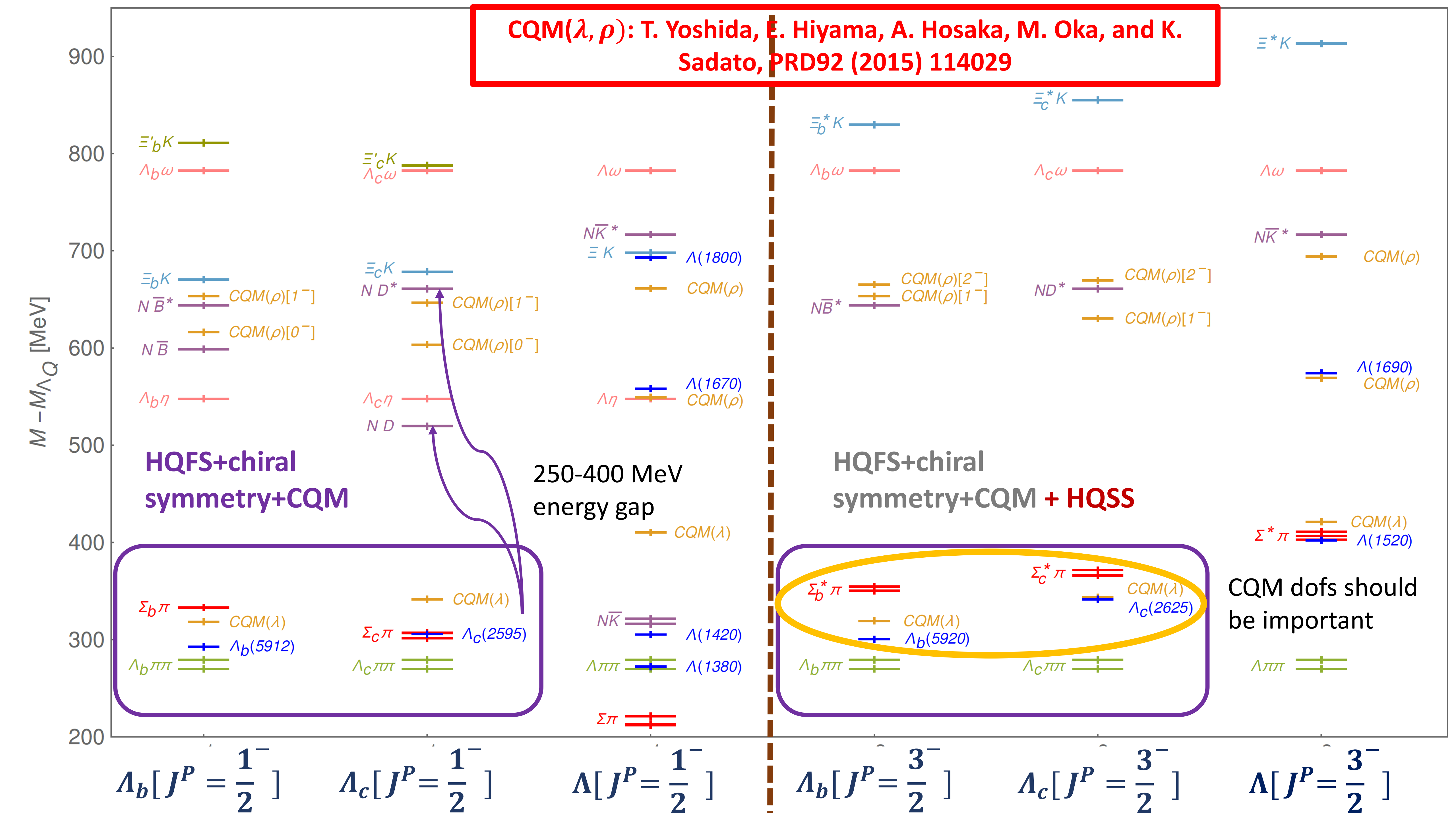


the vertical range shows masses $\pm$ widths of our predicted resonances. The horizontal range does not have any meaning since the resonances have $(1/2)^-$ and $(3/2)^-$ spin-parities

CQM(λ, ρ): T. Yoshida, E. Hiyama, A. Hosaka, M. Oka, and K. Sadato, PRD92 (2015) 114029

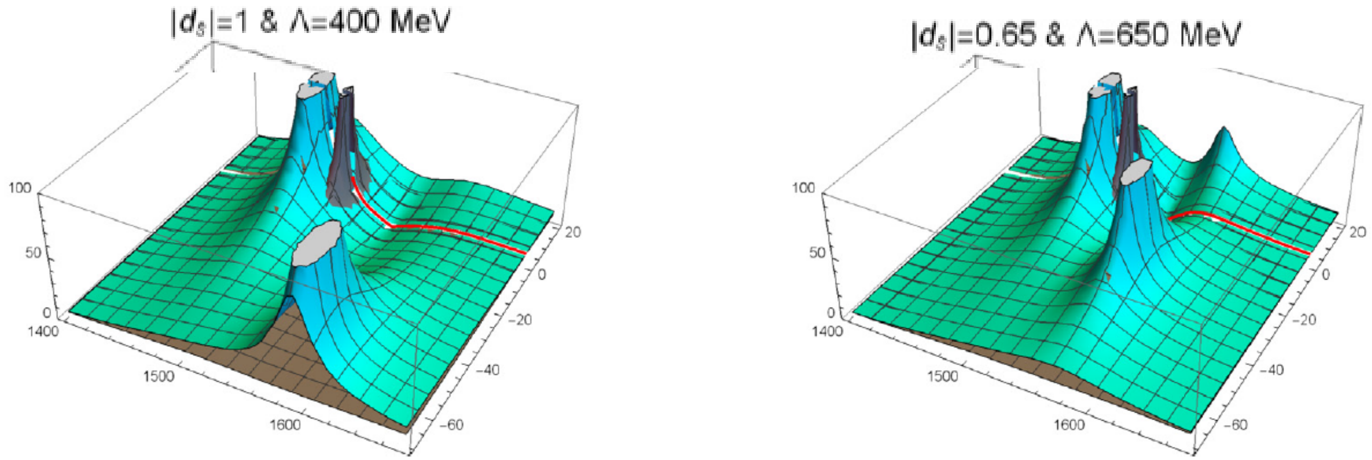
$\Lambda_c(2765)$ or $\Sigma_c(2765)$
or
M=2766 $\pm$ 3 MeV
$\Gamma \simeq 50$ MeV

CLEO



CQM(λ, ρ): T. Yoshida, E. Hiyama, A. Hosaka, M. Oka, and K. Sadato, PRD92 (2015) 114029
M − M_ΛQ [MeV]
900
800
700
600
500
400
300
200
Ξ'_b K
Λ_b ω
Ξ_b K
CQM(ρ)[1⁻]
N B̄*
CQM(ρ)[0⁻]
N B̄
Λ_b η
Σ_b π
CQM(λ)
Λ_b(5912)
Λ_b ππ
Ξ'_c K
Λ_c ω
Ξ_c K
N D*
CQM(ρ)[1⁻]
CQM(ρ)[0⁻]
Λ_c η
N D
CQM(λ)
Σ_c π
Λ_c(2595)
Λ_c ππ
Λω
NK̄*
Ξ K
Λ(1800)
CQM(ρ)
Λ(1670)
Λη
CQM(ρ)
CQM(λ)
NK̄
Λ(1420)
Λππ
Λ(1380)
Σπ
HQFS+chiral symmetry+CQM
250-400 MeV energy gap
Ξ*_b K
Λ_b ω
CQM(ρ)[2⁻]
CQM(ρ)[1⁻]
NB̄*
Σ*_b π
CQM(λ)
Λ_b(5920)
Λ_b ππ
Ξ*_c K
Λ_c ω
ND*
CQM(ρ)[2⁻]
CQM(ρ)[1⁻]
Σ*_c π
CQM(λ)
Λ_c(2625)
Λ_c ππ
Ξ* K
Λω
NK̄*
CQM(ρ)
Λ(1690)
CQM(ρ)
CQM(λ)
Σ* π
Λ(1520)
Λππ
HQFS+chiral symmetry+CQM + HQSS
CQM dofs should be important
Λ_b[J^P = 1⁻/2]
Λ_c[J^P = 1⁻/2]
Λ[J^P = 1⁻/2]
Λ_b[J^P = 3⁻/2]
Λ_c[J^P = 3⁻/2]
Λ[J^P = 3⁻/2]

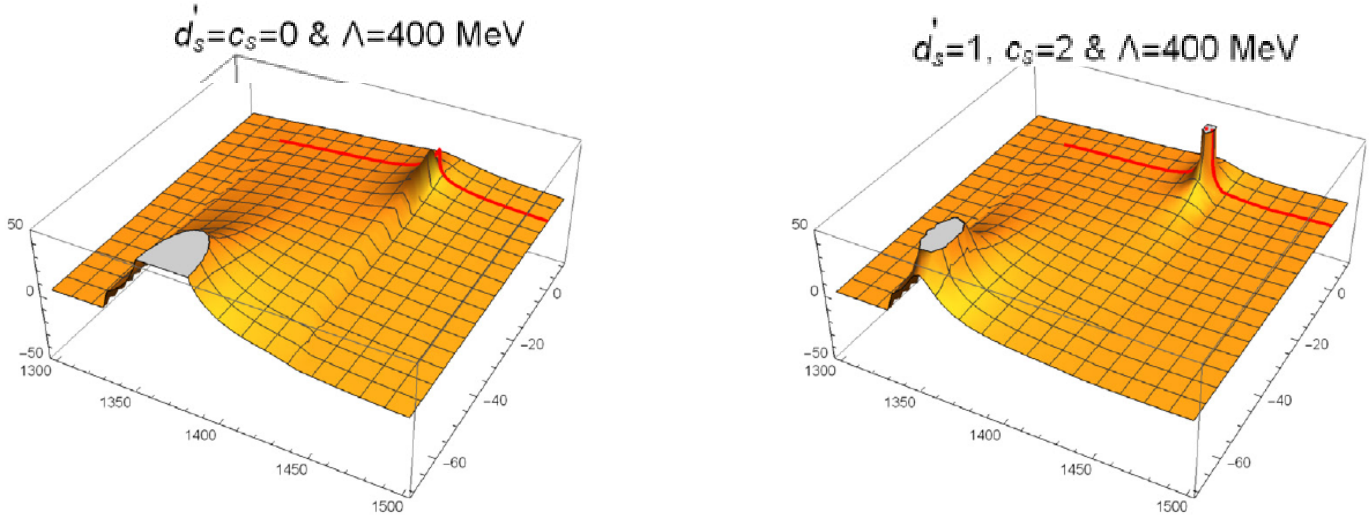
strange sector



$J^P = 3/2^-$ $\Lambda(1520) + 1R$

$\pi\Sigma^* \longrightarrow \pi\Sigma^*$

Fig. 3.8. Absolute value of the $T_{\Sigma^*\pi}$-matrix (fermi units), both in the FRS (gray) and SRS (greenish hues) and for ($|d_Q| = 1.0$, $\Lambda = 400$ MeV (left) and ($|d_Q| = 0.65$, $\Lambda = 650$ MeV (right), as a function of complex $\sqrt{s} = x + iy$ in MeV. The FRS pole is placed at 1518 MeV in both cases, while the above threshold SRS ones are located at $(M, \Gamma) = (1590, 115)$ MeV and $(M, \Gamma) = (1571, 60)$ MeV, resp



$J^P = 1/2^-$

double pole $\Lambda(1405)$

$\bar{K}N \rightarrow \pi\Sigma$

Fig. 3.9. Absolute value of the $[J^P = 1/2^-]$ $T_{N\bar{K}\to\Sigma\pi}$ matrix element (in fermi units) for both the FRS [$\mathrm{Im}\sqrt{s} > 0$] and the SRS [$\mathrm{Im}\sqrt{s} < 0$] as a function of the complex $\sqrt{s} = x + iy$ in MeV. The UV cutoff is $\Lambda = 400$ MeV, and CQM degrees of freedom are disconnected in the left plot, while they are coupled to the baryon–meson pairs in the right panel using $d'_s = 1$ and $c_s = 2$. We also display the scattering line (red solid curve) in both cases. As noted in Table 3.5, in the left panel, the higher $\Lambda(1405)$ pole is related to a virtual state which produces peaks in the FRS and SRS. In the right panel, the higher $\Lambda(1405)$ shows up as a narrow resonance (pole in the SRS) close, but below, the $N\bar{K}$ threshold.

Backup Slides