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Lowest-lying odd parity open heavy-flavor hyperons

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CHARMED BARYONS ($C = +1$)

PDG particle data group Live

$\Lambda_c^+ = udc$, $\Sigma_c^{++} = uuc$, $\Sigma_c^+ = udc$, $\Sigma_c^0 = ddc$,

$\Xi_c^+ = usc$, $\Xi_c^0 = dsc$, $\Omega_c^0 = ssc$

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

$\Lambda_b(5920)^0$

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%

bottom sector

$\Lambda_b(5920)^0$ Decay Modes

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

$\Lambda_b(5912)^0$

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

charm sector

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

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

$\Lambda_c(2625)^+$ 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

Outline

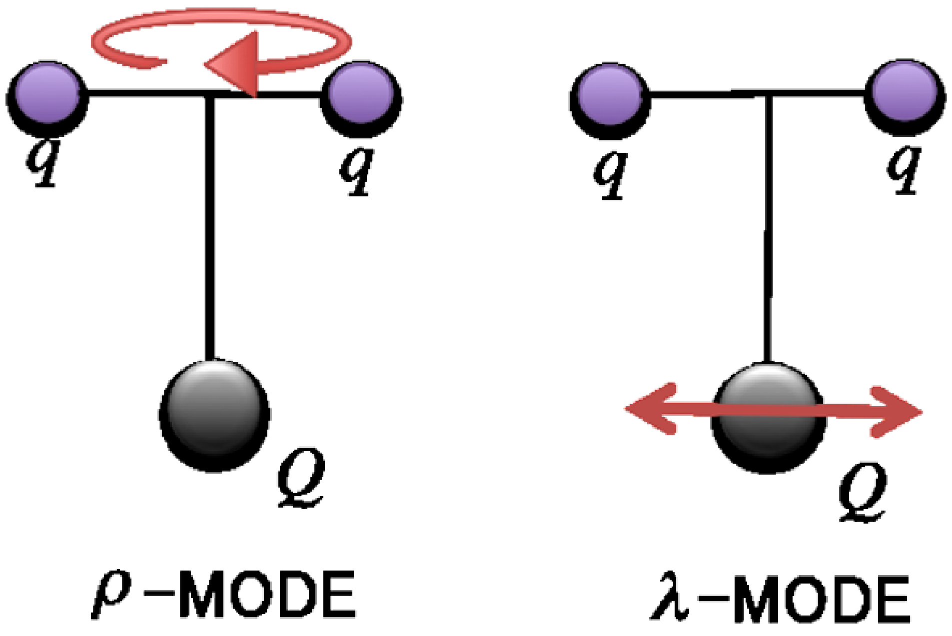
1. Low-lying odd-parity baryon states: PDG and CQM
2. Chiral and heavy-quark symmetries. CQM and Golstone boson-baryon (ϕB) degrees of freedom
3. Odd parity charm and bottom Λ_Q baryons: **chiral $\boldsymbol{\Sigma_Q^{(*)}\pi}$ and CQM exchange potentials**
4. The $\Lambda_b(5912)$, $\Lambda_b(5920)$, $\Lambda_c(2595)$ and $\Lambda_c(2625)$ states
5. The $\Lambda_b(6070)$ and $\Lambda_c(2765)$ heavy quark flavor sibling resonances
6. Conclusions

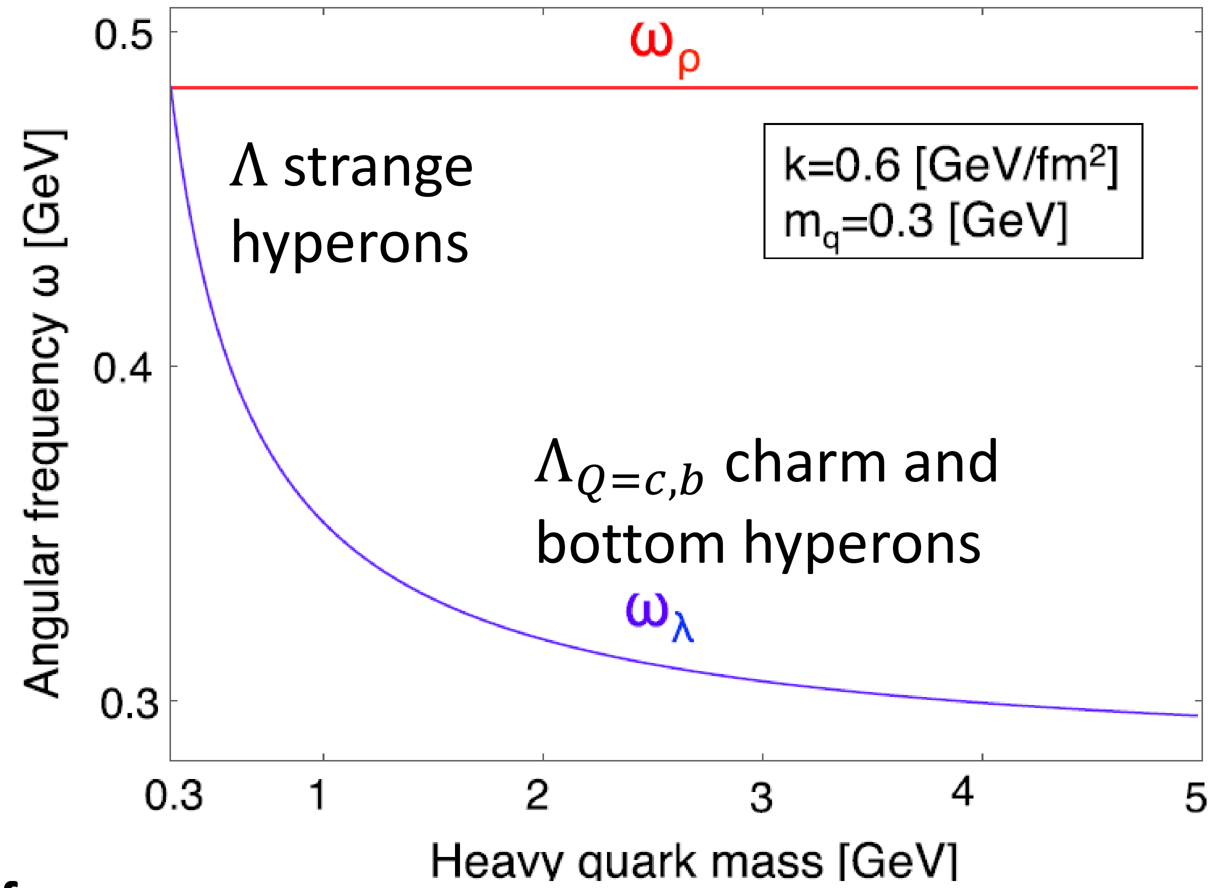
PHYSICAL REVIEW D **92**, 114029 (2015)

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)

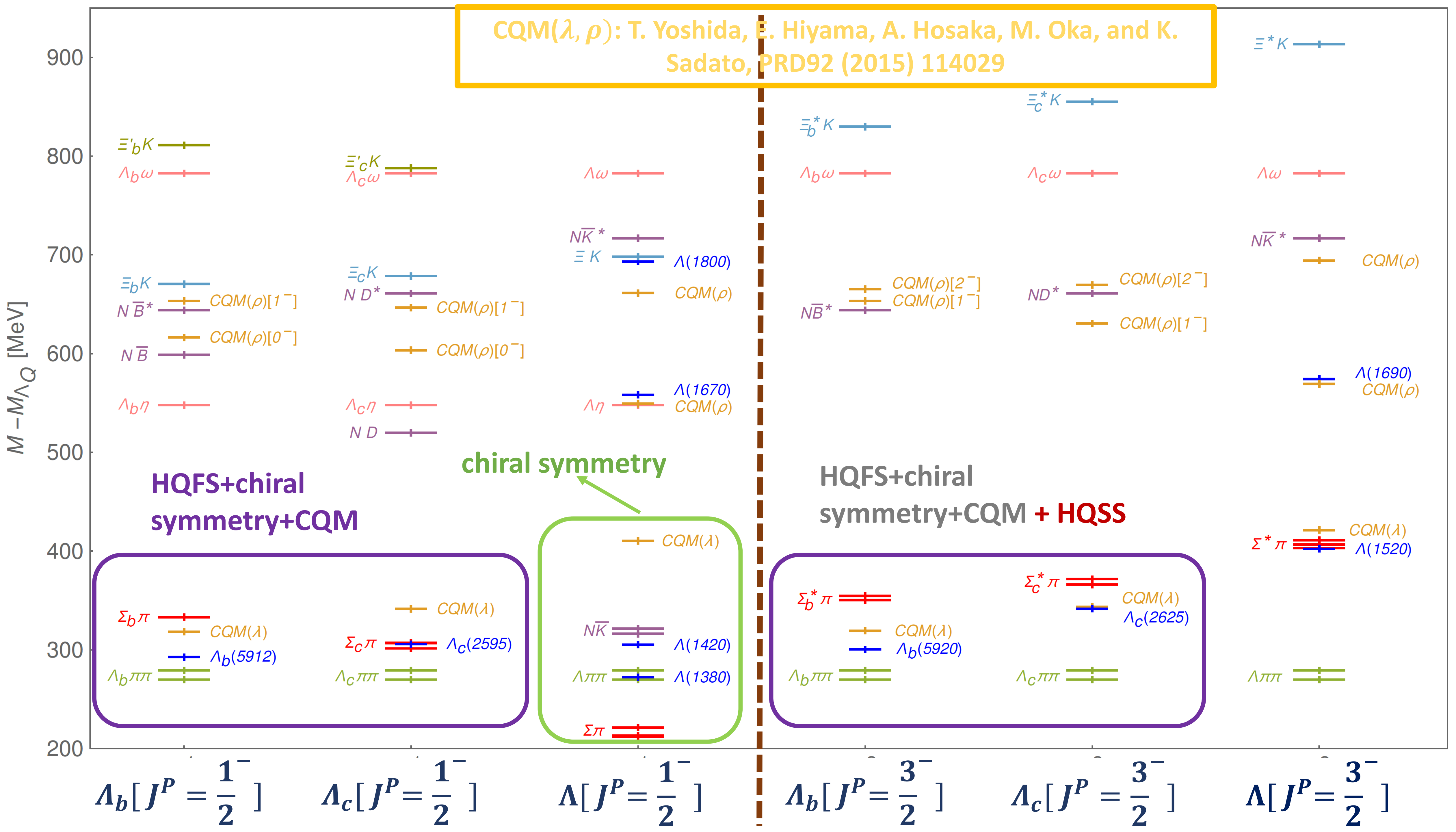




ρ- and λ-mode excitations of a **single-heavy baryon**

λ mode: excitations between the Q and the ldof

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


CQM(λ, ρ): T. Yoshida, E. Hiyama, A. Hosaka, M. Oka, and K. Sadato, PRD92 (2015) 114029
M − M_ΛQ [MeV]
chiral symmetry
HQFS+chiral symmetry+CQM
HQFS+chiral symmetry+CQM + HQSS
Λb[J^P = 1/2^−]
Λc[J^P = 1/2^−]
Λ[J^P = 1/2^−]
Λb[J^P = 3/2^−]
Λc[J^P = 3/2^−]
Λ[J^P = 3/2^−]
Λb(5912)
Λc(2595)
Λ(1420)
Λ(1380)
Λ(1670)
Λ(1800)
Λb(5920)
Λc(2625)
Λ(1520)
Λ(1690)
CQM(λ)
CQM(ρ)
CQM(ρ)[0^−]
CQM(ρ)[1^−]
CQM(ρ)[2^−]

Chiral symmetry ⟹ EFT: Chiral perturbation theory

effective field theory constructed with a Lagrangian consistent with the (approximate) chiral symmetry of quantum chromodynamics (QCD), as well as the other symmetries of parity and charge conjugation. ChPT is a theory which allows one to study the low-energy dynamics of QCD: take explicitly into account the relevant degrees of freedom, i.e. those states with m << Λ, while the heavier excitations with M >> Λ are integrated out from the action. One gets in this way ***a string of non-renormalizable interactions among the light states, which can be organized as an expansion in powers of energy/Λ. The information on the heavier degrees of freedom is then contained in the couplings of the resulting low-energy Lagrangian.*** *Although EFTs contain an infinite number of terms, renormalizability is not an issue since, at a given order in the energy expansion, the low-energy theory is specified by a finite number of couplings; this allows for an order-by-order renormalization.*

Goldstone boson $(K, \pi, \eta, \bar{K})$ interactions with other hadrons could be described using a perturbartive chiral $[SU(3)_L \times SU(3)_R]$ EFT: **ChPT**

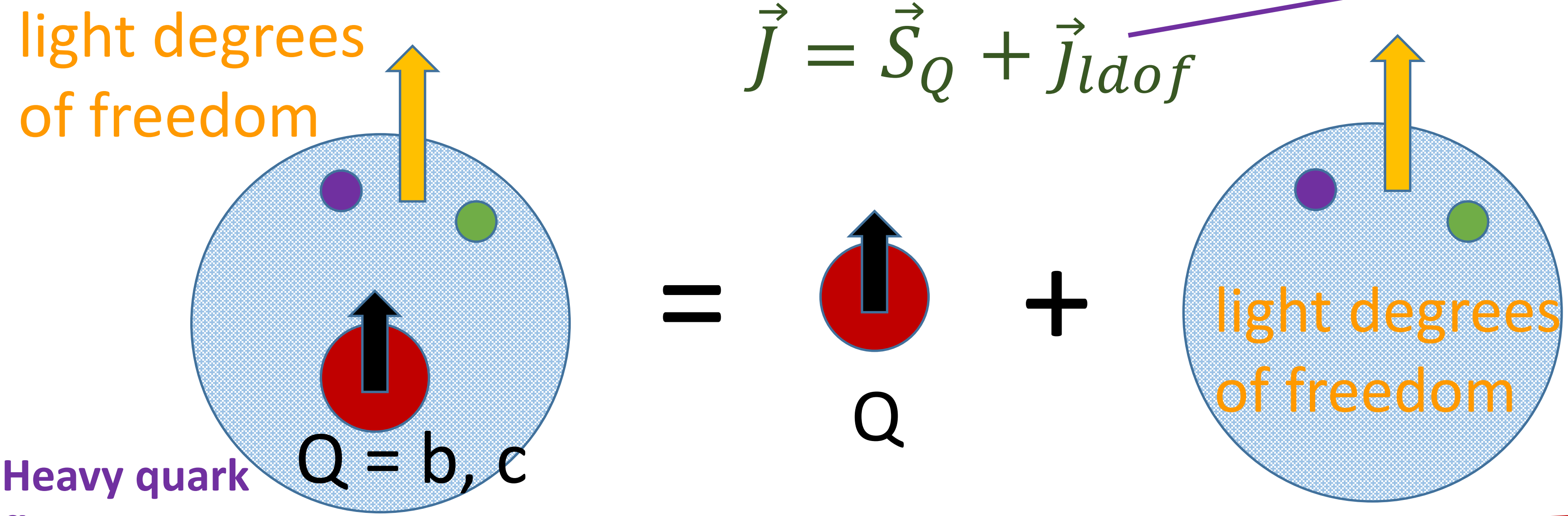
Heavy quark spin-flavor symmetry

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

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

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

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 $1/m_Q$, $\boldsymbol{M_H/m_Q \sim (1 + \frac{O(\Lambda_{QCD})}{M_Q})}$

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

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

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

1^- 0^-

Odd parity charm and bottom Λ_Q baryons: general remarks

HQSFS: ground states

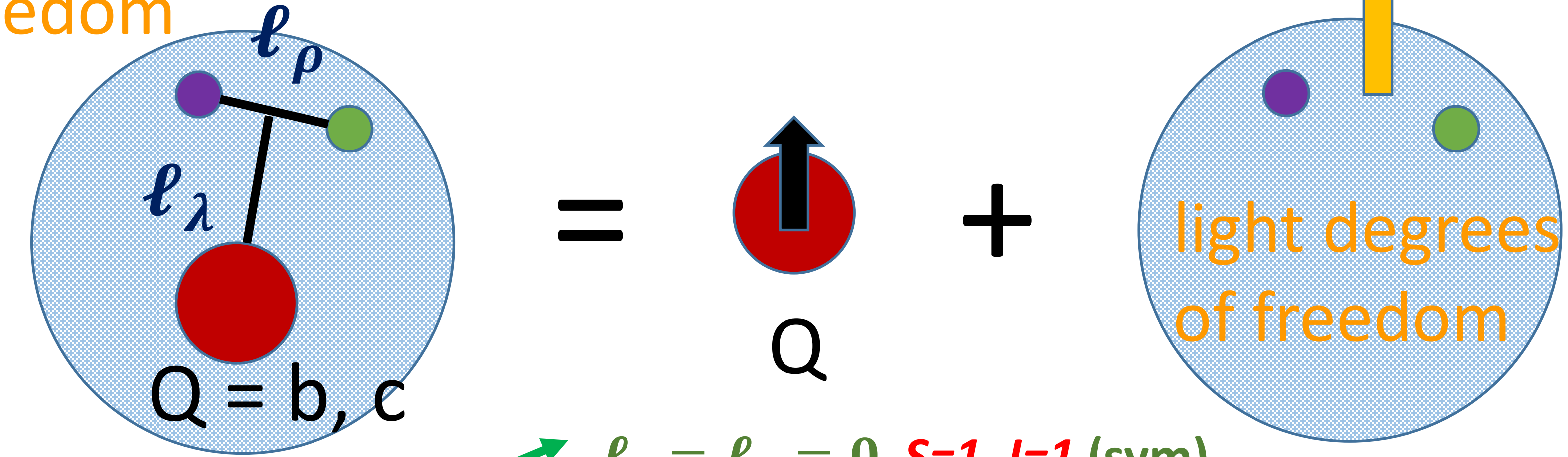
The light degrees of freedom in the hadron orbit around the heavy quark, which acts as a source of color moving with the hadrons's velocity. On average, this is also the velocity of the "brown muck".

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

HQSS

light degrees of freedom

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



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

$\ell_\lambda = \ell_\rho = 0$, **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

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

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

HQSFS: odd parity excited states

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

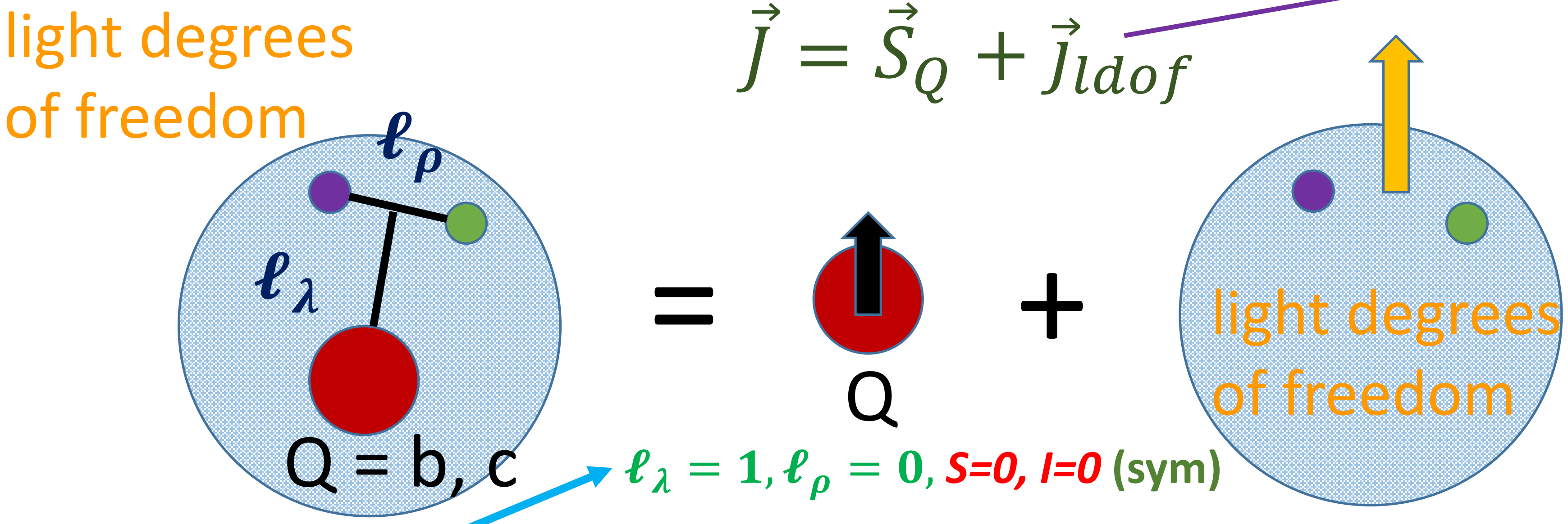
The light degrees of freedom in the hadron orbit around the heavy quark, which acts as a source of color moving with the hadrons's velocity. On average, this is also the velocity of the "brown muck".

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

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

HQSS

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



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

$\ell_\lambda = 0, \ell_\rho = 1$, *S=1, 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

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

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 ?

- ✓ 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

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

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

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

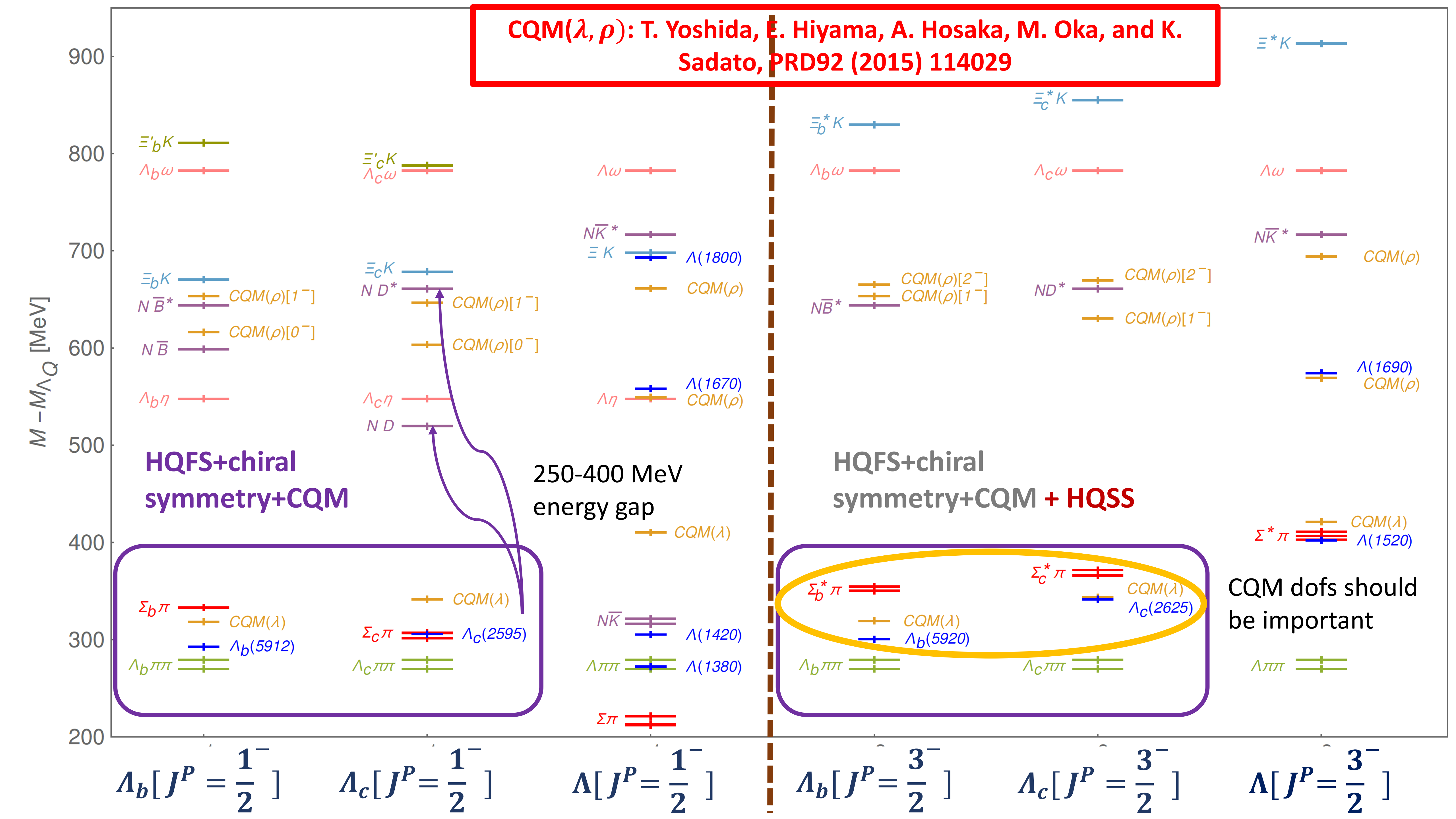
$\bar{\ell}$

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]
HQFS+chiral symmetry+CQM
250-400 MeV energy gap
HQFS+chiral symmetry+CQM + HQSS
CQM dofs should be important
Ξ'bK
ΛbΩ
ΞbK
CQM(ρ)[1⁻]
N B̄*
CQM(ρ)[0⁻]
N B̄
Λbη
Σbπ
CQM(λ)
Λb(5912)
Λbππ
Ξ'cK
Λcω
ΞcK
N D*
N D
Λcη
Σcπ
Λc(2595)
Λcππ
Λω
NK̄*
Ξ K
Λ(1800)
CQM(ρ)
Λ(1670)
Λη
NK̄
Λ(1420)
Ληπ
Λ(1380)
Σπ
Ξb*K
Λbω
CQM(ρ)[2⁻]
NB̄*
Σb*π
Λb(5920)
Ξc*K
ND*
Σc*π
Λc(2625)
Ξ*K
Λ(1690)
Σ*π
Λ(1520)
Λππ
Λb[J^P = 1⁻/2]
Λc[J^P = 1⁻/2]
Λ[J^P = 1⁻/2]
Λb[J^P = 3⁻/2]
Λc[J^P = 3⁻/2]
Λ[J^P = 3⁻/2]

Odd parity charm and bottom Λ_Q baryons: interplay between CQM and chiral $\Sigma_Q^{(*)}\pi$ degrees of freedom

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

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

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

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

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

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

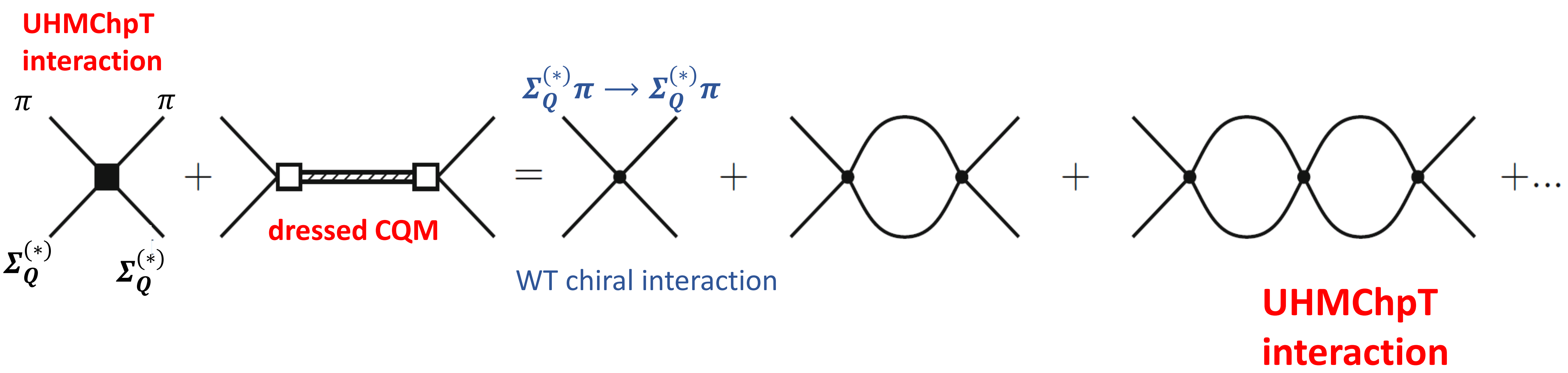
$$G_i^\mu(s_{i+}) = -\overline{G}_i(\mu^2)$$

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

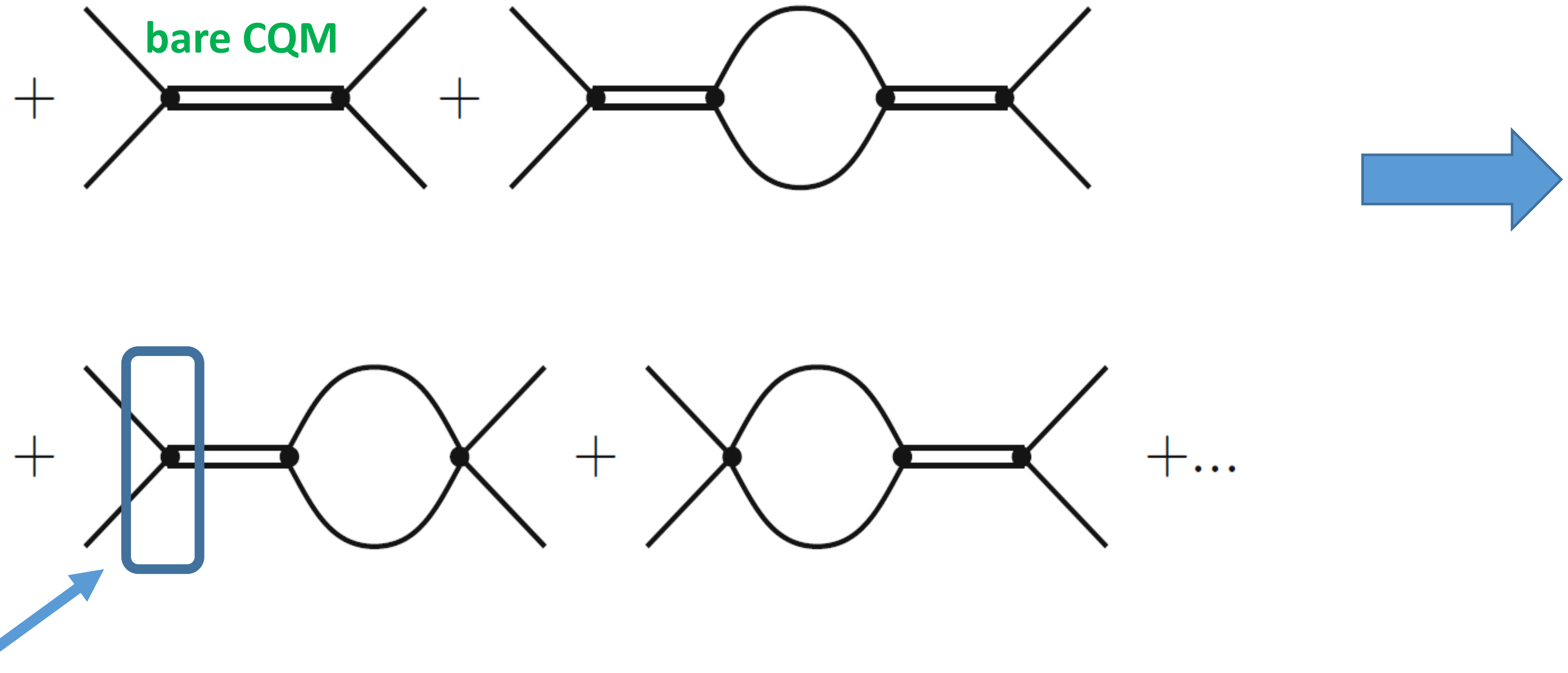
$$G_i^\Lambda(s_{i+}) = \frac{1}{4\pi^2}\frac{M_i}{m_i + M_i}\left(m_i \ln\frac{m_i}{\Lambda + \sqrt{\Lambda^2 + m_i^2}} + M_i \ln\frac{M_i}{\Lambda + \sqrt{\Lambda^2 + M_i^2}}\right)$$

renormalization scheme consistent with HQS

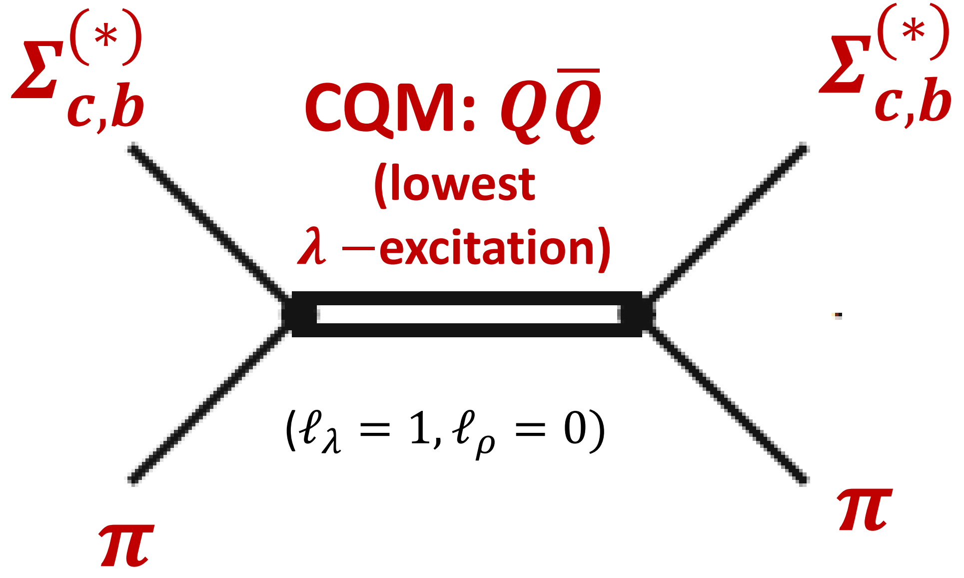
J.-X. Lu et al., PRD92 (2015) 014036



... <u>coupling</u> **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



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

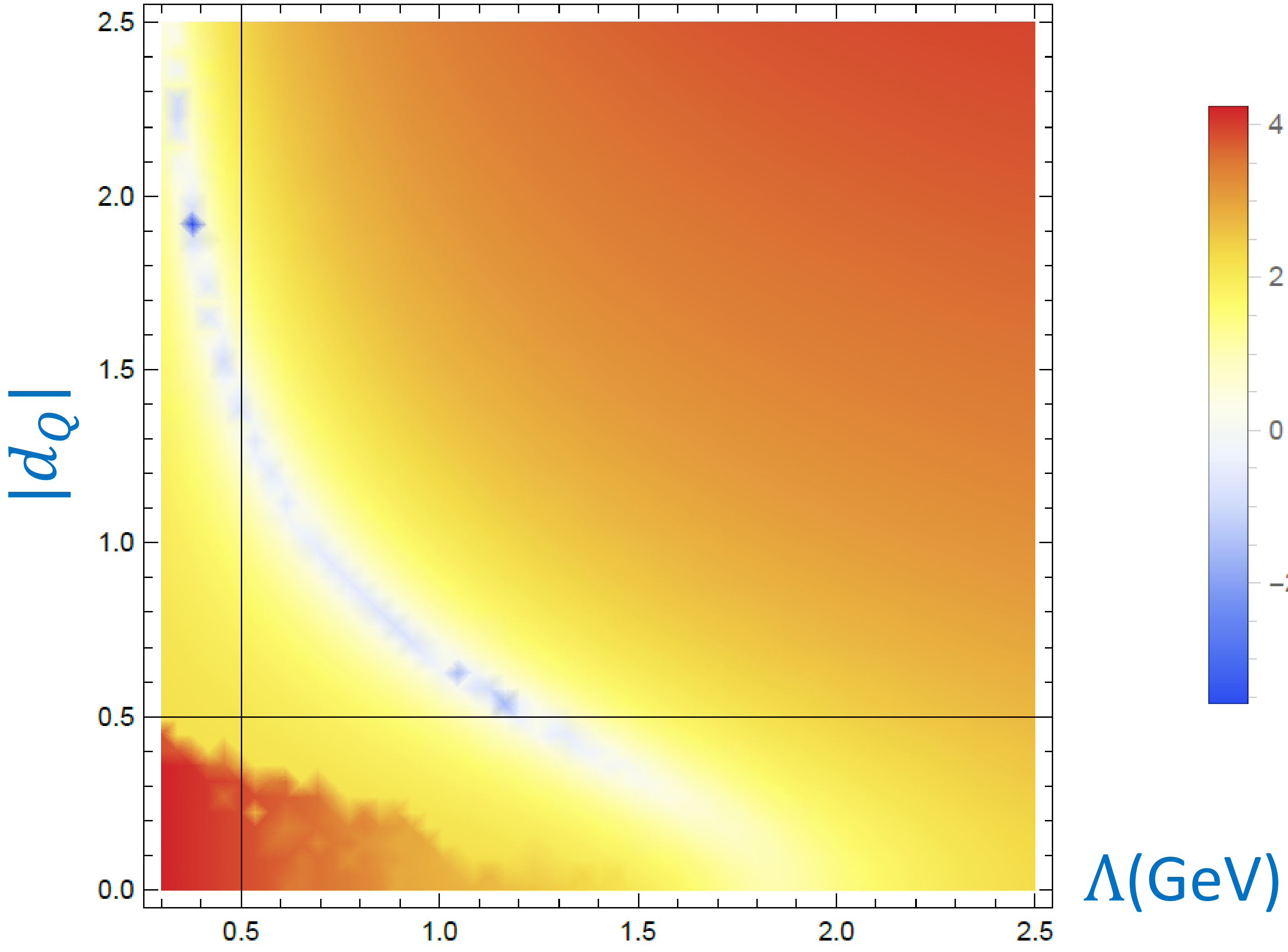
$$\underbrace{1/2^+}_{S_Q^P} \otimes \underbrace{1^-}_{j_{ldof}^P} = \underbrace{1/2^-}_{\substack{\Lambda_b(5912) \\ \Lambda_c(2595)}} , \underbrace{3/2^-}_{\substack{\Lambda_b(5920) \\ \Lambda_c(2625)}}$$

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

molecular probability

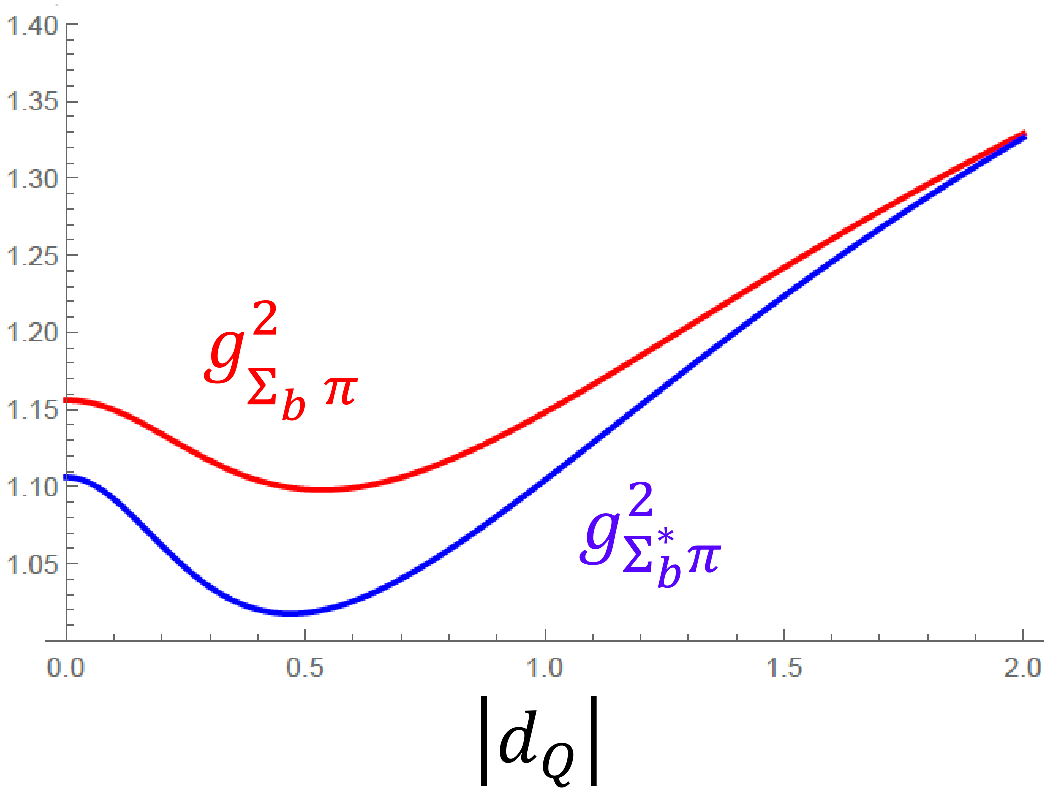
~ -0.1

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

$\sim 0.15 - 0.35$

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

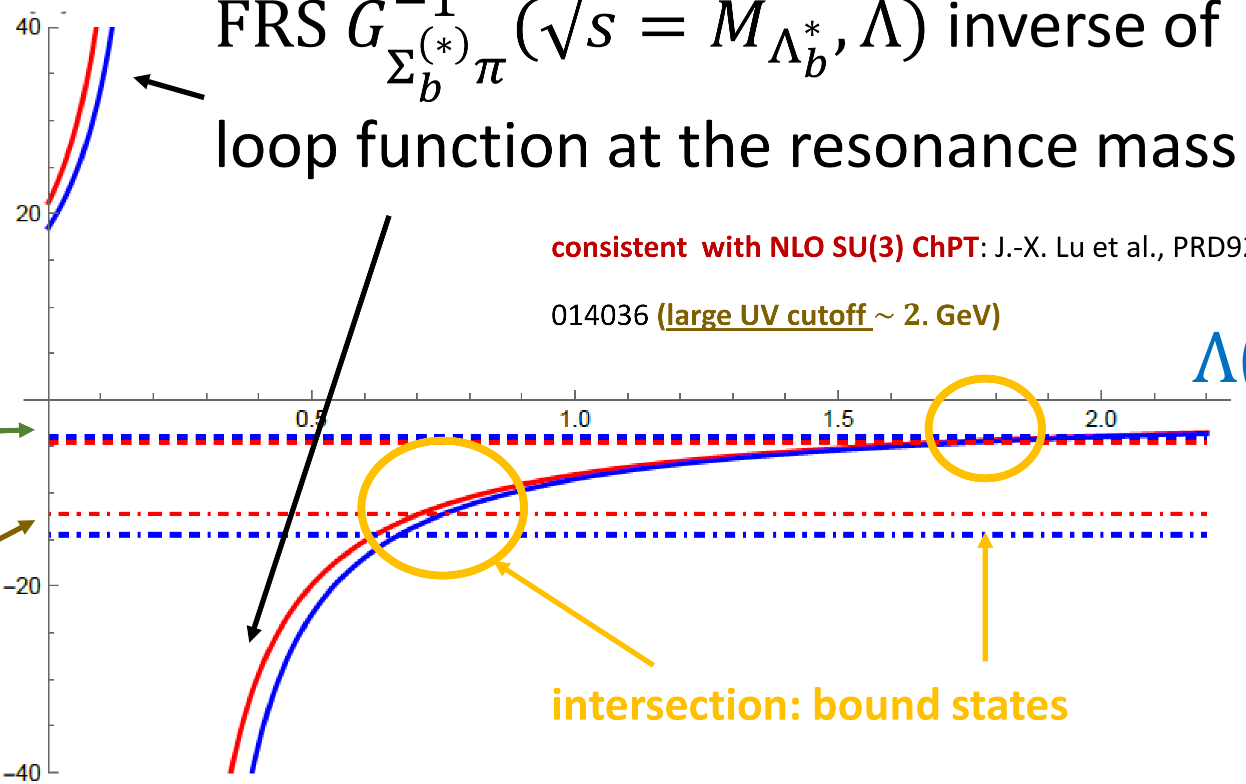
- largely CQM states
- HQSS partners



			$\Lambda_b(5912)$				$\Lambda_b(5920)$			
			$\Sigma_b\pi \;\; J^P=\frac{1}{2}^-$				$\Sigma_b^*\pi \;\; J^P=\frac{3}{2}^-$			
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)

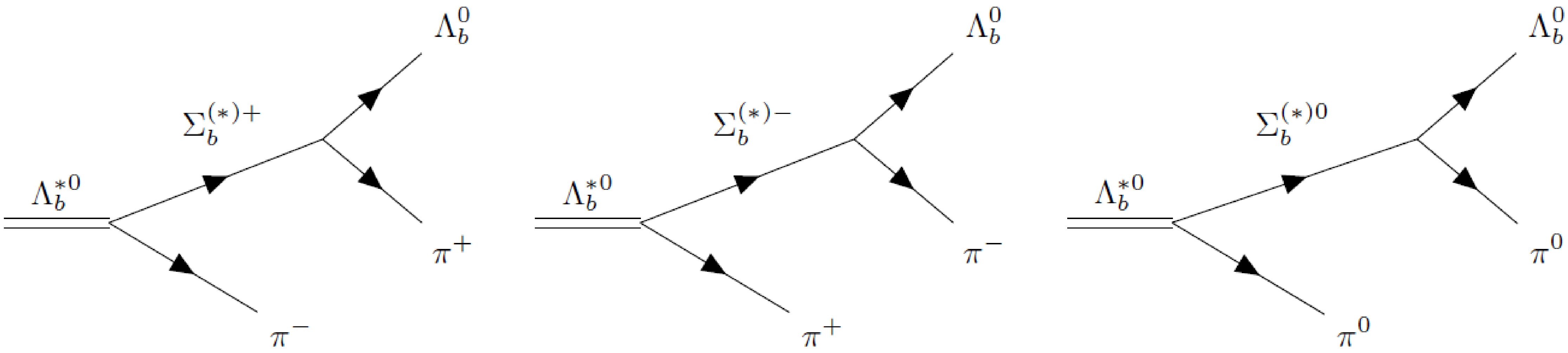
$V^J_\chi(\sqrt{s}=M_{\Lambda_b^*})$ chiral interaction

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

CQM exchange potential for $d_Q=1$

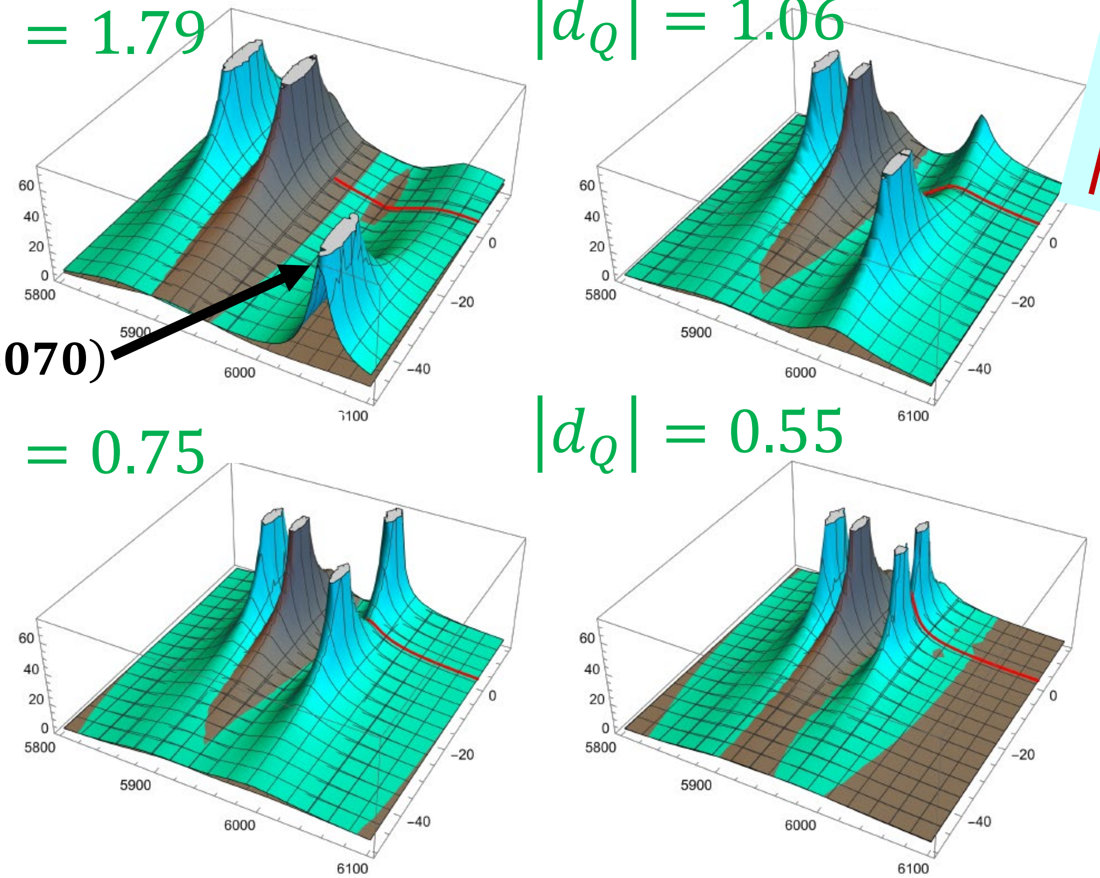
intersection: bound states

			$\Lambda_b(5912)$				$\Lambda_b(5920)$			
			$\Sigma_b\pi\ J^P=\frac{1}{2}^-$				$\Sigma_b^*\pi\ J^P=\frac{3}{2}^-$			
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)

$|d_Q| = 1.79$ $|d_Q| = 1.06$ $|d_Q| = 0.75$ $|d_Q| = 0.55$

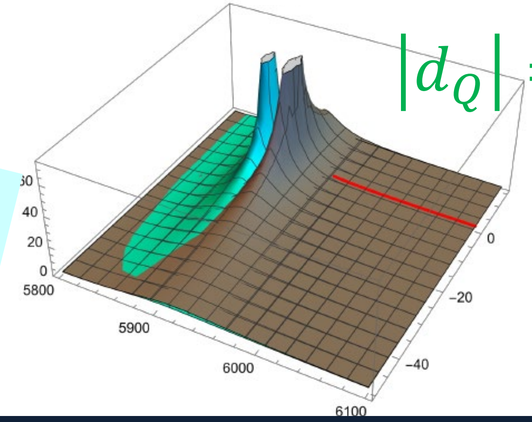


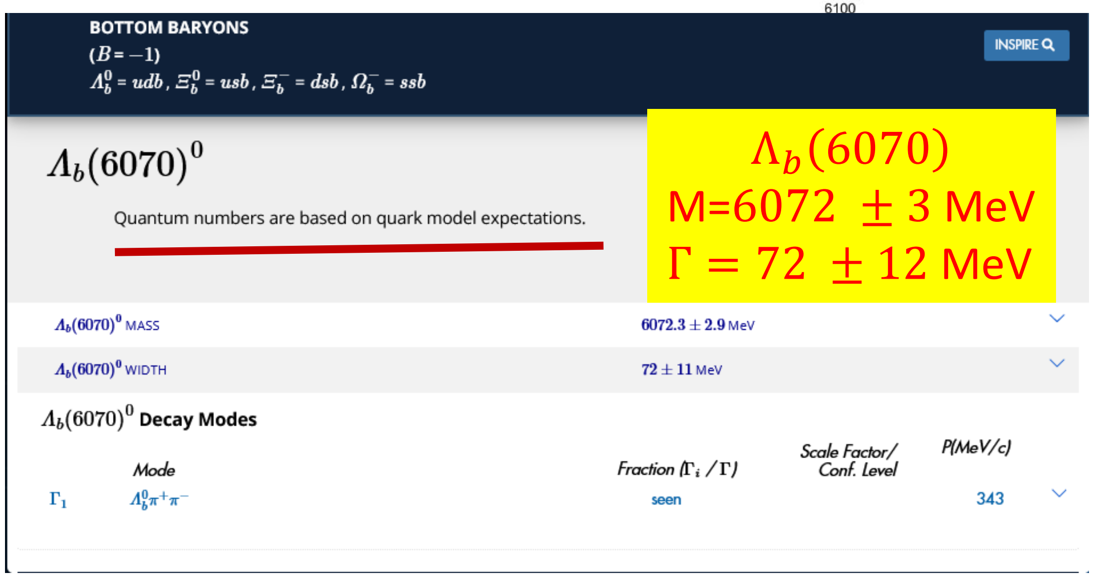
$\Lambda_b(6070)$

FRS & SRS

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

$|d_Q| = 0$





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

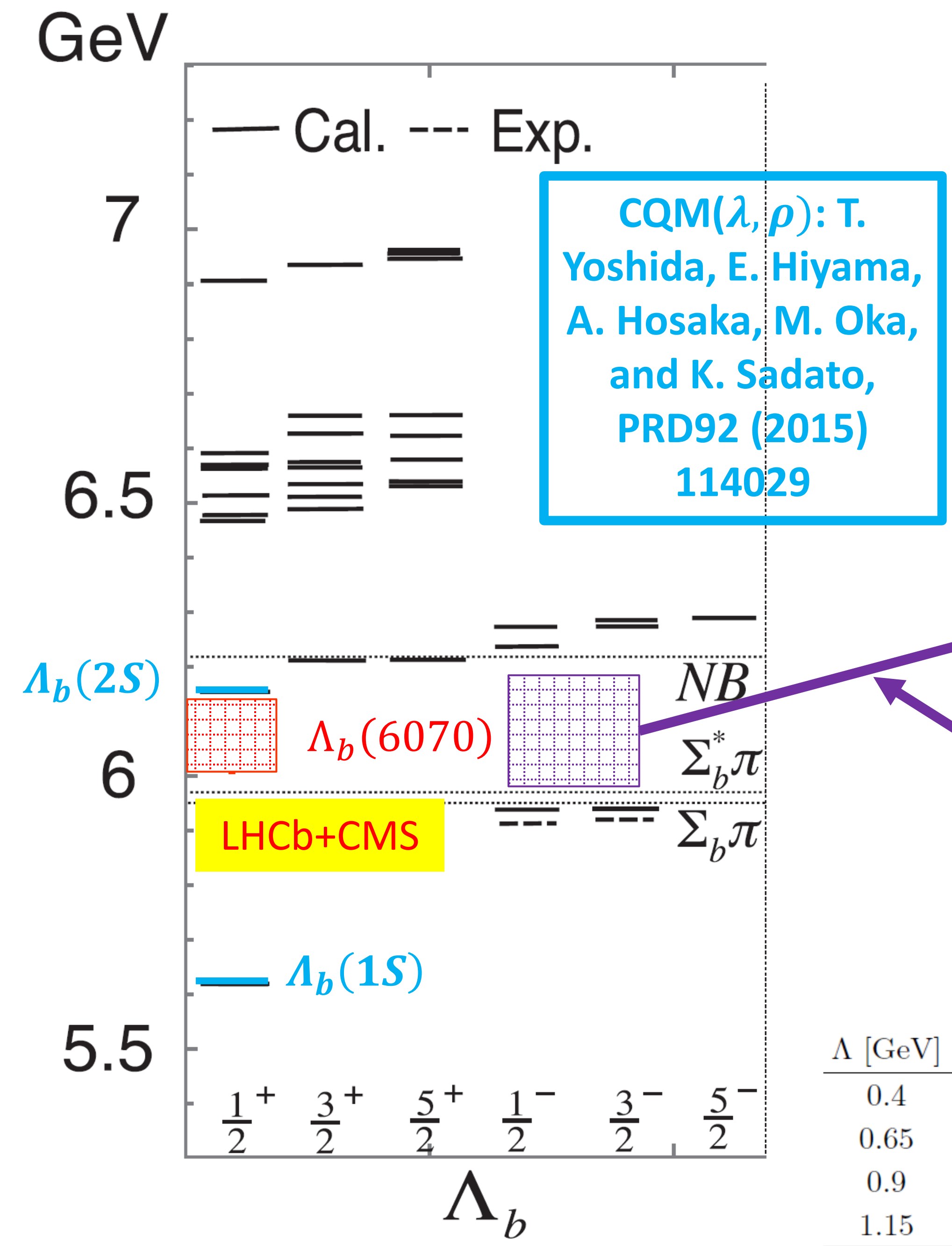
$\Lambda_b(6070)$

M=6072 $\pm$ 3 MeV

$\Gamma = 72 \pm 12$ 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]	$\lvert d_Q \rvert$	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	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
1.15	0.55 ± 0.04	5966 ± 3	9.5 ± 1.1	0.97 ± 0.01	-0.30 ± 0.01	5976 ± 3	7 ± 2	$1.15^{+0.06}_{-0.02}$	$-0.30^{+0.01}_{-0.05}$

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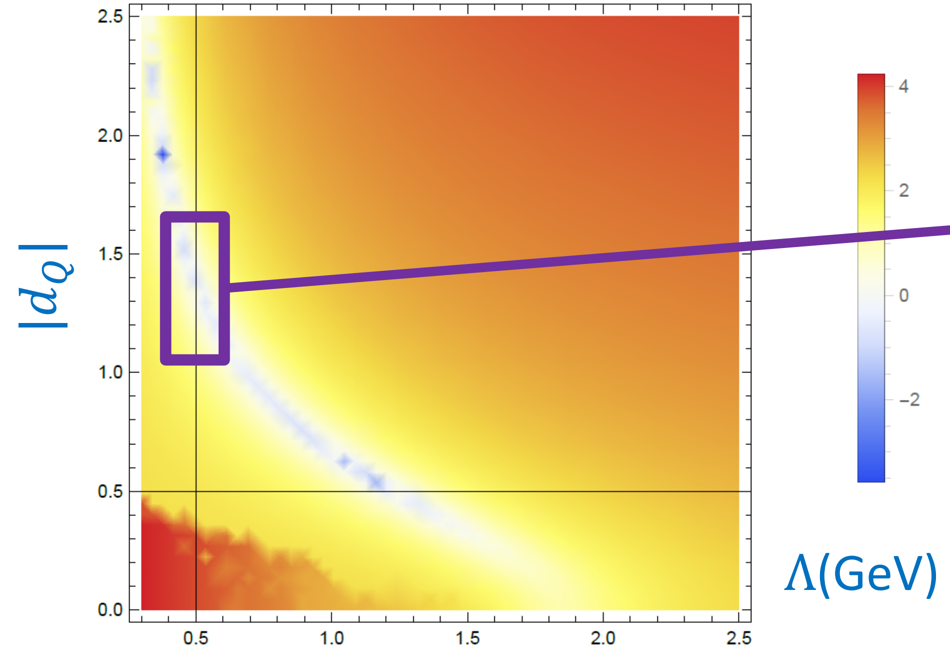
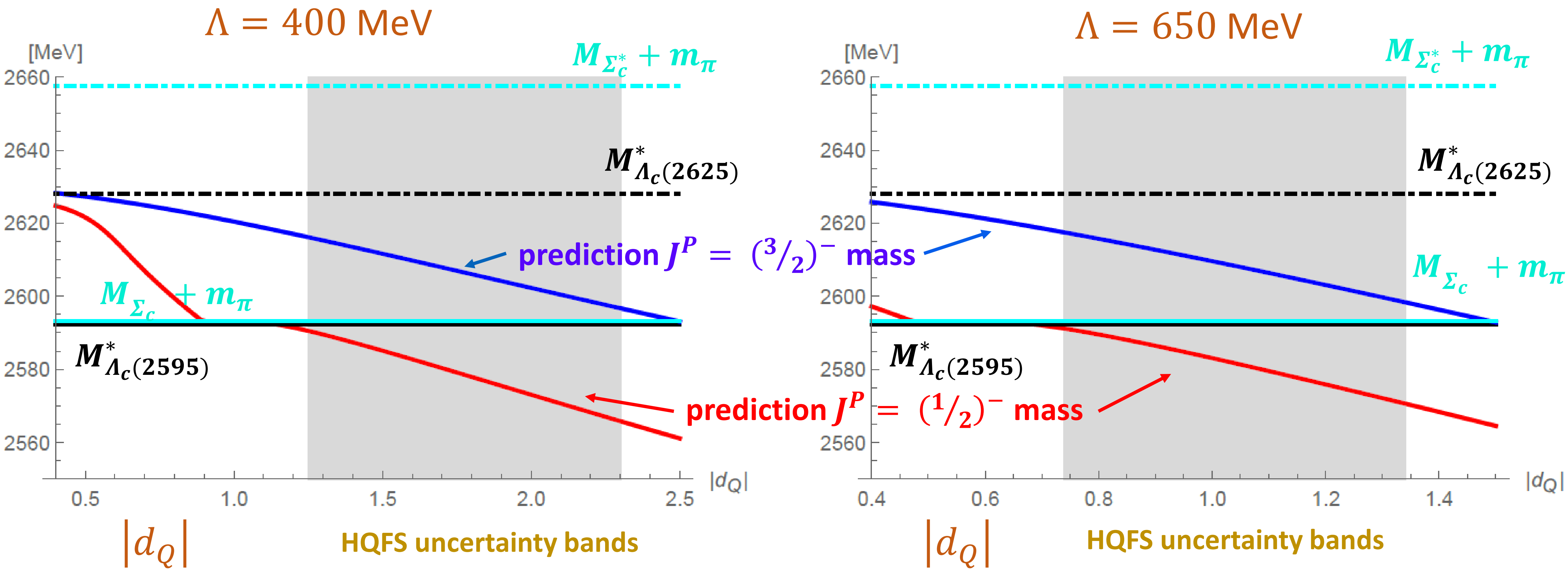
- We naturally find **for UV cutoffs around 500 MeV** two resonances ($J^P = (1/2)^-$ and $J^P = (3/2)^-$) which should be observed in the $\Lambda_b\pi^+\pi^-$ in the region of 6050 MeV
- Hence, we can fix the UV cutoffs and the strength d_Q of the coupling of the $\Sigma_c^{(*)}\pi$ pair to the CQM lowest-lying $\lambda-$mode excitation, which are now fully determined by the pole position of the $\Lambda_b(5912)$ and $\Lambda_b(5920)$ resonances
- Now using **Heavy Quark Flavor Symmetry** we can make predictions in the **charm sector**

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



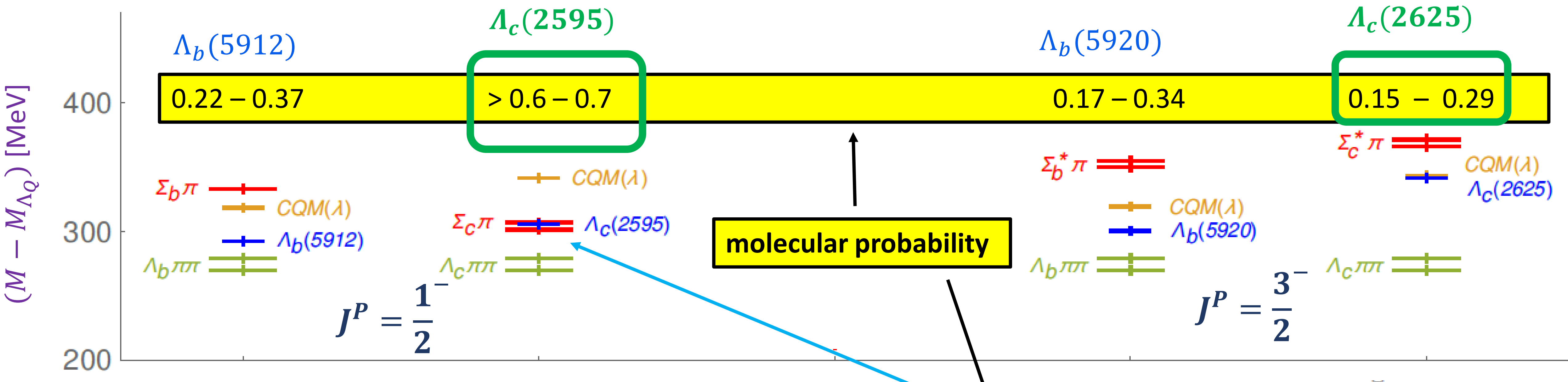
favored natural size UV cutoffs
$\Lambda \sim 650 - 400$ MeV
and $|d_Q(\Lambda)| \sim$ 1-1.8

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 λ–mode CQM states fixed in the bottom sector from $\Lambda_b(5912)$, $\Lambda_b(5920)$ and $\Lambda_b(6070)$



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

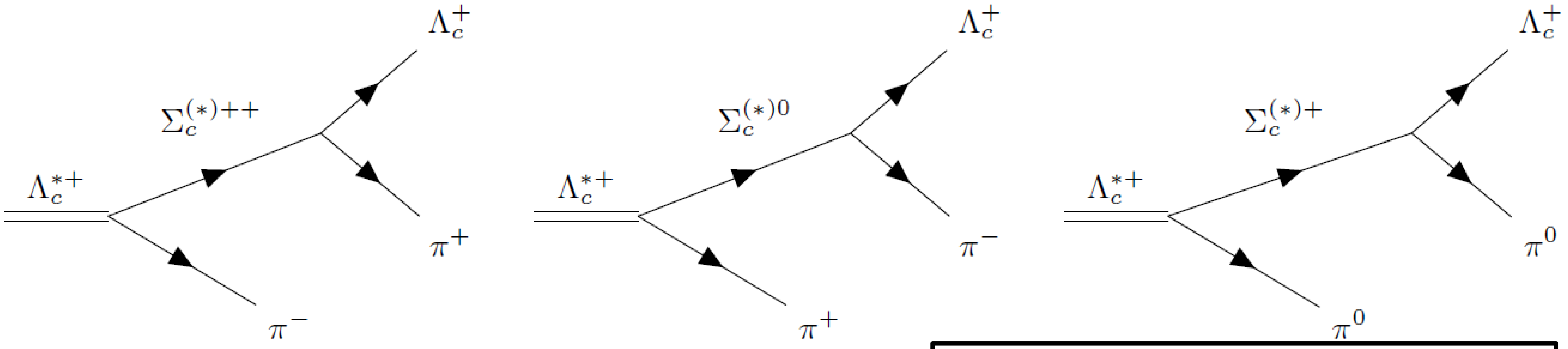
diverges at threshold!

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

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



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

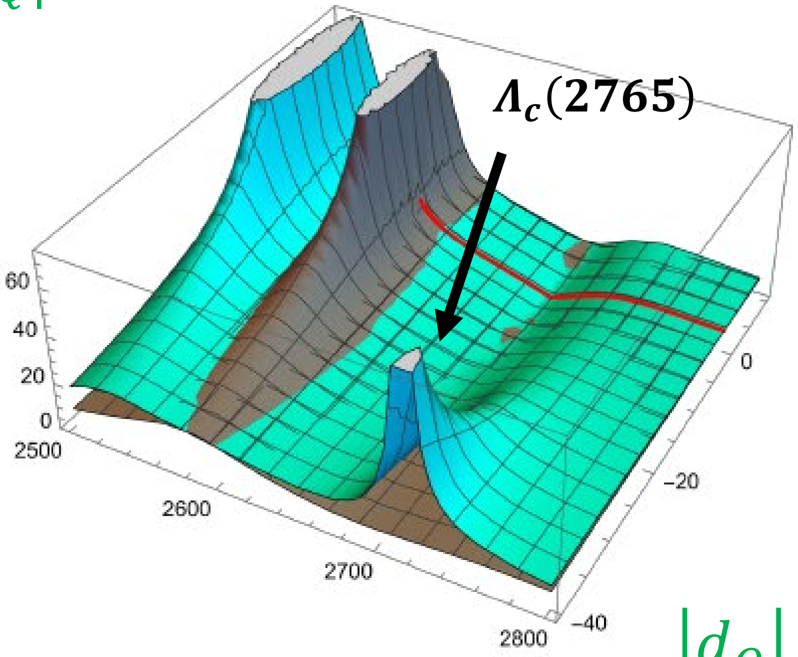
$\boldsymbol{\Gamma[\Lambda_c(2595)) = 2.6 \pm 0.6}$ **MeV**

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

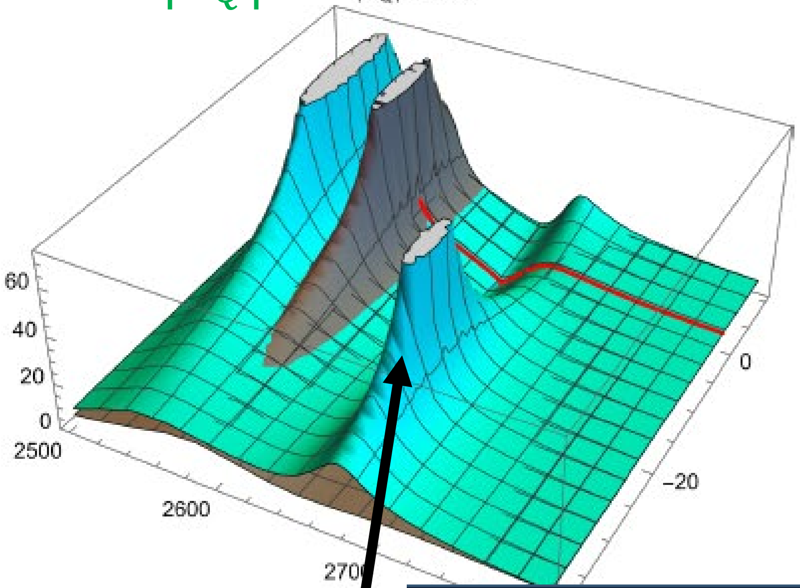
In the charm sector, these resonant contributions to the $\Lambda_c\pi\pi$ three-body decay channel are much larger than in the bottom sector because **the intermediate Σ_c and Σ_c^* states are closer to be on the mass shell**, especially for the $\Lambda_c(2595)$

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

$\Lambda_c(2765)$



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



$\Lambda_c(2765)$

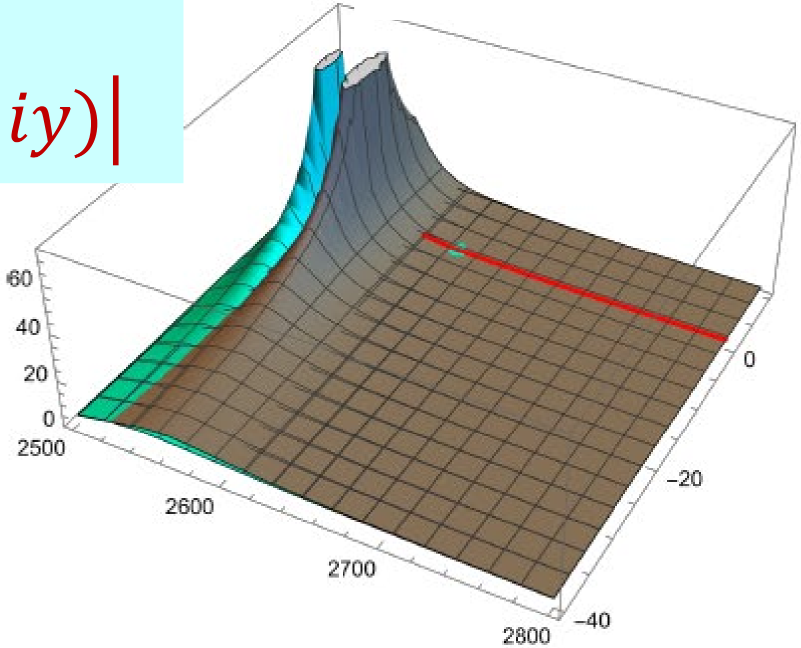
$I(J^P) = ?(?^?)$

$\Lambda_c(2765)$ 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

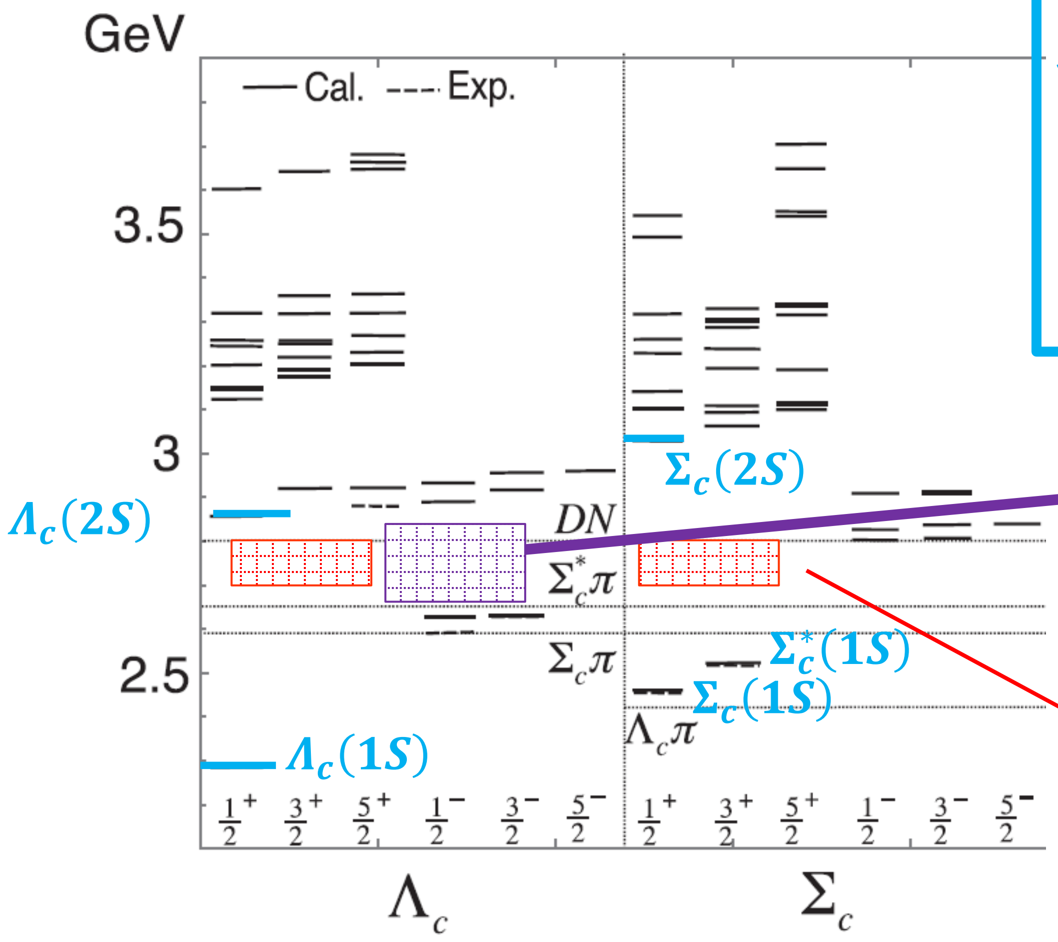
		$\Sigma_c\pi$ $[J^P=1/2^-]$				$\Sigma_c^*\pi$ $[J^P=3/2^-]$			
Λ [GeV]	$\lvert d_Q \rvert$	M [MeV]	Γ [MeV]	$\lvert g_{\Sigma_c\pi} \rvert$	$\phi_{\Sigma_c\pi}$	M [MeV]	Γ [MeV]	$\lvert g_{\Sigma_c^*\pi} \rvert$	$\phi_{\Sigma_c^*\pi}$
0.4	1.79 ± 0.11	2714 ± 6	85.7 ± 0.6	1.60 ± 0.02	-0.92 ± 0.01	2754 ± 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

Λ [GeV]	$\lvert d_Q \rvert$	$\Sigma_c\pi$ $[J^P = 1/2^-]$ M [MeV]	Γ [MeV]	$\lvert g_{\Sigma_c\pi} \rvert$	$\phi_{\Sigma_c\pi}$	$\Sigma_c^*\pi$ $[J^P = 3/2^-]$ 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



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

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

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

CLEO

CONCLUSIONS

- **Unitarized chiral $\Sigma_Q^{(*)}\pi$ + CQM exchange interaction**: heavy quark symmetry consistent description of lowest lying S-wave bottom and charm resonances: $\Lambda_b(5912)$, $\Lambda_b(5920)$, $\Lambda_c(2595)$ and $\Lambda_c(2625)$

  ✓ The $\Lambda_b(5912)$ and the $\Lambda_b(5920)$ are HQSS partners and largely CQM states

  ✓ 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

  ✓ **At higher energies**, we find **heavy quark flavor sibling resonances** (bottom and charm sectors) with spin-parities $J^P = (^1/_2)^-$ and $(^3/_2)^-$ which would contribute to the broad excesses of events in the $\Lambda_{b,c}\pi^+\pi^-$ spectra associated to the $\boldsymbol{\Lambda_b(6070)}$ and $\boldsymbol{\Lambda_c(2765)}$ resonances.

Final remark: dynamics of the $\Lambda_c(2595)$ and the $\Lambda_c(2625)$ is complicated

- **Λ_c^* −puzzle and HQSS**
- **role played by the CQM degrees of freedom**
- **role played by the chiral $\Sigma_c^{(*)}\pi$ thresholds**

... LQCD seems to support our findings!

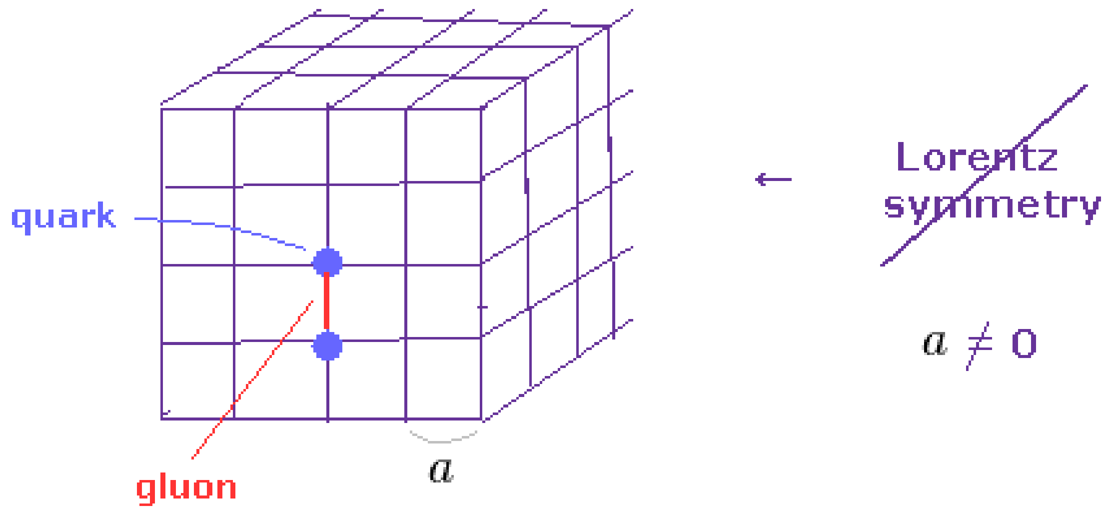
PHYSICAL REVIEW D 94, 114518 (2016)

Flavor structure of Λ baryons from lattice QCD: From strange to charm quarks

Philipp Gubler,[1,*] Toru T. Takahashi,[2] and Makoto Oka[3,4]

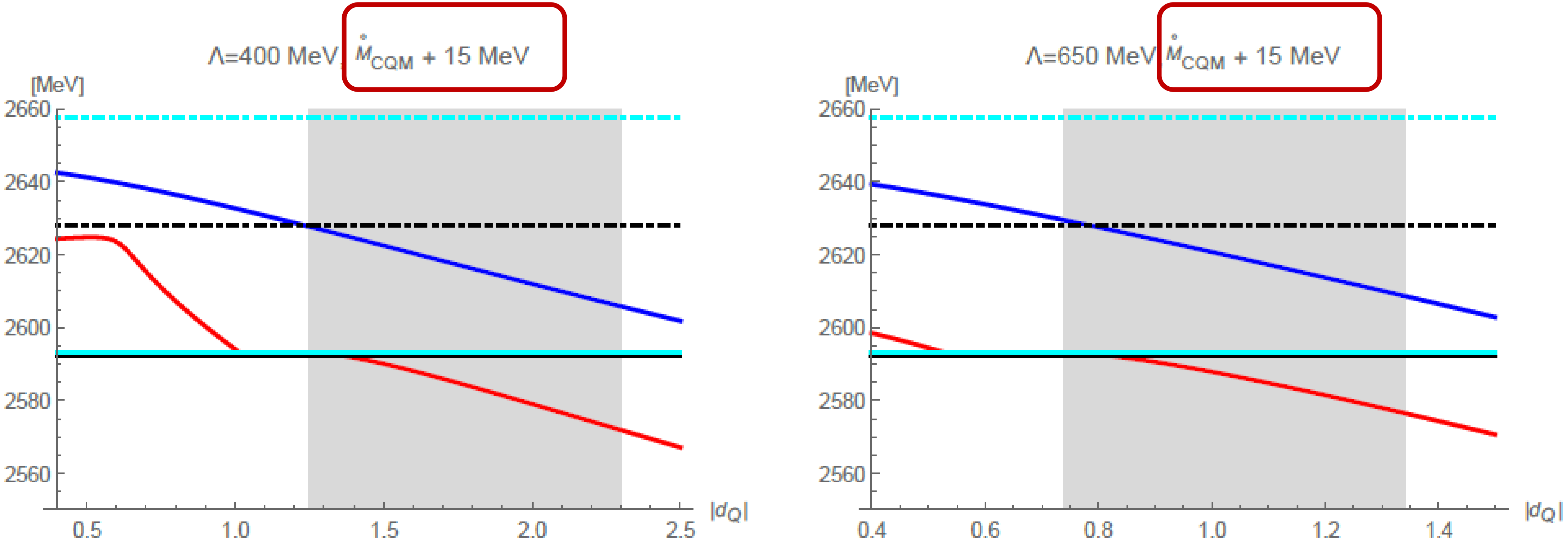
Thanks to all my collaborators!

Back up



and Lattice QCD…
[J. Bulava et al. (Snowmass 2021)
arXiv:2203.03230]

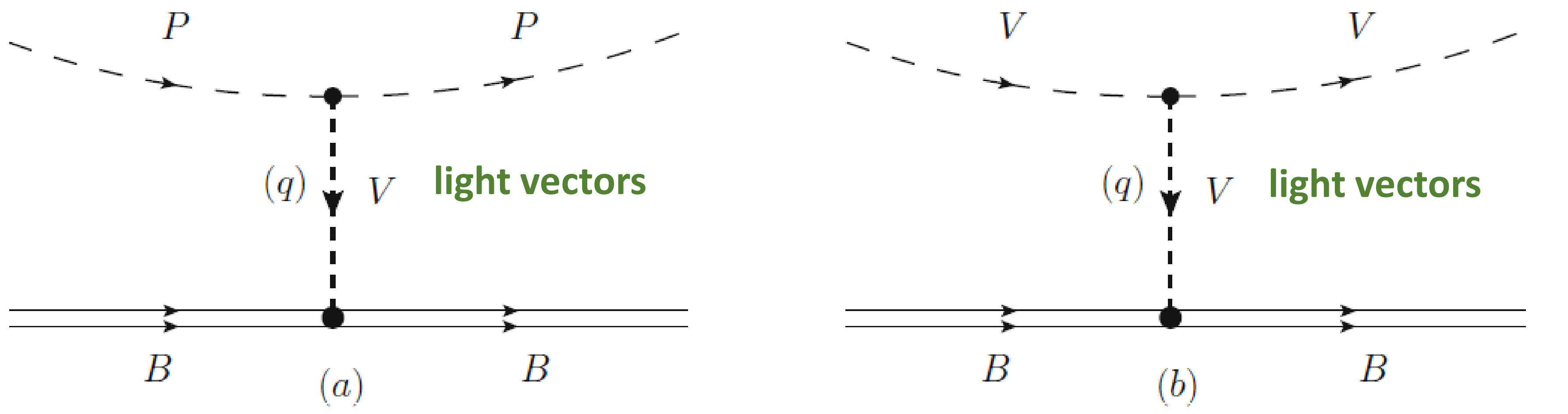
<u>strategy</u>: combining effective field theory methods with LQCD results to describe data!



increasing by 15 MeV the mass of the bare CQM state the agreement is excellent!

LO HQSS does not fix $ND^{(*)} \longrightarrow ND^{(*)}, \Sigma_c^{(*)}\pi$ coupled-channels interaction; There exist several models in the literature consistent with LO HQSS constraints. Moreover, renormalization parameters can be fine tuned to reproduce the position of the $\Lambda_c(2595)$ and $\Lambda_c(2625)$ resonances.... (see detailed discussion in JN+R.Pavao, PRD101 (2020) 014018

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



+

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

- ✓ π −octet, ρ −nonet, $D^{(*)}_{(s)}, \bar{D}^{(*)}_{(s)}$
- ✓ N −octet, Δ −decuplet, $\Lambda_c, \Sigma_c^{(*)}, \Xi_c^{(*,\prime)}, \Omega_c^{(*)}$

light spin-flavor (mesons and baryons)

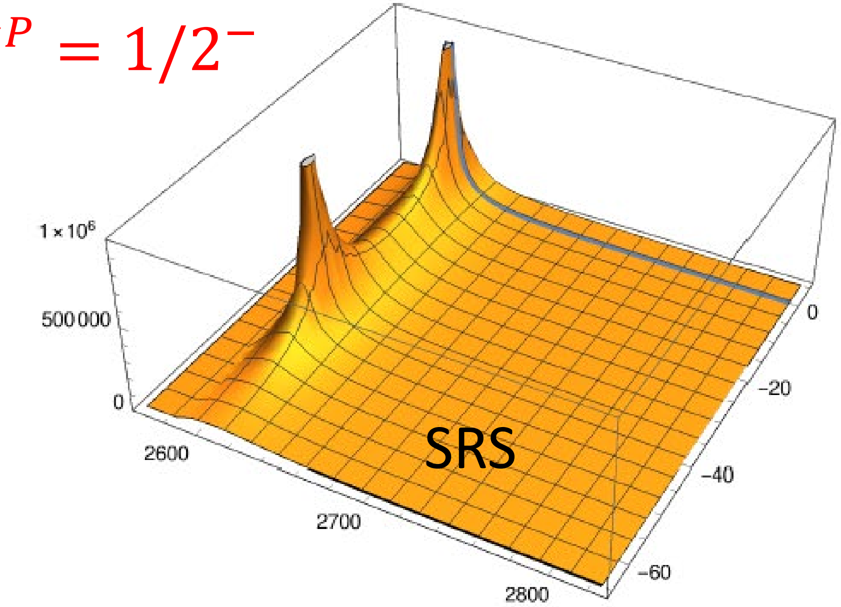
- ✓ consistent with HQSS and chiral symmetry
- ✓ dependence of renormalization scheme [see also JN+R.Pavao, PRD101 (2020) 014018]

- $C = 1$, 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.

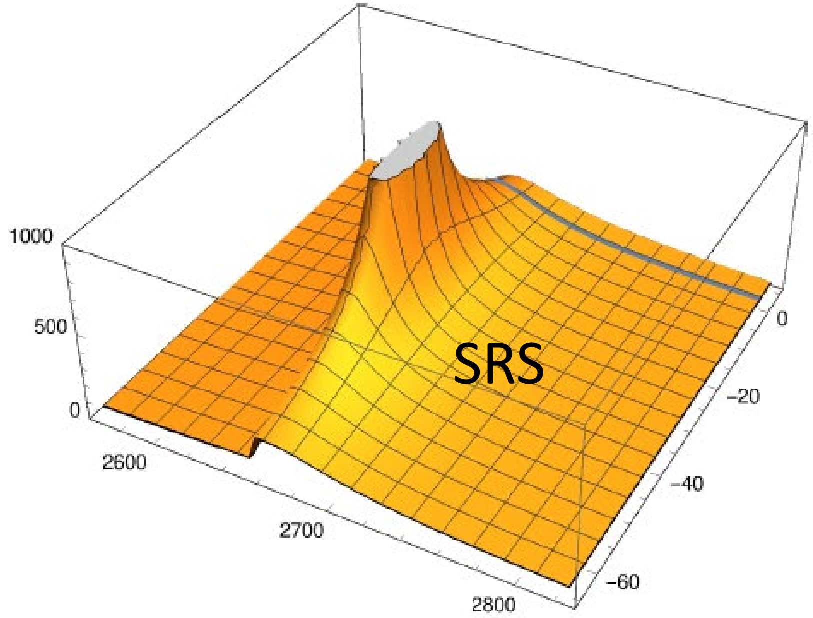
- LHCb Ω_c^* states, $\Xi_{c,b}$ JN, R. Pavao and L. Tolos, EPJC78 (2018) 114; EPJC80 (2020) 22

Absolute value of the determinant of the T −matrix

$J^P = 1/2^-$

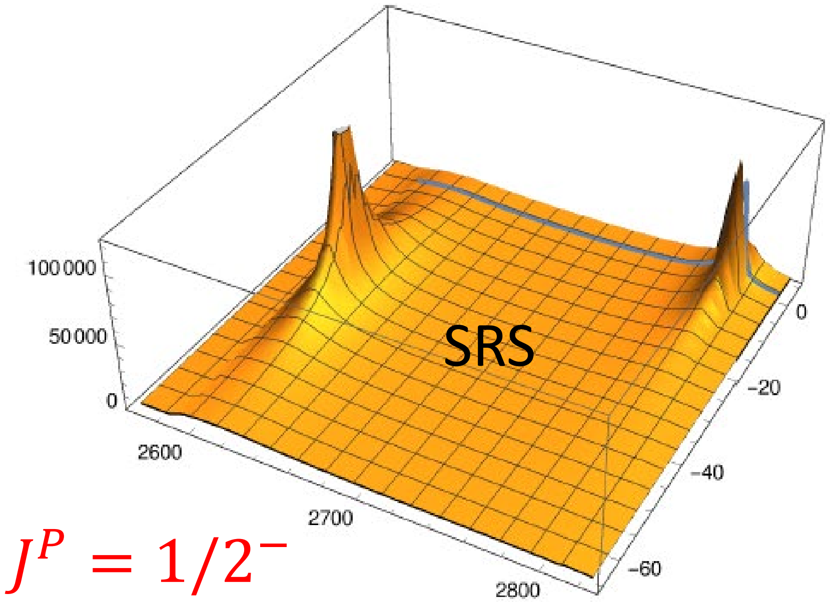


$J^P = 3/2^-$

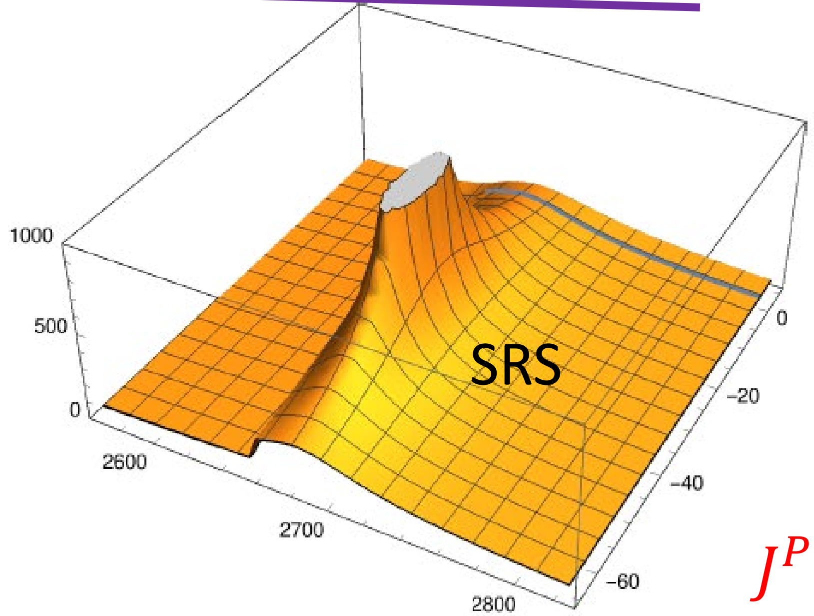


subtraction at a common scale **(no fit!)**

- ✓ 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 $\Lambda_c(2625)$.**



$J^P = 1/2^-$

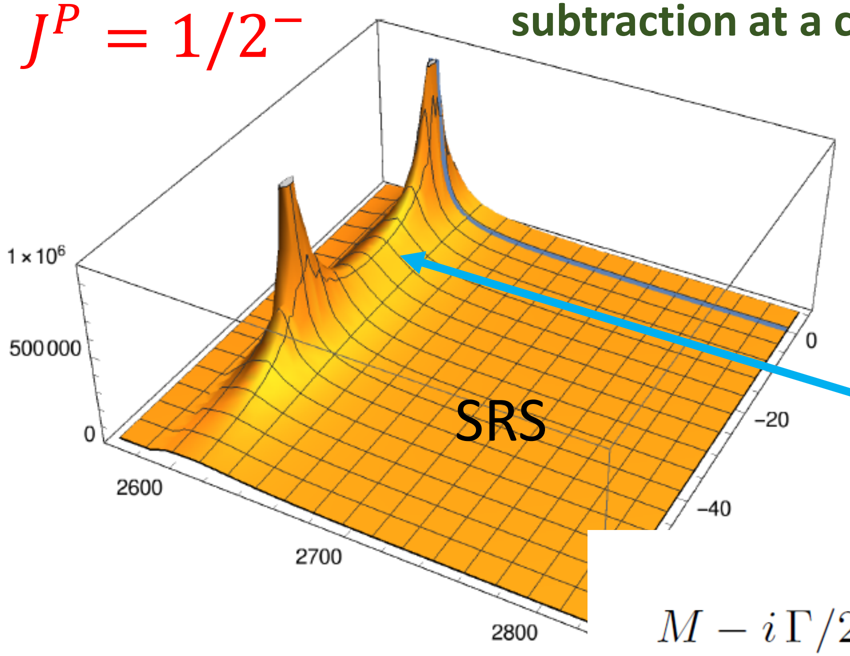


$J^P = 3/2^-$

- ✓ **spectrum in the $1/2^-$ sector depends strongly on the adopted RS**

common UV cutoff 650 MeV **(no fit!)**

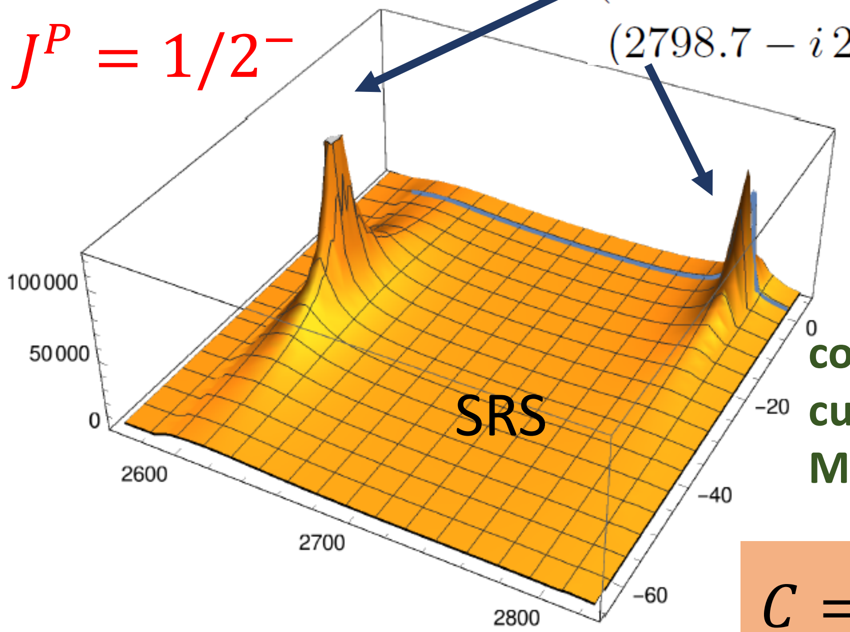
$C = 1,\ ND^{(*)}, \Sigma_c^{(*)}\pi$ coupled-channels



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



- ✓ **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 $\Lambda_c(2595)$.

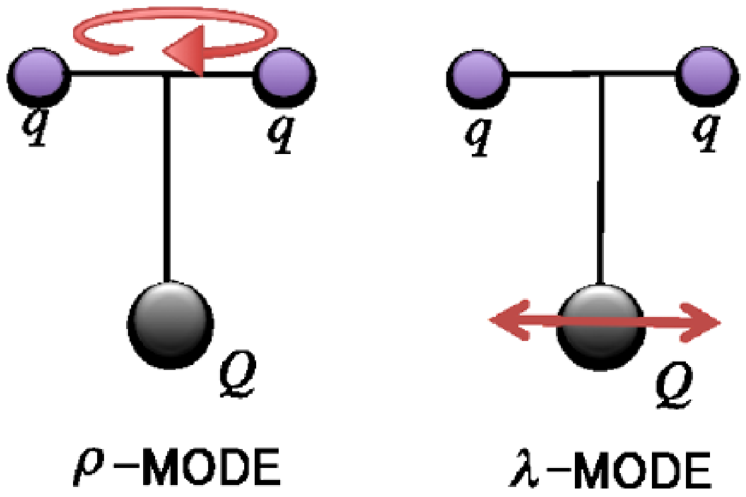
$C = 1,\ ND^{(*)}, \Sigma_c^{(*)}\pi$ coupled-channels

...and CQM predictions:

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

λ –mode excitations

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



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

Spectrum of heavy baryons in the quark model

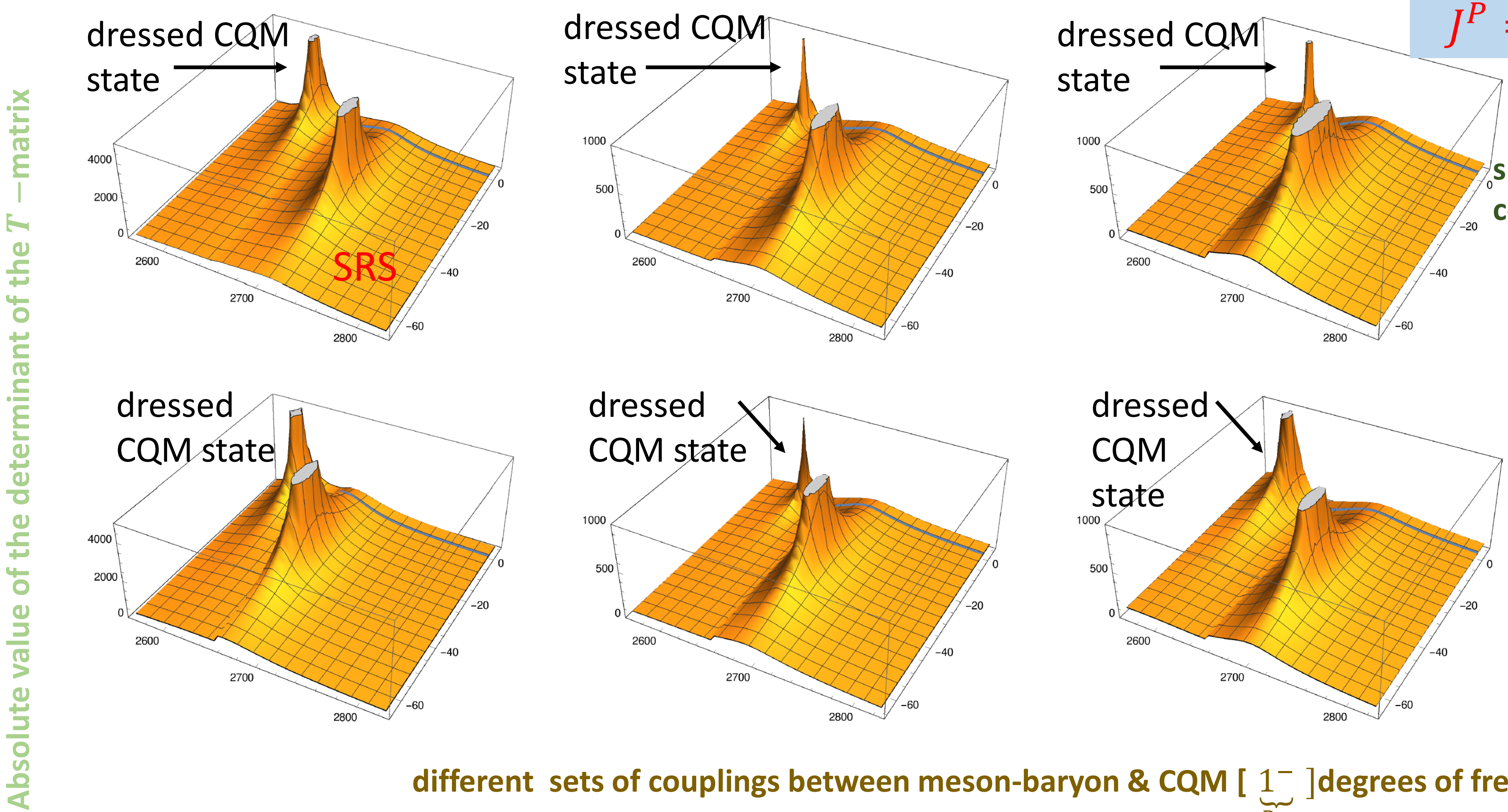
T. Yoshida,[1,*] E. Hiyama,[2,1,3] A. Hosaka,[4,3] M. Oka,[1,3] and K. Sadato[4,†]

J^P	Λ_c 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	

J^P	Λ_c 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

$J^P = 3/2^-$



subtraction at a common scale

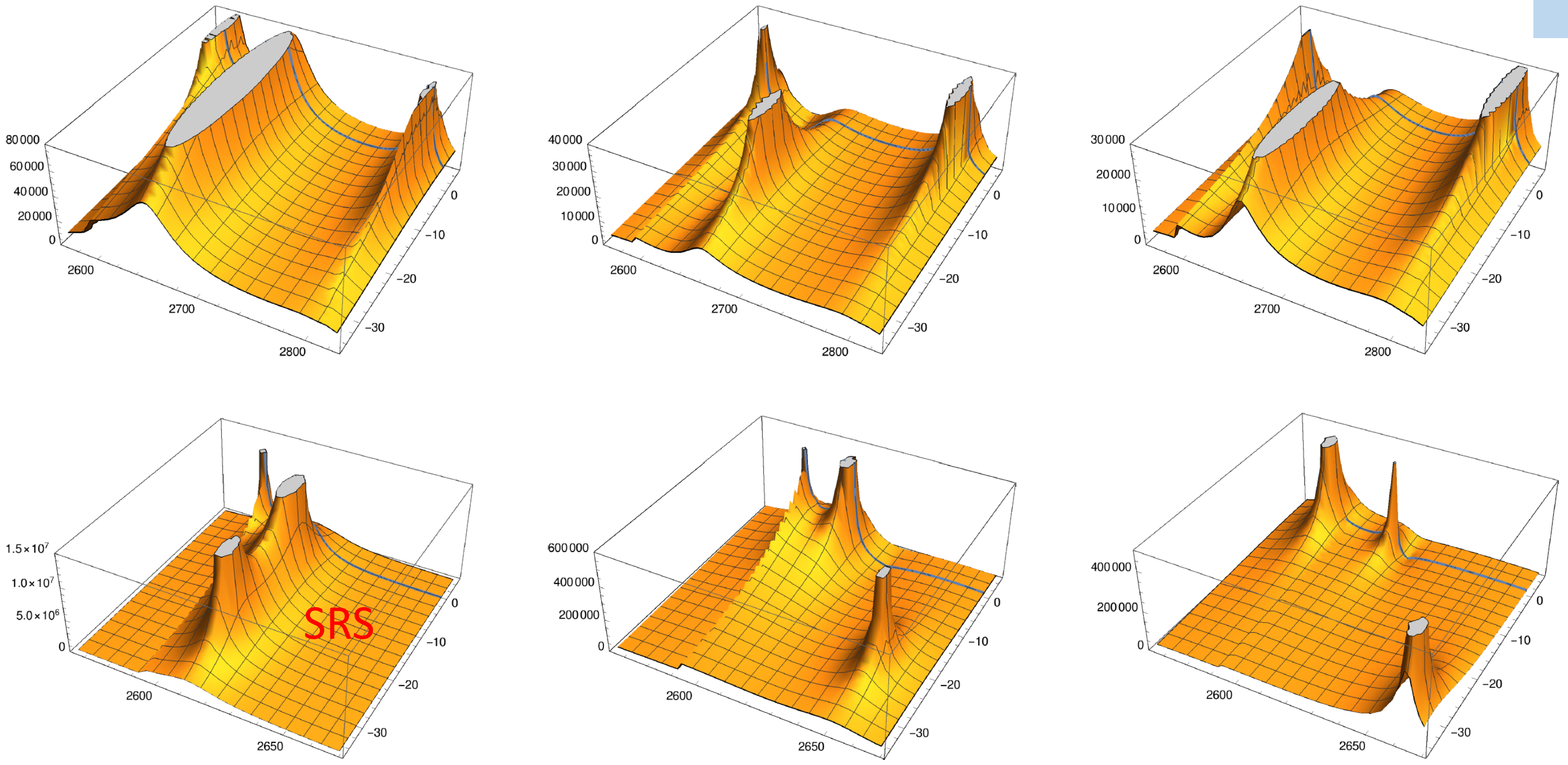
common UV cutoff 650 MeV

different sets of couplings between meson-baryon & CQM [$\underbrace{1^-}_{j^P_{ldof}}$]degrees of freedom

- ✓ In both RSs, the dressed CQM state describes fairly well de $\Lambda_c(2625)$ resonance. Moreover, the coupling to $\Sigma_c^*\pi$ is compatible with the existing measurements of the resonant contribution to $\Gamma[\Lambda_c(2625) \longrightarrow \Lambda\pi\pi]$
- ✓ In addition, a second broad pole is predicted in the region of 2.7 GeV.

$J^P = 1/2^-$

Absolute value of the determinant of the T −matrix



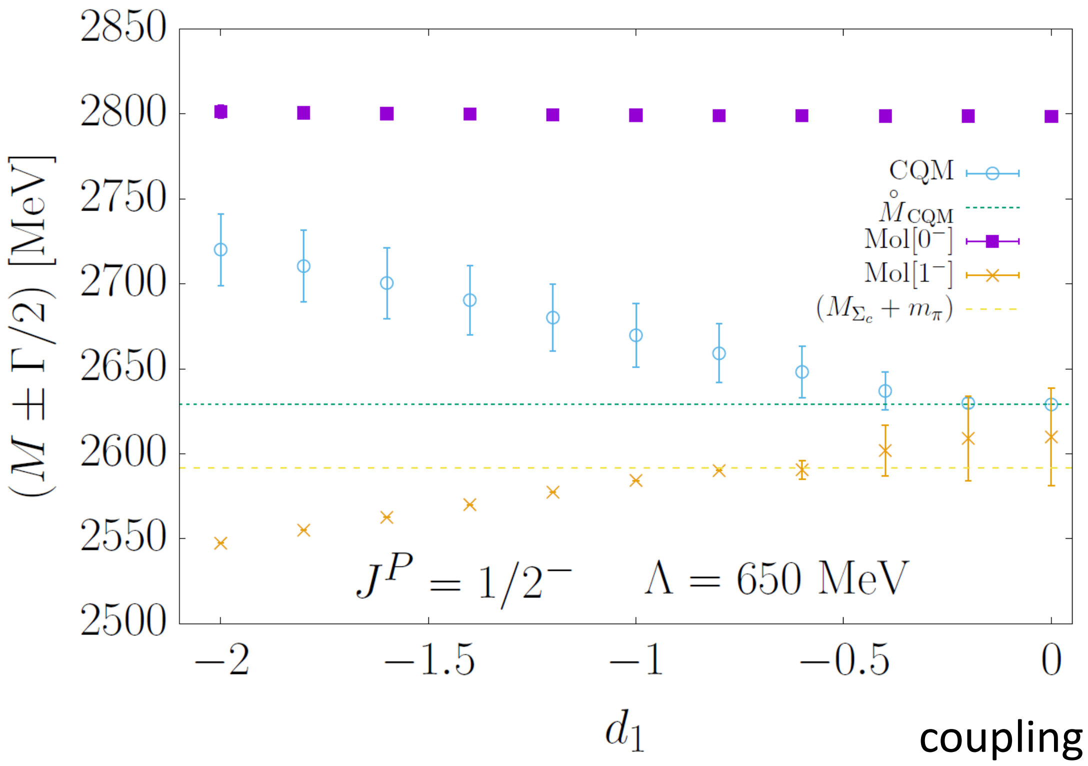
subtraction at a common scale

common UV cutoff 650 MeV

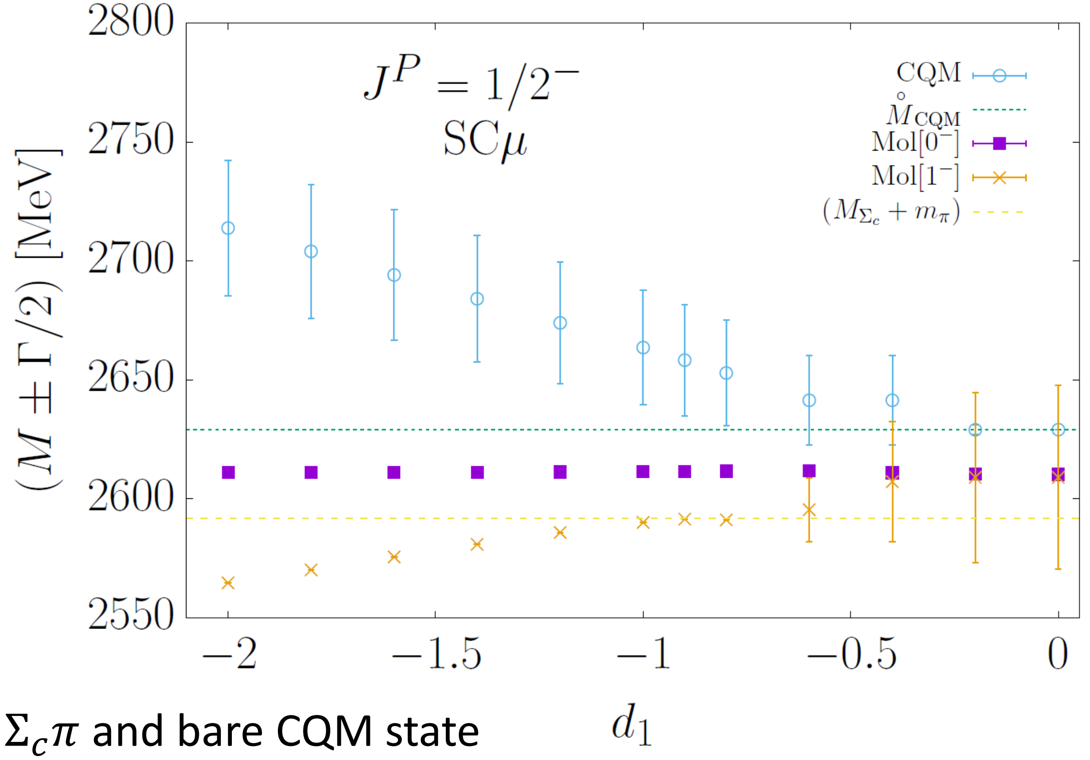
different sets of couplings between meson-baryon & CQM [$\underbrace{1^-}_{j^P_{ldof}}$]degrees of freedom

- ✓ $(j^P_{ldof} = 0^-)$ −components are not affected by the consideration of the CQM degrees of freedom
- ✓ There are appear three poles, but their characteristics and interpretations depend on the RS and the interplay between CQM and meson-baryon degrees of freedom

common UV cutoff 650 MeV



subtraction at a common scale



coupling between $\Sigma_c\pi$ and bare CQM state

- ✓ The mass and the width of the narrow state at 2800 MeV (common UV cutoff 650 MeV) or 2610 MeV (subtraction at a common scale) are practically unaltered by the coupling between meson-baryon and CQM degrees of freedom. This is a trivial consequence of the largely dominant $j^P_{ldof} = 0^-$ configuration of these states, since HQSS forbids their coupling to the $(j^P_{ldof}= 1^-)$ −CQM bare state.
- ✓ in both renormalization schemes we obtain the dressed CQM pole at masses around 2640-2660 MeV and with a width of the order of 30-50 MeV, depending on the chosen regulator and on the details of coupling meson-baryon and CQM degrees of freedom.

- ✓ 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. In addition, there will exist a molecular baryon, moderately broad, with a mass of about 2.7 GeV and sizable couplings to both $\Sigma_c^*\pi$ and ND^* that will fit into the expectations of being $\Sigma_c^*\pi$ molecule generated by the chiral interaction of this pair.
- ✓ The $\Lambda_c(2595)$ is predicted, however, to have a predominant molecular structure. This is because, it is either the result of the chiral $\Sigma_c\pi$ interaction [J.-X. Lu, Y. Zhou, H.-X. Chen, J.-J. Xie, and L.-S. Geng, PRD92 (2015) 014036; but this contradicts the conclusions of T. Hyodo in PRL 111 (2013) 132002], which threshold is located much more closer than the mass of the bare three-quark state, or because the *ldof* in its inner structure are coupled to the unnatural 0^- quantum-numbers, depending on the RS. In the latter case, the resonance would have dominant $ND^{(*)}$ components.
- ✓ The relative importance of 0^- and 1^- components in the $\Lambda_c(2595)$ can be extracted from the ratio between the widths of the semileptonic decays $\Lambda_b[gs] \longrightarrow \Lambda_c(2595)$ and $\Lambda_b[gs] \longrightarrow \Lambda_c(2625)$ [W.-H. Liang, E. Oset, Z.-S. Xie, PRD95 (2017) 014015; JN, R. Pavao and S. Sakai, EPJC79 (2019) 417]