Constituent-Quark Masses, Baryon Spectroscopy, and Electroweak Baryon Structure

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Sanctus Willibaldus of Eichstätt (Germany)

Sanctus Willibaldus ('Willibald' $\hookrightarrow$ prompta voluntas), 709 (?) – 7.7.787 A.D.

- Son of Anglo-Saxon (Holy) King Richard and Wunna (not really)
- Bishop of Eichstätt, Bavaria, Germany (indeed)



http://www.bistum-eichstaett.de/willibaldswoche/

http://www.heiligenlexikon.de/Stadler/Willibald_von_Eichstaett.html

Some Particular Remarks

A few remarks on the quark model and constituent quarks:

- 2014: 50th anniversary of the quark model (M. Gell-Mann / G. Zweig)
- 42 years after the invention of QCD in late 1972 (M. Gell-Mann and H. Fritzsch) – not yet solved in the non-perturbative regime
- Problems: Confinement and spontaneous breaking of chiral symmetry (SBχS) towards lower energies
- SBχS: Clue to generation of dynamical masses of constituent quarks and their interactions (mediated by Goldstone bosons rather than by gluons)

Outline

Low-Energy QCD / Effective D.o.F.

Low-energy QCD of three flavors u, d, s is characterized by:

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

$$SU(3)_L \times SU(3)_R \rightarrow SU(3)_V$$

$\rightarrow$ appearance of $(N_f^2 - 1) = 8$ **Goldstone bosons** $\vec{\phi}$
$\rightarrow$ generation of quasiparticles with dynamical mass, i.e. **constituent quarks** ψ

- thus (effective) interaction Lagrangian:

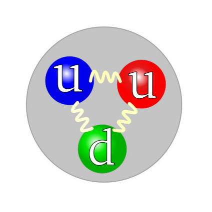
$$\mathcal{L}_{\text{int}} \sim ig\bar{\psi}\gamma_5\vec{\lambda}^F \cdot \vec{\phi}\psi$$

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.

Framework

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

Goldstone-Boson-Exchange RCQM

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

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

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

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

Extended version (EGBE RCQM):
K. Glantschnig, R. Kainhofer, W. Plessas, B. Sengl, and R.F. Wagenbrunn: Eur. Phys. J. A **23**, 507 (2005)

GBE RCQM Parametrization

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

$V_0 = -416$ MeV, $C = 2.33$ fm^{-2}

$\gamma = \pi, K, \eta, \eta'$:

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

$$\Lambda_\gamma = \Lambda_0 + \kappa\mu_\gamma$$

$\frac{g_8^2}{4\pi} = 0.67$, $m_u = m_d = 340$ MeV, $m_s = 500$ MeV,
μ_γ as measured (taken from PDG)

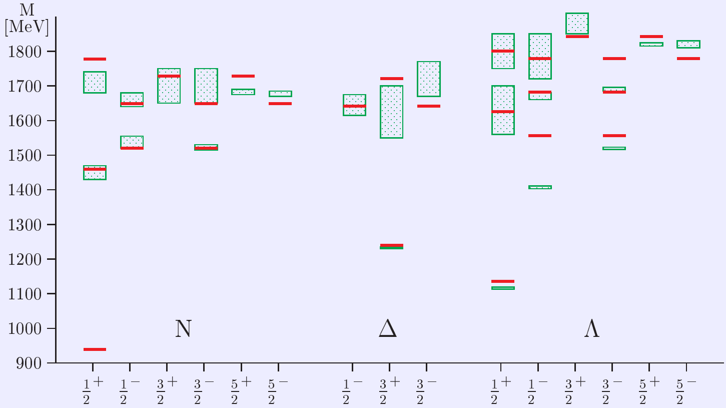
$\left(\frac{g_0}{g_8}\right)^2 = 1.34$, $\Lambda_0 = 2.87$ fm^{-1}, $\kappa = 0.81$

Excitation Spectra

of

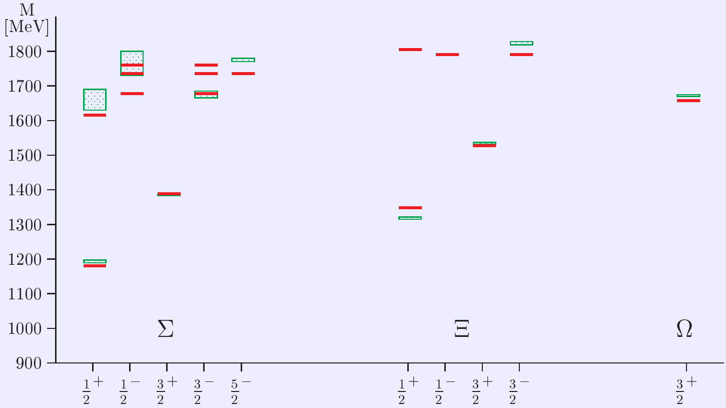
u, d, s Baryons

Excitation spectra of the GBE RCQM:



u, d, s Baryon Spectroscopy

Excitation spectra of the GBE RCQM:



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: arXiv:1205.6918
J.P. Day, K.-S. Choi, and W. Plessas: Few-Body Syst. **54**, 329 (2013)

Universal GBE RCQM Parametrization

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

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

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

$B = -402$ 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,

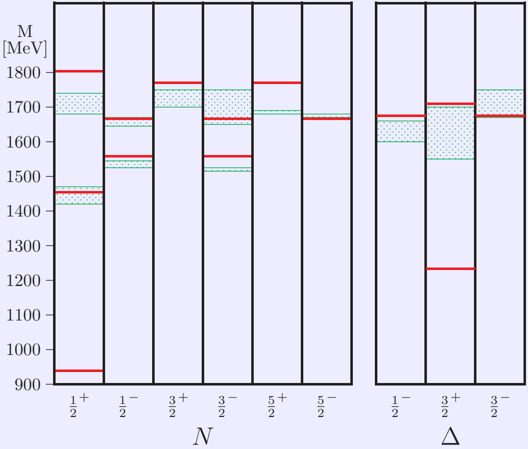
$m_c = 1675$ MeV, $m_b = 5055$ MeV

All Baryon **Excitation Spectra**

of

u, d, s, c, b Flavors

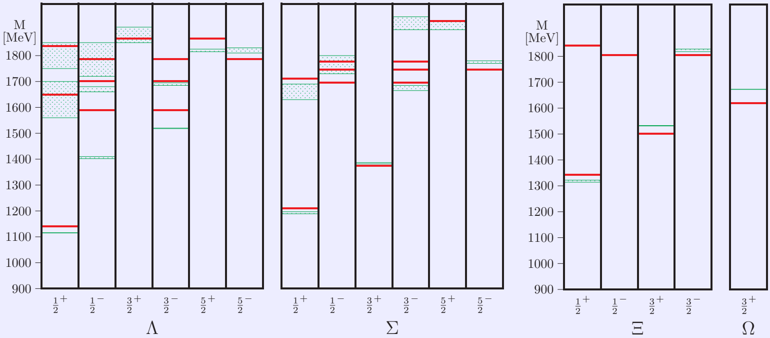
Light Baryon Spectra



red Universal GBE RCQM

green PDG 2013 (experiment)

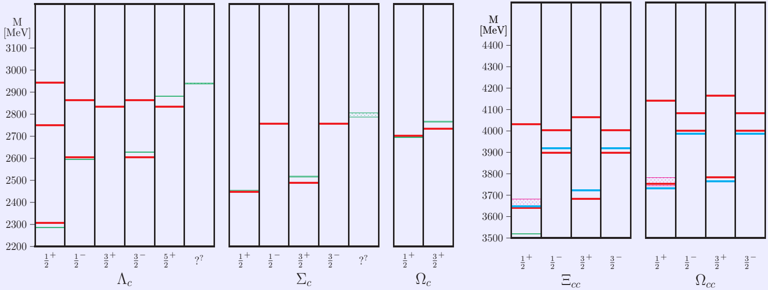
Strange Baryon Spectra



red Universal GBE RCQM

green PDG 2013 (experiment)

Charm Baryon Spectra



Left panel – single charm:

red Universal GBE RCQM prediction

green PDG 2013 (experiment)

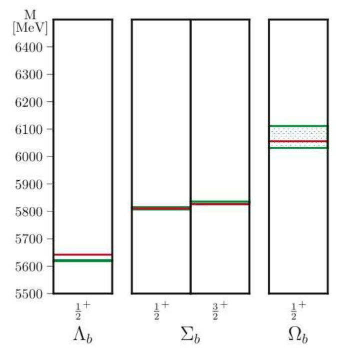
Right panel – double charm:

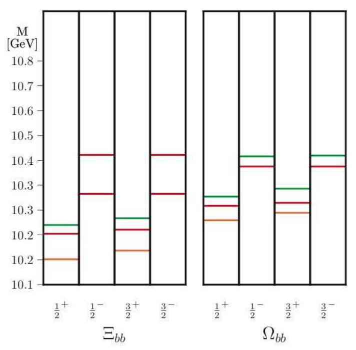
green M. Mattson et al.: Phys. Rev. Lett. 89 (2002) 112001 (SELEX experiment)

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

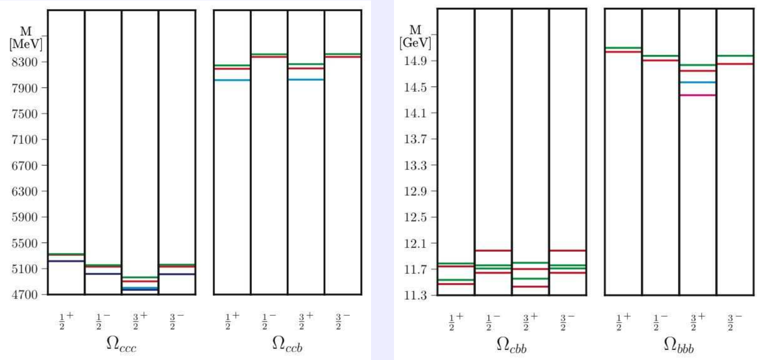
green PDG 2013 (experiment)

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)

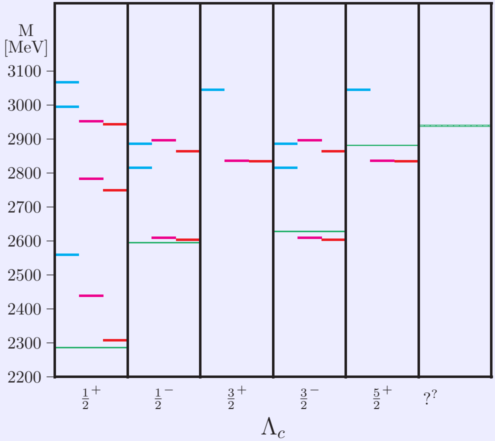
blue S. Migura, D. Merten, B. Metsch, and H.-R. Petry: Eur. Phys. J. A 28 (2006) 41 (Bonn RCQM)

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

Low-energy QCD
RCQM
Universal RCQM
Spectroscopy
Light, strange, charm, bottom
Quark Masses
Structure
Nucleon E.m.
Baryon E.m.
Axial FFs
Gravitational FF
Strong FFs
πNN, $\pi N\Delta$
Summary



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

Systematics of Constituent-Quark Masses

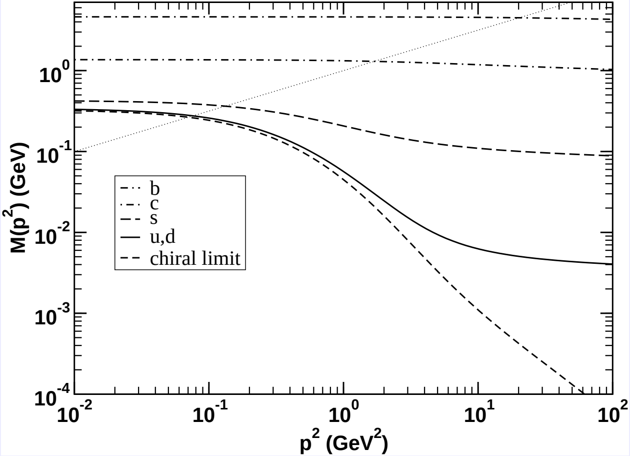
Dynamical mass gain $\Delta m = m_Q - m_q$ due to SBχS is similar for all flavors:

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

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

Rest-Frame Baryon States

Mass operator eigenstates

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

represented in configuration space

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

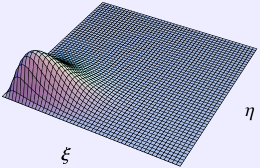
with $\vec{\xi}$ and $\vec{\eta}$ the usual Jacobi coordinates.

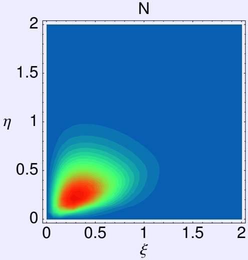
Picture the baryon wave functions through
spatial probability density distributions

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

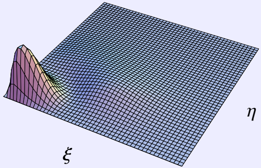
Pictures of Baryons (rest frame)

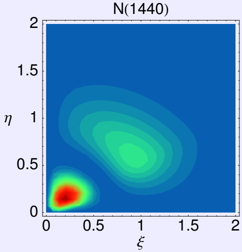
N GBE CQM





N(1440) GBE CQM

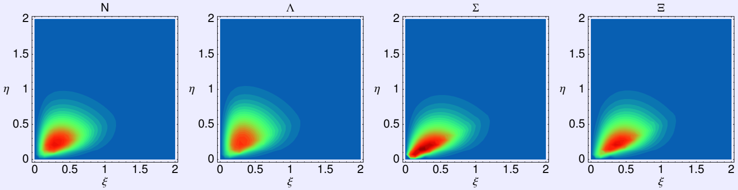




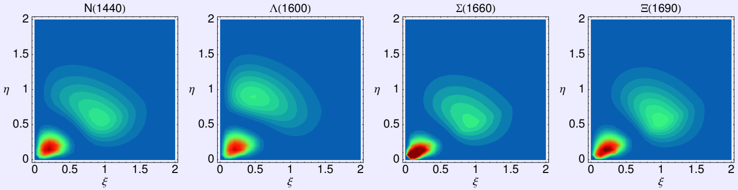
T. Melde, W. Plessas, and B. Sengl: Phys. Rev. D **77** (2008) 114002

Spatial Probability Density Distributions

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



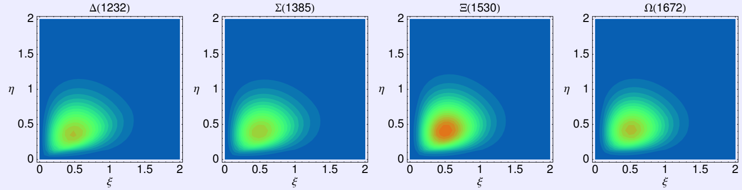
$\rho(\xi,\eta)$ for the $\frac{1}{2}^{+}$ **octet** baryon states $N(1440)$, $\Lambda(1600)$, $\Sigma(1660)$, $\Xi(1690)$:



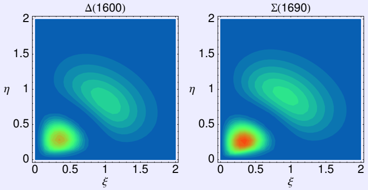
T. Melde, W. Plessas, and B. Sengl: Phys. Rev. D **77** (2008) 114002

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

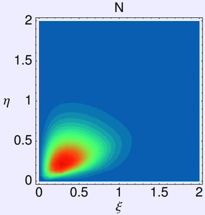
Root-Mean-Square Radii

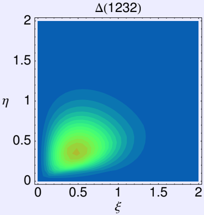
The **root-mean-square radius** (in the rest frame):

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

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

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





$r^N_{\rm rms} = 0.304$ fm

$r^\Delta_{\rm rms} = 0.390$ fm

Exp.: $r_E^p \sim 0.88$ fm

$(r_E^n)^2 \sim -0.12$ fm^2

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

$r_E^{\Delta^0} = 0$ fm

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)

Baryon Reactions

Applications of the RCQM

RCQM studies of various baryon reactions:

- Nucleon electromagnetic form factors (including flavor content of the nucleons)
- Nucleon axial form factors
- Δ and hyperon electroweak structures
- Nucleon gravitational form factors
- $NN\pi$ and $N\Delta\pi$ strong vertex form factors

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

Electroweak Structure

of

the Nucleons / Baryons

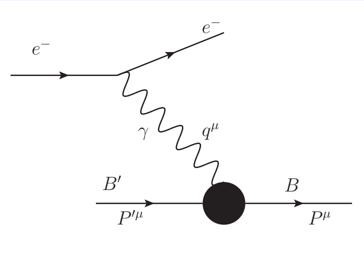
Electromagnetic Nucleon Observables

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:

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

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

Elastic Sachs Form Factors

Spin-$\frac{1}{2}$ baryons:

$$G_E^B(Q^2) = \frac{1}{2M} F^{\nu=0}_{\frac{1}{2}\frac{1}{2}}(Q^2)$$

$$G_M^B(Q^2) = \frac{1}{Q} F^{\nu=1}_{\frac{1}{2}-\frac{1}{2}}(Q^2)$$

Spin-$\frac{3}{2}$ baryons:

$$G_E^B(Q^2) = \frac{1}{4M}[F^{\nu=0}_{\frac{1}{2}\frac{1}{2}}(Q^2) + F^{\nu=0}_{\frac{3}{2}\frac{3}{2}}(Q^2)]$$

$$G_M^B(Q^2) = \frac{3}{5Q}[F^{\nu=1}_{\frac{1}{2}-\frac{1}{2}}(Q^2) + \sqrt{3}F^{\nu=1}_{\frac{3}{2}\frac{1}{2}}(Q^2)]$$

Electric/charge radius r_E:

$$r_E^2 = -6 \frac{d}{d\,Q^2} G_E(Q^2)\Big|_{Q^2=0}$$

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: $\hat{O} = \hat{J}^{\mu}_{\rm em}$

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

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

$$\times \sqrt{\frac{\left(\sum_i \omega'_i\right)^3}{\prod_i 2\omega'_i}} \prod_{\sigma'_i} D^{\star \frac{1}{2}}_{\sigma'_i \mu'_i} \left\{R_W\left[k'_i; B\left(V'\right)\right]\right\} \Psi^{\star}_{M'J'\Sigma'}\left(\vec{k}'_1, \vec{k}'_2, \vec{k}'_3; \mu'_1, \mu'_2, \mu'_3\right)$$

$$\times \langle p'_1, p'_2, p'_3; \sigma'_1, \sigma'_2, \sigma'_3 | \hat{J}^{\mu}_{rd} | p_1, p_2, p_3; \sigma_1, \sigma_2, \sigma_3\rangle$$

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

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

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

Point-Form Spectator-Model (PFSM) Currents

Electromagnetic current

$$\left\langle p_1', p_2', p_3'; \sigma_1', \sigma_2', \sigma_3' \right| \hat{J}^\mu_{\mathrm{rd}} \left| p_1, p_2, p_3; \sigma_1, \sigma_2, \sigma_3 \right\rangle =$$
$$= 3\mathcal{N} \left\langle p_1', \sigma_1' \right| \hat{J}^\mu_{\mathrm{spec}} \left| p_1, \sigma_1 \right\rangle 2p_{20}\delta\left(\vec{p}_2 - \vec{p}_2'\right) 2p_{30}\delta\left(\vec{p}_3 - \vec{p}_3'\right) \delta_{\sigma_2\sigma_2'}\delta_{\sigma_3\sigma_3'}$$

with

$$\left\langle p_1', \sigma_1' \right| \hat{J}^\mu_{\mathrm{spec}} \left| p_1, \sigma_1 \right\rangle =$$
$$= e_1 \bar{u}\left(p_1', \sigma_1'\right) \left[f_1(\tilde{Q}^2)\gamma^\mu + \frac{i}{2m_1} f_2(\tilde{Q}^2)\sigma^{\mu\nu}\tilde{q}_\nu \right] u\left(p_1, \sigma_1\right)$$

Axial current:

$$\left\langle p_1', p_2', p_3'; \sigma_1', \sigma_2', \sigma_3' \right| \hat{A}^\mu_{a,\mathrm{rd}} \left| p_1, p_2, p_3; \sigma_1, \sigma_2, \sigma_3 \right\rangle =$$
$$= 3\mathcal{N} \left\langle p_1', \sigma_1' \right| \hat{A}^\mu_{a,\mathrm{spec}} \left| p_1, \sigma_1 \right\rangle 2p_{20}\delta\left(\vec{p}_2 - \vec{p}_2'\right) 2p_{30}\delta\left(\vec{p}_3 - \vec{p}_3'\right) \delta_{\sigma_2\sigma_2'}\delta_{\sigma_3\sigma_3'}$$

with

$$\left\langle p_1', \sigma_1' \right| \hat{A}^\mu_{a,\mathrm{spec}} \left| p_1, \sigma_1 \right\rangle =$$
$$= \bar{u}\left(p_1', \sigma_1'\right) \left[g_A^q\gamma^\mu + \frac{2f_\pi}{\widetilde{Q}^2 + m_\pi^2} g_{qq\pi}\widetilde{q}^\mu \right] \gamma_5 \frac{1}{2}\tau_a u\left(p_1, \sigma_1\right)$$

Peculiarities of the PFSM

Point-like constituent quarks:

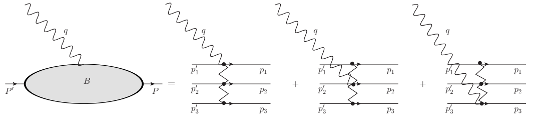
$$f_1(\tilde{Q}^2) = 1\,, \qquad f_2(\tilde{Q}^2) = 0\,; \qquad \tilde{Q}^2 = -\tilde{q}^\mu \tilde{q}_\mu$$

$$\Rightarrow \quad \langle p_i', \sigma_i' | \hat{J}^\mu_{\rm spec} | p_i, \sigma_i \rangle = e_i \bar{u}\left(p_i', \sigma_i'\right) \gamma^\mu u\left(p_i, \sigma_i\right)$$

with

$$p_i'^\mu - p_i^\mu = \tilde{q}^\mu \neq Q^\mu = P'^\mu - P^\mu\,; \qquad \tilde{q}^\mu = \xi Q^\mu$$

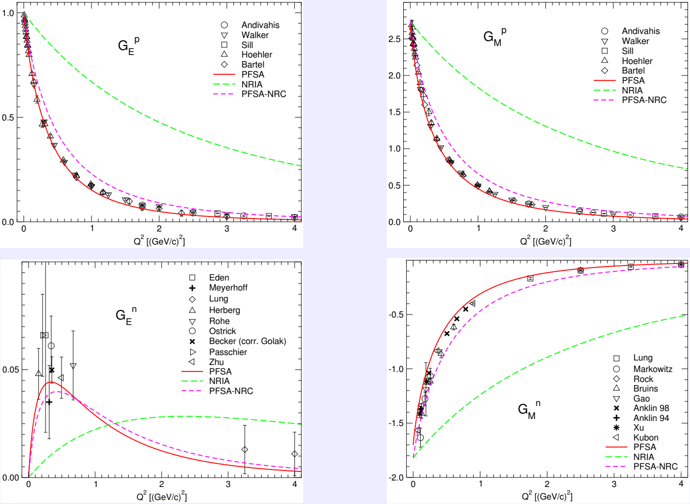
$$\mathcal{N} = \left(\frac{M}{\sum_i \omega_i}\right)^{\frac{3}{2}} \left(\frac{M'}{\sum_i \omega_i'}\right)^{\frac{3}{2}}$$



The **PFSM** current operator ME is **manifestly covariant** (has the **same form** in **any reference frame**)!
It is an **effective many-body operator** through the appearance of $\tilde{q}$ and $\mathcal{N}$, which are both completely determined, however.

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

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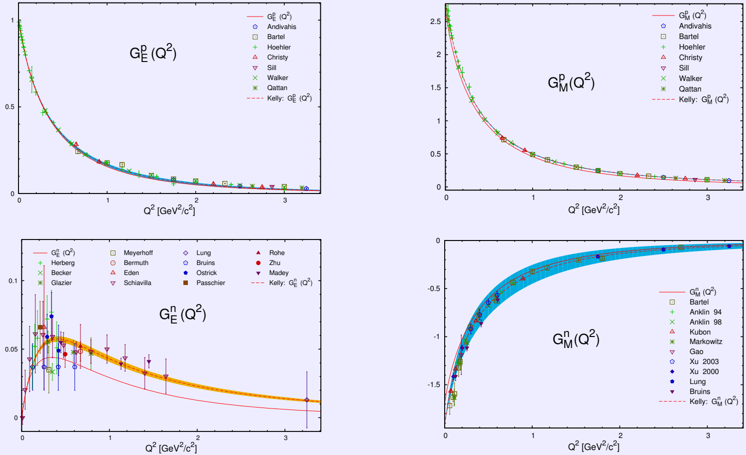
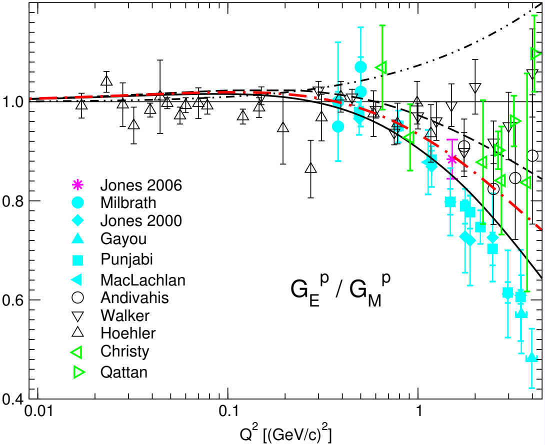


R.F. Wagenbrunn, S. Boffi, W. Klink, W. Plessas, and M. Radici: Phys. Lett. **B511** (2001) 33

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
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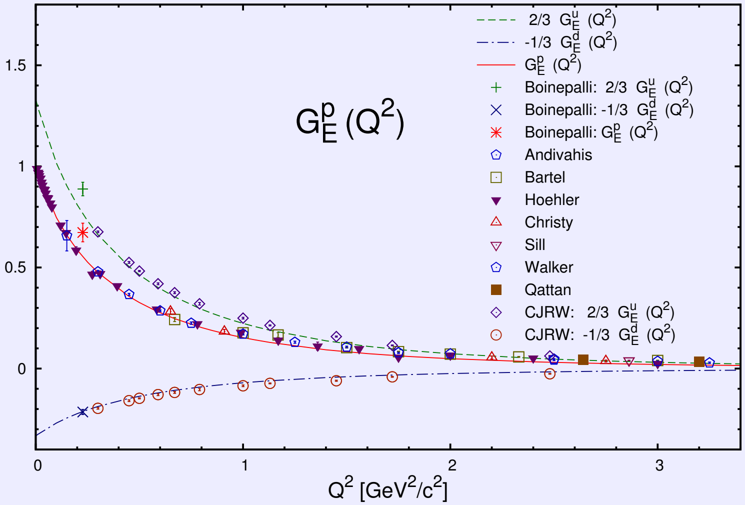
Nucleons N

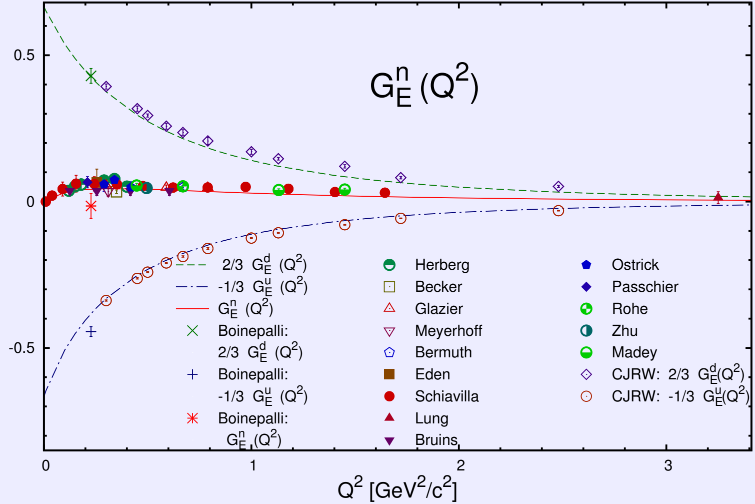
$$G_E^p = \frac{2}{3} G_E^u - \frac{1}{3} G_E^d$$



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

Neutron Electric Form Factor

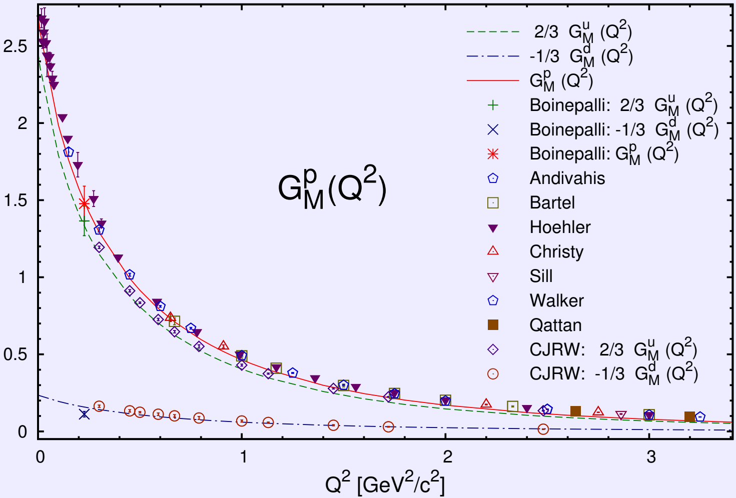
$$G_E^n = \frac{2}{3} G_E^d - \frac{1}{3} G_E^u$$



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

Proton Magnetic Form Factor

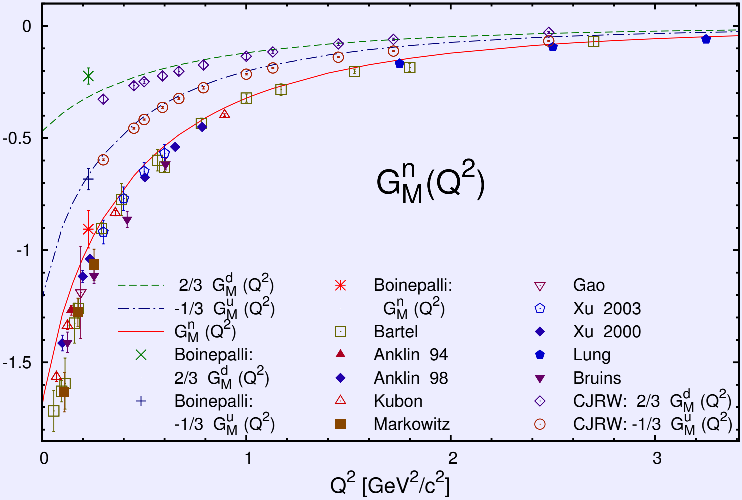
$$G_M^p = \frac{2}{3} G_M^u - \frac{1}{3} G_M^d$$



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

Neutron Magnetic Form Factor

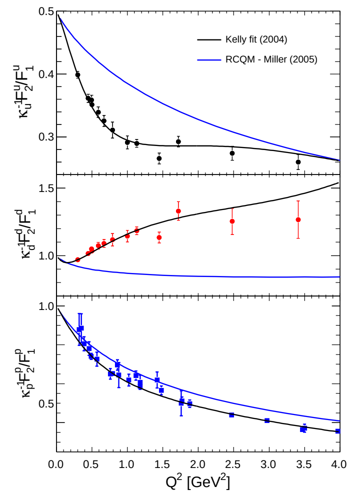
$$G_M^n = \frac{2}{3} G_M^d - \frac{1}{3} G_M^u$$



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

F_2/F_1 Ratios

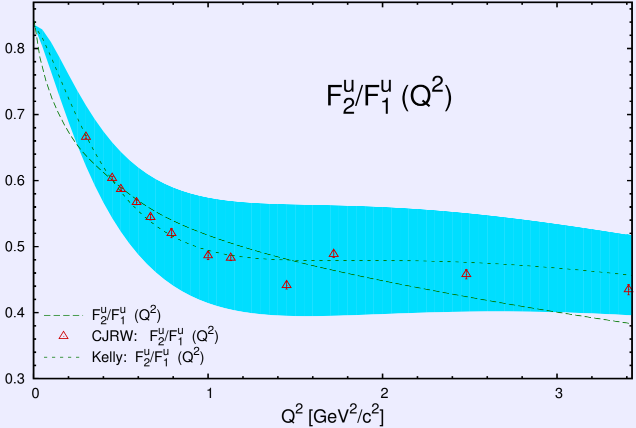
Low-energy QCD
RCQM
Universal RCQM
Spectroscopy
Light, strange, charm, bottom
Quark Masses
Structure
Nucleon E.m.
Baryon E.m.
Axial FFs
Gravitational FF
Strong FFs
πNN, $\pi N\Delta$
Summary



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

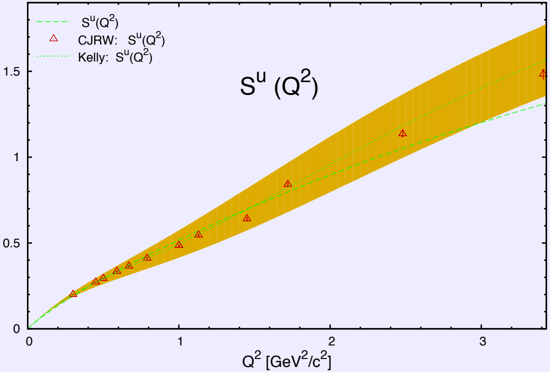


- - - - - - dashed green line: GBE RCQM ······· dotted line and blue area: Kelly fit with $\frac{1}{2}*$error

No indication for 5-Q components in the nucleons!

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

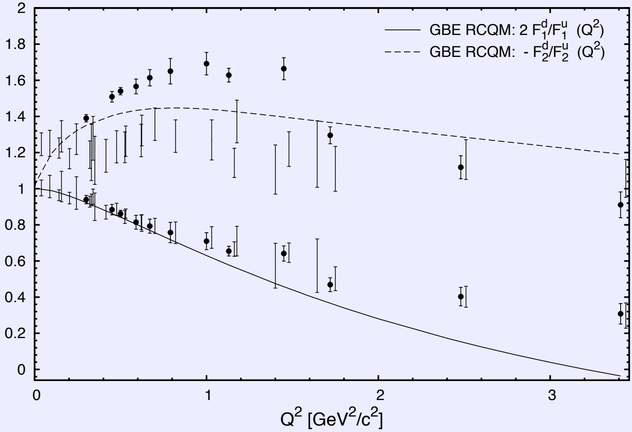
$$S^u(Q^2) = Q^2 \frac{F_2^u(Q^2)}{F_1^u(Q^2)}$$



- - - - - - 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

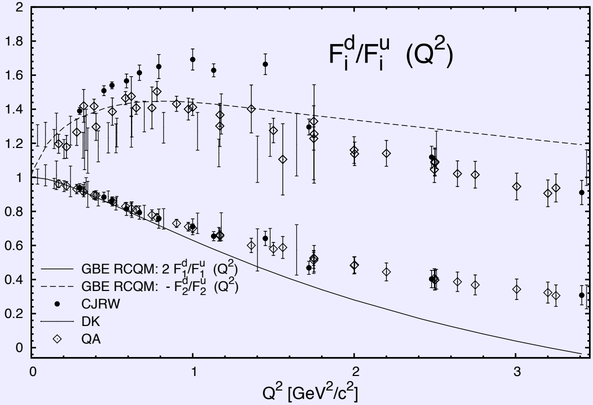


Fall-off is **no indication for diquark clustering** in the nucleons!

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)
- Ι M. Diehl and P. Kroll: Europ. Phys. J. A **73**, 2397 (2013)

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



Problems between three different phenomenological analyses!

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: Europ. Phys. J. A **73**, 2397 (2013)
- ◇ I.A. Qattan and J. Arrington: Phys. Rev. C **86**, 065210 (2012)

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)

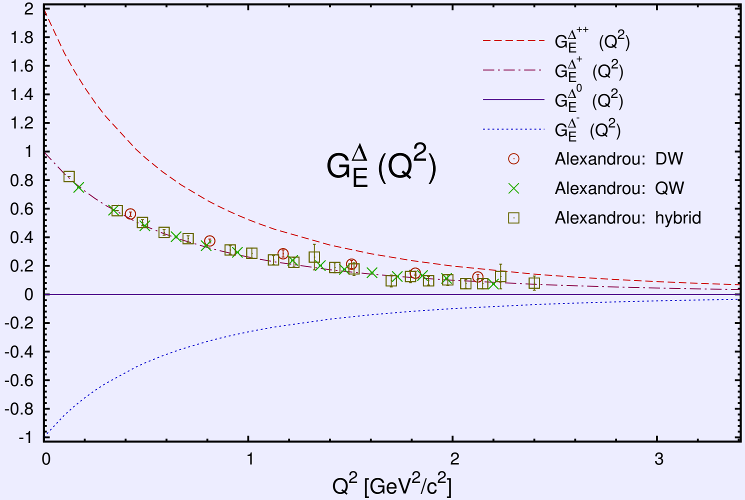
Δ and Hyperon E.m. Form Factors

$$\Delta$$

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

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

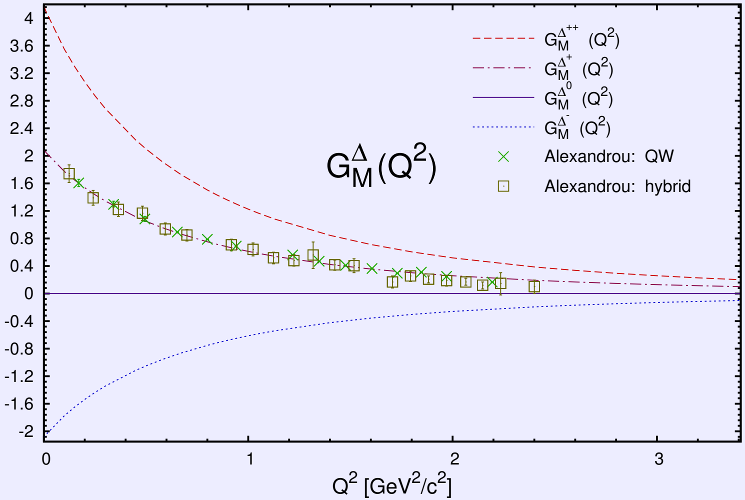
Electric Δ Form Factors



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

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

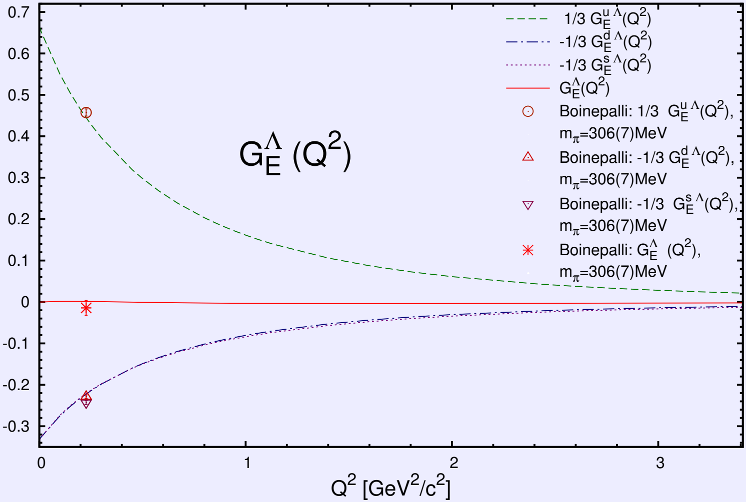
Magnetic Δ Form Factors



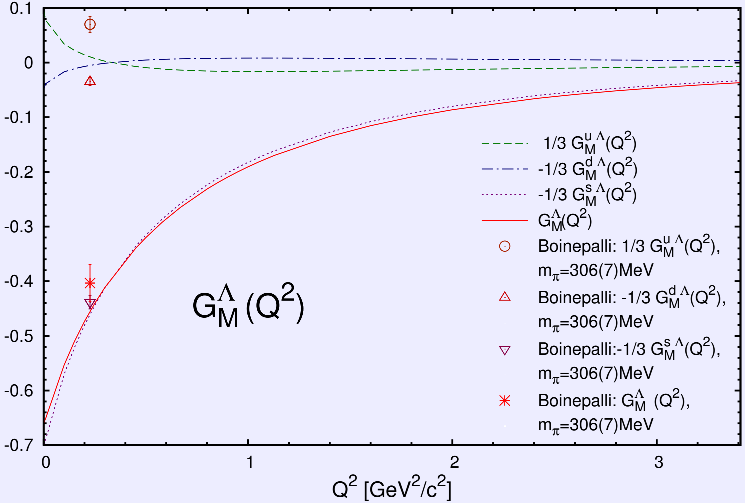
GBE RCQM: Ki-Seok Choi: PhD Thesis, Univ. Graz, 2011

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

Octet $\Lambda(uds)$ Electric Form Factor

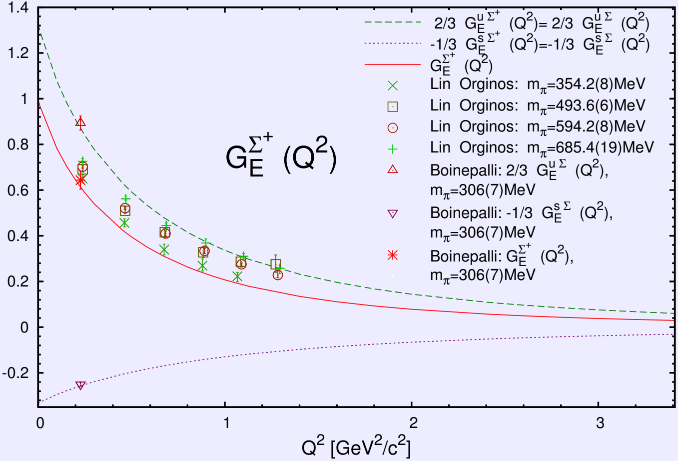


Octet $\Lambda(uds)$ Magnetic Form Factor



Octet $\Sigma^+(uus)$ Electric Form Factor

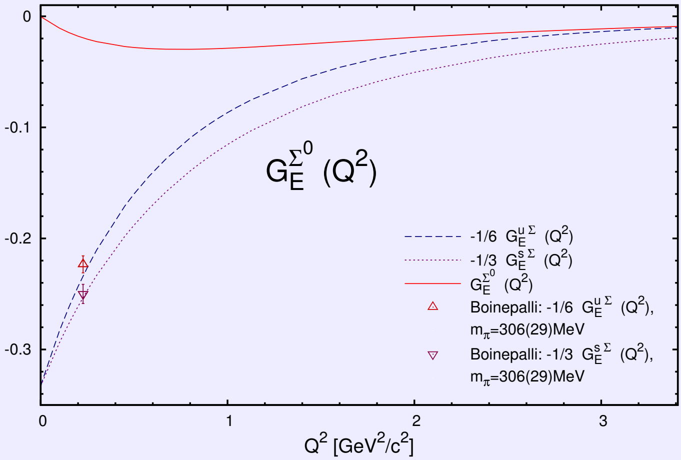
$$G_E^{\Sigma^+} = \frac{2}{3} G_E^{u,\Sigma} - \frac{1}{3} G_E^{s,\Sigma}$$



Lattice-QCD: H.-W. Lin and K. Orginos: Phys. Rev. D **79** (2009) 074507
S. Boinepalli et al. Phys. Rev. D **74** (2006) 093005

Octet $\Sigma^0(uds)$ Electric Form Factor

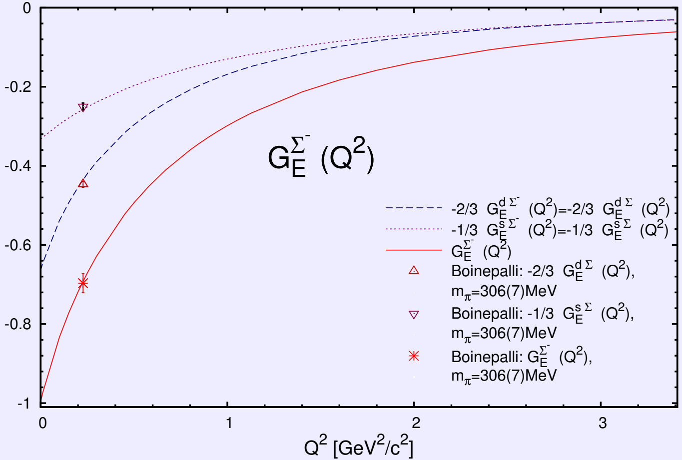
$$G_E^{\Sigma^0} = \frac{1}{6} G_E^{u,\Sigma} - \frac{1}{3} G_E^{s,\Sigma}$$



Lattice-QCD: S. Boinepalli et al. Phys. Rev. D**74** (2006) 093005

Octet $\Sigma^-(dds)$ Electric Form Factor

$$G_E^{\Sigma^-} = -\frac{1}{3} G_E^{u,\Sigma} - \frac{1}{3} G_E^{s,\Sigma}$$

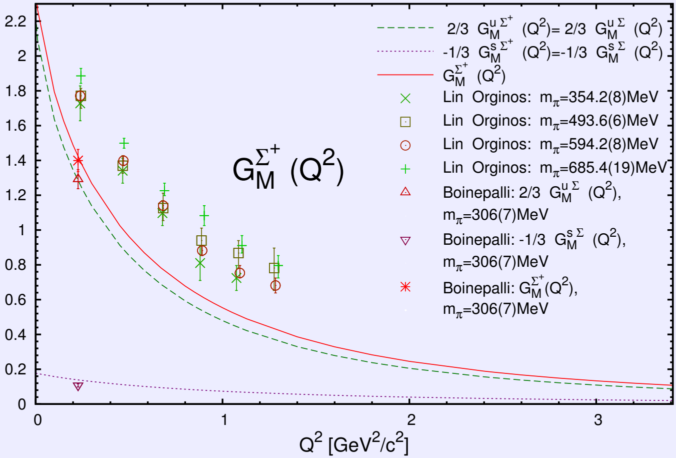


Lattice-QCD: S. Boinepalli et al. Phys. Rev. D**74** (2006) 093005

Octet $\Sigma^+(uus)$ Magnetic Form Factor

Low-energy QCD
RCQM
Universal RCQM
Spectroscopy
Light, strange, charm, bottom
Quark Masses
Structure
Nucleon E.m.
Baryon E.m.
Axial FFs
Gravitational FF
Strong FFs
πNN, $\pi N\Delta$
Summary

$$G_M^{\Sigma^+} = \frac{2}{3} G_M^{u,\Sigma} - \frac{1}{3} G_M^{s,\Sigma}$$



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S. Boinepalli et al. Phys. Rev. D **74** (2006) 093005

Octet $\Sigma^0(uds)$ Magnetic Form Factor

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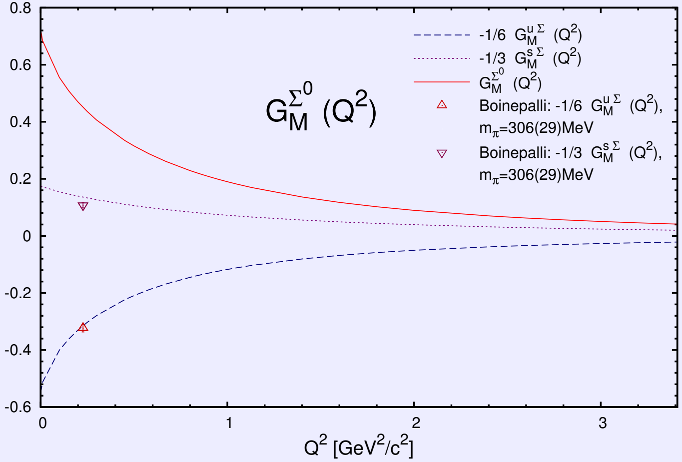

Lattice-QCD: S. Boinepalli et al. Phys. Rev. D**74** (2006) 093005

Octet $\Sigma^-(dds)$ Magnetic Form Factor

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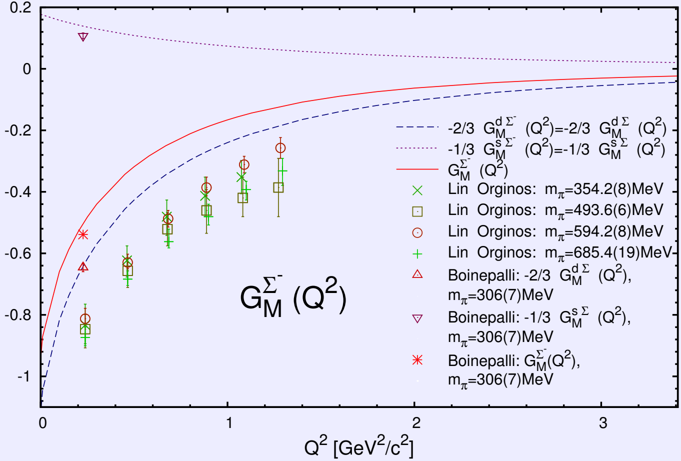

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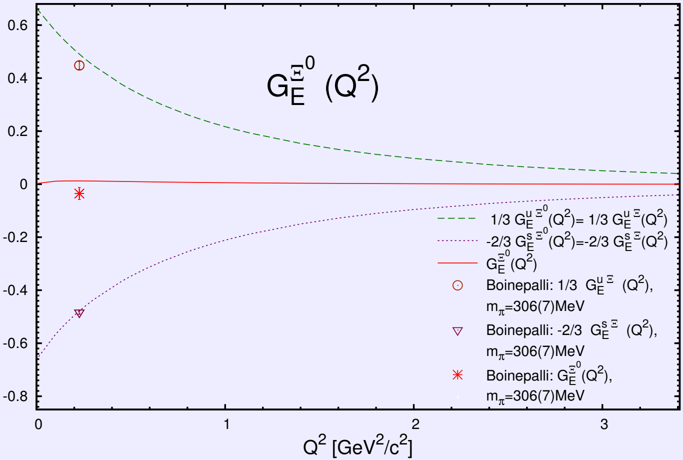
S. Boinepalli et al. Phys. Rev. D **74** (2006) 093005

Octet $\Xi^0(uss)$ Electric Form Factor

Low-energy QCD
RCQM
Universal RCQM
Spectroscopy
Light, strange, charm, bottom
Quark Masses
Structure
Nucleon E.m.
Baryon E.m.
Axial FFs
Gravitational FF
Strong FFs
πNN, $\pi N\Delta$
Summary

$$G_E^{\Xi^0} = \frac{1}{3} G_E^{u,\Xi} - \frac{1}{3} G_E^{s,\Xi}$$



Lattice-QCD: S. Boinepalli et al. Phys. Rev. D**74** (2006) 093005

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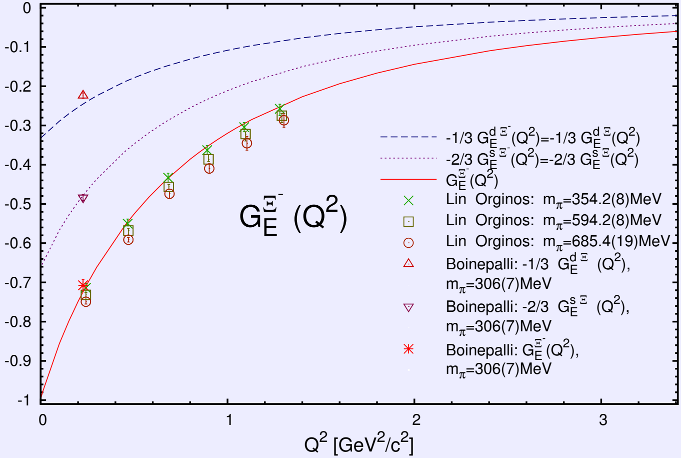

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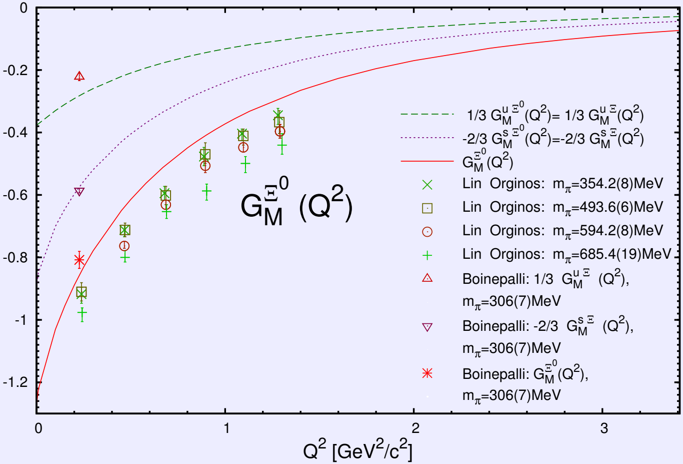
Octet $\Xi^0(uss)$ Magnetic Form Factor

$$G_M^{\Xi^0} = \frac{1}{3} G_M^{u,\Xi} - \frac{1}{3} G_M^{s,\Xi}$$



Lattice-QCD: H.-W. Lin and K. Orginos: Phys. Rev. D **79** (2009) 074507
S. Boinepalli et al. Phys. Rev. D **74** (2006) 093005

Octet $\Xi^-(dss)$ Magnetic Form Factor

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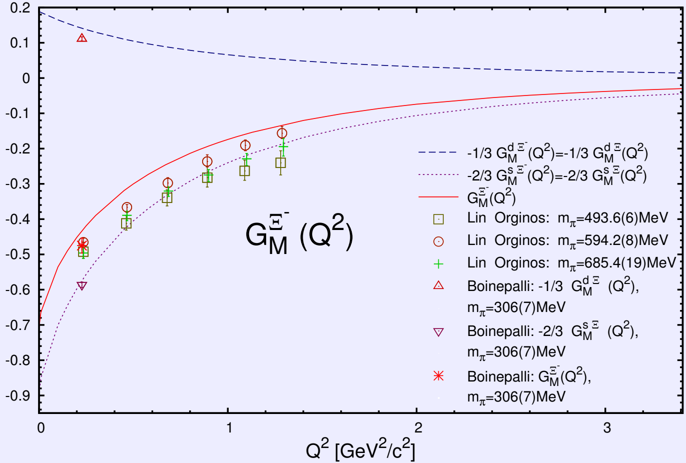
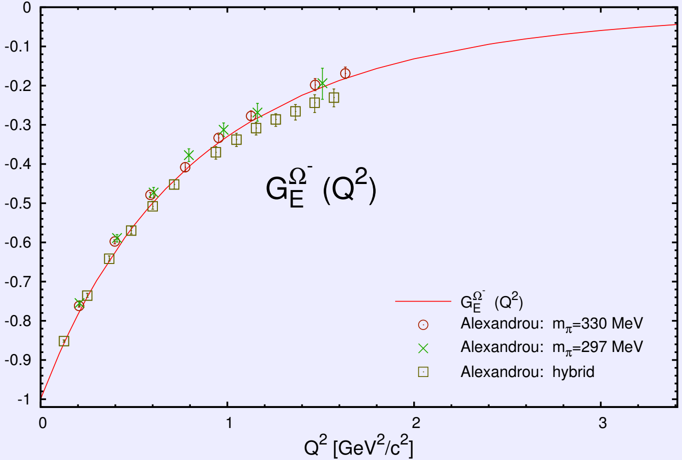


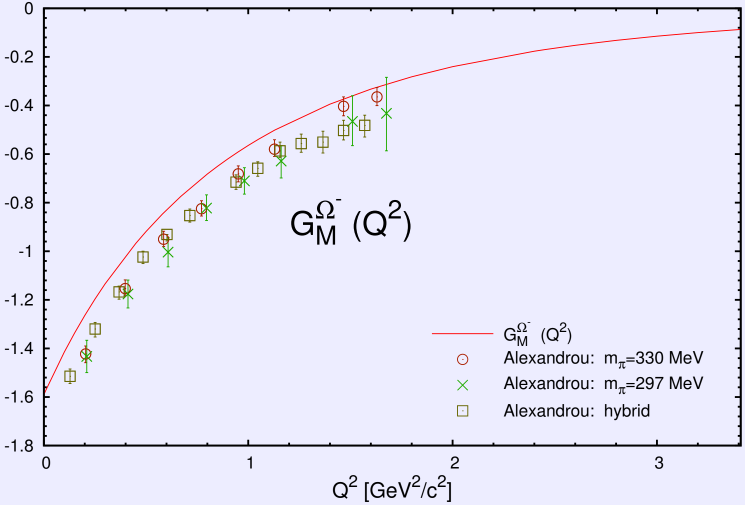
Lattice-QCD: H.-W. Lin and K. Orginos: Phys. Rev. D **79** (2009) 074507
S. Boinepalli et al. Phys. Rev. D **74** (2006) 093005

Decuplet $\Omega^-(sss)$ Electric Form Factor



Lattice-QCD: C. Alexandrou et al.: Phys. Rev. D**82** (2010) 034504

Decuplet $\Omega^-(sss)$ Magnetic Form Factor

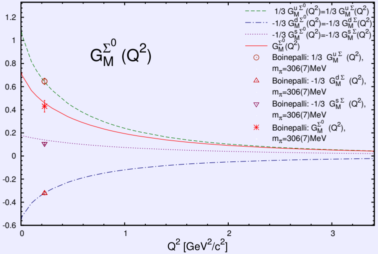


Lattice-QCD: C. Alexandrou et al.: Phys. Rev. D**82** (2010) 034504

Octet $\Sigma^0(dds)$ vs. Decuplet $\Sigma^{*0}(dds)$

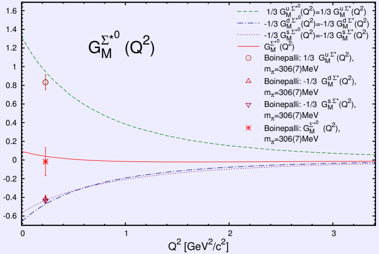
Octet

$$G_M^{\Sigma^0} = \frac{1}{3} G_M^{u,\Sigma} - \frac{1}{3} G_M^{d,\Sigma} - \frac{1}{3} G_M^{s,\Sigma}$$



Decuplet

$$G_M^{\Sigma^{*0}} = \frac{1}{3} G_M^{u,\Sigma^*} - \frac{1}{3} G_M^{d,\Sigma^*} - \frac{1}{3} G_M^{s,\Sigma^*}$$



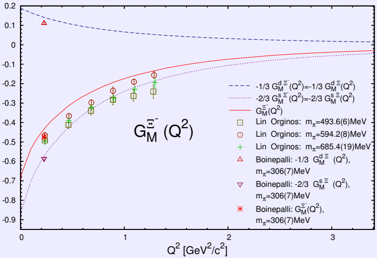
Lattice-QCD: S. Boinepalli et al.: Phys. Rev. D **74**, 093005 (2006)

S. Boinepalli et al.: Phys. Rev. D **80**, 054505 (2009)

Octet $\Xi^-(dss)$ vs. Decuplet Octet $\Xi^{*-}(dss)$

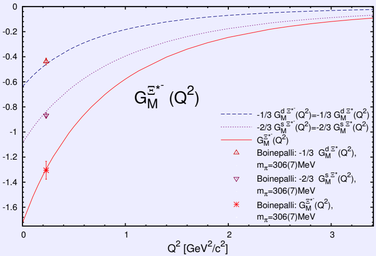
Octet

$$G_M^{\Xi^-} = -\frac{1}{3} G_M^{d,\Xi} - \frac{2}{3} G_M^{s,\Xi}$$



Decuplet

$$G_M^{\Xi^{*-}} = -\frac{1}{3} G_M^{d,\Xi^*} - \frac{2}{3} G_M^{s,\Xi^*}$$



Lattice-QCD: S. Boinepalli et al.: Phys. Rev. D **74**, 093005 (2006)

S. Boinepalli et al.: Phys. Rev. D **80**, 054505 (2009)

Baryon Electric Radii and Magnetic Moments

Electric radii r_E^2 [fm^2]

Baryon	GBE PFSM	Experiment
p	0.82	0.7692 ± 0.0123
n	-0.13	-0.1161 ± 0.0022
Σ^-	0.72	$0.61 \pm 0.12 \pm 0.09$

Magnetic moments μ [n.m.]

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

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

of

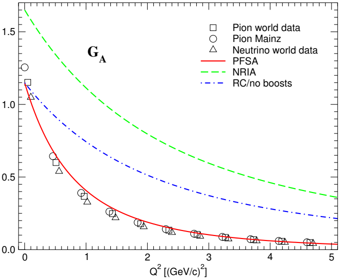
N Ground State and N^* Resonances

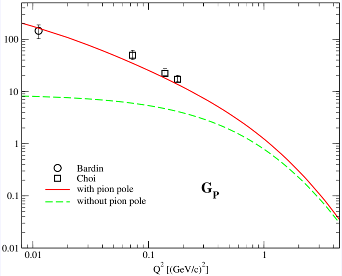
as well as

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

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

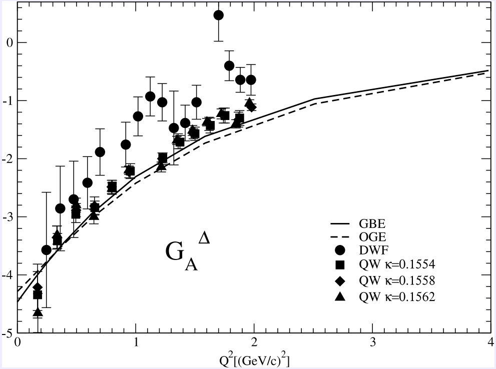
K.-S. Choi, W. Plessas, and R.F. Wagenbrunn: Phys. Rev. C **81**, 028201 (2010)

Axial Charges of N and N^* Resonances

		EGBE		psGBE		OGE	
State	J^P	Mass	g_A	Mass	g_A	Mass	g_A
N(939)	$\frac{1}{2}^+$	939	1.15	939	1.15	939	1.11
N(1520)	$\frac{3}{2}^-$	1524	-0.64	1519	-0.21	1520	-0.15
N(1440)	$\frac{1}{2}^+$	1464	1.16	1459	1.13	1578	1.10
N(1535)	$\frac{1}{2}^-$	1498	0.02	1519	0.09	1520	0.13
N(1680)	$\frac{5}{2}^+$	1689	0.89	1728	0.83	1858	0.70
N(1675)	$\frac{5}{2}^-$	1676	0.84	1647	0.83	1690	0.80
N(1710)	$\frac{1}{2}^+$	1757	0.35	1776	0.37	1860	0.32
N(1650)	$\frac{1}{2}^-$	1581	0.51	1647	0.46	1690	0.44
N(1720)	$\frac{3}{2}^+$	1746	0.35	1728	0.34	1858	0.25
N(1700)	$\frac{3}{2}^-$	1608	-0.10	1647	-0.50	1690	-0.47

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

Covariant predictions of the GBE and OGE RCQMs:



Ki-Seok Choi: PhD Thesis, Graz, 2011

(Lattice QCD data from C. Alexandrou et al., PoS LATTICE2010, 141 (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

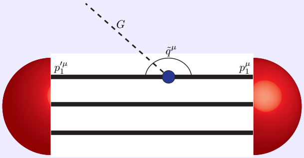
K.-S. Choi, W. Plessas, and R.F. Wagenbrunn: Phys. Rev. D **82**, 014007 (2010)

Gravitational Form Factors

of

the Nucleon

Gravitational Form Factors

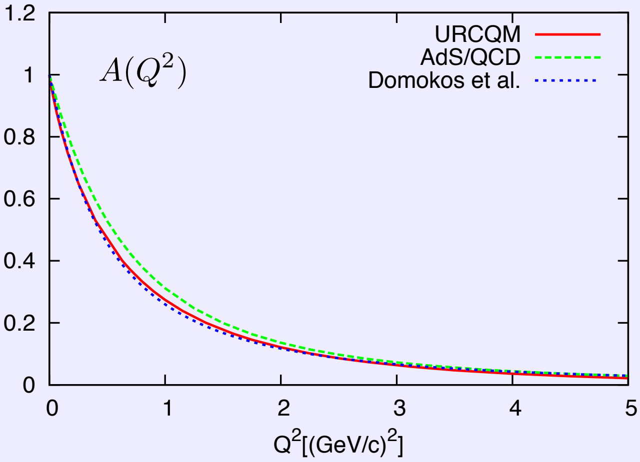


Invariant ME of **energy-momentum tensor** $\hat{\Theta}^{\mu\nu}$:

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

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

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



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

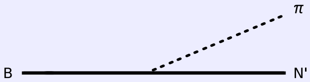
Microscopic Description

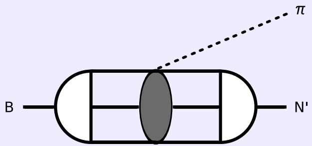
of

Meson-Baryon Interaction Vertices

Meson-Baryon Interaction Vertices

Interaction vertices





$$F_{i\to f} = (2\pi)^4 \langle f|\,\mathcal{L}_I(0)\,|i\rangle \qquad \equiv \qquad \langle V', M', J', \Sigma'|\,\hat{D}^{\pi}_{\rm rd}\,|V, M, J, \Sigma\rangle$$

where

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

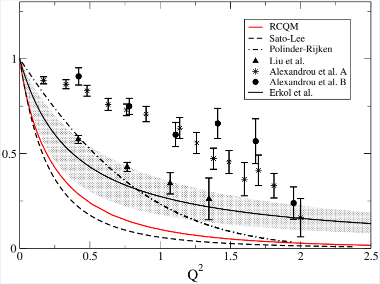
$$3\mathcal{N}_{\rm S} \frac{i g_{qqm}}{2m_1 (2\pi)^{\frac{3}{2}}} \bar{u}(p_1', \sigma_1')\gamma_5\gamma_\mu\lambda_m u(p_1, \sigma_1)\tilde{q}^\mu 2p_{20}\delta(\vec{p}_2 - \vec{p}_2')2p_{30}\delta(\vec{p}_3 - \vec{p}_3')\delta_{\sigma_2\sigma_2'}\delta_{\sigma_3\sigma_3'}$$

and

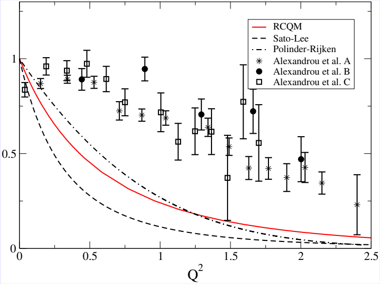
$$G_{\pi NN}\left(Q^2\right) = \frac{1}{f_{\pi NN}} \frac{m_\pi\sqrt{2\pi}}{\sqrt{2M_N}} \frac{\sqrt{E_N' + M_N'}}{E_N' + M_N' + \omega} \frac{F_{i\to f}}{Q_z}$$

$$G_{\pi N\Delta}\left(Q^2\right) = -\frac{1}{f_{\pi N\Delta}} \frac{3\sqrt{2\pi}}{2} \frac{m_\pi}{\sqrt{E_N' + M_N'}\sqrt{2M_\Delta}} \frac{F_{i\to f}}{Q_z}$$

πNN and $\pi N\Delta$ Interaction Vertices



$G_{\pi NN}$



$G_{\pi N\Delta}$

T. Melde, L. Canton, and W. Plessas: Phys. Rev. Lett. **102**, 132002 (2009)

Form-Factor Parametrizations

$$G\left(\vec{q}^{\,2}\right) = \frac{1}{1+\left(\frac{\vec{q}}{\Lambda_1}\right)^2+\left(\frac{\vec{q}}{\Lambda_2}\right)^4} \qquad G\left(Q^2\right) = \frac{1}{1+\left(\frac{Q}{\Lambda}\right)^2}$$

		RCQM	SL	PR		LIU	ERK	ALX
N	$\frac{f_N^2}{4\pi}$	0.0691	0.08	0.075		0.0649	0.0481	0.0412
	Λ_1	0.451	0.453	0.940	Λ	0.747	0.614	1.65
	Λ_2	0.931	0.641	1.102		-	-	-
Δ	$\frac{f_\Delta^2}{4\pi}$	0.188	0.334	0.478				
	Λ_1	0.594	0.458	0.853				
	Λ_2	0.998	0.648	1.014				

T. Melde, L. Canton, and W. Plessas: Phys. Rev. Lett. **102**, 132002 (2009)

Summary and Conclusions

- Finally: **Full success** of the CQM – but relativistic!
- 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

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Forthcoming Oberwölz Symposium 2014

Thank you very much

for

your attention!