Spectroscopy of Heavy-Flavor Baryons

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Outline

Low-Energy QCD / Relevant Degrees of Freedom

Universal Relativistic Constituent-Quark Model (URCQM)
for all known baryons, including heavy flavors

Spectroscopy of All Baryons

Strong Baryon Resonance Decays

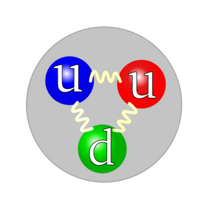
Coupled-Channels Theory

Conclusions and Outlook

Constituent-Quark Picture of Baryons

Baryons are considered as colorless bound states of three constituent quarks.

Here the proton:



- 'Constituent' quarks are quasiparticles with dynamical mass, NOT the original QCD d.o.f. (i.e. 'current' quarks).
- 'Constituent' quarks are confined and interact via hyperfine interactions associated with $SB\chi S$, i.e. Goldstone-boson exchange.

Relativistic quantum mechanics (RQM)

i.e. **quantum theory** respecting **Poincaré invariance**

(theory on a Hilbert space $\mathcal{H}$ corresponding to a finite number of particles, not a field theory)

Invariant mass operator

$$\hat{M} = \hat{M}_{free} + \hat{M}_{int}$$

Eigenvalue equations

$$\hat{M}\,|P, J, \Sigma\rangle = M\,|P, J, \Sigma\rangle \quad , \qquad \hat{M}^2 = \hat{P}^\mu \hat{P}_\mu$$

$$\hat{P}^\mu\,|P, J, \Sigma\rangle = P^\mu\,|P, J, \Sigma\rangle \quad , \qquad \hat{P}^\mu = \hat{M}\hat{V}^\mu$$

Interacting mass operator

$$
\begin{aligned}
\hat{M} &= \hat{M}_{free} + \hat{M}_{int} \\
\hat{M}_{free} &= \sqrt{\hat{H}^2_{free} - \hat{\vec{P}}^2_{free}} \\
\hat{M}^{rest\ frame}_{int} &= \sum_{i<j}^{3} \hat{V}_{ij} = \sum_{i<j}^{3} [\hat{V}^{conf}_{ij} + \hat{V}^{hf}_{ij}]
\end{aligned}
$$

fulfilling the **Poincaré algebra**

$$
\begin{array}{lll}
[\hat{P}_i, \hat{P}_j] = 0, & [\hat{J}_i, \hat{H}] = 0, & [\hat{P}_i, \hat{H}] = 0, \\
[\hat{K}_i, \hat{H}] = -i\hat{P}_i & [\hat{J}_i, \hat{J}_j] = i\epsilon_{ijk}\hat{J}_k & [\hat{J}_i, \hat{K}_j] = i\epsilon_{ijk}\hat{K}_k, \\
[\hat{J}_i, \hat{P}_j] = i\epsilon_{ijk}\hat{P}_k, & [\hat{K}_i, \hat{K}_j] = -i\epsilon_{ijk}\hat{J}_k, & [\hat{K}_i, \hat{P}_j] = -i\delta_{ij}\hat{H}
\end{array}
$$

$\hat{H}, \hat{P}_i$ ... time and space translations,
$\hat{J}_i$ ... rotations, $\hat{K}_i$ ... Lorentz boosts

Universal GBE RCQM

Phenomenologically, baryons with 5 flavors: u, d, s, c, b

$$\Rightarrow \quad H_{free} = \sum_{i=1}^{3} \sqrt{m_i^2 + \vec{k}_i^2}$$

$$V^{conf}(\vec{r}_{ij}) = B + C\, r_{ij}$$

$$V^{hf}(\vec{r}_{ij}) = \left[V_{24}(\vec{r}_{ij}) \sum_{f=1}^{24} \lambda_i^f \lambda_j^f + V_0(\vec{r}_{ij}) \lambda_i^0 \lambda_j^0 \right] \vec{\sigma}_i \cdot \vec{\sigma}_j$$

- i.e., for $N_f = 5$, we have the exchange of a **24-plet** plus a **singlet** of Goldstone bosons.

L.Ya. Glozman and D.O. Riska: Nucl. Phys. A **603**, 326 (1996)
J.P. Day, K.-S. Choi, and W. Plessas: Few-Body Syst. **54**, 329 (2013)
W. Plessas: Int. J. Mod. Phys. A30, 1530013 (2015)

Universal GBE RCQM Parametrization

$$V^{conf}(\vec{r}_{ij}) = B + C\, r_{ij}$$

$$V_\beta(\vec{r}_{ij}) = \frac{g_\beta^2}{4\pi}\frac{1}{12 m_i m_j}\left\{\mu_\beta^2 \frac{e^{-\mu_\beta r_{ij}}}{r_{ij}} - 4\pi\delta(\vec{r}_{ij})\right\}$$

$$= \frac{g_\beta^2}{4\pi}\frac{1}{12 m_i m_j}\left\{\mu_\beta^2 \frac{e^{-\mu_\beta r_{ij}}}{r_{ij}} - \Lambda_\beta^2 \frac{e^{-\Lambda_\beta r_{ij}}}{r_{ij}}\right\}$$

$B = -402$ MeV, $C = 2.33$ fm^{-2}

$\beta = 24$: $\frac{g_{24}^2}{4\pi} = 0.7$, $\mu_{24} = \mu_\pi = 139$ MeV, $\Lambda_{24} = 700.5$ MeV

$\beta = 0$: $\left(\frac{g_0}{g_{24}}\right)^2 = 1.5$, $\mu_0 = \mu_{\eta'} = 958$ MeV, $\Lambda_0 = 1484$ MeV

$m_u = m_d = 340$ MeV, $m_s = 480$ MeV,
$m_c = 1675$ MeV, $m_b = 5055$ MeV

Systematics of Constituent-Quark Masses

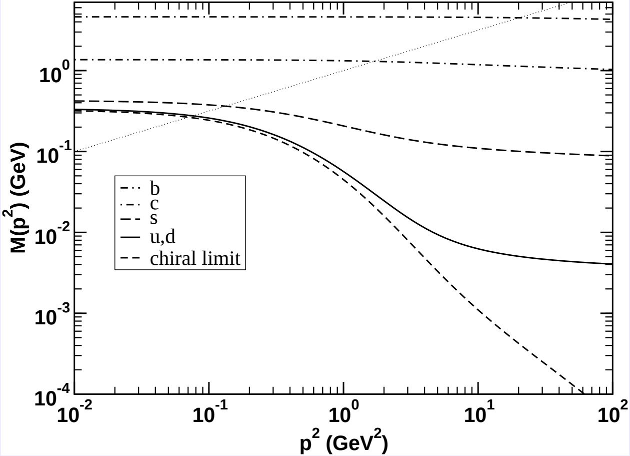
Dynamical mass gain $\Delta m = m_Q - m_q$ due to SBχS is similar for all flavors:

Quark flavor	PDG m_q	RCQM m_Q	RCQM Δm	DSE Δm
$\frac{1}{2}(u+d)$	$3.3 - 4.2$	340	~ 336	~ 276
s	95 ± 5	480	~ 385	~ 278
c	1275 ± 25	1675	~ 400	~ 330
b	4660 ± 30	5055	~ 395	~ 400

PDG: Particle Data Group (i.e. current-quark masses)
RCQM: Relativistic Constituent-Quark Model
DSE: Dyson-Schwinger Equation
CST: Covariant Spectator Theory – not shown here
see the talk by A. Stadler @EFB24

Is Δm a new challenge for flavor physics?

Quark Mass Functions from DSE



A. Höll, A. Krassnigg, C.D. Roberts, and S.V. Wright: Int. J. Mod. Phys. A **20** (2005) 1778

Solution of Mass-Operator EV Problem

$$\hat{M}\,|P,J,\Sigma,F_{abc}\rangle = M\,|P,J,\Sigma,F_{abc}\rangle$$
$$= M\,|M,V,J,\Sigma,F_{abc}\rangle$$

$\rightarrow$ baryon wave functions (initially in rest frame)

$$\Psi_{PJ\Sigma F_{abc}}(\vec{\xi},\vec{\eta}) = \left\langle \vec{\xi},\vec{\eta} \middle| P,J,\Sigma,F_{abc} \right\rangle \; ,$$

where $\vec{\xi}$ and $\vec{\eta}$ are the usual Jacobi coordinates and

P	.....	momentum eigenvalues
$(M, V$	.....	mass resp. velocity eigenvalues)
J	.....	intrinsic spin $\hat{=}$ total angular momentum)
Σ	.....	z-component of J
F_{abc}	.....	flavor content

Advanced Few-Body Methods – 1

A) **Stochastic Variational Method** (SVM)

$$\Psi_{PJ\Sigma F_{abc}}(\mathbf{x}) = \sum_i c_i \left\{ e^{-\frac{1}{2}\tilde{\mathbf{x}}A\mathbf{x}} \left[\Theta_{LM_L}(\hat{\mathbf{x}})\chi_S\right]_{J\Sigma} \phi_{F_{abc}} \right\}_i$$

with linear and nonlinear variational parameters

$$c_i\,, \quad A = \{\beta, \delta, \nu, n, \lambda, l, L, s, S, F_{abc}, d\}$$

searched by a generalized Rayleigh-Ritz principle through a stochastic selection of basis states

V.I. Kukulin and V.M. Krasnopol'sky: J. Phys. G **3**, 795 (1977)

Y. Suzuki and K. Varga: *Stochastic Variational Approach to Quantum-Mechanical Few-Body Problems* (Springer, Berlin, 1998)

B) Modified Faddeev Integral Equations

$$\begin{aligned} H &= H_0 + v_\alpha + v_\beta + v_\gamma = \\ &\quad H_0 + v_\alpha^{\mathrm{conf}} + v_\beta^{\mathrm{conf}} + v_\gamma^{\mathrm{conf}} + \tilde{v}_\alpha + \tilde{v}_\beta + \tilde{v}_\gamma = \\ &\quad H^{\mathrm{conf}} + \tilde{v}_\alpha + \tilde{v}_\beta + \tilde{v}_\gamma \,, \end{aligned}$$

with $$H^{\mathrm{conf}} = H_0 + v_\alpha^{\mathrm{conf}} + v_\beta^{\mathrm{conf}} + v_\gamma^{\mathrm{conf}}$$

$$\begin{aligned} \Psi_{PJ\Sigma F_{abc}}(\mathbf{k}) &= \left(\tilde{\psi}_\alpha + \tilde{\psi}_\beta + \tilde{\psi}_\gamma\right)_{PJ\Sigma F_{abc}}(\mathbf{k}) \\ \tilde{\psi}_\alpha &= G_\alpha^{\mathrm{conf}}(E)\tilde{v}_\alpha\left(\tilde{\psi}_\beta + \tilde{\psi}_\gamma\right) \\ & G_\alpha^{\mathrm{conf}}(E) = \left(E - H^{\mathrm{conf}} - \tilde{v}_\alpha\right)^{-1} \end{aligned}$$

Z. Papp: Few-Body Syst. **26**, 99 (1999)

Z. Papp, A. Krassnigg, and W. Plessas: Phys. Rev. C **62**, 044004 (2000)

J. McEwen, J. Day, A. Gonzalez, Z. Papp, and W. Plessas: Few-Body Syst. **47**, 225 (2010)

Solution Accuracy

Baryon	J^P	Faddeev GBE	Faddeev OGE	SVM GBE	SVM OGE	Experiment
N(939)	$\frac{1}{2}^+$	939	940	939	939	938-940
N(1440)	$\frac{1}{2}^+$	1459	1578	1459	1577	1420-1470
N(1520)	$\frac{3}{2}^-$	1520	1521	1519	1521	1515-1525
N(1535)	$\frac{1}{2}^-$	1520	1521	1519	1521	1525-1545
N(1650)	$\frac{1}{2}^-$	1646	1686	1647	1690	1645-1670
N(1675)	$\frac{5}{2}^-$	1646	1686	1647	1690	1670-1680
Δ(1232)	$\frac{3}{2}^+$	1240	1229	1240	1231	1231-1233
Δ(1600)	$\frac{3}{2}^+$	1718	1852	1718	1854	1550-1700
Δ(1620)	$\frac{1}{2}^-$	1640	1618	1642	1621	1600-1660
Δ(1700)	$\frac{3}{2}^-$	1640	1618	1642	1621	1670-1750
Λ(1116)	$\frac{1}{2}^+$	1133	1127	1136	1113	1116
Λ(1405)	$\frac{1}{2}^-$	1561	1639	1556	1628	1401-1410
Λ(1520)	$\frac{3}{2}^-$	1561	1639	1556	1628	1519-1521
Λ(1600)	$\frac{1}{2}^+$	1607	1749	1625	1747	1560-1700
Λ(1670)	$\frac{1}{2}^-$	1672	1723	1682	1734	1660-1680
Λ(1690)	$\frac{3}{2}^-$	1672	1723	1682	1734	1685-1695

Z. Papp, A. Krassnigg, and W. Plessas: Phys. Rev. C **62**, 044004 (2000)

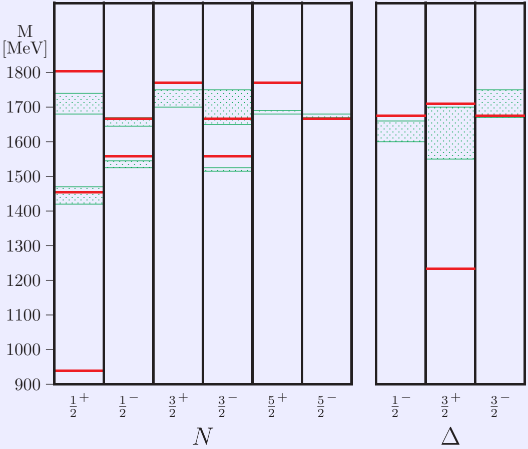
J. McEwen, J. Day, A. Gonzalez, Z. Papp, and W. Plessas: Few-Body Syst. **47**, 225 (2010)

Spectroscopy

of Baryons with All Flavors

u, d, s, c, b

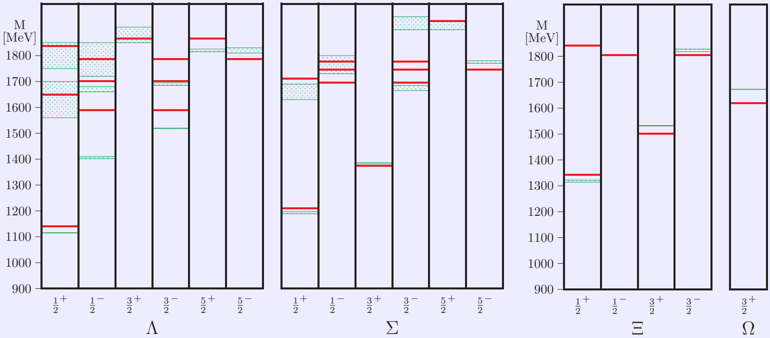
Light Baryon Spectra



red Universal GBE RCQM

green Particle Data Group (experiment)

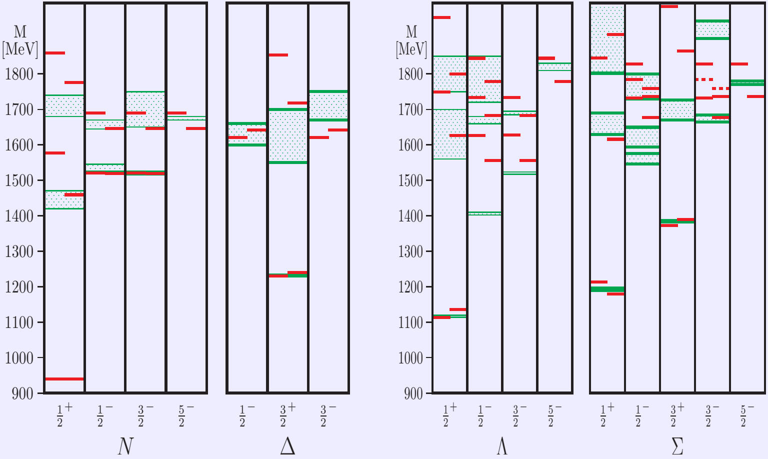
Strange Baryon Spectra



red Universal GBE RCQM

green Particle Data Group (experiment)

Comparison of N and Λ Excitation Spectra

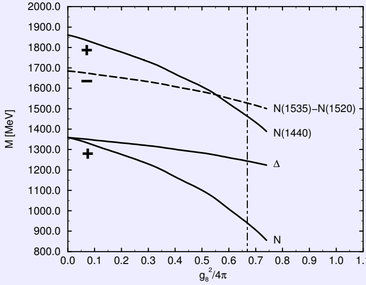


left **levels**: **One-gluon-exchange** RCQM
right **levels**: **Goldstone-boson-exchange** RCQM

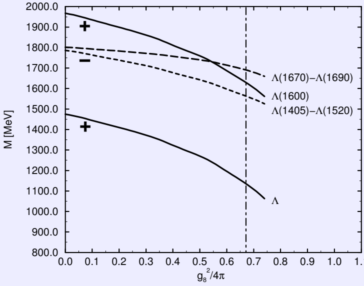
W. Plessas: Few-Body Syst. Suppl. **15**, 139 (2003)

Level shifts due to hyperfine interaction:

N

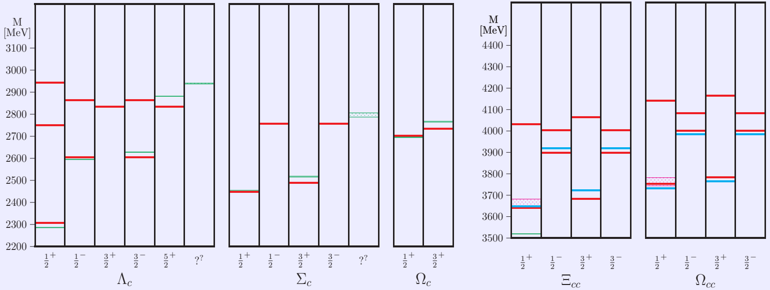


Λ



L.Ya. Glozman, Z. Papp, W. Plessas, K. Varga, and R.F. Wagenbrunn, Phys. Rev. C **57**, 3406 (1998)

Charm Baryon Spectra



↑ our value $m(\Xi_{cc}) = 3642$ MeV

Left panel – single charm:

red Universal GBE RCQM prediction

green Particle Data Group (experiment)

Right panel – double charm:

green M. Mattson et al.: Phys. Rev. Lett. 89 (2002) 112001 (SELEX experiment)

New datum from LHCb 2017: $m(\Xi_{cc})$= 3621.40±0.72(stat.)±0.27(syst.)±0.14(Λ_c) MeV

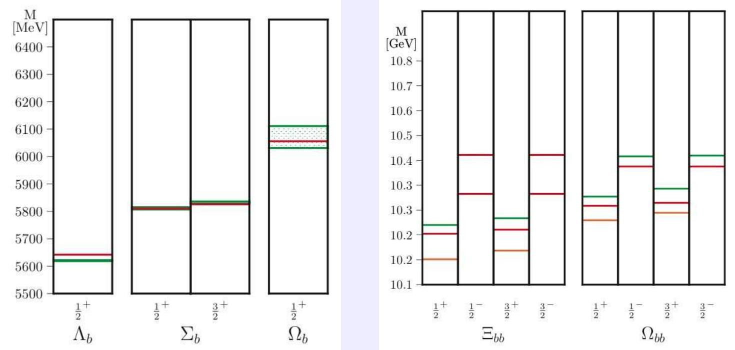
cyan S. Migura, D. Merten, B. Metsch, and H.-R. Petry: Eur. Phys. J. A 28 (2006) 41 (Bonn RCQM)

magenta L. Liu et al.: Phys. Rev. D 81 (2010) 094505 (Lattice QCD)

Universal GBE RCQM predictions

Baryon	J^P	URCQM
Ξ_{cc}	$\frac{1}{2}^+$	3642
Ξ_{cc}	$\frac{3}{2}^+$	3683
Ξ_{cc}	$\frac{1}{2}^-$	3899
Ξ_{cc}	$\frac{3}{2}^-$	3899
Ξ_{cc}	$\frac{1}{2}^-$	4004
Ξ_{cc}	$\frac{3}{2}^-$	4004
Ξ_{cc}	$\frac{1}{2}^+$	4032
Ξ_{cc}	$\frac{3}{2}^+$	4064

Bottom Baryon Spectra



Left panel – single bottom:

red Universal GBE RCQM prediction

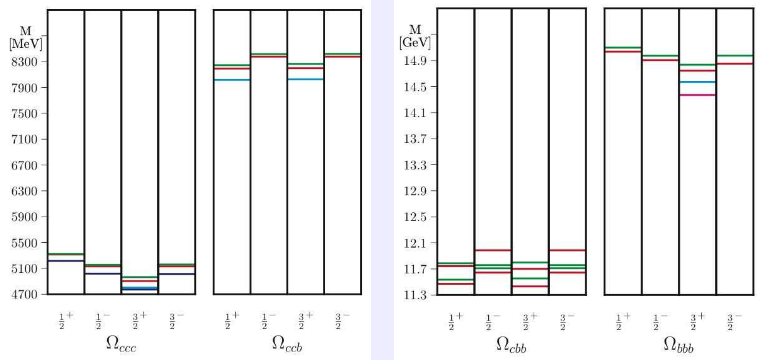
green Particle Data Group (experiment)

Right panel – double bottom:

green W. Roberts and M. Pervin: Int. J. Mod. Phys. A 23 (2008) 2817 (nonrel. one-gluon-exchange CQM)

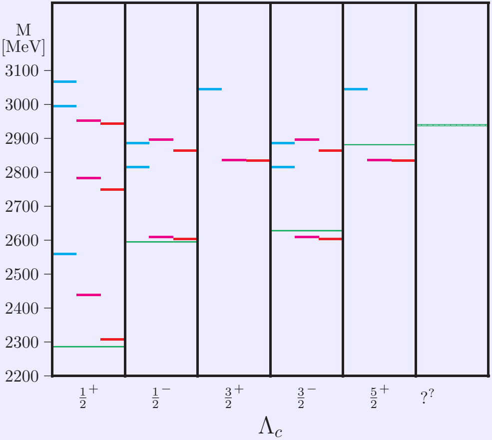
orange D. Ebert, R.N. Faustov, V.O. Galkin, and A.P. Martynenko: Phys. Rev. D 66 (2002) 014008 (RCQM)

Triple-Heavy Baryon Spectra



red	Universal GBE RCQM
green	W. Roberts and M. Pervin: Int. J. Mod. Phys. A 23 (2008) 2817 (nonrelativistic one-gluon-exchange CQM)
blue	S. Migura, D. Merten, B. Metsch, and H.-R. Petry: Eur. Phys. J. A 28 (2006) 41 (Bonn RCQM)
cyan	A.P. Martynenko: Phys. Lett. B 663 (2008) 317 (RCQM)
magenta	S. Meinel: Phys. Rev. D 82 (2010) 114502 (lattice QCD)

Influence of Light-Heavy Q-Q Interaction



leftmost cyan levels	confinement only
middle magenta levels	including only light-light GBE
rightmost red levels	including full GBE RCQM

π, η, and K Decay Modes

of

N^*, Δ^*, Λ^*, Σ^*, Ξ^* Resonances

Spectator Model Decay Operator

$$\left\langle V', M', J', \Sigma', T', M_{T'} \right| \hat{D}^m_{\mathrm{rd}} \left| V, M, J, \Sigma, T, M_T \right\rangle =$$

$$\frac{2}{MM'} \sum_{\sigma_i \sigma_i'} \sum_{\mu_i \mu_i'} \int d^3\vec{k}_2 d^3\vec{k}_3 d^3\vec{k}_2' d^3\vec{k}_3' \sqrt{\frac{\left(\sum_i \omega_i'\right)^3}{\prod_i 2\omega_i'}} \sqrt{\frac{\left(\sum_i \omega_i\right)^3}{\prod_i 2\omega_i}}$$

$$\times \prod_{\sigma_i'} D^{\star \frac{1}{2}}_{\sigma_i' \mu_i'} \left\{ R_W \left[k_i'; B\left(V'\right)\right] \right\} \Psi^\star_{M'J'\Sigma'T'M_{T'}} \left(\vec{k}_1', \vec{k}_2', \vec{k}_3'; \mu_1', \mu_2', \mu_3' \right)$$

$$\times \left\langle p_1', p_2', p_3'; \sigma_1', \sigma_2', \sigma_3' \right| \hat{D}^m_{\mathrm{rd}} \left| p_1, p_2, p_3; \sigma_1, \sigma_2, \sigma_3 \right\rangle$$

$$\times \prod_{\sigma_i} D^{\frac{1}{2}}_{\sigma_i \mu_i} \left\{ R_W \left[k_i; B\left(V\right)\right] \right\} \Psi_{MJ\Sigma TM_T} \left(\vec{k}_1, \vec{k}_2, \vec{k}_3; \mu_1, \mu_2, \mu_3 \right)$$

with the **hadronic decay operator** in the point-form spectator model

$$\left\langle p_1', p_2', p_3'; \sigma_1', \sigma_2', \sigma_3' \right| \hat{D}^m_{\mathrm{rd}} \left| p_1, p_2, p_3; \sigma_1, \sigma_2, \sigma_3 \right\rangle =$$

$$-3\mathcal{N} \frac{ig_{qqm}}{2m_1} \frac{1}{\sqrt{2\pi}} \bar{u}\left(p_1', \sigma_1'\right) \gamma_5 \gamma^\mu \mathcal{F}^m u\left(p_1, \sigma_1\right) q_\mu$$

$$\times 2p_{20} \delta\left(\vec{p}_2 - \vec{p}_2'\right) 2p_{30} \delta\left(\vec{p}_3 - \vec{p}_3'\right) \delta_{\sigma_2 \sigma_2'} \delta_{\sigma_3 \sigma_3'}$$

π Decay Widths of N^* and Δ^*

N^*, Δ^* $\to N\pi$	Experiment [MeV]	Relativistic GBE	Relativistic OGE	Nonrel. EEM GBE	Nonrel. EEM OGE
$N(1440)$	$(227 \pm 18)^{+70}_{-59}$	30	59	7	27
$N(1520)$	$(66 \pm 6)^{+\ 9}_{-\ 5}$	21	23	38	37
$N(1535)$	$(67 \pm 15)^{+28}_{-17}$	25	39	559	1183
$N(1650)$	$(109 \pm 26)^{+36}_{-\ 3}$	6.3	9.9	157	352
$N(1675)$	$(68 \pm 8)^{+14}_{-\ 4}$	8.4	10.4	13	16
$N(1700)$	$(10 \pm 5)^{+\ 3}_{-\ 3}$	1.0	1.3	2.2	2.7
$N(1710)$	$(15 \pm 5)^{+30}_{-\ 5}$	19	21	8	6
$\Delta(1232)$	$(119 \pm 1)^{+\ 5}_{-\ 5}$	35	31	89	85
$\Delta(1600)$	$(61 \pm 26)^{+26}_{-10}$	0.5	5.1	93	86
$\Delta(1620)$	$(38 \pm 8)^{+\ 8}_{-\ 6}$	1.2	2.8	76	177
$\Delta(1700)$	$(45 \pm 15)^{+20}_{-10}$	3.8	4.1	10.4	9.1

With theoretical masses

T. Melde, W. Plessas, and R.F. Wagenbrunn: Phys. Rev. C **72**, 015207 (2005); ibid. **74**, 069901 (2006)

η Decay Widths of N^*

$N \to N\eta$	Experiment [MeV]	Relativistic GBE	Relativistic OGE	Nonrel. EEM GBE	Nonrel. EEM OGE
$N(1520)$	$(0.28 \pm 0.05)^{+0.03}_{-0.01}$	0.1	0.1	0.04	0.04
$N(1535)$	$(64 \pm 19)^{+\ 28}_{-\ 28}$	27	35	127	236
$N(1650)$	$(10 \pm 5)^{+\ 4}_{-\ 1}$	50	74	283	623
$N(1675)$	$(0 \pm 1.5)^{+\ 0.3}_{-\ 0.1}$	1.5	2.4	1.1	1.8
$N(1700)$	$(0 \pm 1)^{+\ 0.5}_{-\ 0.5}$	0.5	0.9	0.2	0.3
$N(1710)$	$(6 \pm 1)^{+\ 11}_{-\ 4}$	0.02	0.06	2.9	9.3

With theoretical masses

T. Melde, W. Plessas, and R.F. Wagenbrunn: Phys. Rev. C **72**, 015207 (2005); ibid. **74**, 069901 (2006)

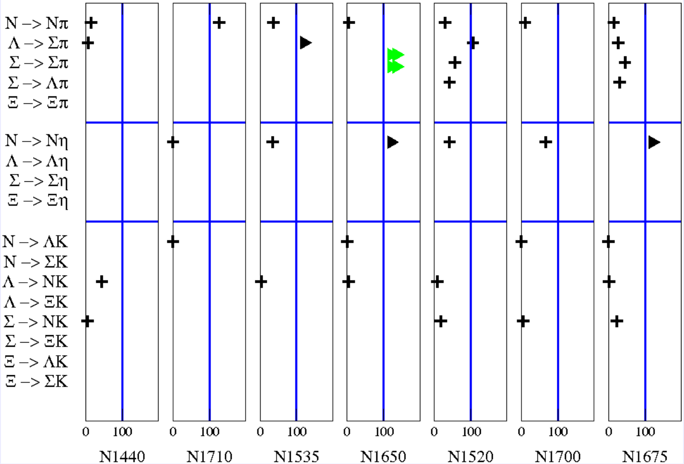
K Decay Widths of Λ^* and Σ^*

Λ^*, Σ^* $\to NK$	Experiment [MeV]	Relativistic GBE	Relativistic OGE	Nonrel. EEM GBE	Nonrel. EEM OGE
$\Lambda(1520)$	$(7.02 \pm 0.16)^{+0.46}_{-0.44}$	12	24	23	63
$\Lambda(1600)$	$(33.75 \pm 11.25)^{+30}_{-15}$	15	35	4.1	23
$\Lambda(1670)$	$(8.75 \pm 1.75)^{+4.5}_{-2}$	0.3	≈ 0	45	86
$\Lambda(1690)$	$(15 \pm 3)^{+3}_{-2}$	1.2	1.0	4.2	6.5
$\Lambda(1800)$	$(97.5 \pm 22.5)^{+40}_{-25}$	4.2	6.4	3.1	8.6
$\Lambda(1810)$	$(52.5 \pm 22.5)^{+50}_{-20}$	4.1	12	23	44
$\Lambda(1830)$	$(6.18 \pm 3.33)^{+1.05}_{-1.05}$	0.1	0.9	0.1	0.1
$\Sigma(1660)$	$(20 \pm 10)^{+30}_{-6}$	0.9	0.9	0.4	≈ 0
$\Sigma(1670)$	$(6.0 \pm 1.8)^{+2.6}_{-1.4}$	1.1	1.0	1.9	2.0
$\Sigma(1750)$	$(22.5 \pm 13.5)^{+28}_{-3}$	≈ 0	1.4	10	48
$\Sigma(1775)$	$(48.0 \pm 3.6)^{+6.5}_{-5.6}$	11	15	20	41
$\Sigma(1940)$	$(22 \pm 22)^{+16}$	1.1	1.5	3.3	6.8

With theoretical masses

T. Melde, W. Plessas, and B. Sengl: Phys. Rev. D 76, 054008 (2007)

Decay Widths of Octet Baryon Resonances



T. Melde, W. Plessas, and B. Sengl: Phys. Rev. D 77, 114002 (2008)

Lesson from $\{QQQ\}$ Constituent-Quark Model

- **Baryon spectroscopy of all flavors** consistently described in a **universal relativistic constituent-quark model** based on GBE dynamics
- The **covariant structures** of the ground states (N, Δ, Λ, ..., Ω) in good agreement with experiment (wherever such data are available)
- Predictions by the GBE RCQM reasonably consistent with (reliable) **lattice-QCD** results.
- **Disturbing shortcomings** of the $\{QQQ\}$ quark model for hadronic decays
- Obviously certain observables require **more than $\{QQQ\}$** degrees of freedom

Introducing

explicit mesonic degrees of freedom

$\{QQQ\}$ Cluster with Explicit Pions

Coupled-channels mass-operator eigenvalue equation

for π-dressing of a given bare $\{\widetilde{QQQ}\}$ cluster state

$$\begin{pmatrix} M_{\widetilde{QQQ}} & K_{\pi\widetilde{QQQ}} \\ K^{\dagger}_{\pi\widetilde{QQQ}} & M_{\widetilde{QQQ+\pi}} \end{pmatrix} \begin{pmatrix} |\psi_{QQQ}\rangle \\ |\psi_{QQQ+\pi}\rangle \end{pmatrix} = m \begin{pmatrix} |\psi_{QQQ}\rangle \\ |\psi_{QQQ+\pi}\rangle \end{pmatrix},$$

where $M_{\widetilde{QQQ}}$ is the $\{\widetilde{QQQ}\}$ mass operator with confinement.

After Feshbach elimination of the $|\psi_{QQQ+\pi}\rangle$ channel:

$$[M_{\widetilde{QQQ}} + \underbrace{K_{\pi\widetilde{QQQ}}(m - M_{\widetilde{QQQ+\pi}})^{-1}K^{\dagger}_{\pi\widetilde{QQQ}}}_{V_{opt}}]|\psi_{QQQ}\rangle = m|\psi_{QQQ}\rangle.$$

It is an exact eigenvalue equation for $|\psi_{QQQ}\rangle$, yielding in general a complex eigenvalue m of the π-dressed $\{QQQ\}$ system.

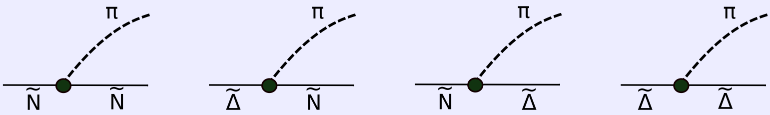
Strong $\pi\widetilde{N}\widetilde{N}$, $\pi\widetilde{N}\widetilde{\Delta}$, $\pi\widetilde{\Delta}\widetilde{N}$, and $\pi\widetilde{\Delta}\widetilde{\Delta}$ FFs

Equating the microscopic optical potential with the hadronic one (including vertex FF's)

$$\int K_{\pi\widetilde{QQQ}}(m - M_{\widetilde{QQQ}+\pi})^{-1} K^{\dagger}_{\pi\widetilde{QQQ}}$$

$$\sim \int \mathcal{F}_{\pi\widetilde{B}\widetilde{B}}(\vec{k}_{\pi}^{2}) K_{\pi\widetilde{B}\widetilde{B}}(m - M_{\widetilde{B}+\pi})^{-1} K^{\dagger}_{\pi\widetilde{B}\widetilde{B}} \mathcal{F}^{*}_{\pi\widetilde{B}\widetilde{B}}(\vec{k}_{\pi}^{2})$$

allows to determine the various strong $\pi\widetilde{B}\widetilde{B}$ form factors $\mathcal{F}_{\pi\widetilde{B}\widetilde{B}}(\vec{k}_{\pi}^{2})$ at the followingvertices:



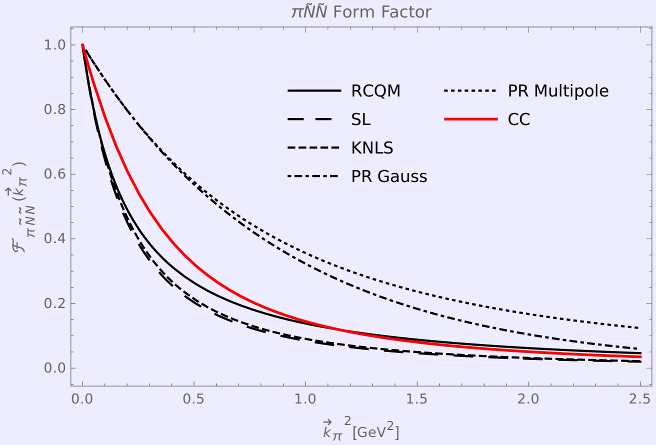
Consistent Solution of the CC RCQM for N

$$\left[m_{\widetilde{N}} + \int \frac{d^3 k_\pi}{(2\pi)^3} \frac{1}{2\omega_\pi 2\omega_{\widetilde{N}} 2m_{\widetilde{N}}} \mathcal{F}_{\pi\widetilde{N}\widetilde{N}}(\vec{k}_\pi^2) \left\langle \widetilde{N} \mid \mathcal{L}_{\pi\widetilde{N}\widetilde{N}}(0) \mid \widetilde{N}, \pi : \vec{k}_\pi \right\rangle \right.$$
$$\times \quad \left(m - \sqrt{m_{\widetilde{N}}{}^2 + \vec{k}_\pi^2} - \sqrt{m_\pi^2 + \vec{k}_\pi^2} \right)^{-1}$$
$$\times \quad \left. \mathcal{F}^*_{\pi\widetilde{N}\widetilde{N}}(\vec{k}_\pi^2) \left\langle \widetilde{N}, \pi : \vec{k}_\pi \mid \mathcal{L}^\dagger_{\pi\widetilde{N}\widetilde{N}}(0) \mid \widetilde{N} \right\rangle \right] \left\langle \widetilde{N} \mid \psi_N \right\rangle = m \left\langle \widetilde{N} \mid \psi_N \right\rangle$$

- Start with an arbitrary value $m_{\widetilde{N}}^{(0)}$ for $m_{\widetilde{N}}$ and calculate $\mathcal{F}^{(0)}_{\pi\widetilde{N}\widetilde{N}}(\vec{k}_\pi)$
- Use $\mathcal{F}^{(0)}_{\pi\widetilde{N}\widetilde{N}}(\vec{k}_\pi)$ in the eigenvalue equation to obtain $m = 939$ MeV and a corresponding bare mass $m_{\widetilde{N}}^{(1)}$
- Take $m_{\widetilde{N}}^{(1)}$ and calculate $\mathcal{F}^{(1)}_{\pi\widetilde{N}\widetilde{N}}(\vec{k}_\pi)$
- Repeat this iteration until a consistent solution is achieved

$\pi\widetilde{N}\widetilde{N}$ Form Factor from Microscopic Theory

Result of the **CC RCQM** compared to other models



Predictions of the **CC RCQM**

	CC	RCQM	SL	KNLS	PR Gauss	PR Multipole
$\frac{f^2_{\pi\tilde{N}\tilde{N}}}{4\pi}$	0.071	0.0691	0.08	0.08	0.013	0.013
m_N	939	939	939	939	939	939
$m_{\tilde{N}}$	1096	1067	1031	1037	1025	1051
$m_N - m_{\tilde{N}}$	-157	-128	-92	-98	-86	-112

(all values in MeV)

Consistent Solution of the CC RCQM for Δ

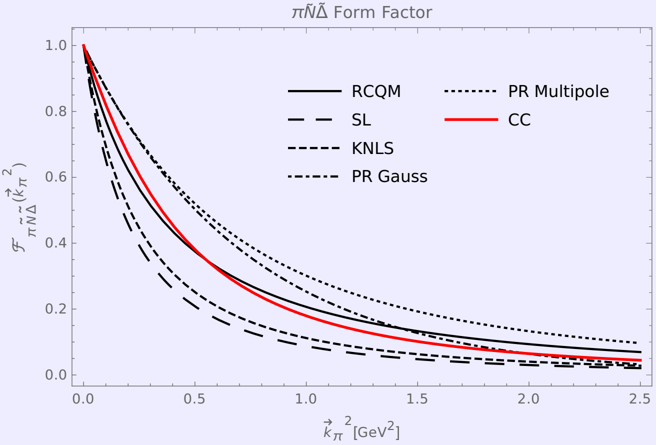
$$\Bigg[m_{\tilde\Delta} + \int \frac{d^3k_\pi}{(2\pi)^3}\frac{1}{2\omega_\pi 2\omega_{\tilde N} 2 m_{\tilde\Delta}} \mathcal{F}_{\pi\tilde N\tilde\Delta}(\vec k_\pi^2)\left\langle \tilde\Delta \mid \mathcal{L}_{\pi\tilde N\tilde\Delta}(0) \mid \tilde N, \pi : \vec k_\pi\right\rangle \times \left(m - \sqrt{m_{\tilde N}{}^2 + \vec k_\pi^2} - \sqrt{m_\pi^2 + \vec k_\pi^2}\right)^{-1} \times \mathcal{F}^*_{\pi\tilde N\tilde\Delta}(\vec k_\pi^2)\left\langle \tilde N, \pi : \vec k_\pi \mid \mathcal{L}^\dagger_{\pi\tilde N\tilde\Delta}(0) \mid \tilde\Delta\right\rangle\Bigg]\left\langle \tilde\Delta \mid \psi_\Delta\right\rangle = m\left\langle \tilde\Delta \mid \psi_\Delta\right\rangle$$

- The bare N mass $m_{\tilde N}$ is determined from above
- Assume an arbitrary value $m^{(0)}_{\tilde\Delta}$ for $m_{\tilde\Delta}$ and calculate $\mathcal{F}^{(0)}_{\pi\tilde N\tilde\Delta}(\vec k_\pi)$
- Use $\mathcal{F}^{(0)}_{\pi\tilde N\tilde\Delta}(\vec k_\pi)$ in the eigenvalue equation to obtain the physical Δ mass m and a corresponding bare mass $m^{(1)}_{\tilde\Delta}$
- Take $m^{(1)}_{\tilde\Delta}$ and calculate $\mathcal{F}^{(1)}_{\pi\tilde N\tilde\Delta}(\vec k_\pi)$
- Repeat this iteration until a consistent solution is achieved

Low-energy QCD
RCQM
Universal RCQM
Spectroscopy
Decays
Decay Systematics
CC Theory
Form Factors
N and Δ Masses
Summary

$\pi\widetilde{N}\widetilde{\Delta}$ Form Factor from Microscopic Theory

Result of the **CC RCQM** compared to other models



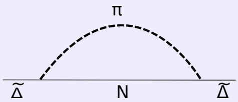
Pionic (Dressing) Effects on Δ Mass and Width

Predictions of the **CC RCQM**

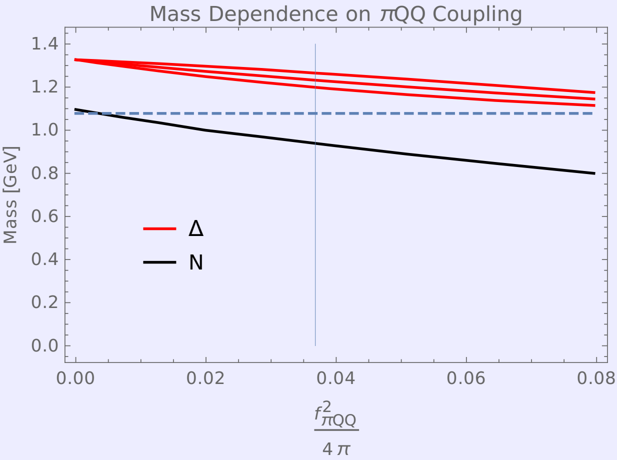
	CC	RCQM	SL	KNLS	PR Gauss	PR Multipole
$\frac{f^2_{\pi\tilde{N}\tilde{\Delta}}}{4\pi}$	0.239	0.188	0.334	0.126	0.167	0.167
m_N	939	939	939	939	939	939
$Re[m_\Delta]$	1232	1232	1232	1232	1232	1232
$m_{\tilde{\Delta}}$	1327	1309	1288	1261	1329	1347
$Re[m_\Delta] - m_{\tilde{\Delta}}$	-95	-77	-56	-29	-96	-115
$2\ Im[m_\Delta] = \Gamma$	67	47	64	27	52	52
$\Gamma_{exp}(\Delta \to \pi N)$			~ 117			

(all values in MeV)

Δ decay to physical N:



Mass Dependence on Coupling Strength



Blue dotted line: decay threshold $m_N + m_\pi = 1078$ MeV

$(m_N = 939$ MeV, $m_\pi = 139$ MeV$)$

Pionic (Dressing) Effects on Δ Mass and Width

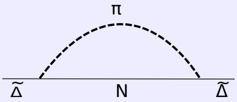
Predictions of the **CC RCQM**

with dressed coupling constant $f_{\pi N\Delta} = 1.3 \times f_{\pi\tilde{N}\tilde{\Delta}}$:

	CC	RCQM	SL	KNLS	PR Gauss	PR Multipole
$\frac{f^2_{\pi N\Delta}}{4\pi}$	0.403	0.318	0.564	0.213	0.282	0.282
m_N	939	939	939	939	939	939
$Re[m_\Delta]$	1232	1232	1232	1232	1232	1232
$m_{\tilde{\Delta}}$	1381	1356	1319	1279	1387	1418
$Re[m_\Delta] - m_{\tilde{\Delta}}$	-149	-124	-87	-47	-155	-186
$2\ Im[m_\Delta] = \Gamma$	118	83	106	45	94	97
$\Gamma_{exp}(\Delta \to \pi N)$			$\sim$ 117			

(all values in MeV)

Δ decay to physical N:



Conclusions and Outlook

- A $\{QQQ\}$ constituent-quark model **cannot provide** a comprehensive, simultaneous description of baryon ground **AND** resonant states
- A **coupled-channels theory** taking into account the π, as the Goldstone boson of spontaneous chiral-symmetry breaking of low-energy QCD, immediately offers new degrees of freedom
- A **consistent implementation** of pionic effects for the N and the Δ has now been achieved (in a relativistically-invariant framework)
- **Extensions to further resonances** are called for
- **Other** than just π couplings will presumably be needed

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Thank you very much

for

your attention!