HEAVY BARYON SPECTROSCOPY

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- D. Ebert, R. N. Faustov and V. O. Galkin, "Masses of excited heavy baryons in the relativistic quark model," Phys. Lett. B **659**, 612 (2008) [arXiv:0705.2957 [hep-ph]]
- D. Ebert, R. N. Faustov and V. O. Galkin, "Spectroscopy and Regge trajectories of heavy baryons in the relativistic quark-diquark picture," Phys. Rev. D **84**, 014025 (2011) [arXiv:1105.0583 [hep-ph]]
- D. Ebert, R. N. Faustov, V. O. Galkin and A. P. Martynenko, "Mass spectra of doubly heavy baryons in the relativistic quark model," Phys. Rev. D **66**, 014008 (2002) [hep-ph/0201217].

Workshop on heavy hadron spectroscopy
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INTRODUCTION

- R. Aaij *et al.* [LHCb Collaboration], "Study of the $D^0 p$ amplitude in $\Lambda_b^0 \to D^0 p \pi^-$ decays," arXiv:1701.07873 [hep-ex].

  An amplitude analysis of the decay $\Lambda_b^0 \to D^0 p \pi^-$ was performed in the region of the phase space containing $D^0 p$ resonant contributions.

  $\Lambda_c(2880)^+$: preferred spin-parity – $J^P = 5/2^+$, with the $J = 7/2$ hypothesis disfavoured by 4.0 standard deviations. The solutions with $J = 1/2$ and $3/2$ are excluded with a significance of more than 5 standard deviations.

$$m(\Lambda_c(2880)^+) = 2881.75 \pm 0.29(\text{stat}) \pm 0.07(\text{syst})^{+0.14}_{-0.20}(\text{model})\mathrm{MeV},$$

$$\Gamma(\Lambda_c(2880)^+) = 5.43^{+0.77}_{-0.71}(\text{stat}) \pm 0.29(\text{syst})^{+0.75}_{-0.00}(\text{model})\mathrm{MeV}.$$

$\Lambda_c(2860)^+$ (new state): quantum numbers $J^P = 3/2^+$, with the parity measured relative to that of the $\Lambda_c(2880)^+$ state. The other quantum numbers are excluded with a significance of more than 6 standard deviations.

$$m(\Lambda_c(2860)^+) = 2856.1^{+2.0}_{-1.7}(\text{stat}) \pm 0.5(\text{syst})^{+1.1}_{-5.6}(\text{model})\mathrm{MeV},$$

$$\Gamma(\Lambda_c(2860)^+) = 67.6^{+10.1}_{-8.1}(\text{stat}) \pm 1.4(\text{syst})^{+5.9}_{-20.0}(\text{model})\mathrm{MeV}.$$

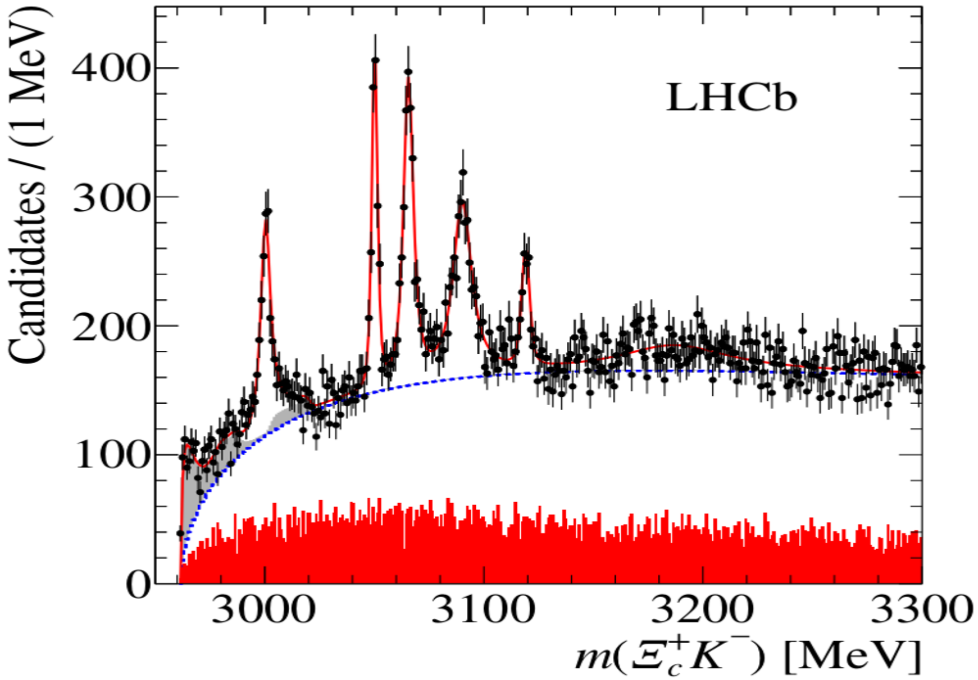
$\Lambda_c(2940)^+$: most likely spin-parity assignment is $J^P = 3/2^-$ but the other solutions with spins $1/2$ to $7/2$ cannot be excluded.

$$m(\Lambda_c(2940)^+) = 2944.8^{+3.5}_{-2.5}(\text{stat}) \pm 0.4(\text{syst})^{+0.1}_{-4.6}(\text{model})\mathrm{MeV}.$$

$$\Gamma(\Lambda_c(2940)^+) = 27.7^{+8.2}_{-6.0}(\text{stat}) \pm 0.9(\text{syst})^{+5.2}_{-10.4}\mathrm{MeV}.$$

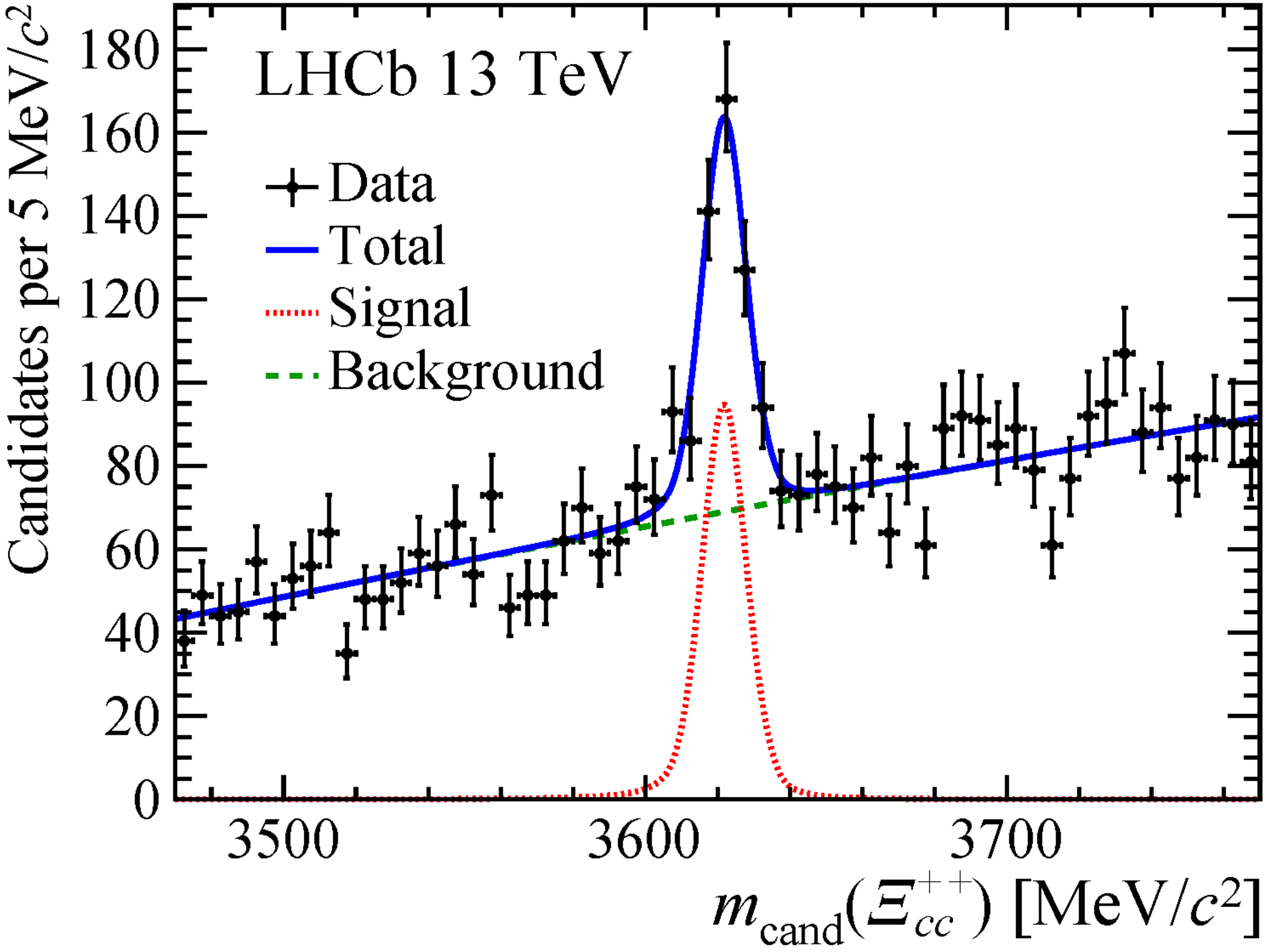
- R. Aaij *et al.* [LHCb Collaboration], "Observation of five new narrow Ω_c^0 states decaying to $\Xi_c^+ K^-$," arXiv:1703.04639 [hep-ex].
  Five new, narrow excited Ω_c states decaying to $\Xi_c^+ K^-$ are observed: the $\Omega_c(3000)^0$, $\Omega_c(3050)^0$, $\Omega_c(3066)^0$, $\Omega_c(3090)^0$, and $\Omega_c(3119)^0$.

State	Mass (MeV)	Width (MeV)
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1$	$4.5 \pm 0.6 \pm 0.3$
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1$	$0.8 \pm 0.2 \pm 0.1$
		< 1.2 MeV, 95% CL
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3$	$3.5 \pm 0.4 \pm 0.2$
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5$	$8.7 \pm 1.0 \pm 0.8$
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9$	$1.1 \pm 0.8 \pm 0.4$
		< 2.6 MeV, 95% CL



- R. Aaij *et al.* [LHCb Collaboration], “Observation of the doubly charmed baryon Ξ_{cc}^{++},” CERN-EP-2017-156
  Highly significant narrow structure in the $\Lambda_c^+ K^- \pi^+ \pi^+$ mass spectrum
  Consistent with Ξ_{cc}^{++}

$$M(\Xi_{cc}^{++}) = 3621.40 \pm 0.72 \pm 0.27 \pm 0.14 \text{ MeV}$$



Quark–diquark picture of baryons

Convincing evidence of the existence of diquark correlations in hadrons has been collected

- In light meson sector it has been argued for a long time that mesons forming inverted lightest scalar nonet can be well described as tetraquarks treated as diquark-antidiquark bound states
- In heavy meson sector several charged charmonium- and bottomonium-like states were discovered. They should be inevitably multiquark, at least four quark — tetraquark, states. One of the most successful pictures of such tetraquark states is the diquark-antidiquark model
- In baryon sector the number of observed excited states both in light and heavy sectors is considerably lower than the number of excited states predicted in three-quark picture

— Introduction of diquarks significantly reduces the number of baryon states since some of degrees of freedom are frozen and thus the number of possible excitations is substantially smaller

Baryons with one and two heavy quarks:

- Heavy baryons qqQ $(Q = c, b)$

— two light quarks form a diquark $d = qq$

— all excitations occur in the quark-diquark bound system (no internal diquark excitations)

— in the last few years the number of the observed charmed and bottom baryons almost doubled

— due to the poor statistics, the quantum numbers of most of the excited states of heavy baryons are not known experimentally and are usually prescribed following the quark model predictions

- Doubly heavy baryons qQQ $(q = u, d, s,\ Q = c, b)$

— two heavy quarks form a diquark $d = QQ$

— excitations both in diquark and in quark-diquark systems are considered

— lowest excitations occur in diquark

— first reliable experimental data on Ξ_{cc}^{++} just presented by LHCb

Baryon spectroscopy

- Main assumption: quark–diquark picture of baryons

Three-body calculation ⟶ two-step two-body calculation

- Diquark is a composite (qq') system:

– diquark is not point-like object: Its interaction with gluons is smeared by the form factor expressed through the overlap integral of diquark wave functions

- Pauli principle for ground state diquarks:

– (qq') diquark can have $S = 0, 1$ (scalar $[q, q']$, axial vector $\{q, q'\}$)
– (qq) diquarks can have only $S = 1$ (axial vector $\{q, q\}$)

- Light quarks, light diquarks and heavy quarks are considered fully relativistically without v/c expansion

RELATIVISTIC QUARK MODEL

Relativistic quasipotential equation of Schrödinger type:

$$\left(\frac{b^2(M)}{2\mu_R}-\frac{\mathbf{p}^2}{2\mu_R}\right)\Psi_M(\mathbf{p})=\int\frac{d^3q}{(2\pi)^3}V(\mathbf{p},\mathbf{q};M)\Psi_M(\mathbf{q})$$

$\mathbf{p}$ - center-of-mass relative momentum of quarks (diquarks)
M - bound state mass ($M = E_1 + E_2$)
μ_R - relativistic reduced mass:

$$\mu_R=\frac{E_1E_2}{E_1+E_2}=\frac{M^4-(m_1^2-m_2^2)^2}{4M^3}$$

$b(M)$ - on-mass-shell relative momentum in cms:

$$b^2(M)=\frac{[M^2-(m_1+m_2)^2][M^2-(m_1-m_2)^2]}{4M^2}$$

$E_{1,2}$ - center-of-mass energies:

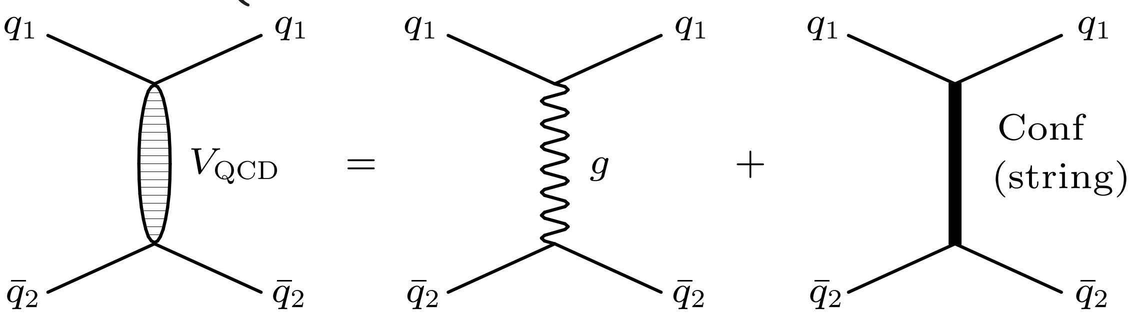
$$E_1=\frac{M^2-m_2^2+m_1^2}{2M},\quad E_2=\frac{M^2-m_1^2+m_2^2}{2M}$$

- **Baryons in quark-diquark picture**

(qq)-interaction:

$$V_{qq} = \frac{1}{2} V_{q\bar{q}}$$

$$V_{q\bar{q}}(\mathbf{p},\mathbf{q};M) = \bar{u}_1(p)\bar{u}_2(-p)\left\{\frac{4}{3}\alpha_s D_{\mu\nu}(\mathbf{k})\gamma_1^{\mu}\gamma_2^{\nu} + V_{\rm conf}^{V}(\mathbf{k})\Gamma_1^{\mu}\Gamma_{2;\mu} + V_{\rm conf}^{S}(\mathbf{k})\right\}u_1(q)u_2(-q)$$



$\mathbf{k} = \mathbf{p} - \mathbf{q}$
$D_{\mu\nu}(\mathbf{k})$ - (perturbative) gluon propagator
$\Gamma_{\mu}(\mathbf{k})$ - effective long-range vertex with Pauli term:

$$\Gamma_{\mu}(\mathbf{k}) = \gamma_{\mu} + \frac{i\kappa}{2m}\sigma_{\mu\nu}k^{\nu},$$

κ - anomalous chromomagnetic moment of quark,

$$u^{\lambda}(p) = \sqrt{\frac{\epsilon(p)+m}{2\epsilon(p)}}\begin{pmatrix} 1 \\ \dfrac{\boldsymbol{\sigma}\mathbf{p}}{\epsilon(p)+m}\end{pmatrix}\chi^{\lambda}, \qquad \epsilon(p) = \sqrt{\mathbf{p}^2+m^2}$$

.

- Lorentz structure of the quark potential

$$V_{\text{conf}} = V_{\text{conf}}^{V} + V_{\text{conf}}^{S}$$

In nonrelativistic limit

$$\left.\begin{array}{rcl} V_{\text{conf}}^{V}(r) & = & (1-\varepsilon)(Ar+B) \\ V_{\text{conf}}^{S}(r) & = & \varepsilon(Ar+B) \end{array}\right\} \quad \text{Sum :} \quad (Ar+B)$$

ε - mixing parameter

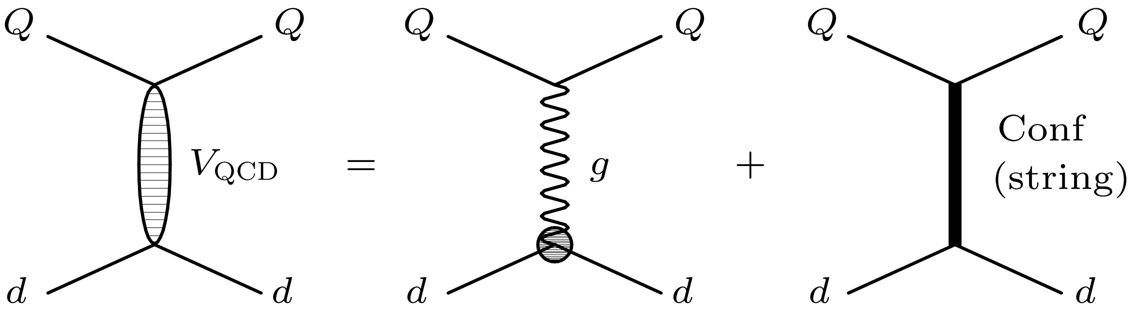
$$V_{\text{NR}}(r) = V_{\text{Coul}}(r) + V_{\text{conf}}(r) = -\frac{4}{3}\frac{\alpha_s}{r} + Ar + B$$

$$V_{\text{Coul}}(r) = -\frac{4}{3}\frac{\alpha_s}{r}$$

(dQ)-interaction: $\quad d=(qq')$

$$V(\mathbf{p},\mathbf{q};M)=\frac{\langle d(P)|J_\mu|d(Q)\rangle}{2\sqrt{E_d(p)E_d(q)}}\bar{u}_Q(p)\frac{4}{3}\alpha_s D_{\mu\nu}(\mathbf{k})\gamma^\nu u_Q(q)$$

$$+\psi_d^*(P)\bar{u}_Q(p)J_{d;\mu}\Gamma_Q^\mu V_{\rm conf}^V(\mathbf{k})u_Q(q)\psi_d(Q)+\psi_d^*(P)\bar{u}_Q(p)V_{\rm conf}^S(\mathbf{k})u_Q(q)\psi_d(Q)$$



$J_{d,\mu}$ – effective long-range vector vertex of diquark:

$$J_{d;\mu}=\begin{cases}\dfrac{(P+Q)_\mu}{2\sqrt{E_d(p)E_d(q)}} & \text{for scalar diquark}\\[2ex] -\dfrac{(P+Q)_\mu}{2\sqrt{E_d(p)E_d(q)}}+\dfrac{i\mu_d}{2M_d}\Sigma_\mu^\nu k_\nu & \text{for axial vector diquark } (\mu_d=0)\end{cases}$$

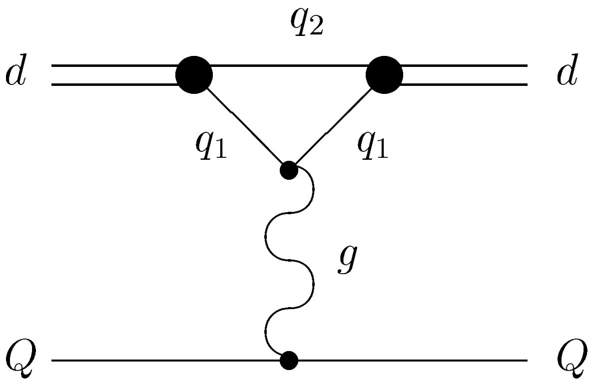
μ_d - total chromomagnetic moment of axial vector diquark
diquark spin matrix: $\quad (\Sigma_{\rho\sigma})_\mu^\nu=-i(g_{\mu\rho}\delta_\sigma^\nu-g_{\mu\sigma}\delta_\rho^\nu)$
$\mathbf{S}_d$ - axial vector diquark spin: $\quad (S_{d;k})_{il}=-i\varepsilon_{kil}$

$\psi_d(P)$ – diquark wave function:

$$\psi_d(p) = \begin{cases} 1 & \text{for scalar diquark} \\ \varepsilon_d(p) & \text{for axial vector diquark} \end{cases}$$

$\varepsilon_d(p)$ – polarization vector of axial vector diquark

Vertex of diquark-gluon interaction:



$$\langle d(P)|J_\mu(0)|d(Q)\rangle = \int \frac{d^3p\, d^3q}{(2\pi)^6} \bar{\Psi}^d_P(\mathbf{p})\Gamma_\mu(\mathbf{p},\mathbf{q})\Psi^d_Q(\mathbf{q}) \Rightarrow F(k^2)$$

Γ_μ – two-particle vertex function of the diquark-gluon interaction

The calculated diquark-gluon interaction form factor can be parameterized by

$$F(r) = 1 - e^{-\xi r - \zeta r^2}$$

- Parameters of the model

Parameters A, B, κ, ε and quark masses fixed from analysis of meson masses and radiative decays:

$\varepsilon = -1$ from heavy quarkonium radiative decays $(J/\psi \to \eta_c + \gamma)$ and HQET

$\kappa = -1$ from fine splitting of heavy quarkonium ${}^3P_J$ states and HQET

$(1+\kappa) = 0 \Longrightarrow$ vanishing long-range chromomagnetic interaction ! (flux tube model)

Freezing of α_s

$$\alpha_s(\mu) = \frac{4\pi}{\beta_0 \ln \frac{\mu^2+M_0^2}{\Lambda^2}}, \quad \beta_0 = 11 - \frac{2}{3}n_f, \quad \mu = \frac{2m_1m_2}{m_1+m_2},$$

$$M_0 = 2.24\sqrt{A} = 0.95 \text{ GeV}$$

Quasipotential parameters:

$A = 0.18$ GeV^2, $B = -0.30$ GeV,

$\Lambda = 0.413$ GeV (from M_ρ)

Quark masses:

$m_b = 4.88$ GeV	$m_s = 0.50$ GeV
$m_c = 1.55$ GeV	$m_{u,d} = 0.33$ GeV

MASSES OF HEAVY BARYONS

Quark-diquark picture of heavy baryons reduces relativistic three-body problem to two step two-body calculation:

First step

- Masses and form factors of light and heavy diquarks are calculated

— Only ground-state scalar and axial vector diquarks are considered for heavy baryons

— Ground-state as well as orbital and radial excitations of heavy diquarks are necessary for doubly heavy baryons

Second step

- Heavy baryon is considered as a bound heavy-quark–light-diquark state

— All excitations are assumed to occur between heavy quark and light diquark

- Doubly heavy baryon is considered as a bound light-quark–heavy-diquark state

— Both excitations in quark-diquark system and excitations of heavy diquark are considered

- Significantly less excited states than in genuine three-quark picture

Light diquarks

Table 1: Masses of light ground state diquarks (in MeV)

Quark content	Diquark type	Mass				
		our	NJL	BSE	BSE	Lattice
$[u,d]$	S	710	705	737	820	694(22)
$\{u,d\}$	A	909	875	949	1020	806(50)
$[u,s]$	S	948	895	882	1100	
$\{u,s\}$	A	1069	1050	1050	1300	
$\{s,s\}$	A	1203	1215	1130	1440	

Table 2: Masses M and form factor parameters of light diquarks.

Quark content	Diquark type	M (MeV)	ξ (GeV)	ζ (GeV^2)
$[u, d]$	S	710	1.09	0.185
$\{u, d\}$	A	909	1.185	0.365
$[u, s]$	S	948	1.23	0.225
$\{u, s\}$	A	1069	1.15	0.325
$\{s, s\}$	A	1203	1.13	0.280

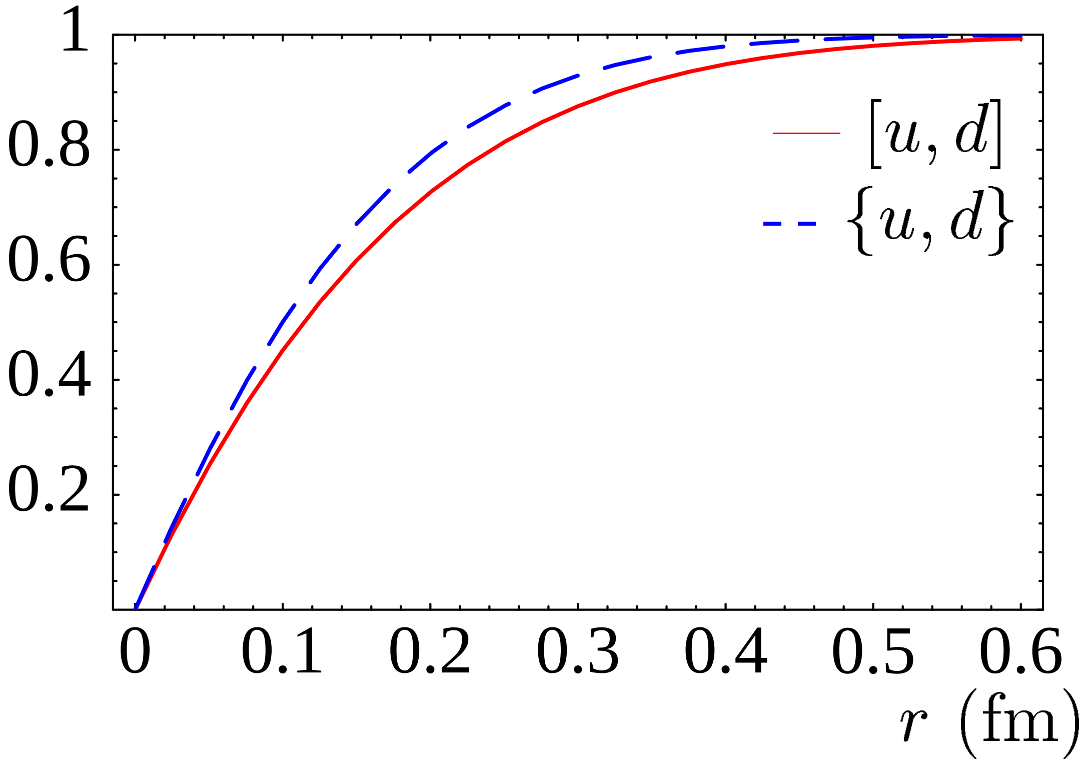


Figure 1: Form factors $F(r)$ for scalar $[u, d]$ (solid line) and axial vector $\{u, d\}$ (dashed line) diquarks.

Heavy diquarks

Table 3: Masses M and form factor parameters of light diquarks.

Diquark State	cc			bb		
	Mass (GeV)	ξ (GeV)	ζ (GeV^2)	Mass (GeV)	ξ (GeV)	ζ (GeV^2)
1^3S_1	3.226	1.30	0.42	9.778	1.30	1.60
1^1P_1	3.460	0.74	0.315	9.944	0.90	0.59
2^3S_1	3.535	0.67	0.19	10.015	0.85	0.31
2^1P_1	3.712	0.60	0.155	10.132	0.65	0.215
3^3S_1	3.782	0.57	0.12	10.196	0.66	0.155
3^1P_1	3.928	0.55	0.075	10.305	0.58	0.120

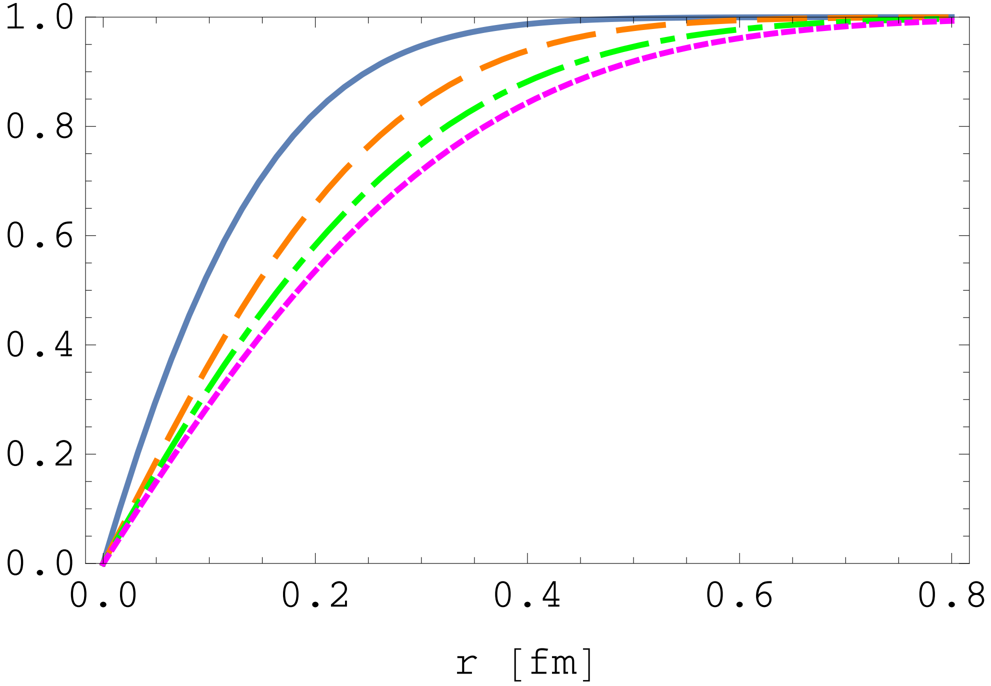


Figure 2: The form factors $F(r)$ for the cc diquark. The solid curve is for the $1S$ state, the dashed curve for the $1P$ state, the dashed-dotted curve for the $2S$ state, and the dotted curve for the $2P$ state.

Heavy baryon masses

We do not expand the potential of the quark–diquark interaction either in p/m_Q or in p/m_d and treat both diquark and quark fully relativistically.
The resulting quasipotential of Qd interaction is extremely nonlocal in configuration space.
To simplify the potential and to make it local in configuration space we replace:

- the diquark energies

$$E_d(p) \equiv \sqrt{\mathbf{p}^2 + M_d^2} \to E_d = \frac{M^2 - m_Q^2 + M_d^2}{2M},$$

- the quark energies

$$\epsilon_Q(p) \equiv \sqrt{\mathbf{p}^2 + m_Q^2} \to E_Q = \frac{M^2 - M_d^2 + m_Q^2}{2M}.$$

These substitutions make the Fourier transform of the potential local, but introduce a complicated nonlinear dependence of the potential on the baryon mass M through the on-mass-shell energies E_d and E_Q.

The resulting Qd potential

$$V(r) = V_{\rm SI}(r) + V_{\rm SD}(r),$$

where $V_{\rm SI}(r)$ is the spin-independent part, and the structure of the spin-dependent potential is given by

$$V_{\rm SD}(r) = a_1\,\mathbf{L}\mathbf{S}_d + a_2\,\mathbf{L}\mathbf{S}_Q + b\left[-\mathbf{S}_d\mathbf{S}_Q + \frac{3}{r^2}(\mathbf{S}_d\mathbf{r})(\mathbf{S}_Q\mathbf{r})\right] + c\,\mathbf{S}_d\mathbf{S}_Q,$$

where $\mathbf{L}$ is the orbital angular momentum, $\mathbf{S}_d$ and $\mathbf{S}_Q$ are the diquark and quark spin operators, respectively. The coefficients a_1, a_2, b and c are expressed through the corresponding derivatives of the smeared Coulomb and confining potentials, e.g.:

$$c = \frac{2}{3}\frac{1}{E_dE_Q}\left\{\Delta\hat{V}_{\rm Coul}(r) - \frac{\mu_d}{2}\frac{E_d}{M_d}\left[\frac{E_Q - m_Q}{2m_Q} - (1+\kappa)\frac{E_Q + m_Q}{2m_Q}\right]\Delta V^V_{\rm conf}(r)\right\}.$$

The smeared Coulomb potential which accounts for the diquark internal structure

$$\hat{V}_{\rm Coul}(r) = -\frac{4}{3}\alpha_s\frac{F(r)}{r}.$$

Heavy baryons

Table 4: Masses of the ground state heavy baryons (in MeV). our – EFG, Phys. Rev. D (2005)

Baryon	$I(J^P)$	Theory						Experiment
		our (2005)	Capstick Isgur	Roncaglia et al.	Savage	Jenkins	Mathur* et al.	PDG
Λ_c	$0(\frac{1}{2}^+)$	2286	2265	2285			2290	2286.46(14)
Σ_c	$1(\frac{1}{2}^+)$	2443	2440	2453			2452	2453.76(18)
Σ_c^*	$1(\frac{3}{2}^+)$	2519	2495	2520	2518		2538	2518.0(0.5)
Ξ_c	$\frac{1}{2}(\frac{1}{2}^+)$	2476		2468			2473	$2470.88(^{34}_{80})$
Ξ_c'	$\frac{1}{2}(\frac{1}{2}^+)$	2579		2580	2579	2580.8(2.1)	2599	2577.9(2.9)
Ξ_c^*	$\frac{1}{2}(\frac{3}{2}^+)$	2649		2650			2680	2645.9(0.5)
Ω_c	$0(\frac{1}{2}^+)$	2698		2710			2678	2695.2(1.7)
Ω_c^*	$0(\frac{3}{2}^+)$	2768		2770	2768	2760.5(4.9)	2752	2765.9(2.0)
Λ_b	$0(\frac{1}{2}^+)$	5620	5585	5620			5672	5619.51(23)
Σ_b	$1(\frac{1}{2}^+)$	5808	5795	5820		5824.2(9.0)	5847	5811.3(1.9)
Σ_b^*	$1(\frac{3}{2}^+)$	5834	5805	5850		5840.0(8.8)	5871	5832.1(1.9)
Ξ_b	$\frac{1}{2}(\frac{1}{2}^+)$	5803		5810		5805.7(8.1)	5788	5794.4(1.2)
Ξ_b'	$\frac{1}{2}(\frac{1}{2}^+)$	5937		5950		5950.9(8.5)	5936	5935.02(5)
Ξ_b^*	$\frac{1}{2}(\frac{3}{2}^+)$	5963		5980		5966.1(8.3)	5959	5955.33(13)
Ω_b	$0(\frac{1}{2}^+)$	6064		6060		6068.7(11.1)	6040	6048.0(1.9)
Ω_b^*	$0(\frac{3}{2}^+)$	6088		6090		6083.2(11.0)	6060	

[*] error estimates of lattice calculations — ∼50 MeV for charmed, ∼100 MeV for bottom baryons

Table 5: Masses M of the Λ_Q ($Q = c, b$) heavy baryons (in MeV).

		$Q = c$			$Q = b$		
$I(J^P)$	Qd state	M	status	M^{exp}	M	status	M^{exp}
$0(\frac{1}{2}^+)$	$1S$	2286	****	2286.46(14)	5620	***	5619.51(23)
	$2S$	2769	*	2766.6(2.4)?	6089		
	$3S$	3130			6455		
	$4S$	3437			6756		
	$5S$	3715			7015		
	$6S$	3973			7256		
$0(\frac{1}{2}^-)$	$1P$	2598	***	2592.25(28)	5930	***	5912.11(26)
	$2P$	2983	***	$2939.3(^{1.4}_{1.5})$?	6326		
	$3P$	3303			6645		
	$4P$	3588			6917		
	$5P$	3852			7157		
$0(\frac{3}{2}^-)$	$1P$	2627	***	2628.1(6)	5942	***	5919.81(23)
	$2P$	3005			6333		
	$3P$	3322			6651		
	$4P$	3606			6922		
	$5P$	3869			7171		
$0(\frac{3}{2}^+)$	$1D$	2874	new	$2856.1.3(^{2.3}_{5.9})$	6190		
	$2D$	3189			6526		
	$3D$	3480			6811		
	$4D$	3747			7060		

Table 5: (continued)

$I(J^P)$	Qd state	$Q=c$			$Q=b$		
		M	status	$M^{\rm exp}$	M	status	$M^{\rm exp}$
$0(\frac{5}{2}^+)$	$1D$	2880	***	2881.53(35)	6196		
	$2D$	3209			6531		
	$3D$	3500			6814		
	$4D$	3767			7063		
$0(\frac{5}{2}^-)$	$1F$	3097			6408		
	$2F$	3375			6705		
	$3F$	3646			6964		
	$4F$	3900			7196		
$0(\frac{7}{2}^-)$	$1F$	3078			6411		
	$2F$	3393			6708		
	$3F$	3667			6966		
	$4F$	3922			7197		
$0(\frac{7}{2}^+)$	$1G$	3270			6598		
	$2G$	3546			6867		
$0(\frac{9}{2}^+)$	$1G$	3284			6599		
	$2G$	3564			6868		
$0(\frac{9}{2}^-)$	$1H$	3444			6767		
$0(\frac{11}{2}^-)$	$1H$	3460			6766		

Table 6: Comparison of theoretical predictions for masses of the Λ_c baryons (in MeV).

J^P	Experiment			Theory			
	State	Status	Mass	our	Chen et al.	Roberts Pervin	Capstick Isgur
$\frac{1}{2}^+$	Λ_c	****	2286.46	2286	2286	2286	2265
	$\Lambda_c(2765)$	*	2766.6	2769	2766	2791	2775
				3130	3112	3154	3170
				3437	3397		
$\frac{1}{2}^-$	$\Lambda_c(2595)$	***	2592.3	2598	2591	2625	2630
	$\Lambda_c(2940)$	***	2939.3	2983	2989		2780
				3303	3296		2830
$\frac{3}{2}^-$	$\Lambda_c(2625)$	***	2628.1	2627	2629	2636	2640
				3005	3000		2840
				3322	3301		2885
$\frac{3}{2}^+$	$\Lambda_c(2860)$	new	2856.1	2874	2857	2887	2910
				3189	3188	3120	3035
$\frac{5}{2}^+$	$\Lambda_c(2880)$	***	2881.53	2880	2879	2887	2910
				3209	3198	3125	3140
$\frac{5}{2}^-$				3097	3075	2872	2900
$\frac{7}{2}^-$				3078	3092		3125
$\frac{7}{2}^+$				3270	3267		3175
$\frac{9}{2}^+$				3284	3280		

Table 7: Masses M of the Ω_Q $(Q = c, b)$ heavy baryons (in MeV).

		$Q = c$			$Q = b$		
$I(J^P)$	Qd state	M	status	$M^{\rm exp}$	M	status	$M^{\rm exp}$
$0(\frac{1}{2}^+)$	$1S$	2698	***	2695.2(1.7)	6064	***	6046.4(1.9)
$0(\frac{1}{2}^+)$	$2S$	3088	new	$3090.2\binom{7}{8}$	6450		
$0(\frac{1}{2}^+)$	$3S$	3489			6804		
$0(\frac{1}{2}^+)$	$4S$	3814			7091		
$0(\frac{1}{2}^+)$	$5S$	4102			7338		
$0(\frac{3}{2}^+)$	$1S$	2768	***	2765.9(2.0)	6088		
$0(\frac{3}{2}^+)$	$2S$	3123	new	$3119.1\binom{1.0}{1.1}$	6461		
$0(\frac{3}{2}^+)$	$3S$	3510			6811		
$0(\frac{3}{2}^+)$	$4S$	3830			7096		
$0(\frac{3}{2}^+)$	$5S$	4114			7343		
$0(\frac{1}{2}^-)$	$1P$	3055	new	$3065.6\binom{6}{7}$	6339		
$0(\frac{1}{2}^-)$	$2P$	3435			6710		
$0(\frac{1}{2}^-)$	$3P$	3754			7009		
$0(\frac{1}{2}^-)$	$4P$	4037			7265		
$0(\frac{1}{2}^-)$	$1P$	2966	new	$3000.4\binom{4}{6}$	6330		
$0(\frac{1}{2}^-)$	$2P$	3384			6706		
$0(\frac{1}{2}^-)$	$3P$	3717			7003		
$0(\frac{1}{2}^-)$	$4P$	4009			7257		

Table 7: (continued)

		$Q=c$			$Q=b$		
$I(J^P)$	Qd state	M	status	M^{exp}	M	status	M^{exp}
$0(\frac{3}{2}^-)$	$1P$	3054	new	$3065.6(^{6}_{7})$	6340		
$0(\frac{3}{2}^-)$	$2P$	3433			6705		
$0(\frac{3}{2}^-)$	$3P$	3752			7002		
$0(\frac{3}{2}^-)$	$4P$	4036			7258		
$0(\frac{3}{2}^-)$	$1P$	3029	new	$3000.4(^{4}_{6})$	6331		
$0(\frac{3}{2}^-)$	$2P$	3415			6699		
$0(\frac{3}{2}^-)$	$3P$	3737			6998		
$0(\frac{3}{2}^-)$	$4P$	4023			7250		
$0(\frac{5}{2}^-)$	$1P$	3051	new	$3050.2(^{4}_{5})$	6334		
$0(\frac{5}{2}^-)$	$2P$	3427			6700		
$0(\frac{5}{2}^-)$	$3P$	3744			6996		
$0(\frac{5}{2}^-)$	$4P$	4028			7251		
$0(\frac{1}{2}^+)$	$1D$	3287			6540		
$0(\frac{3}{2}^+)$	$1D$	3298			6549		
$0(\frac{3}{2}^+)$	$1D$	3282			6530		
$0(\frac{5}{2}^+)$	$1D$	3297			6529		
$0(\frac{5}{2}^+)$	$1D$	3286			6520		
$0(\frac{7}{2}^+)$	$1D$	3283			6517		
$0(\frac{3}{2}^-)$	$1F$	3533			6763		

Table 8: Comparison of theoretical predictions for the masses of the Ω_c states.

State nL, J^P	our RQM	Roberts QM	Shah QM	Perez-Rubio lattice	Chen lattice	Agaev QCD SR	Experiment. PDG+LHCb
$1S, 1/2^+$	2698	2718	2695	2648(28)	2695(28)	2685(123)	2695.2(1.7)
$2S, 1/2^+$	3088	3152	3100	3294(73)		3066(138)	$3090.2(^{7}_{8})$
$1S, 3/2^+$	2768	2776	2767	2709(32)	2781(25)	2769(89)	2765.9(2.0)
$2S, 3/2^+$	3123	3190	3126	3355(92)		3119(114)	$3119.1(^{1.0}_{1.1})$
$1P, 1/2^-$	2966	2977	3028	2995(46)	3015(45)		
$1P, 1/2^-$	3055	2990	3011				
$1P, 3/2^-$	3054	2986	2976	3016(69)			$3065.6(^{6}_{7})$
$1P, 3/2^-$	3029	2994	2993				$3000.4(^{4}_{6})$
$1P, 5/2^-$	3051	3014	2947				$3050.2(^{4}_{5})$

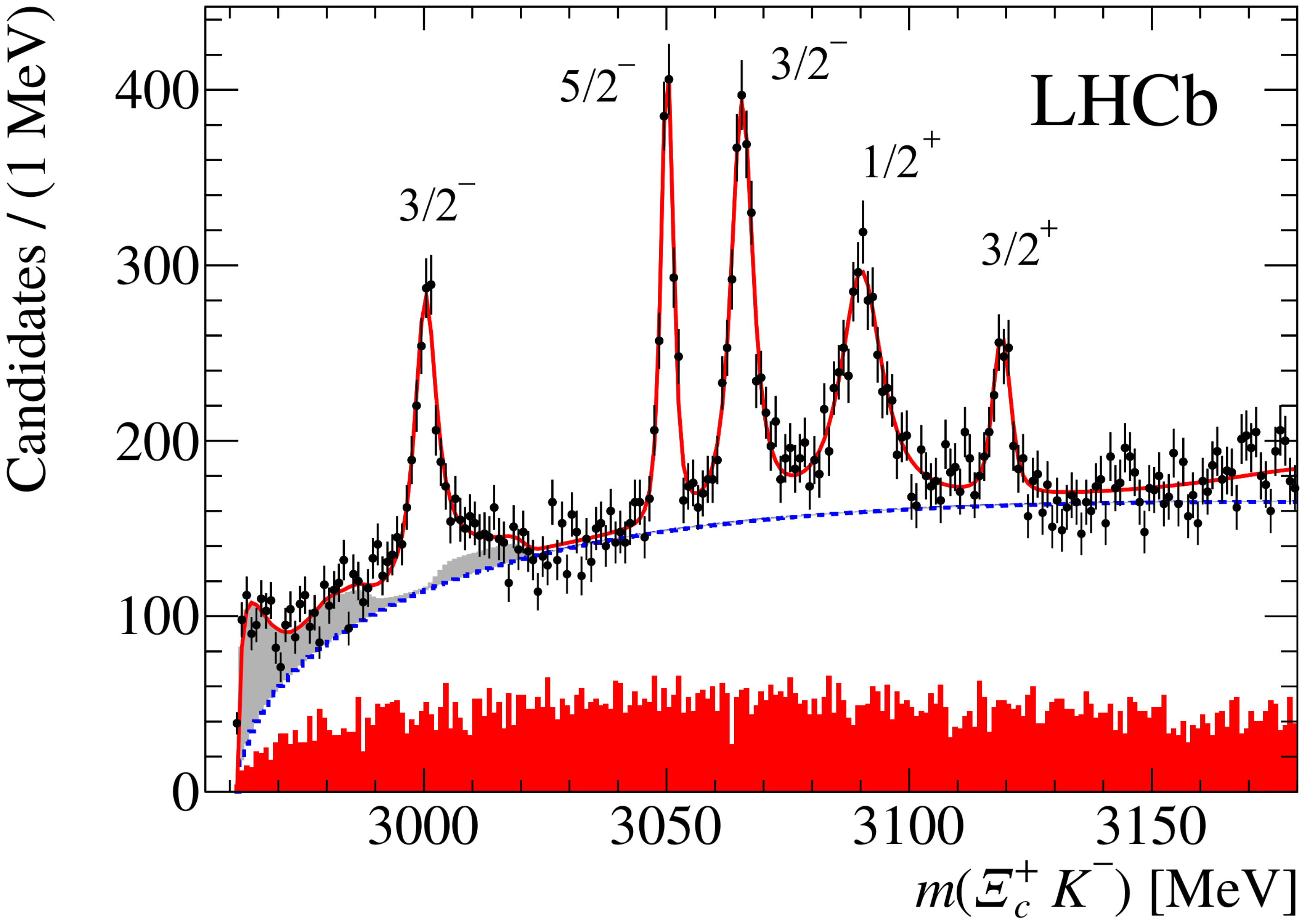


Figure 3: Proposed assignment of spins and parities of excited Ω_c states observed by LHCb Collaboration.

Doubly heavy baryons

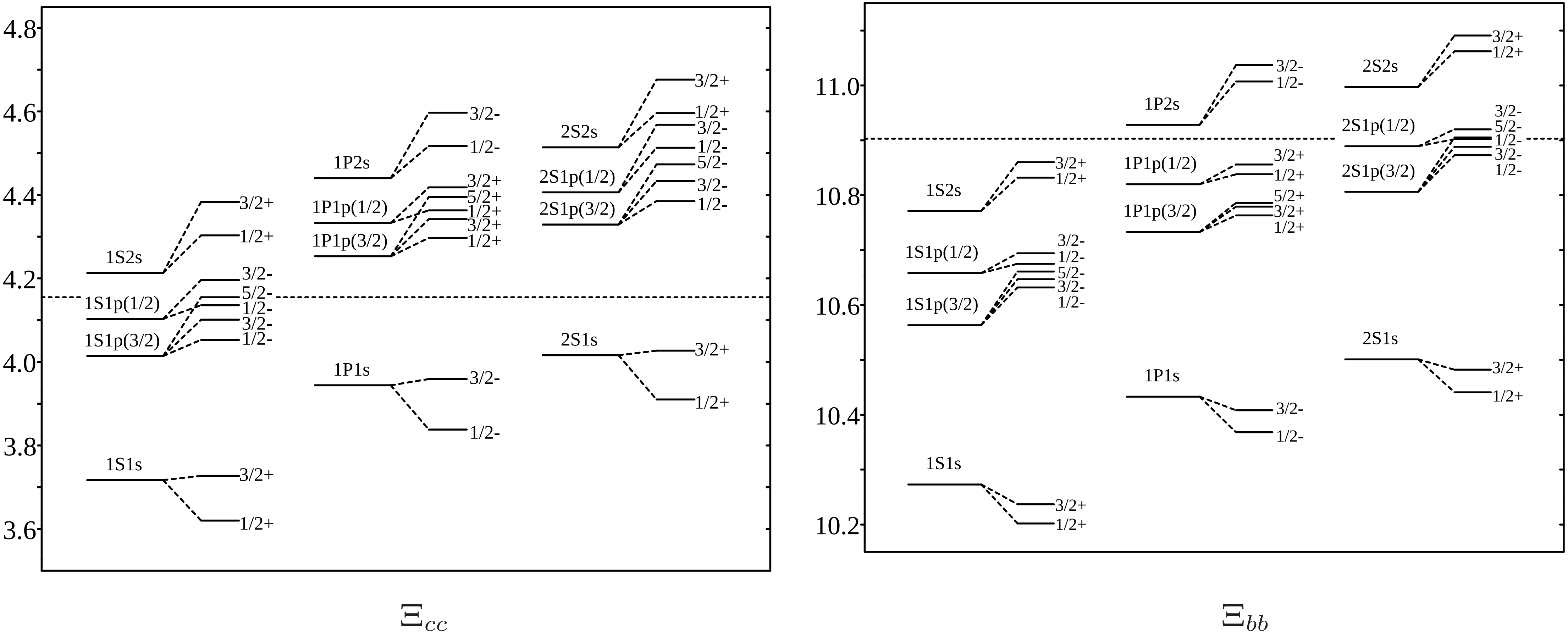


Figure 4: Mass spectrum of Ξ_{cc} and Ξ_{bb} baryons. The horizontal dashed line shows the $\Lambda_c D$ and $\Lambda_b B$ thresholds.

Table 9: Mass spectrum of ground states of doubly heavy baryons (in GeV). Comparison of different predictions. $\{QQ\}$ denotes the diquark in the axial vector state and $[QQ]$ denotes diquark in the scalar state.

Baryon	Quark content	J^P	our	Gershtein et al.	Roncaglia et al.	Narodetskii Trusov	Martynenko	Roberts Pervin	Karliner Rosner
Ξ_{cc}	$\{cc\}q$	$\frac{1}{2}^+$	3.620	3.478	3.66	3.69	3.510	3.676	3.627(12)
Ξ^*_{cc}	$\{cc\}q$	$\frac{3}{2}^+$	3.727	3.61	3.74		3.548	3.753	3.690(12)
Ω_{cc}	$\{cc\}s$	$\frac{1}{2}^+$	3.778	3.59	3.74	3.86	3.719	3.815	
Ω^*_{cc}	$\{cc\}s$	$\frac{3}{2}^+$	3.872	3.69	3.826		3.746	3.876	
Ξ_{bb}	$\{bb\}q$	$\frac{1}{2}^+$	10.202	10.093	10.34	10.16	10.130	10.340	10.162(12)
Ξ^*_{bb}	$\{bb\}q$	$\frac{3}{2}^+$	10.237	10.133	10.37		10.144	10.367	10.184(12)
Ω_{bb}	$\{bb\}s$	$\frac{1}{2}^+$	10.359	10.18	10.37	10.34	10.422	10.454	
Ω^*_{bb}	$\{bb\}s$	$\frac{3}{2}^+$	10.389	10.20	10.40		10.432	10.486	
Ξ_{cb}	$\{cb\}q$	$\frac{1}{2}^+$	6.933	6.82	7.04	6.96	6.792	7.011	6.914(13)
Ξ'_{cb}	$[cb]q$	$\frac{1}{2}^+$	6.963	6.85	6.99		6.825	7.047	6.933(12)
Ξ^*_{cb}	$\{cb\}q$	$\frac{3}{2}^+$	6.980	6.90	7.06		6.827	7.074	6.969(14)
Ω_{cb}	$\{cb\}s$	$\frac{1}{2}^+$	7.088	6.91	7.09	7.13	6.999	7.136	
Ω'_{cb}	$[cb]s$	$\frac{1}{2}^+$	7.116	6.93	7.06		7.022	7.165	
Ω^*_{cb}	$\{cb\}s$	$\frac{3}{2}^+$	7.130	6.99	7.12		7.024	7.187	

$$M(\Xi_{cc}^{++}) = 3621.40 \pm 0.72 \pm 0.27 \pm 0.14 \text{ MeV} \qquad \text{LHCb 2017}$$

CONCLUSIONS

- Heavy baryons

Recent observations of excited charm baryons confirm predictions of the relativistic heavy-quark–light-diquark model of heavy baryons

- New state $\Lambda_c(2860)$ is in accord with the predicted $1D$- state with $J^P=\frac{3}{2}^+$
- The experimentally preferred quantum numbers $J^P=\frac{5}{2}^+$ of $\Lambda_c(2880)$ agree with our assignment of this state to $1D$- state with $J^P=\frac{5}{2}^+$
- Observation of five new narrow Ω_c states in the mass range 3000-3200 MeV agrees with our prediction of orbitally excited $1P$-states and radially excited $2S$-states in this mass region.
- $\Omega_c(3000)$, $\Omega_c(3066)$, $\Omega_c(3050)$ can be $1P$-states with $J^P=\frac{3}{2}^-,\frac{3}{2}^-,\frac{5}{2}^-$
- $\Omega_c(3090)$ and $\Omega_c(3119)$ states are most likely the first radially excited $2S$ states with $J^P=\frac{1}{2}^+,\frac{3}{2}^+$

All observed bottom baryon masses agree with predictions of our model.

- Doubly heavy baryons

- Mass of just observed Ξ_{cc}^{++} baryon is in excellent agreement with our prediction
- Masses of ground state doubly charm baryons are predicted to be in 3.5 - 3.9 GeV range.
- Masses of ground state doubly bottom baryons are predicted to be in 10.1 - 10.5 GeV range.
- Masses of ground state bottom-charm baryons are predicted to be in 6.8 - 7.2 GeV range.
- Rich spectra of narrow excited states below strong decay thresholds are expected.

We strongly encourage experimenters to search for new and excited states of heavy baryons and especially for doubly heavy baryons!

We are eagerly waiting for new discoveries!

BACKUP SLIDES

Table 10: Masses of the Σ_Q ($Q = c, b$) heavy baryons (in MeV).

		$Q = c$			$Q = b$		
$I(J^P)$	Qd state	M	status	$M^{\exp}$	M	status	$M^{\exp}$
$1(\frac{1}{2}^+)$	$1S$	2443	****	2453.76(18)	5808	***	5807.8(2.7)
$1(\frac{1}{2}^+)$	$2S$	2901			6213		
	$3S$	3271			6575		
	$4S$	3581			6869		
	$5S$	3861			7124		
$1(\frac{3}{2}^+)$	$1S$	2519	***	2518.0(5)	5834	***	5829.0(3.4)
	$2S$	2936	***	$2939.3(^{1.4}_{1.5})$?	6226		
	$3S$	3293			6583		
	$4S$	3598			6876		
	$5S$	3873			7129		
$1(\frac{1}{2}^-)$	$1P$	2799	***	$2802(^{4}_{7})$	6101		
	$2P$	3172			6440		
	$3P$	3488			6756		
	$4P$	3770			7024		
	$1P$	2713			6095		
	$2P$	3125			6430		
	$3P$	3455			6742		
	$4P$	3743			7008		
$1(\frac{3}{2}^-)$	$1P$	2798	***	$2802(^{4}_{7})$	6096		
	$2P$	3172			6430		
	$3P$	3486			6742		
	$4P$	3768			7009		

Table 10: (continued)

$I(J^P)$	Qd state	$Q=c$			$Q=b$		
		M	status	M^{exp}	M	status	M^{exp}
$1(\frac{3}{2}^-)$	$1P$	2773	*	2766.6(2.4)?	6087		
	$2P$	3151			6423		
	$3P$	3469			6736		
	$4P$	3753			7003		
$1(\frac{5}{2}^-)$	$1P$	2789			6084		
	$2P$	3161			6421		
	$3P$	3475			6732		
	$4P$	3757			6999		
$1(\frac{1}{2}^+)$	$1D$	3041			6311		
	$2D$	3370			6636		
$1(\frac{3}{2}^+)$	$1D$	3043			6326		
	$2D$	3366			6647		
	$1D$	3040			6285		
	$2D$	3364			6612		
$1(\frac{5}{2}^+)$	$1D$	3038			6284		
	$2D$	3365			6612		
	$1D$	3023			6270		
	$2D$	3349			6598		
$1(\frac{7}{2}^+)$	$1D$	3013			6260		
	$2D$	3342			6590		

Regge trajectories of heavy baryons

(a) The (J, M^2) Regge trajectory:

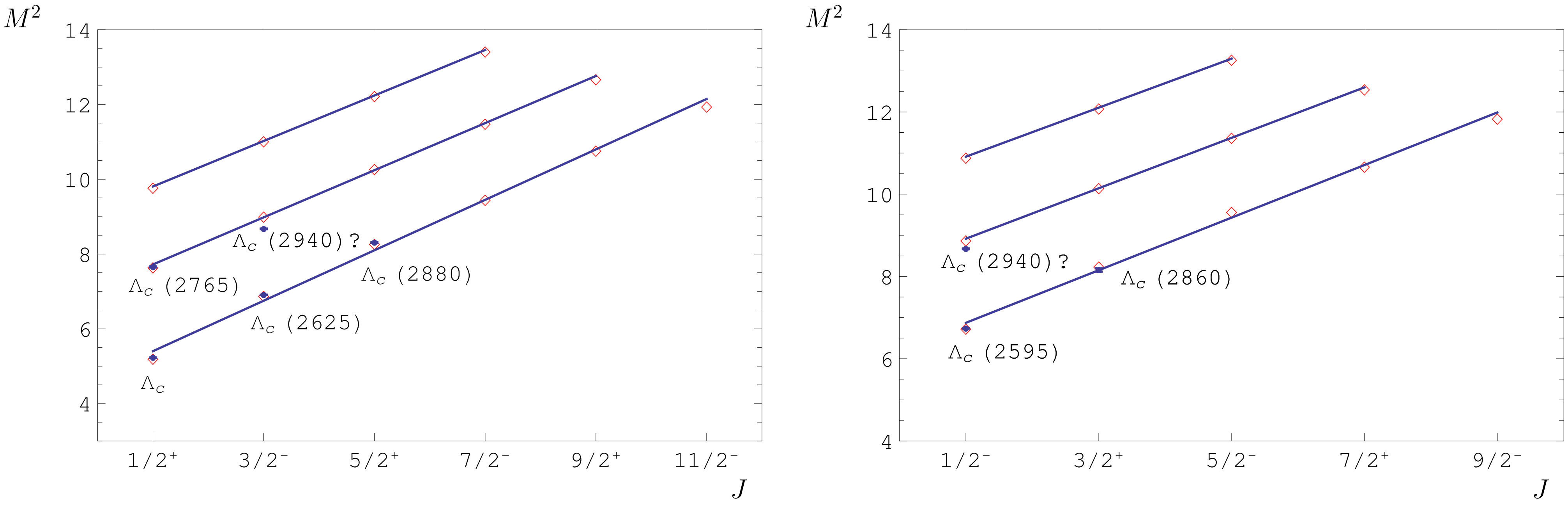
$$J = \alpha M^2 + \alpha_0$$

(b) The (n_r, M^2) Regge trajectory:

$$n_r = \beta M^2 + \beta_0,$$

α, β – slopes
α_0, β_0 – intercepts.

Baryons:
$P = (-1)^{J-1/2}$ – natural parity
$P = (-1)^{J+1/2}$ – unnatural parity



(a) (b)

Figure 5: Parent and daughter (J, M^2) Regge trajectories for the Λ_c baryons with natural (a) and unnatural (b) parities. Diamonds are predicted masses. Available experimental data are given by dots with particle names; M^2 is in GeV^2.

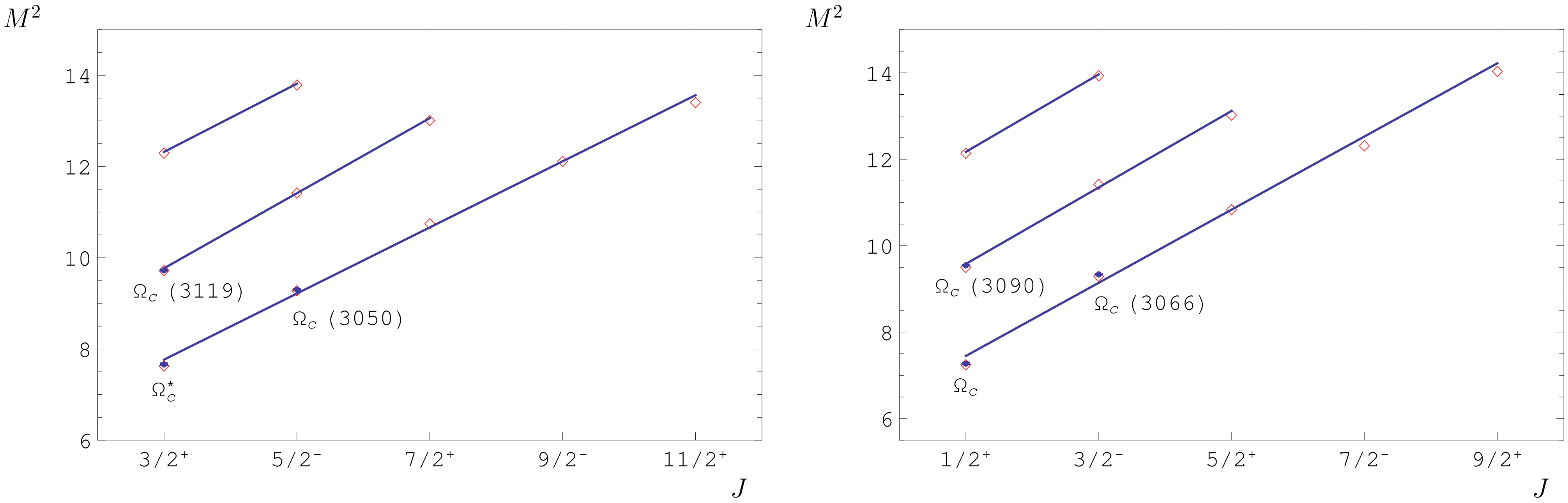


Figure 6: The (J, M^2) Regge trajectories for the Ω_c baryons. Diamonds are predicted masses. Available experimental data are given by dots with particle names; M^2 is in GeV^2.

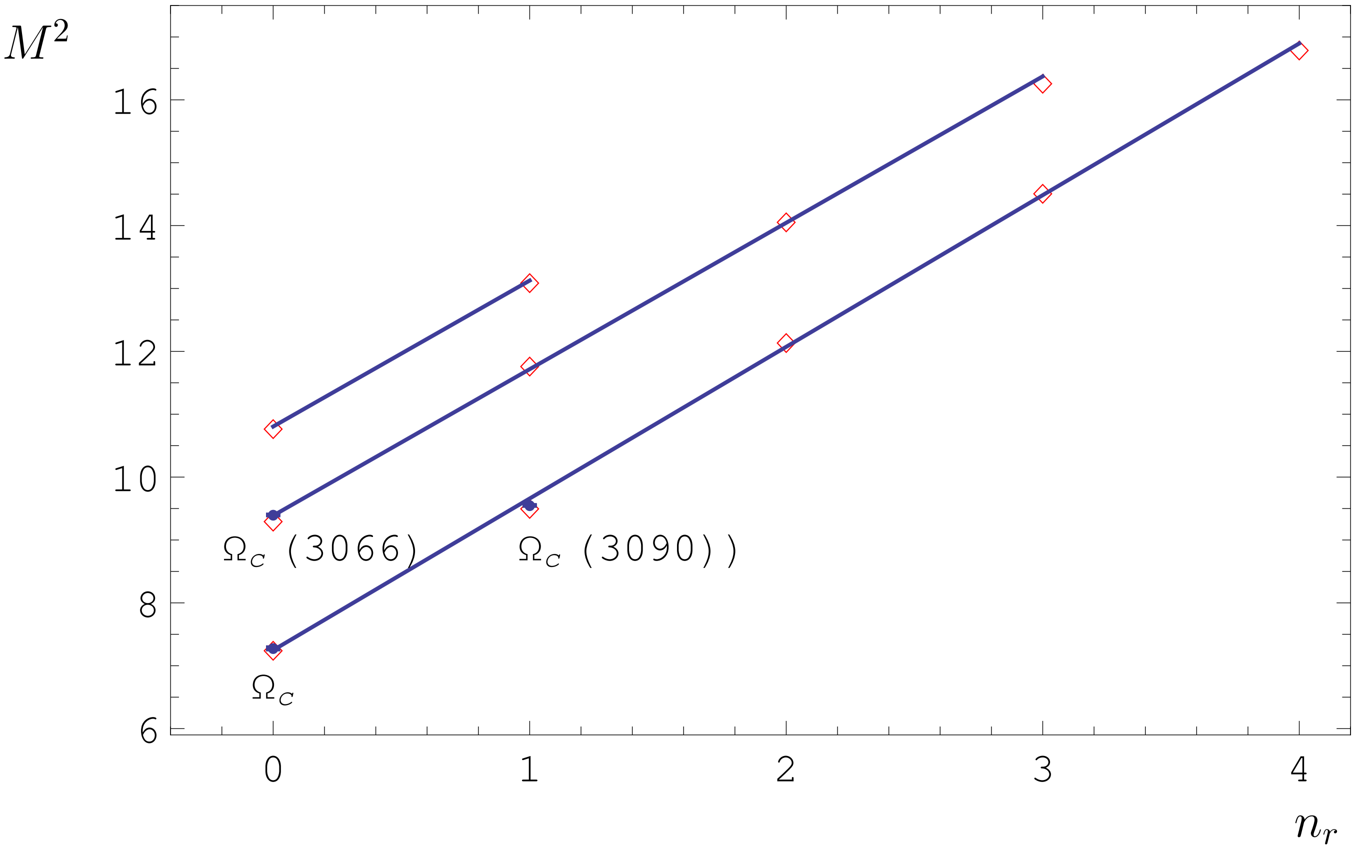


Figure 7: The (n_r, M^2) Regge trajectories for $\Omega_c\left(\frac{1}{2}^+, S\right)$, $\Omega_c\left(\frac{3}{2}^-, P\right)$ and $\Omega_c\left(\frac{1}{2}^+, D\right)$ baryons (from bottom to top).

Table 11: Fitted parameters for the slope and intercept of the (J, M^2) parent and daughter Regge trajectories for heavy baryons with scalar and axial vector diquark.

Trajectory	α (GeV^{-2})	α_0	α (GeV^{-2})	α_0
$c[u,d]$	$\Lambda_c\left(\frac{1}{2}^+\right)$		$\Lambda_c\left(\frac{1}{2}^-\right)$	
parent	0.741 ± 0.024	-3.504 ± 0.205	0.782 ± 0.030	-4.874 ± 0.276
1 daughter	0.793 ± 0.013	-5.626 ± 0.129	0.815 ± 0.009	-6.769 ± 0.099
$c\{q,q\}$	$\Sigma_c\left(\frac{1}{2}^+\right)$		$\Sigma_c^*\left(\frac{3}{2}^+\right)$	
parent	0.679 ± 0.032	-3.670 ± 0.278	0.778 ± 0.019	-3.498 ± 0.164
1 daughter	0.686 ± 0.016	-5.289 ± 0.158	0.785 ± 0.001	-5.264 ± 0.012
$c[s,q]$	$\Xi_c\left(\frac{1}{2}^+\right)$		$\Xi_c\left(\frac{1}{2}^-\right)$	
parent	0.686 ± 0.025	-3.852 ± 0.240	0.728 ± 0.020	-5.249 ± 0.211
1 daughter	0.739 ± 0.015	-6.025 ± 0.169	0.764 ± 0.012	-7.244 ± 0.142
$c\{s,s\}$	$\Omega_c\left(\frac{1}{2}^+\right)$		$\Omega_c^*\left(\frac{3}{2}^+\right)$	
parent	0.615 ± 0.023	-4.065 ± 0.023	0.690 ± 0.020	-3.858 ± 0.205
1 daughter	0.565 ± 0.028	-4.910 ± 0.316	0.608 ± 0.012	-4.436 ± 0.133
$b[u,d]$	$\Lambda_b\left(\frac{1}{2}^+\right)$		$\Lambda_b\left(\frac{1}{2}^-\right)$	
parent	0.352 ± 0.017	-10.83 ± 0.65	0.376 ± 0.014	-12.82 ± 0.58
1 daughter	0.397 ± 0.015	-14.33 ± 0.64	0.419 ± 0.010	-16.33 ± 0.45
$b[s,q]$	$\Xi_b\left(\frac{1}{2}^+\right)$		$\Xi_b\left(\frac{1}{2}^-\right)$	
parent	0.349 ± 0.019	-11.49 ± 0.80	0.381 ± 0.014	-13.88 ± 0.60
1 daughter	0.399 ± 0.016	-15.27 ± 0.69	0.423 ± 0.011	-17.40 ± 0.49
$b\{s,s\}$	$\Omega_b\left(\frac{1}{2}^+\right)$		$\Omega_b^*\left(\frac{3}{2}^+\right)$	
parent	0.365 ± 0.013	-13.04 ± 0.58	0.389 ± 0.011	-13.02 ± 0.47
1 daughter	0.378 ± 0.052	-15.30 ± 2.35	0.401 ± 0.062	-15.33 ± 2.74

The slopes of the heavy and strange baryon Regge trajectories follow in both planes the regularities previously observed for light and heavy mesons:

- decrease with the increase of the diquark mass
- decrease with the increase of the parent baryon mass

The latter decrease is significantly more pronounced.

The ratio of slopes for heavy baryons and heavy-light mesons:

$$\langle\alpha_{Qqq}\rangle/\langle\alpha_{Q\bar{q}}\rangle \sim \langle\beta_{Qqq}\rangle/\langle\beta_{Q\bar{q}}\rangle \sim 1.4$$

Strange baryons

Table 12: Masses of the ground states of hyperons (in MeV).

J^P	Experiment			Theory					
	State	Status	Mass	Our	Capstick Isgur	Loring et al.	Melde et al.	Santopinto Ferretti	Engel et al.
$\frac{1}{2}^+$	Λ	****	1115.683(6)	1115	1115	1108	1136	1116	1149(18)
$\frac{1}{2}^+$	Σ	****	1189.37(7)	1187	1190	1190	1180	1211	1216(15)
$\frac{3}{2}^+$	$\Sigma(1385)$	****	1382.80(35)	1381	1370	1411	1389	1334	1471(23)
$\frac{1}{2}^+$	Ξ	****	1321.71(7)	1330	1305	1310	1348	1317	1303(13)
$\frac{3}{2}^+$	$\Xi(1530)$	****	1531.80(32)	1518	1505	1539	1528	1552	1553(18)
$\frac{3}{2}^+$	Ω	****	1672.45(29)	1678	1635	1636	1672		1642(17)

Table 13: Masses of the positive parity Λ states (in MeV).

J^P	Experiment			Theory					
	State	Status	Mass	Our	Capstick Isgur	Loring et al.	Melde et al.	Santopinto Ferretti	Engel et al.
$\frac{1}{2}^+$	Λ	****	1115.683(6)	1115	1115	1108	1136	1116	1149(18)
	$\Lambda(1600)$	***	1560-1600	1615	1680	1677	1625	1518	1807(94)
	$\Lambda(1710)$	*	1713(13)						
	$\Lambda(1810)$	***	1750-1810	1901	1830	1747	1799	1666	2112(54)
				1972	1910	1898		1955	2137(69)
				1986	2010	2077		1960	
				2042	2105	2099			
				2099	2120	2132			
$\frac{3}{2}^+$	$\Lambda(1890)$	****	1850-1890	1854	1900	1823		1896	1991(103)
				1976	1960	1952			2058(139)
				2130	1995	2045			2481(111)
				2184	2050	2087			
				2202	2080	2133			
$\frac{5}{2}^+$	$\Lambda(1820)$	****	1815-1820	1825	1890	1834		1896	
	$\Lambda(2110)$	***	2090-2110	2098	2035	1999			
				2221	2115	2078			
				2255	2115	2127			
				2258	2180	2150			
$\frac{7}{2}^+$	$\Lambda(2020)$	*	≈2020	2251	2120	2130			
				2471		2331			
$\frac{9}{2}^+$	$\Lambda(2350)$	***	2340-2350	2360		2340			

Table 14: Masses of the negative parity Λ states (in MeV).

	Experiment			Theory					
J^P	State	Status	Mass	Our	Capstick Isgur	Loring et al.	Melde et al.	Santopinto Ferretti	Engel et al.
$\frac{1}{2}^-$	$\Lambda(1405)$	****	$1405.1\left({}^{1.3}_{1.0}\right)$	1406	1550	1524	1556	1431	1416(81)
	$\Lambda(1670)$	****	1660-1670	1667	1615	1630	1682	1443	1546(110)
	$\Lambda(1800)$	***	1720-1800	1733	1675	1816	1778	1650	1713(116)
				1927	2015	2011		1732	2075(249)
				2197	2095	2076		1785	
				2218	2160	2117		1854	
$\frac{3}{2}^-$	$\Lambda(1520)$	****	1519.5(1.0)	1549	1545	1508	1556	1431	1751(40)
	$\Lambda(1690)$	****	1685-1690	1693	1645	1662	1682	1443	2203(106)
				1812	1770	1775		1650	2381(87)
	$\Lambda(2050)$	*	2056(22)	2035	2030	1987		1732	
				2319	2110	2090		1785	
	$\Lambda(2325)$	*	≈2325	2322	2185	2147		1854	
				2392	2230	2259		1928	
				2454	2290	2275		1969	
				2468		2313			
$\frac{5}{2}^-$	$\Lambda(1830)$	****	1810-1830	1861	1775	1828	1778	1785	
				2136	2180	2080			
				2350	2250	2179			
$\frac{7}{2}^-$	$\Lambda(2100)$	****	2090-2100	2097	2150	2090			
				2583	2230	2227			
$\frac{9}{2}^-$				2665		2370			

Table 15: Masses of the positive parity Σ states (in MeV).

J^P	Experiment			Theory					
	State	Status	Mass	Our	Capstick Isgur	Loring et al.	Melde et al.	Santopinto Ferretti	Engel et al.
$\frac{1}{2}^+$	Σ	****	1189.37(7)	1187	1190	1190	1180	1211	1216(15)
	$\Sigma(1660)$	***	1630-1660	1711	1720	1760	1616	1546	2069(74)
	$\Sigma(1770)$	*	≈1770	1922	1915	1947	1911	1668	2149(66)
	$\Sigma(1880)$	*	≈1880	1983	1970	2009		1801	2335(63)
				2028	2005	2052			
				2180	2030	2098			
				2292	2105	2138			
				2472	2195				
$\frac{3}{2}^+$	$\Sigma(1385)$	****	1382.80(35)	1381	1370	1411	1389	1334	1471(23)
	$\Sigma(1730)$	*	1727(27)		1920	1896	1865	1439	
	$\Sigma(1840)$	*	≈1840	1862	1970	1961		1924	2194(81)
	$\Sigma(1940)$	*	1941(18)	2025	2010	2011			2250(79)
	$\Sigma(2080)$	**	≈2080	2076	2030	2044			2468(67)
				2096	2045	2062			
				2157	2085	2103			
				2186	2115	2112			
$\frac{5}{2}^+$	$\Sigma(1915)$	****	1900-1915	1991	1995	1956		2061	
	$\Sigma(2070)$	*	≈2070	2062	2030	2027			
				2221	2095	2071			
$\frac{7}{2}^+$	$\Sigma(2030)$	****	2025-2030	2033	2060	2070			
				2470	2125	2161			

Table 16: Masses of the negative parity Σ states (in MeV).

J^P	Experiment			Theory					
	State	Status	Mass	Our	Capstick Isgur	Loring et al.	Melde et al.	Santopinto Ferretti	Engel et al.
$\frac{1}{2}^-$	$\Sigma(1620)$	*	≈1620	1620	1630	1628	1677	1753	1603(38)
				1693	1675	1771	1736	1868	1718(58)
	$\Sigma(1750)$	***	1730-1750	1747	1695	1798	1759	1895	1730(34)
	$\Sigma(1900)$	*	1900(21)	2115	2110	2111			2478(104)
	$\Sigma(2000)$	*	≈2000	2198	2155	2136			
				2202	2165	2251			
				2289	2205	2264			
				2381	2260	2288			
$\frac{3}{2}^-$	$\Sigma(1580)$	*	≈1580						
	$\Sigma(1670)$	***	1665-1670	1706	1655	1669	1677	1753	1736(40)
				1731	1750	1728	1736	1868	1861(20)
	$\Sigma(1940)$	***	1900-1940	1856	1755	1781	1759	1895	2297(122)
				2175	2120	2139			2394(74)
				2203	2185	2171			
				2300	2200	2203			
$\frac{5}{2}^-$	$\Sigma(1775)$	****	1770-1775	1757	1755	1770	1736	1753	
				2214	2205	2174			
				2347	2250	2226			
$\frac{7}{2}^-$	$\Sigma(2100)$	*	≈2100	2259	2245	2236			
				2349		2285			
$\frac{9}{2}^-$				2289		2325			

Table 17: Masses of the positive parity Ξ states (in MeV).

J^P	Experiment			Theory					
	State	Status	Mass	Our	Capstick Isgur	Loring et al.	Melde et al.	Santopinto Ferretti	Engel et al.
$\frac{1}{2}^+$	Ξ	****	1321.71(7)	1330	1305	1310	1348	1317	1303(13)
				1886	1840	1876	1805	1772	2178(48)
				1993	2040	2062		1868	2231(44)
				2012	2100	2131		1874	2408(45)
				2091	2130	2176			
				2142	2150	2215			
				2367	2230	2249			
$\frac{3}{2}^+$	$\Xi(1530)$	****	1531.80(32)	1518	1505	1539	1528	1552	1553(18)
				1966	2045	1988		1653	2228(44)
				2100	2065	2076			2398(52)
				2121	2115	2128			2574(52)
				2122	2165	2170			
				2144	2170	2175			
				2149	2210	2219			
				2421	2230	2257			
$\frac{5}{2}^+$				2108	2045	2013			
				2147	2165	2141			
				2213	2230	2197			
$\frac{7}{2}^+$				2189	2180	2169			

Table 18: Masses of the negative parity Ξ states (in MeV).

J^P	Experiment			Theory					
	State	Status	Mass	Our	Capstick Isgur	Loring et al.	Melde et al.	Santopinto Ferretti	Engel et al.
$\frac{1}{2}^-$				1682	1755	1770			1716(43)
				1758	1810	1922			1837(28)
				1839	1835	1938			1844(43)
				2160	2225	2241			2758(78)
				2210	2285	2266			
				2233	2300	2387			
				2261	2320	2411			
$\frac{3}{2}^-$				1764	1785	1780	1792	1861	1894(38)
	$\Xi(1820)$	***	1823(5)	1798	1880	1873		1971	1906(29)
				1904	1895	1924			2426(73)
				2245	2240	2246			2497(61)
				2252	2305	2284			
				2350	2330	2353			
				2352	2340	2384			
$\frac{5}{2}^-$				1853	1900	1955	1881		
				2333	2345	2292			
				2411	2350	2409			
$\frac{7}{2}^-$				2460	2355	2320			
				2474		2425			
$\frac{9}{2}^-$				2502		2505			

Table 19: Fitted parameters α, α_0 for the slope and intercept of the (J, M^2) Regge trajectories of strange baryons.

Baryon	α (GeV^{-2})	α_0	Baryon	α (GeV^{-2})	α_0
Λ $(\frac{1}{2}^+)$	0.923 ± 0.016	-0.648 ± 0.057	Λ $(\frac{1}{2}^-)$	0.732 ± 0.018	-0.951 ± 0.074
Σ $(\frac{1}{2}^+)$	0.799 ± 0.029	-0.676 ± 0.100	Σ $(\frac{3}{2}^+)$	0.897 ± 0.010	-0.225 ± 0.037
Ξ $(\frac{1}{2}^+)$	0.694 ± 0.007	-0.721 ± 0.024	Ξ $(\frac{3}{2}^+)$	0.769 ± 0.032	-0.249 ± 0.098
			Ω $(\frac{3}{2}^+)$	0.712 ± 0.002	-0.504 ± 0.007