Baryon Properties from a Relativistic Constituent-Quark Model

Willibald Plessas

Theoretical Physics / Institute of Physics
University of Graz, Austria

42nd Hirschegg International Workshop

"Hadrons from Quarks and Gluons"

Hirschegg, Kleinwalsertal, Austria, January 15th, 2014

Motivation for Resorting to Quark Models

To be able to describe/understand

- in a consistent manner
- on the microscopic level
- in accordance with the properties of low-energy QCD such phenomena like

- **hadron spectra**: ground states & excitations
- **hadron structure**: r_E, μ, g_A ; G_E, G_M, G_A, G_P, ...
  i.e. electroweak form factors etc.
- **resonance excitations**: $\gamma N \to N^*$, $e^- N \to N^*$, ...
- **resonance decays**:
  $\rho \to \pi\pi$, $\omega \to \pi\pi\pi$, $N^* \to N\pi$, $\Delta \to N\pi$, $\Lambda^* \to KN$, ...
- **meson-baryon interactions**: $\pi - N$, $K - N$, ...
- **hyperon-hyperon interactions**: $N - N$, $N - Y$, ...
  etc. etc.

Outline

Low-Energy QCD

Low-energy QCD of N_f flavors is characterized by:

- spontaneous breaking of chiral symmetry ($SB\chi S$):

$$SU(N_f)_L \times SU(N_f)_R \to SU(N_f)_V$$

$\to$ appearance of $(N_f^2 - 1)$ **Goldstone bosons** $\vec{\phi}$
$\to$ generation of quasiparticles with dynamical mass, i.e. **constituent quarks** ψ

- thus (effective) interaction Lagrangian:

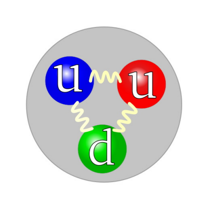
$$\mathcal{L}_{\mathrm{int}} \sim ig\bar{\psi}\gamma_5\vec{\lambda}^f \cdot \vec{\phi}\psi$$

A. Manohar and H. Georgi: Nucl. Phys. B 234 (1984) 189
E.V. Shuryak: Phys. Rep. **115**, 151 (1984)
L.Ya. Glozman and D.O. Riska: Phys. Rep. **268**, 263 (1996)
see also:
S. Weinberg: Phys. Rev. Lett. **105**, 261601 (2010)

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

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

$$\hat{M}_{free} = \sqrt{\hat{H}^2_{free} - \hat{\vec{P}}^2_{free}}$$

$$\hat{M}^{rest\ frame}_{int} = \sum_{i<j}^{3} \hat{V}_{ij} = \sum_{i<j}^{3} [\hat{V}^{conf}_{ij} + \hat{V}^{hf}_{ij}]$$

fulfilling the **Poincaré algebra**

$$[\hat{P}_i, \hat{P}_j] = 0, \quad [\hat{J}_i, \hat{H}] = 0, \quad [\hat{P}_i, \hat{H}] = 0,$$
$$[\hat{K}_i, \hat{H}] = -i\hat{P}_i \quad [\hat{J}_i, \hat{J}_j] = i\epsilon_{ijk}\hat{J}_k \quad [\hat{J}_i, \hat{K}_j] = i\epsilon_{ijk}\hat{K}_k,$$
$$[\hat{J}_i, \hat{P}_j] = i\epsilon_{ijk}\hat{P}_k, \quad [\hat{K}_i, \hat{K}_j] = -i\epsilon_{ijk}\hat{J}_k, \quad [\hat{K}_i, \hat{P}_j] = -i\delta_{ij}\hat{H}$$

$\hat{H}, \hat{P}_i$ ... 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, W. Plessas, K. Varga, and R.F. Wagenbrunn: Phys. Rev. D **58**, 094030 (1998)

J.P. Day, K.-S. Choi, and W. Plessas: arXiv:1205.6918

J.P. Day, K.-S. Choi, and W. Plessas: Few-Body Syst. **54**, 329 (2013)

Universal GBE RCQM Parametrization

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

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

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

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

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

$m_u = m_d = 340$ MeV, $\quad m_s = 480$ MeV,

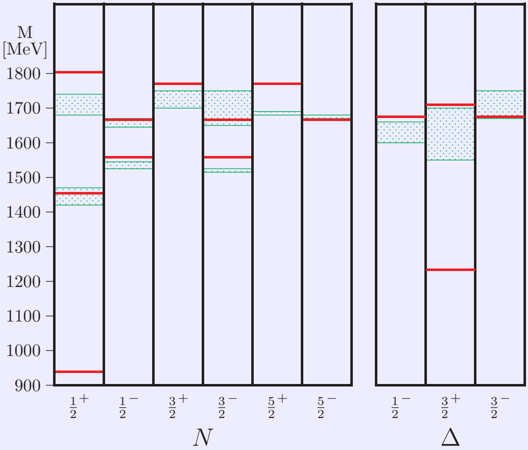
$m_c = 1675$ MeV, $\quad m_b = 5055$ MeV

Baryon **Excitation Spectra**

and

Mass-Operator **Eigenstates**

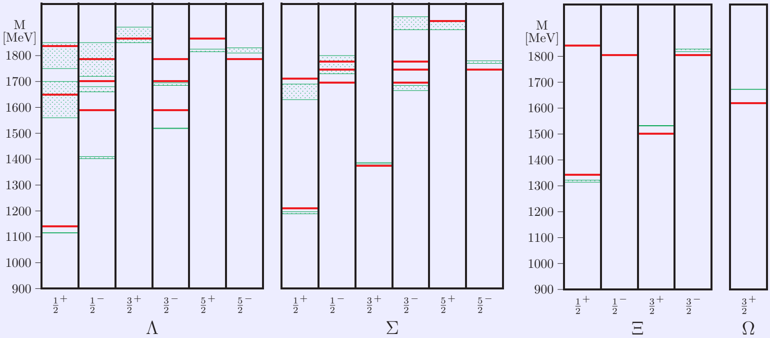
Light Baryon Spectra



red Universal GBE RCQM

green PDG 2013 (experiment)

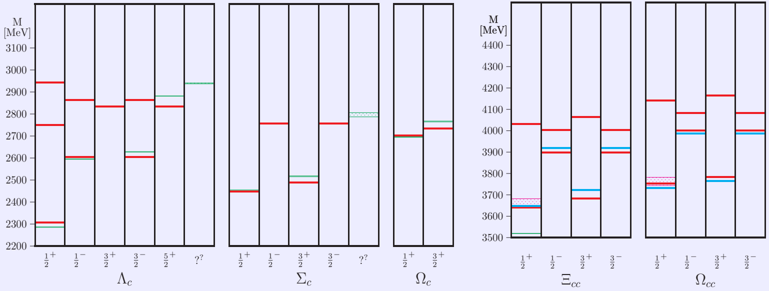
Strange Baryon Spectra



red Universal GBE RCQM

green PDG 2013 (experiment)

Charm Baryon Spectra



Left panel – single charm:

red   Universal GBE RCQM prediction

green   PDG 2013 (experiment)

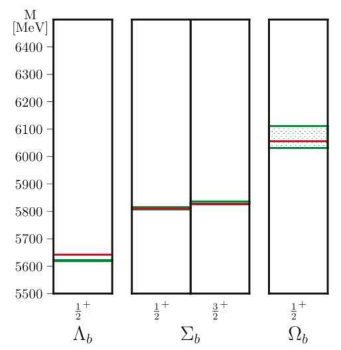
Right panel – double charm:

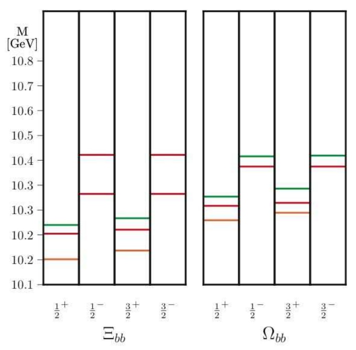
green   M. Mattson et al.: Phys. Rev. Lett. 89 (2002) 112001 (SELEX experiment)

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)

Bottom Baryon Spectra





Left panel – single bottom:

red Universal GBE RCQM prediction

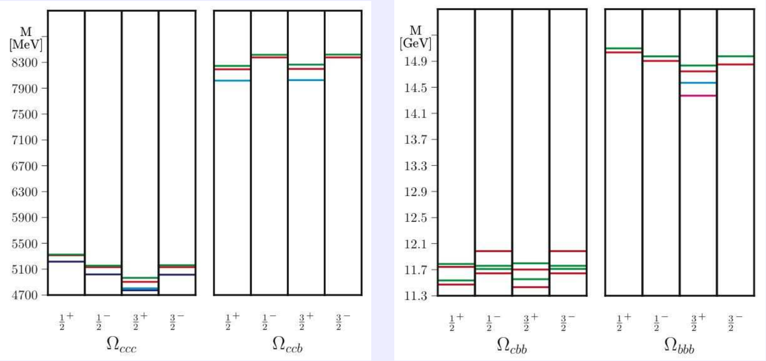
green PDG 2013 (experiment)

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

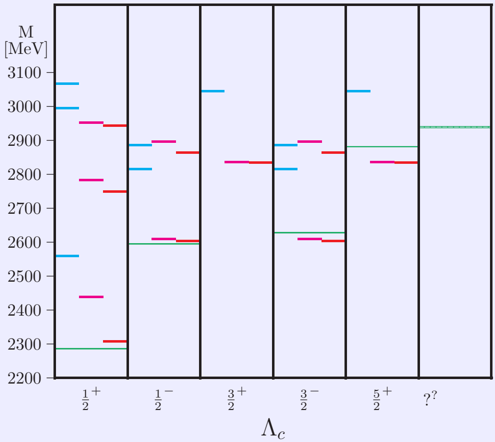
green W. Roberts and M. Pervin: Int. J. Mod. Phys. A 23 (2008) 2817 (nonrelativistic one-gluon-exchange CQM)

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

Mass operator eigenstates

$$\hat{M}\,|P,J,\Sigma,T,M_T\rangle = M\,|P,J,\Sigma,T,M_T\rangle$$

represented in configuration space

$$\left\langle \vec{\xi},\vec{\eta}\,\middle|\,P,J,\Sigma,T,M_T\right\rangle = \Psi_{PJ\Sigma TM_T}(\vec{\xi},\vec{\eta})$$

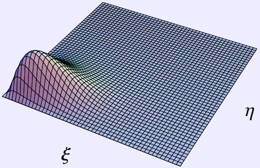
with $\vec{\xi}$ and $\vec{\eta}$ the usual Jacobi coordinates.

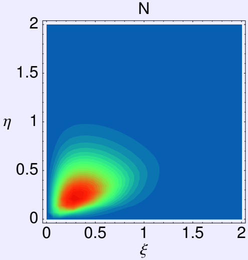
Picture the baryon wave functions through
spatial probability density distributions

$$\rho(\xi,\eta) = \xi^2\eta^2 \int d\Omega_\xi d\Omega_\eta \; \Psi^\star_{PJ\Sigma TM_T}(\xi,\Omega_\xi,\eta,\Omega_\eta)\Psi_{PJ\Sigma TM_T}(\xi,\Omega_\xi,\eta,\Omega_\eta)$$

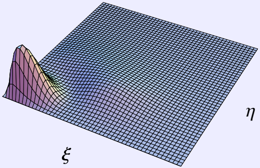
Pictures of Baryons (rest frame)

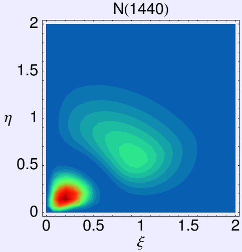
N GBE CQM





N(1440) GBE CQM

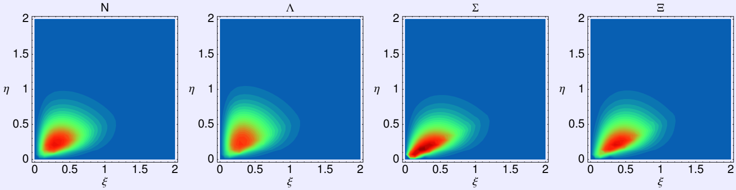




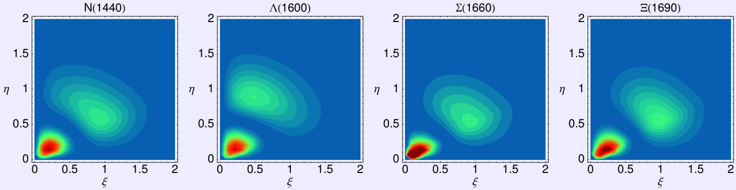
T. Melde, W. Plessas, and B. Sengl: Phys. Rev. D **77** (2008) 114002

Spatial Probability Density Distributions

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



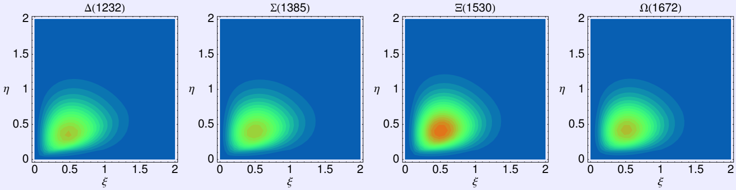
$\rho(\xi, \eta)$ for the $\frac{1}{2}^+$ **octet** baryon states $N(1440)$, $\Lambda(1600)$, $\Sigma(1660)$, $\Xi(1690)$:



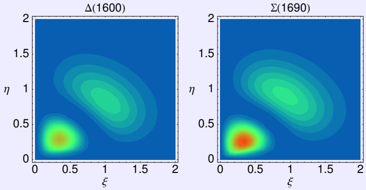
T. Melde, W. Plessas, and B. Sengl: Phys. Rev. D **77** (2008) 114002

Spatial Probability Density Distributions

$\rho(\xi,\eta)$ for the $\frac{3}{2}^+$ **decuplet** baryon states **Δ(1232), Σ(1385), Ξ(1530), Ω(1672)**:



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



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

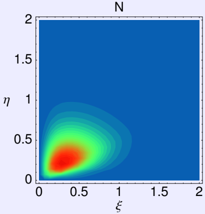
Root-Mean-Square Radii

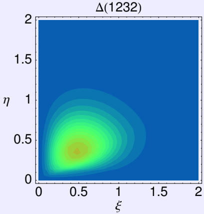
The **root-mean-square radius** (in the rest frame):

$$r_{\mathrm{rms}} = \sqrt{\langle r_i^2 \rangle} = \left(\int d^3 r_i \left\langle P=0, J, \Sigma \left| \hat{r}_i^2 \right| P=0, J, \Sigma \right\rangle \right)^{\frac{1}{2}}$$

Is NOT an **observable**! Is NOT **relativistically invariant**!

$\rightarrow$ Idea about the spatial distribution of constituent quarks.





r^N_{rms}=0.304 fm

r^p_E=0.905 fm, $(r^n_E)^2 = -0.128$ fm^2

r^Δ_{rms}=0.390 fm

$r_E^{\Delta^{++}} = r_E^{\Delta^{+}} = r_E^{\Delta^{-}}$ =0.656 fm, $r_E^{\Delta^0}$=0 fm

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

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

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

See also the PDG: Phys. Rev. D **86**, 010001 (2012)

Various Baryon Reactions

Matrix elements of a transition operator $\hat{O}$ between baryon eigenstates $|P, J, \Sigma, T, T_3, Y\rangle$

$$\langle P', J', \Sigma', T', T_3', Y'|\hat{O}|P, J, \Sigma, T, T_3, Y\rangle$$

$\hat{O}$ ... $\hat{J}^{\mu}_{\rm em}$ $\rightarrow$ electromagnetic FF's
... $\hat{A}^{\mu}_{\rm axial}$ $\rightarrow$ axial FF's
... $\hat{S}$ $\rightarrow$ scalar FF
... $\hat{\Theta}^{\mu\nu}$ $\rightarrow$ gravitational/tensor FF's
... $\hat{D}^{\mu}_{\lambda}$ $\rightarrow$ hadronic decays

To be calculated from microscopic three-quark ME's

$$\langle p_1', p_2', p_3'; \sigma_1', \sigma_2', \sigma_3'; f_{i_1'}, f_{i_2'}, f_{i_3'}|\hat{O}|p_1, p_2, p_3; \sigma_1, \sigma_2, \sigma_3; f_{i_1}, f_{i_2}, f_{i_3}\rangle$$

$\Uparrow$ boosted 3-body states $\Uparrow$ boosted 3-body states

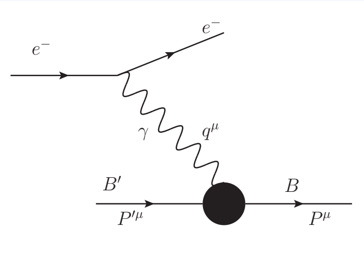
Electromagnetic Nucleon Observables

Covariant predictions for:

- **Electromagnetic** nucleon form factors
  $G_E^p(Q^2)$, $G_M^p(Q^2)$; $G_E^n(Q^2)$, $G_M^n(Q^2)$
- **Electric radii** and **magnetic moments**
  r_E^p, μ^p; r_E^n, μ^n

$\rightarrow$ Comparison to experiment

Elastic electron scattering:



Invariant form factors:

$$F^{\nu}_{\Sigma'\Sigma}(Q^2) = \langle P', J, \Sigma', T, M_T | \hat{J}^{\nu}_{\rm em} | P, J, \Sigma, T, M_T \rangle$$

$$\text{with } Q^2 = -q^2 \,; \qquad q^\mu = P^\mu - P'^\mu$$

Transition Matrix Elements in Point Form

Incoming baryon state: $|V, M, J, \Sigma\rangle \quad \hat{=} \, |P, J, \Sigma\rangle$

Outgoing baryon state: $|V', M', J', \Sigma'\rangle \quad \hat{=} \, |P', J', \Sigma'\rangle$

Transition operator: $\hat{O} = \hat{J}^{\mu}_{\mathrm{em}}$

$$\left\langle V', M', J', \Sigma' \right| \hat{J}^{\mu}_{\mathrm{em}} \left| V, M, J, \Sigma \right\rangle =$$

$$= \frac{2}{MM'} \sum_{\sigma_i \sigma_i'} \sum_{\mu_i \mu_i'} \int d^3\vec{k}_2 d^3\vec{k}_3 d^3\vec{k}_2' d^3\vec{k}_3'$$

$$\times \sqrt{\frac{\left(\sum_i \omega_i'\right)^3}{\prod_i 2\omega_i'}} \prod_{\sigma_i'} D^{\star \frac{1}{2}}_{\sigma_i' \mu_i'} \left\{ R_W \left[k_i'; B\left(V'\right) \right] \right\} \Psi^{\star}_{M'J'\Sigma'} \left(\vec{k}_1', \vec{k}_2', \vec{k}_3'; \mu_1', \mu_2', \mu_3' \right)$$

$$\times \left\langle p_1', p_2', p_3'; \sigma_1', \sigma_2', \sigma_3' \right| \hat{J}^{\mu}_{rd} \left| p_1, p_2, p_3; \sigma_1, \sigma_2, \sigma_3 \right\rangle$$

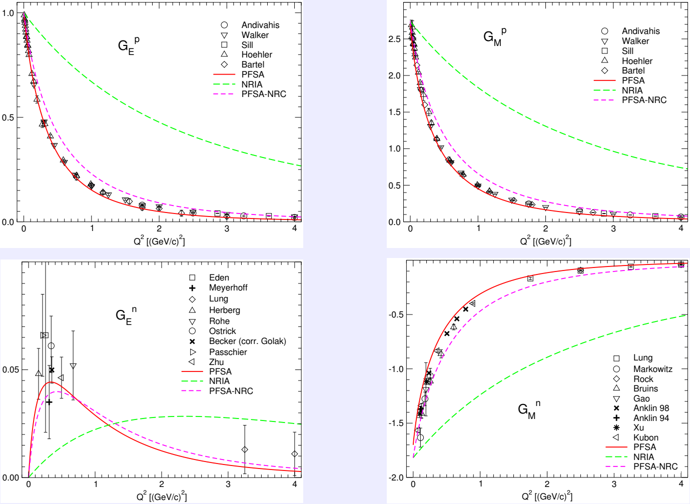
$$\times \sqrt{\frac{\left(\sum_i \omega_i\right)^3}{\prod_i 2\omega_i}} \prod_{\sigma_i} D^{\frac{1}{2}}_{\sigma_i \mu_i} \left\{ R_W \left[k_i; B\left(V\right) \right] \right\} \Psi_{MJ\Sigma} \left(\vec{k}_1, \vec{k}_2, \vec{k}_3; \mu_1, \mu_2, \mu_3 \right)$$

$$\times 2MV_0 \delta^3 \left(M\vec{V} - M'\vec{V}' - \vec{q} \right)$$

where $p_i = B_c(V) k_i$, $p_i' = B_c(V') k_i'$, and $\omega_i = \sqrt{\vec{k}_i^2 + m_i^2}$

Electromagnetic Nucleon Form Factors

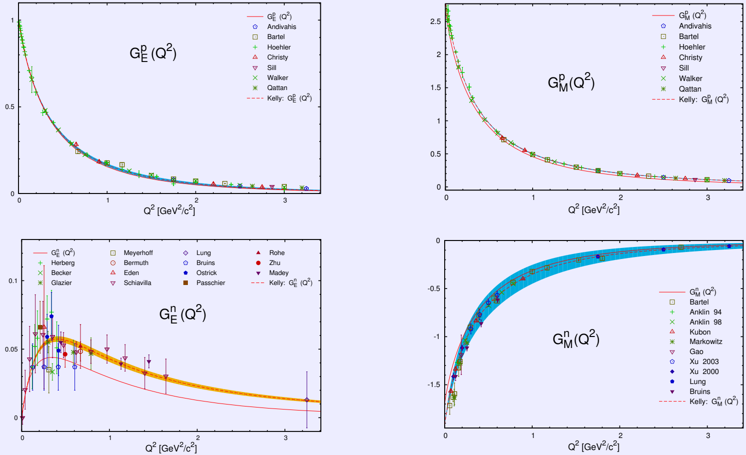
Covariant predictions of the GBE CQM:



R.F. Wagenbrunn, S. Boffi, W. Klink, W. Plessas, and M. Radici: Phys. Lett. **B511** (2001) 33

Electromagnetic Nucleon Form Factors

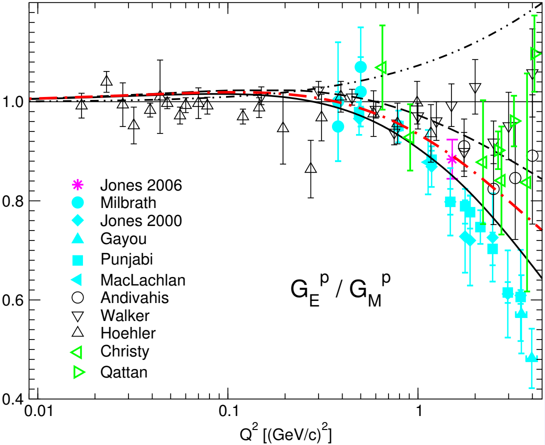
Covariant predictions of the GBE CQM:



R.F. Wagenbrunn, S. Boffi, W. Klink, W. Plessas, and M. Radici: Phys. Lett. **B511** (2001) 33

M. Rohrmoser: Diploma Thesis, Univ. of Graz, 2013

Proton Electric/Magnetic Form Factor Ratio



solid: GBE RCQM PFSM

dash-double-dot: GBE RCQM IFSM

T. Melde, K. Berger, L. Canton, W. Plessas, and R. F. Wagenbrunn: Phys. Rev. D **76**, 074020 (2007)

Electric radii r_E^2 [fm^2]

Baryon	GBE PFSM	Experiment
p	0.82	0.7692 ± 0.0123 1)
		0.70870 ± 0.00113 2)
n	-0.13	-0.1161 ± 0.0022

1) CODATA value (PDG)

2) Pohl et al.: Nature **466** (2010) 213

Magnetic moments μ [n.m.]

Baryon	GBE PFSM	Experiment
p	2.70	2.792847356
n	-1.70	-1.9130427

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

Nucleon r_E^2 and μ – Nonrelativistic !!!

Electric radii r_E^2 [fm^2]

Baryon	GBE PFSM	GBE NRIA	Experiment
p	0.82	0.10	0.7692 ± 0.0123 [1)]
			0.70870 ± 0.00113 [2)]
n	-0.13	-0.01	-0.1161 ± 0.0022

1) CODATA value (PDG)   2) Pohl et al.: Nature **466** (2010) 213

Magnetic moments μ [n.m.]

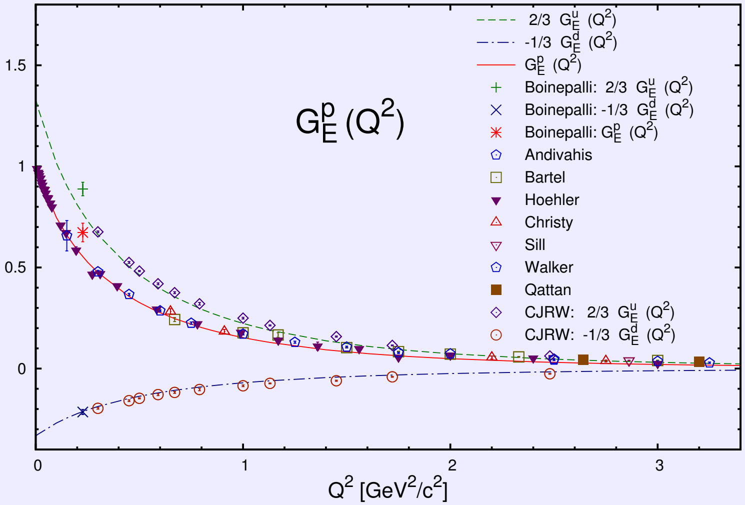
Baryon	GBE PFSM	GBE NRIA	Experiment
p	2.70	2.74	2.792847356
n	-1.70	-1.82	-1.9130427

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

Nucleons N

Proton Electric Form Factor

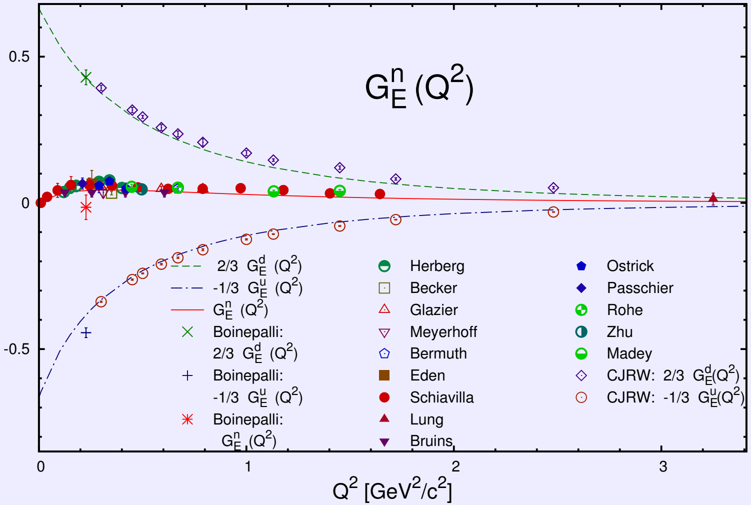
$$G_E^p = \frac{2}{3} G_E^u - \frac{1}{3} G_E^d$$



M. Rohrmoser, Ki-Seok Choi, and W. Plessas: arXiv:1110.3665

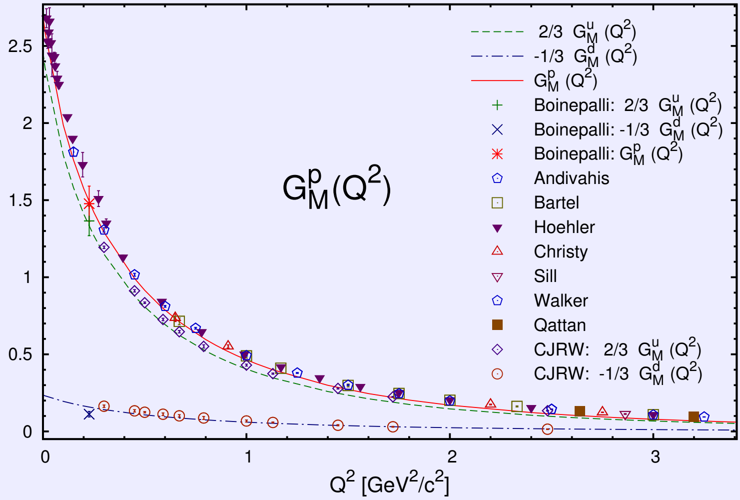
Neutron Electric Form Factor

$$G_E^n = \frac{2}{3} G_E^d - \frac{1}{3} G_E^u$$



M. Rohrmoser, Ki-Seok Choi, and W. Plessas: arXiv:1110.3665

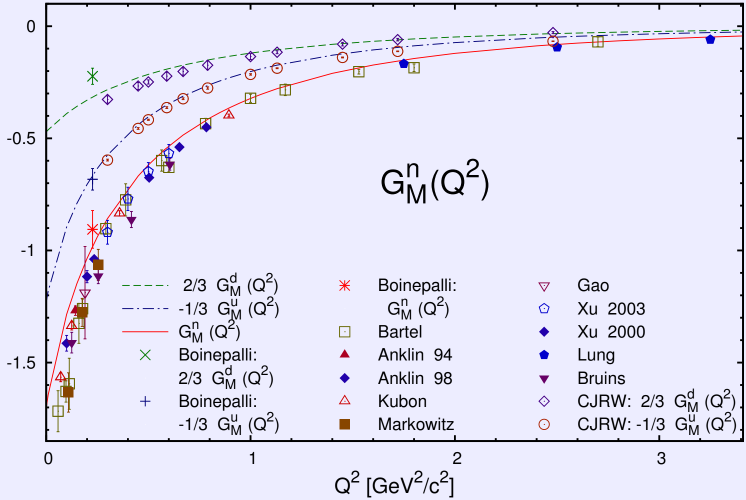
$$G_M^p = \frac{2}{3} G_M^u - \frac{1}{3} G_M^d$$



M. Rohrmoser, Ki-Seok Choi, and W. Plessas: arXiv:1110.3665

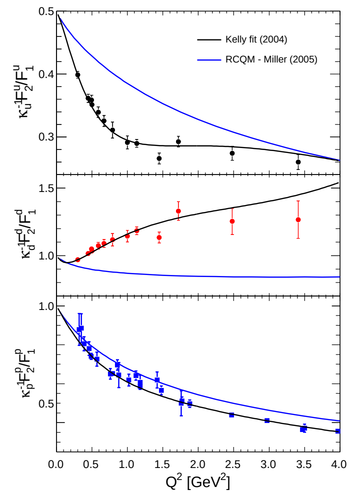
Neutron Magnetic Form Factor

$$G_M^n = \frac{2}{3} G_M^d - \frac{1}{3} G_M^u$$



M. Rohrmoser, Ki-Seok Choi, and W. Plessas: arXiv:1110.3665

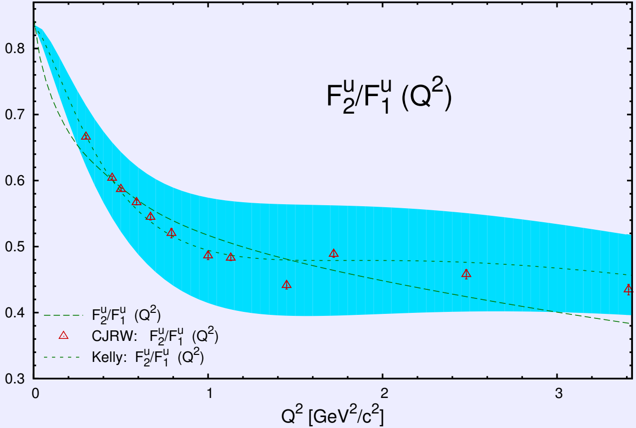
F_2/F_1 Ratios



3-Q vs. 5-Q components?

From: G. D. Cates, C. W. de Jager, S. Riordan, B. Wojtsekhowski: Phys. Rev. Lett. **106**, 252003 (2011)

Ratio F_2^u / F_1^u of u-Flavor Contr. to F_1 and F_2

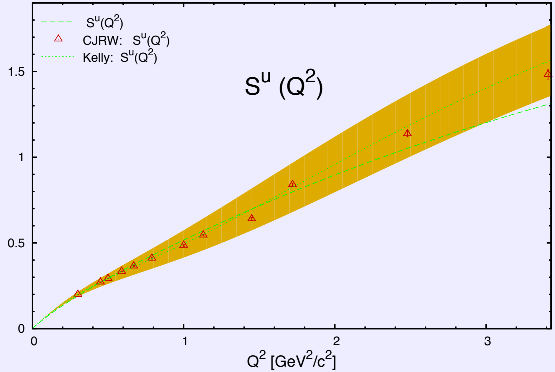


- - - - - - dashed green line: GBE RCQM ······· dotted line and blue area: Kelly fit with $\frac{1}{2}$ $*$error

No indication for 5-Q components in the nucleons!

Ratio of u-Flavor Contr. to F_1 and F_2 by S^q

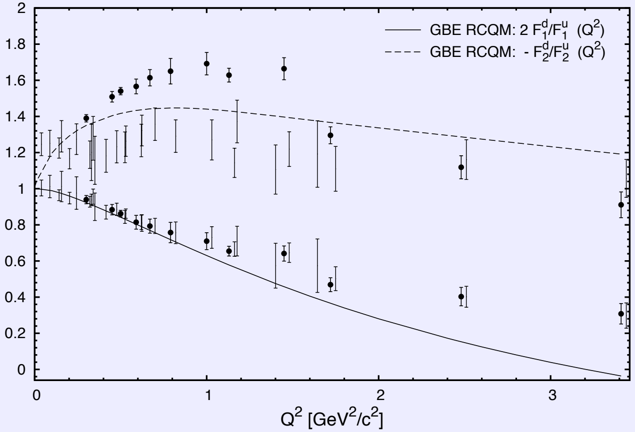
$$S^u(Q^2) = Q^2 \frac{F_2^u(Q^2)}{F_1^u(Q^2)}$$



- - - - - - dashed green line: GBE RCQM ······· dotted line and orange area: Kelly fit with $\frac{1}{2}*$error

No indication for 5-Q components in the nucleons!

Ratios F_i^d / F_i^u of Flavor Contr. to F_1 and F_2



Fall-off is **no indication for diquark clustering** in the nucleons!

GBE RCQM prediction: M. Rohrmoser, Ki-Seok Choi, and W. Plessas: arXiv:1110.3665

Phenomenology: ● G. D. Cates et al.: Phys. Rev. Lett. **106**, 252003 (2011)

I M. Diehl and P. Kroll: arXiv:1302.4604

Conclusions from Nucleon Flavor Analysis

- **Flavor analysis of nucleon e.m. form factors** in a relativistically invariant framework (point form).
- The **GBE RCQM** predicts flavor contributions in reasonable agreement with **experimental data**.
- The GBE RCQM relies on $\{QQQ\}$ degrees of freedom only; no explicit $\{QQQQ\bar{Q}\}$ etc.
- No explicit **meson-cloud effects** are included.
- No **strangeness content** in the nucleon for the low momentum transfers considered here.
- With respect to F_2^d/F_2^u three different phenomenological analyses give **distinct answers**.
- Details:

  M. Rohrmoser, Ki-Seok Choi, and W. Plessas: arXiv:1110.3665

  W. Plessas: Mod. Phys. Lett. A **28**, 136022 (2013)

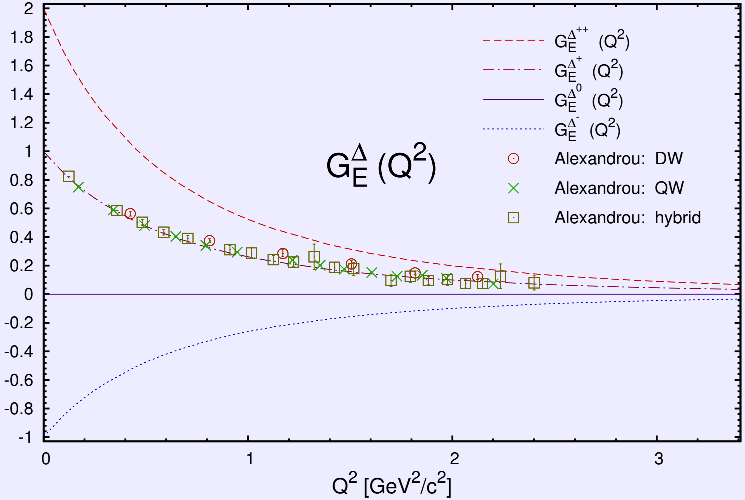
Δ and Hyperon E.m. Form Factors

$$\Delta$$

$$\Lambda, \Sigma, \Xi$$

$$\Sigma^*, \Xi^*, \Omega$$

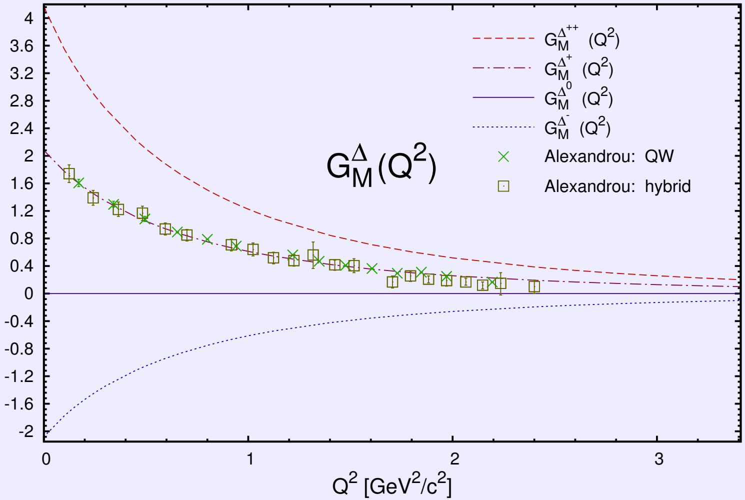
Electric Δ Form Factors



GBE RCQM: Ki-Seok Choi: PhD Thesis, Univ. Graz, 2011

Lattice QCD: C. Alexandrou et al. Phys. Rev. D **79** (2009) 014507

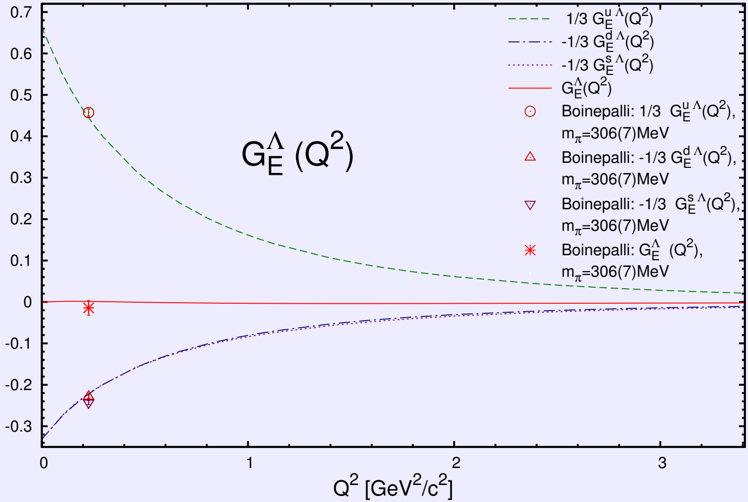
Magnetic Δ Form Factors



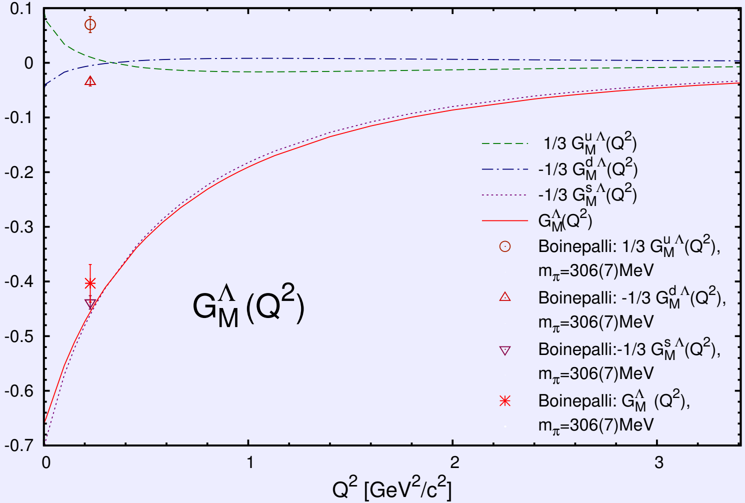
GBE RCQM: Ki-Seok Choi: PhD Thesis, Univ. Graz, 2011

Lattice QCD: C. Alexandrou et al. Phys. Rev. D **79** (2009) 014507

Octet $\Lambda(uds)$ Electric Form Factor



Octet $\Lambda(uds)$ Magnetic Form Factor



Axial **Charges** and Axial **Form Factors**

of

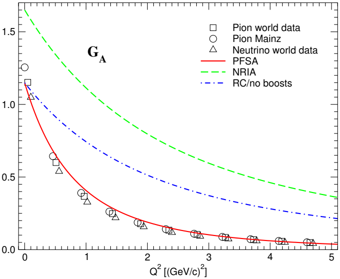
N Ground State and N^* Resonances

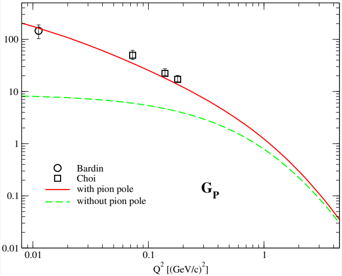
as well as

$\Delta, \Sigma, \Xi, \Sigma^*, \Xi^*$

Axial Nucleon Form Factors

Covariant predictions of the GBE RCQM:





$$g_A^{GBE} = 1.15 \quad \text{vs.} \quad g_A^{exp} = 1.2695 \pm 0.0029$$

L.Ya. Glozman, M. Radici, R.F. Wagenbrunn, S. Boffi, W. Klink, and W. Plessas: Phys. Lett. B **516**, 183 (2001)

Axial Charges of N and N^* Resonances

State	J^P	EGBE	Lattice QCD	GN	NR
N(939)	$\frac{1}{2}^+$	1.15	1.23∼1.26	1.66	1.65
N(1440)	$\frac{1}{2}^+$	1.16	?	1.66	1.61
N(1535)	$\frac{1}{2}^-$	0.02	∼0.00	-0.11	-0.20
N(1710)	$\frac{1}{2}^+$	0.35	?	0.33	0.42
N(1650)	$\frac{1}{2}^-$	0.51	∼0.55	0.55	0.64

EGBE **E**xtended **GBE** RCQM covariant result
Lattice **Lattice QCD** calculations by LHPC Collaboration and Takahashi-Kunihiro (Kyoto)
GN **G**lozman-**N**efediev $SU(6) \times O(3)$ nonrelativistic QM
NR **N**on-**R**elativistic EGBE result

K.-S. Choi, W. Plessas, and R.F. Wagenbrunn: Phys. Rev. C **81**, 028201 (2010)

Axial Charges of $\Delta, \Sigma, \Xi, \Sigma^*, \Xi^*$

	J^P	Exp	EGBE	LO	EOT	JT	NR
N	$\frac{1}{2}^+$	1.2695	1.15	1.18	1.314	1.18	1.65
Σ	$\frac{1}{2}^+$	-	0.65	0.636	0.686	0.73	0.93
Ξ	$\frac{1}{2}^+$	-	-0.21	-0.277	-0.299	-0.23	-0.32
Δ	$\frac{3}{2}^+$	-	-4.48	-	-	$\sim$-4.5	-6.00
Σ^*	$\frac{3}{2}^+$	-	-1.06	-	-	-	-1.41
Ξ^*	$\frac{3}{2}^+$	-	-0.75	-	-	-	-1.00

EGBE — **E**xtended **GBE** RCQM covariant result
LO — **L**in and **O**rginos lattice-QCD calculation
EOT — **E**rkol, **O**ka, and **T**akahashi lattice-QCD calculation
JT — **J**iang and **T**iburzi χPT calculation
NR — **N**on-**R**elativistic EGBE result

K.-S. Choi, W. Plessas, and R.F. Wagenbrunn: Phys. Rev. D **82**, 014007 (2010)

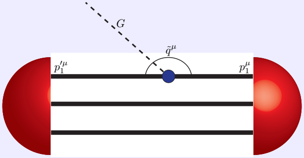
Gravitational Form Factors

of

the Nucleon

Low-energy QCD
RCQM
GBE RCQM
Spectroscopy
Light, strange, charm, bottom
Structure
Nucleon E.m.
Baryon E.m.
Axial FFs
Gravitational FF
Summary

Gravitational Form Factors

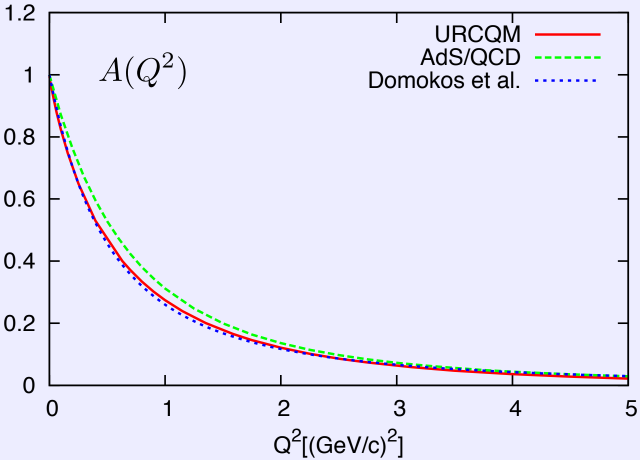


Invariant ME of **energy-momentum tensor** $\hat{\Theta}^{\mu\nu}$:

$$\langle P'J\Sigma'|\hat{\Theta}^{\mu\nu}|PJ\Sigma\rangle = \bar{U}(P')\left[\gamma^{(\mu}\bar{P}^{\nu)}A(Q^2) + \frac{i}{2M}\bar{P}^{(\mu}\sigma^{\nu)}B(Q^2) + \frac{q^{\mu}q^{\nu} - q^2 g^{\mu\nu}}{M}C(Q^2)\right]U(P)$$

$$A(Q^2) \sim \langle P'J\Sigma'|\Theta^{00}|PJ\Sigma\rangle$$

Nucleon Gravitational Form Factor $A(Q^2)$



J.P. Day: PhD Thesis, Univ. Graz, August 2013

Summary and Conclusions

- Surprisingly **good agreement** of predictions by GBE RCQM with experimental data (wherever such data are available)
- **Small deviations** left in some observables, such as electric radii and magnetic moments
- Surprisingly **good agreement** of predictions by GBE RCQM with lattice-QCD results
- Most important symmetries of GBE RCQM:
  - **SBχS**
  - **Lorentz invariance**
  - **time-reversal invariance**
  - **current conservation**
- The **non-relativistic** quark model **does not work** in any instance

Collaborators

Graz

K. Berger, J.P. Day, K.-S. Choi, L. Glozman, T. Melde, M. Rohrmoser, R.C. Schardmüller, B. Sengl, R.F. Wagenbrunn

(Theoretical Physics, University of Graz)

Pavia

S. Boffi and M. Radici

(INFN, Sezione di Pavia)

Padova

L. Canton

(INFN, Sezione di Padova)

Iowa City

W. Klink

(Department of Physics, University of Iowa, USA

Forthcoming Schladming Winter School

52. Internationale Universitätswochen für Theoretische Physik

Physics Beyond the Higgs

Schladming, Styria, Austria, March 1 - 8, 2014

Benjamin Grinstein (University of California, San Diego)	**Beyond the Standard Model and Flavour Physics**
Michele Della Morte (University of Odense)	**Heavy Flavour Physics and Precision Tests of the Standard Model on the Lattice**
Aleandro Nisati (INFN Roma)	**Recent Results from the LHC**
Claudio Pica (University of Odense)	**Conformal Versus Confining Phases on the Lattice**
Antonio Pich (University of Valencia)	**Effective Theories of the Standard Model and Beyond**
Kimmo Tuominen (University of Helsinki)	**LHC Data and Aspects of New Physics**

If you wish to apply, please access the web page and complete the registration form as soon as possible, but not later than **February 17, 2014**. More Information about the school can be found on the web page as well.

Director of the School: Reinhard Alkofer
Organizing Committee: Natália Alkofer, Markus Pak, Willibald Plessas, Francesco Sannino (CP3-Origins)

Institut für Physik, FB Theoretische Physik
Karl-Franzens-Universität Graz
Universitätsplatz 5, A-8010 Graz, Austria
Phone: +43 316 380 5225
Fax: +43 316 380 9820
E-mail: theor.physik@uni-graz.at
http://physik.uni-graz.at/schladming2014/

Thank you very much

for

your attention!