Baryon Resonances and Strong Decays

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Outline

Relativistic quantum mechanics (RQM)

i.e. **quantum theory** respecting **Poincaré invariance**
(theory on $\mathcal{H}$ 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

$$\begin{aligned}
\hat{M} &= \hat{M}_{free} + \hat{M}_{int} \\
\hat{M}_{free} &= \sqrt{\hat{H}_0^2 - \hat{\vec{P}}^2_{free}} \\
\hat{M}_{int} &= \sum_{i<j}^{3} \hat{V}_{ij} = \sum_{i<j} [\hat{V}_{ij}^{conf} + \hat{V}_{ij}^{hf}]
\end{aligned}$$

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

Goldstone-Boson-Exchange CQM

$$H_0 = \sum_{i=1}^{3} \sqrt{\vec{p}_i^{\,2} + m_i^2}$$

$$V_{conf}(\vec{r}_{ij}) = V_0 + C r_{ij}$$

$$V_{hf}(\vec{r}_{ij}) = \left[\sum_{F=1}^{3} V_\pi(\vec{r}_{ij}) \lambda_i^F \lambda_j^F + \sum_{F=4}^{7} V_K(\vec{r}_{ij}) \lambda_i^F \lambda_j^F + V_\eta(\vec{r}_{ij}) \lambda_i^8 \lambda_j^8 + \frac{2}{3} V_{\eta'}(\vec{r}_{ij}) \right] \vec{\sigma}_i \cdot \vec{\sigma}_j$$

L.Ya. Glozman, W. Plessas, K. Varga, and R.F. Wagenbrunn: Phys. Rev. D **58**, 094030 (1998)

One-Gluon-Exchange CQM

(Relativistic version of the Bhaduri-Cohler-Nogami OGE CQM)

$$H_0 = \sum_{i=1}^{3} \sqrt{\vec{p}_i^{\,2} + m_i^2}$$

$$V_{conf} = V_0 + C r_{ij}$$

$$V_{hf} = -\frac{2b}{3r_{ij}} + \frac{\alpha_s}{9m_i m_j}\Lambda^2 \frac{e^{-\Lambda r_{ij}}}{r_{ij}} \vec{\sigma}_i \cdot \vec{\sigma}_j$$

L. Theussl, R.F. Wagenbrunn, B. Desplanques, and W. Plessas: Eur. Phys. J. A **12**, 91 (2001)

Instanton-Induced CQM

(Relativistic CQM by the Bonn group)

$$
\begin{aligned}
H_0 &= \sum_{i=1}^{3} \sqrt{\vec{p}_i^{\,2} + m_i^2} \\
V_{conf} &= V_0 + C r_{ij} \\
V_{hf} &= V_{\text{'t Hooft}}
\end{aligned}
$$

Relativistic framework: Bethe-Salpeter equation

U. Löring, B.Ch. Metsch, and H.R. Petry: Eur. Phys. J. A **10**, 395 (2001); ibid. 447 (2001)

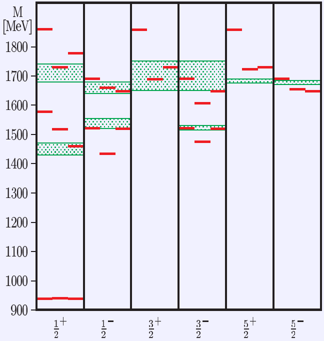
Eigenvalue Spectra

of

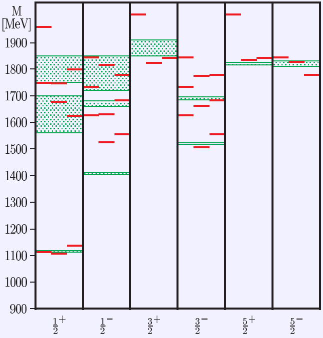
Invariant Mass Operator

N and Λ Excitation Spectra

N



Λ



left: **OGE CQM** middle: **II CQM** right: **GBE CQM**

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

Electromagnetic and Axial Nucleon Form Factors

as well as

Electric Radii and Magnetic Moments of Hyperons

Electroweak Reactions

- **Electron** scattering on the nucleons
  G_E^p, G_M^p, r_E^p, μ^p; G_E^n, G_M^n, r_E^n, μ^n
- **Neutrino** scattering on the nucleon
  G_A, G_P
- **Electron** scattering on the hyperons
  r_E^Y, μ^Y

Point Form and Instant Form Calculations

Poincaré algebra

$$
\begin{array}{lll}
[P_i, P_j] = 0, & [J_i, H] = 0, & [P_i, H] = 0, \\
[K_i, H] = -iP_i & [J_i, J_j] = i\epsilon_{ijk} J_k & [J_i, K_j] = i\epsilon_{ijk} K_k, \\
[J_i, P_j] = i\epsilon_{ijk} P_k, & [K_i, K_j] = -i\epsilon_{ijk} J_k, & [K_i, P_j] = -i\delta_{ij} H
\end{array}
$$

Point form

J_i and K_i interaction-free (6 out of 10 generators)

$P^\mu = (H, \vec{P})$ **interaction-dependent**

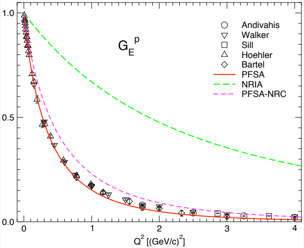
Instant form

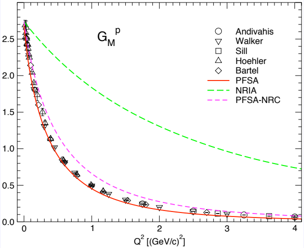
J_i and P_i interaction-free (6 out of 10 generators)

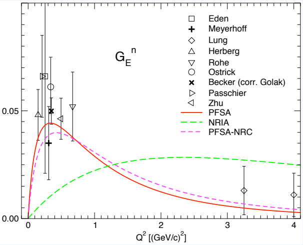
$P^0 = H$ and K_i **interaction-dependent**

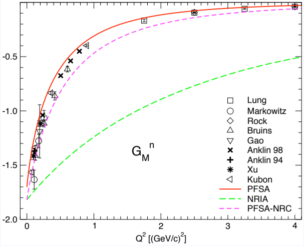
Electromagnetic Form Factors of the Nucleons

Covariant predictions of the GBE CQM:









Electric Radii and Magnetic Moments

Electric radii

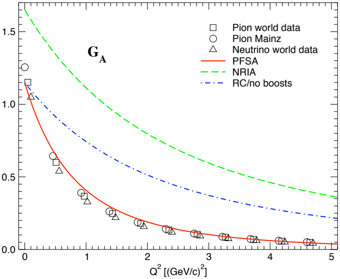
Baryon	GBE PFSA	Experiment
p	0.82	0.7569 ± 0.0139
n	-0.13	-0.1161 ± 0.0022
Σ^-	0.72	$0.61 \pm 0.12 \pm 0.09$

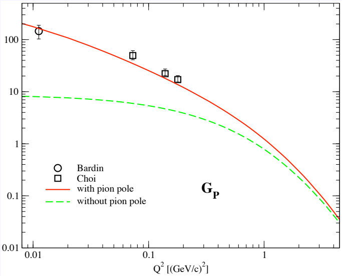
Magnetic moments

Baryon	GBE PFSA	Experiment
p	2.70	2.792847351
n	-1.70	-1.91304273
Λ	-0.64	-0.613 ± 0.004
Σ^+	2.38	2.458 ± 0.010
Σ^-	-0.93	-1.160 ± 0.025
Ξ^0	-1.25	-1.250 ± 0.014
Ξ^-	-0.70	-0.6507 ± 0.0025
Δ^+	2.08	$2.7^{+1.0}_{-1.3} \pm 1.5 \pm 3$
Δ^{++}	4.17	$3.7 - 7.5$
Ω^-	-1.59	-2.020 ± 0.05

K. Berger, R.F. Wagenbrunn, and W. Plessas: Phys. Rev. D **70**, 094027 (2004)

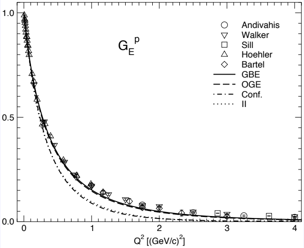
Covariant predictions of the GBE CQM:

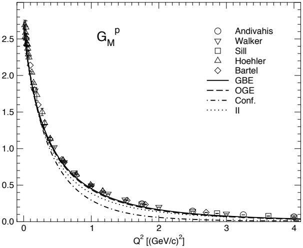


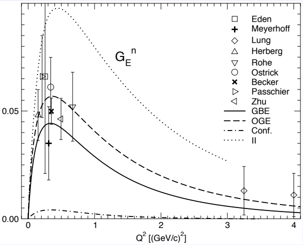


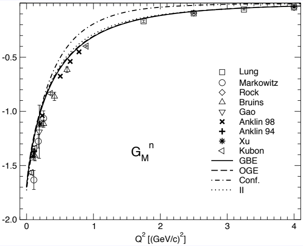
Electromagnetic Form Factors of the Nucleons

Different Quark Model Predictions:

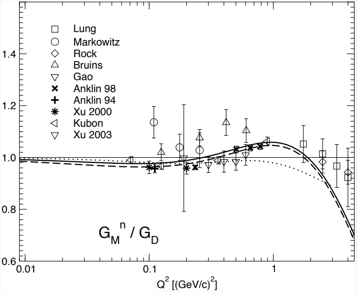


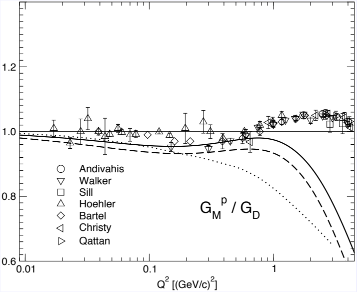






Different Quark Model Predictions:





solid: GBE CQM dashed: OGE CQM dotted: II CQM

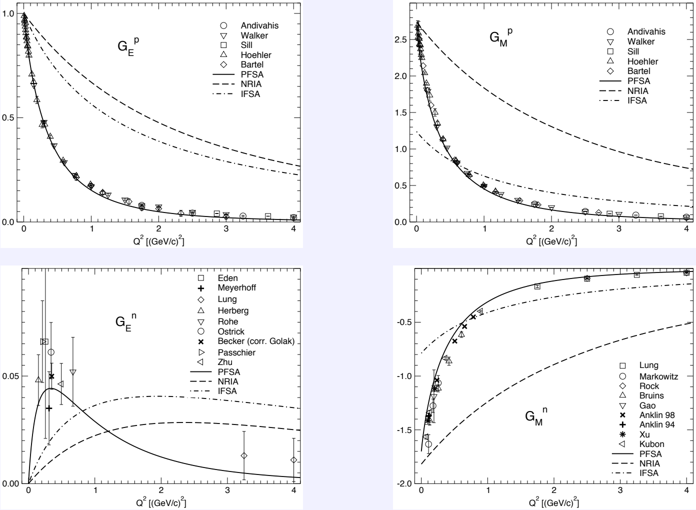
Point Form vs. **Instant Form** Calculations

of

Nucleon Electromagnetic Form Factors

Electromagnetic Form Factors of the Nucleons

Point-Form vs. **Instant-Form** Spectator Approximation:



Electric Radii and Magnetic Moments

Point-Form vs. **Instant-Form** Spectator Approximation:

r_E^2 [fm^2]

	GBE CQM			
	IFSM	PFSM	NRIA	Experiment
Proton	0.156	0.824	0.102	0.7569 ± 0.0139
Neutron	-0.020	-0.135	-0.009	-0.1161 ± 0.0022

μ [n.m.]

	GBE CQM			
	IFSM	PFSM	NRIA	Experiment
Proton	1.24	2.70	2.74	2.792847351
Neutron	-0.79	-1.70	-1.82	-1.91304273

π, η, and K Decay Modes

of

N^*, Δ^*, Λ^*, Σ^*, Ξ^* Resonances

π Decay Widths of N^* and Δ^*

N^*, Δ^* $\to N\pi$	Experiment [MeV]	Relativistic GBE	Relativistic OGE	Relativistic II	Nonrel. EEM GBE	Nonrel. EEM OGE
$N(1440)$	$(227 \pm 18)^{+70}_{-59}$	30	59	38	7	27
$N(1520)$	$(66 \pm 6)^{+\ 9}_{-\ 5}$	21	23	38	38	37
$N(1535)$	$(67 \pm 15)^{+28}_{-17}$	25	39	33	559	1183
$N(1650)$	$(109 \pm 26)^{+36}_{-\ 3}$	6.3	9.9	3	157	352
$N(1675)$	$(68 \pm 8)^{+14}_{-\ 4}$	8.4	10.4	4	13	16
$N(1700)$	$(10 \pm 5)^{+\ 3}_{-\ 3}$	1.0	1.3	0.1	2.2	2.7
$N(1710)$	$(15 \pm 5)^{+30}_{-\ 5}$	19	21		8	6
$\Delta(1232)$	$(119 \pm 1)^{+\ 5}_{-\ 5}$	35	31	62	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	4	76	177
$\Delta(1700)$	$(45 \pm 15)^{+20}_{-10}$	3.8	4.1	2	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)

π Decay Widths of N^* and Δ^*

N^*, Δ^* $\to N\pi$	Experiment [MeV]	Relativistic GBE	Relativistic OGE	Nonrel. EEM GBE	Nonrel. EEM OGE
$N(1440)$	$(227 \pm 18)^{+70}_{-59}$	28	<u>39</u>	6	14
$N(1520)$	$(66 \pm 6)^{+9}_{-5}$	22	23	38	36
$N(1535)$	$(67 \pm 15)^{+28}_{-17}$	24	38	579	1231
$N(1650)$	$(109 \pm 26)^{+36}_{-3}$	6.3	10.5	158	327
$N(1675)$	$(68 \pm 8)^{+14}_{-4}$	9.1	9.9	15	15
$N(1700)$	$(10 \pm 5)^{+3}_{-3}$	1.1	1.3	2.9	2.9
$N(1710)$	$(15 \pm 5)^{+30}_{-5}$	15	<u>12</u>	6.0	3.2
$\Delta(1232)$	$(119 \pm 1)^{+5}_{-5}$	33	31	81	85
$\Delta(1600)$	$(61 \pm 26)^{+26}_{-10}$	0.2	<u>2.4</u>	56	31
$\Delta(1620)$	$(38 \pm 8)^{+8}_{-6}$	1.4	2.8	74	176
$\Delta(1700)$	$(45 \pm 15)^{+20}_{-10}$	4.6	5.4	14	14

With experimental masses

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

π Decay Widths of Λ^*

Λ^* $\to \Sigma\pi$	Experiment [MeV]	Relativistic GBE	Relativistic OGE	Nonrel. EEM GBE	Nonrel. EEM OGE
$\Lambda(1405)$	(50 ± 2)	55	78	320	611
$\Lambda(1520)$	$(6.55 \pm 0.16)^{+0.04}_{-0.04}$	5	9	5	8
$\Lambda(1600)$	$(53 \pm 38)^{+60}_{-10}$	3	33	2	34
$\Lambda(1670)$	$(14.0 \pm 5.3)^{+8.3}_{-2.5}$	69	103	620	1272
$\Lambda(1690)$	$(18 \pm 6)^{+4}_{-2}$	19	25	24	28
$\Lambda(1800)$	*seen*	68	101	473	1175
$\Lambda(1810)$	$(38 \pm 23)^{+40}_{-10}$	3.8	2.1	55	150
$\Lambda(1830)$	$(52 \pm 19)^{+11}_{-12}$	14	19	16	24

With theoretical masses

T. Melde, W. Plessas, and B. Sengl: Phys. Rev. C 76, 025204 (2007)

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

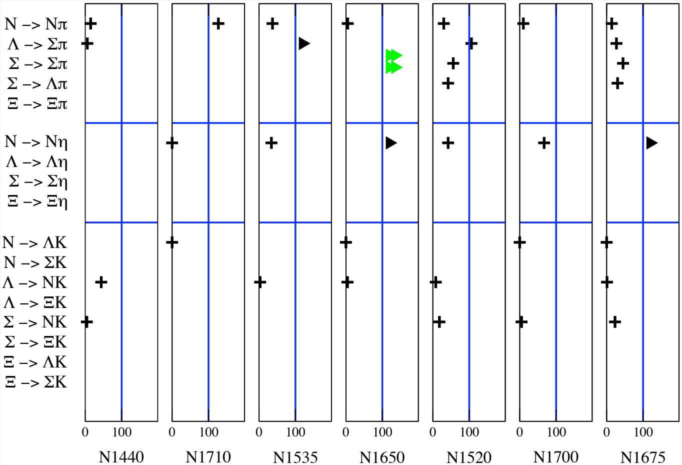
T. Melde, W. Plessas, and B. Sengl: Phys. Rev. D 76, 054008 (2007)

$SU(3)$ Flavor Multiplets

Classification of baryon resonances by the PDG (2008)

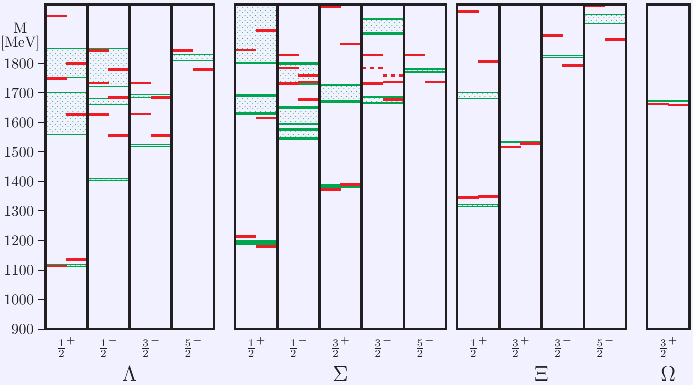
multiplet	$(LS)J^P$				
octet	$(0\frac{1}{2})\frac{1}{2}^+$	$N(939)$	$\Lambda(1116)$	$\Sigma(1193)$	$\Xi(1318)$
octet	$(0\frac{1}{2})\frac{1}{2}^+$	$N(1440)$	$\Lambda(1600)$	$\Sigma(1660)$	$\Xi(?)$
octet	$(0\frac{1}{2})\frac{1}{2}^+$	$N(1710)$	$\Lambda(1810)$	$\Sigma(1880)$	$\Xi(?)$
octet	$(1\frac{1}{2})\frac{1}{2}^-$	$N(1535)$	$\Lambda(1670)$	$\Sigma(1620)$	$\Xi(?)$
octet	$(1\frac{3}{2})\frac{1}{2}^-$	$N(1650)$	$\Lambda(1800)$	$\Sigma(1750)$	$\Xi(?)$
octet	$(1\frac{1}{2})\frac{3}{2}^-$	$N(1520)$	$\Lambda(1690)$	$\Sigma(1670)$	$\Xi(1820)$
octet	$(1\frac{3}{2})\frac{3}{2}^-$	$N(1700)$	$\Lambda(?)$	$\Sigma(?)$	$\Xi(?)$
octet	$(1\frac{3}{2})\frac{5}{2}^-$	$N(1675)$	$\Lambda(1830)$	$\Sigma(1775)$	$\Xi(?)$
decuplet	$(0\frac{3}{2})\frac{3}{2}^+$	$\Delta(1232)$	-	$\Sigma(1385)$	$\Xi(1530)$
decuplet	$(0\frac{3}{2})\frac{3}{2}^+$	$\Delta(1600)$	-	$\Sigma(?)$	$\Xi(?)$
decuplet	$(1\frac{1}{2})\frac{1}{2}^-$	$\Delta(1620)$	-	$\Sigma(?)$	$\Xi(?)$
decuplet	$(1\frac{1}{2})\frac{3}{2}^-$	$\Delta(1700)$	-	$\Sigma(?)$	$\Xi(?)$
singlet	$(1\frac{1}{2})\frac{1}{2}^-$	-	$\Lambda(1405)$	-	-
singlet	$(1\frac{1}{2})\frac{3}{2}^-$	-	$\Lambda(1520)$	-	-

Decay Widths of Octet Baryon Resonances



T. Melde, W. Plessas, and B. Sengl: Phys. Rev. D, to appear

Hyperon Excitation Spectra



For Σ with $J^P = \frac{1}{2}^-$ we have Σ[1560], Σ[1620], and Σ(1750)

For Σ with $J^P = \frac{3}{2}^-$ we have Σ(1670), Σ[1940], and a third Σ{≈ 1770} not yet seen (dashed)

Systematics of Decays

- Consider **spectral** and **decay** data
- Sort results according to **flavor multiplets**
- Examine the **spin**, **flavor**, and **space** symmetries of the various states

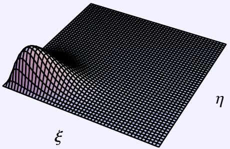
For the latter consider:
Spatial probability density distribution

$$\rho(\xi,\eta) = \xi^2\eta^2 \int d\Omega_\xi d\Omega_\eta \; \Psi^\star_{M\Sigma M_\Sigma T M_T}(\xi,\Omega_\xi,\eta,\Omega_\eta)\Psi_{M\Sigma M_\Sigma T M_T}(\xi,\Omega_\xi,\eta,\Omega_\eta)$$

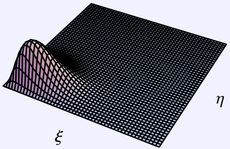
where $\vec{\xi}$ and $\vec{\eta}$ are the usual Jacobi coordinates

Pictures of Baryons (rest frame)

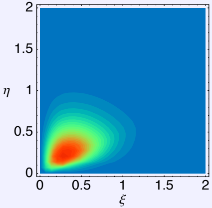
N GBE CQM



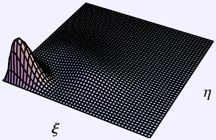
N OGE CQM



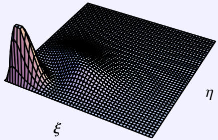
N



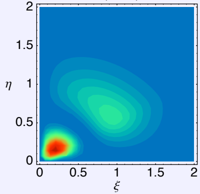
N(1440) GBE CQM



N(1440) OGE CQM



N(1440)



New Quark Model Classification

multiplet	$(LS)J^P$				
octet	$(0\frac{1}{2})\frac{1}{2}^+$	$N(939)^{100}$	$\Lambda(1116)^{100}$	$\Sigma(1193)^{100}$	$\Xi(1318)^{100}$
octet	$(0\frac{1}{2})\frac{1}{2}^+$	$N(1440)^{100}$	$\Lambda(1600)^{96}$	$\Sigma(1660)^{100}$	$\boldsymbol{\Xi}(\mathbf{1690})^{100}$
octet	$(0\frac{1}{2})\frac{1}{2}^+$	$N(1710)^{100}$		$\Sigma(1880)^{99}$	
octet	$(1\frac{1}{2})\frac{1}{2}^-$	$N(1535)^{100}$	$\Lambda(1670)^{72}$	$\boldsymbol{\Sigma}(\mathbf{1560})^{94}$	
octet	$(1\frac{3}{2})\frac{1}{2}^-$	$N(1650)^{100}$	$\Lambda(1800)^{100}$	$\boldsymbol{\Sigma}(\mathbf{1620})^{100}$	
octet	$(1\frac{1}{2})\frac{3}{2}^-$	$N(1520)^{100}$	$\Lambda(1690)^{72}$	$\Sigma(1670)^{94}$	$\Xi(1820)^{97}$
octet	$(1\frac{3}{2})\frac{3}{2}^-$	$N(1700)^{100}$		$\boldsymbol{\Sigma}(\mathbf{1940})^{100}$	
octet	$(1\frac{3}{2})\frac{5}{2}^-$	$N(1675)^{100}$	$\Lambda(1830)^{100}$	$\Sigma(1775)^{100}$	$\boldsymbol{\Xi}(\mathbf{1950})^{100}$
decuplet	$(0\frac{3}{2})\frac{3}{2}^+$	$\Delta(1232)^{100}$	$\Sigma(1385)^{100}$	$\Xi(1530)^{100}$	$\Omega(1672)^{100}$
decuplet	$(0\frac{3}{2})\frac{3}{2}^+$	$\Delta(1600)^{100}$	$\boldsymbol{\Sigma}(\mathbf{1690})^{99}$		
decuplet	$(1\frac{1}{2})\frac{1}{2}^-$	$\Delta(1620)^{100}$	$\boldsymbol{\Sigma}(\mathbf{1750})^{94}$		
decuplet	$(1\frac{1}{2})\frac{3}{2}^-$	$\Delta(1700)^{100}$			
singlet	$(1\frac{1}{2})\frac{1}{2}^-$	$\Lambda(1405)^{71}$			
singlet	$(1\frac{1}{2})\frac{3}{2}^-$	$\Lambda(1520)^{71}$			
singlet	$(0\frac{1}{2})\frac{1}{2}^+$	$\boldsymbol{\Lambda}(\mathbf{1810})^{92}$			

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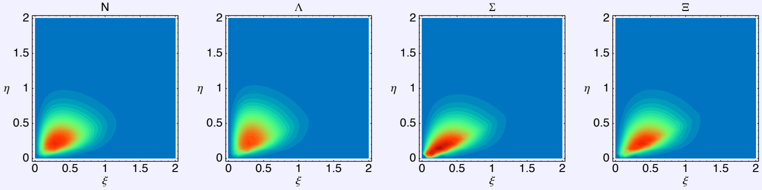
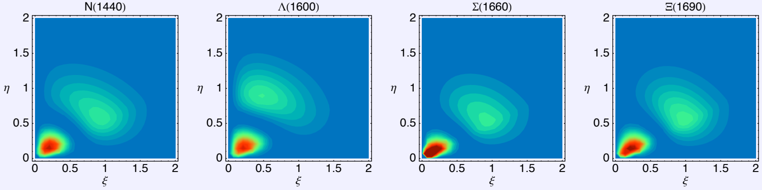
Spatial Probability Density Distributions

$\rho(\xi,\eta)$ for the $\frac{1}{2}^+$ octet baryon ground states $N(939)$, $\Lambda(1116)$, $\Sigma(1193)$, $\Xi(1318)$:

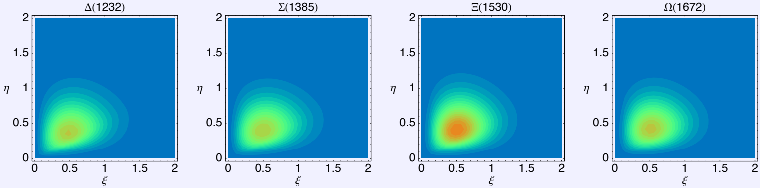


$\rho(\xi,\eta)$ for the $\frac{1}{2}^+$ octet baryon states $N(1440)$, $\Lambda(1600)$, $\Sigma(1660)$, $\Xi(1690)$:

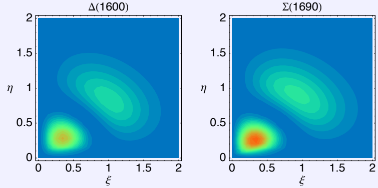


Spatial Probability Density Distributions

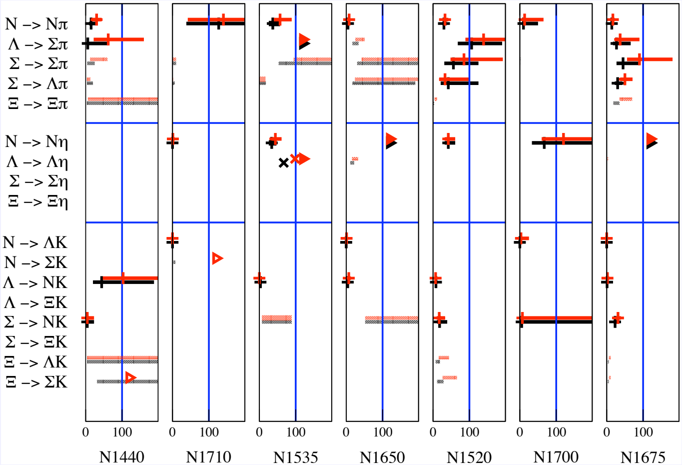
$\rho(\xi, \eta)$ for the $\frac{3}{2}^+$ decuplet baryon states $\Delta(1232)$, $\Sigma(1385)$, $\Xi(1530)$, $\Omega(1672)$:



$\rho(\xi, \eta)$ for the $\frac{3}{2}^+$ decuplet baryon states $\Delta(1600)$, $\Sigma(1690)$:



Decay Widths of Octet Baryon Resonances



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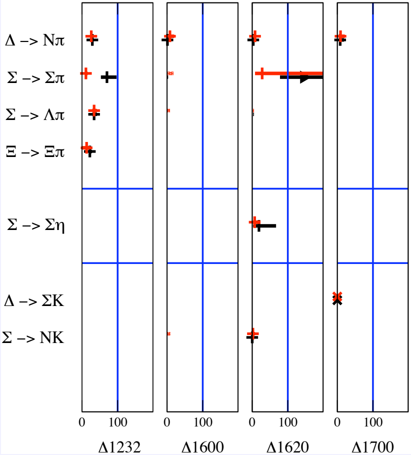
Decay Widths of Decuplet Baryon Resonances



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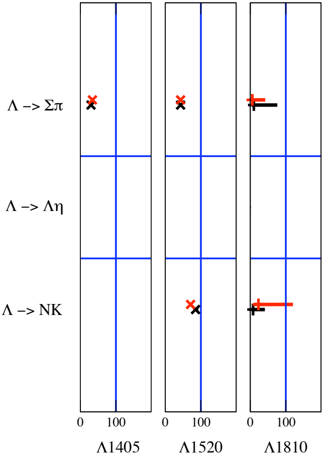
Decay Widths of Singlet Baryon Resonances



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Summary

- **Relativistic CQMs** allow for a unified description of **light and strange baryon spectra** for $E \lesssim 2$ GeV, especially in the case of the **GBE CQM**
  - mass-operator eigenvalues in relatively good order
- **Covariant point-form** predictions for the elastic **electroweak nucleon structure** in surprisingly good agreement with available data for $q^2 \lesssim 4$ GeV^2 (in contrast to the **instant-form spectator-model** results)
  - ground-state wave functions appear reasonable
- **Strong decays** cannot yet be described in agreement with phenomenology
  - refinements necessary, both with respect to **resonance wave functions** and **decay mechanism**.

Summary ctd.

- **Spectra**, **decay widths**, and **spin-flavor-space** symmetries of states allow for a new (extended) **classification of baryon resonances** into flavor multiplets
  - to be confirmed by more experiments

Thank you very much

for

your attention!

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