Point-Form Calculations

vs.

Other Relativistic Approaches

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Issue

Different relativistic approaches

to several hadron observables yield

similar results but not quite **the same**.

Seems to be true for:

- Hamiltonian vs. Hamiltonian approaches
- Bethe-Salpeter vs. Bethe-Salpeter approaches
- Lattice-QCD vs. lattice-QCD approaches

Outline

Formalism

Relativistic quantum mechanics

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

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

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

P^μ ... 4-momentum, J ... baryon spin, Σ ... spin projection

Invariant Mass Operator

Interacting mass operator

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

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

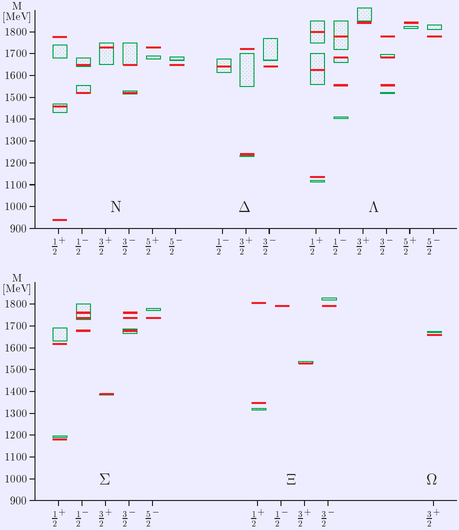
Baryon **Excitation Spectra**

and

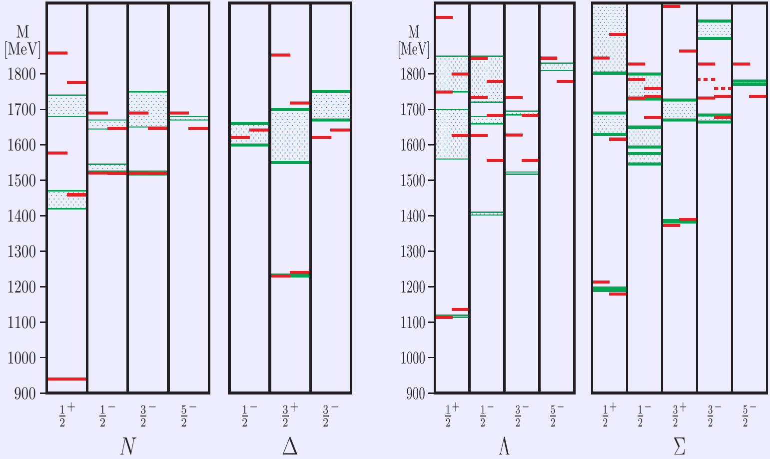
Mass-Operator **Eigenstates**

u, d, s Baryon Spectroscopy

Excitation spectra of the GBE RCQM:



N and Λ Excitation Spectra

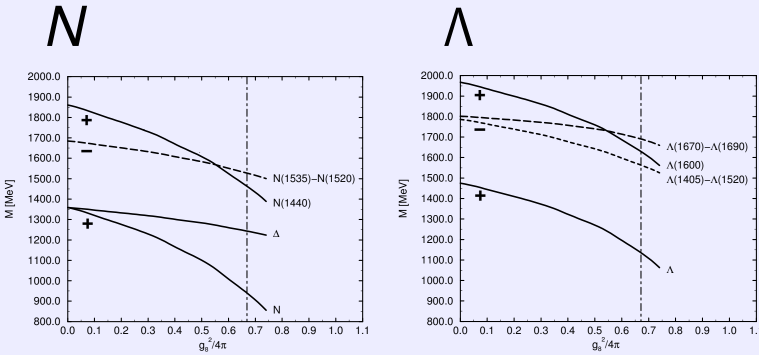


left **levels**: **One-gluon-exchange** RCQM
right **levels**: **Goldstone-boson-exchange** RCQM

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

GBE Hyperfine Interaction

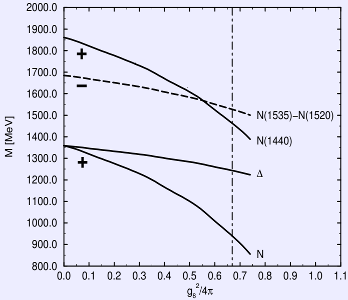
Level shifts due to hyperfine interaction:



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

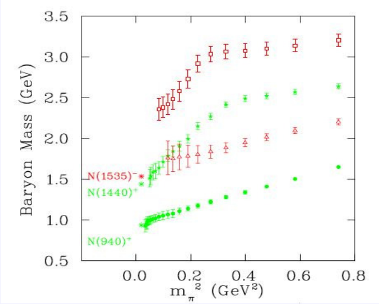
Chiral Interaction

GBE CQM



Lattice calculation

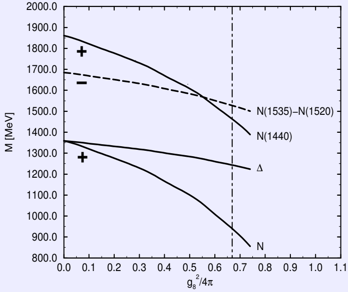
(Kentucky Group)



K.F. Liu et al.: *'Valence QCD: Connecting QCD to the quark model'* Phys. Rev. D **59**, 112001 (1999)

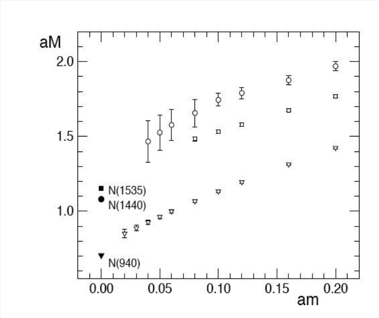
Chiral Interaction

GBE CQM



Lattice calculation

(Graz Group)



T. Burch et al.: Phys. Rev. D **74**, 014504 (2006)

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

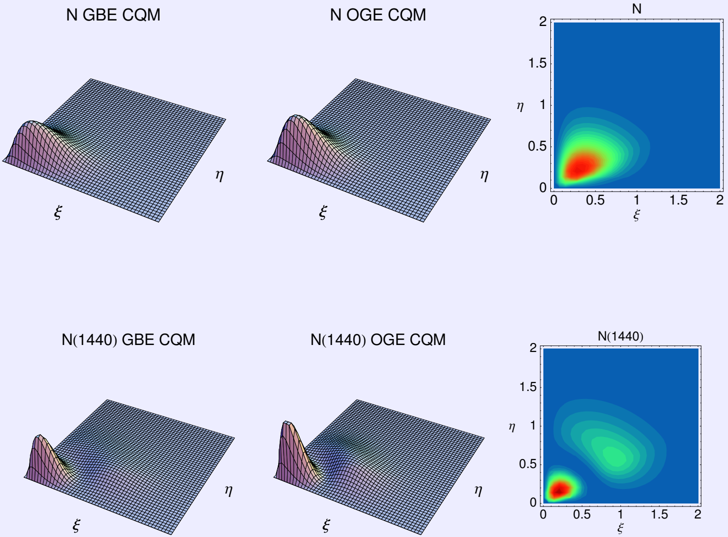
$$\left\langle \vec{\xi}, \vec{\eta} \middle| P, J, \Sigma, T, M_T \right\rangle = \Psi_{PJ\Sigma TM_T}(\vec{\xi}, \vec{\eta})$$

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

Picture the baryon wave functions through
spatial probability density distributions

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

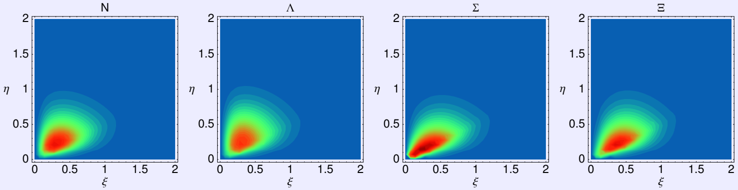
Pictures of Baryons (rest frame)



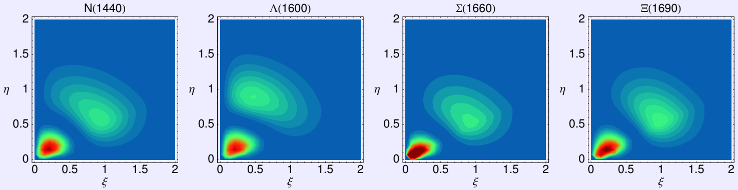
T. Melde, W. Plessas, and B. Sengl: Phys. Rev. D **77**, 114002 (2008)

Spatial Probability Density Distributions

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



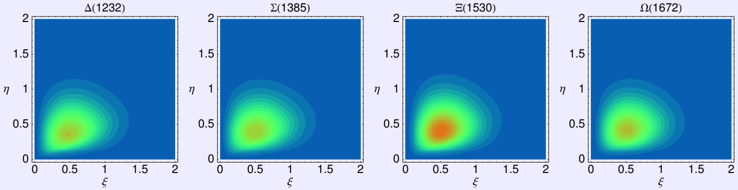
$\rho(\xi, \eta)$ for the $\frac{1}{2}^{+}$ **octet** baryon states $N(1440)$, $\Lambda(1600)$, $\Sigma(1660)$, $\Xi(1690)$:



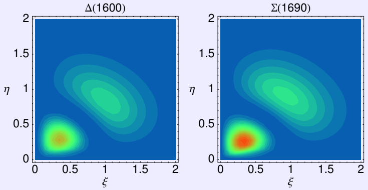
T. Melde, W. Plessas, and B. Sengl: Phys. Rev. D **77**, 114002 (2008)

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 $\Delta(1600)$, $\Sigma(1690)$:



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

Relativistic

Matrix Elements

Matrix Elements of a Transition Operator $\hat{O}$

$\hat{O}$ ... $\hat{J}^{\mu}_{\rm em}$ $\rightarrow$ electromagnetic FF's

... $\hat{A}^{\mu}_{\rm axial}$ $\rightarrow$ axial FF's

... $\hat{S}$ $\rightarrow$ scalar FF

... $\hat{\Theta}^{\mu\nu}$ $\rightarrow$ gravitational FF's

ME's between baryon eigenstates $|P, J, \Sigma, T, T_3, Y\rangle$

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

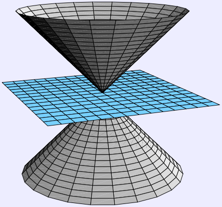
to be calculated from microscopic three-quark ME's

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

Forms of Relativistic Dynamics

Invariant hypersurfaces in Minkowski space:

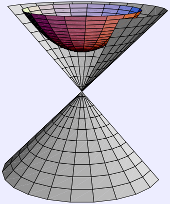
instant



$$x^0 = 0$$

J_i, P_i
$P^0 = H, K_i$

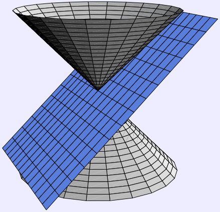
point



$$x^2 - a^2 = 0$$

J_i, K_i
P^μ

front

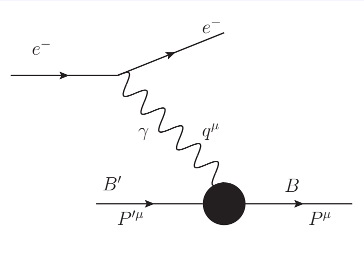


$$x^0 + x^3 = 0$$

$P^+, \vec{P}^\perp, E^1, E^2, J_z, K_z$
P^-, F^1, F^2

are interaction-free and **interaction-dependent** generators

Elastic electron scattering:



Invariant form factors:

$$F^{\mu}_{\Sigma'\Sigma}(Q^2) = \langle P', J, \Sigma', T, T_3 | \hat{J}^{\mu}_{\rm em} | P, J, \Sigma, T, T_3 \rangle$$

with $Q^2 = -q^2$; $\qquad q^\nu = P^\nu - P'^\nu$

Transition Matrix Elements in Point Form

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

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

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 $\omega_i = \sqrt{\vec{k}_i^2 + m_i^2}$

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 PF Spectator Model

Point-like constituent quarks:

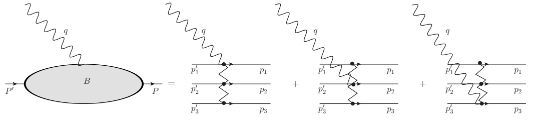
$$f_1(\tilde{Q}^2) = 1\,, \qquad f_2(\tilde{Q}^2) = 0\,; \qquad \tilde{Q}^2 = -\tilde{q}^\mu \tilde{q}_\mu$$

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

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.

Transition Matrix Elements in Instant Form

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

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

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

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

$$2\sqrt{EE'} \sum_{\sigma_i \sigma'_i} \sum_{\mu_i \mu'_i} \int d^3\vec{k}_2 d^3\vec{k}_3 d^3\vec{k}'_2 d^3\vec{k}'_3 \frac{1}{\sqrt{E_{\mathrm{free}} E'_{\mathrm{free}}}}$$

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

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

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

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

Instant-Form Spectator Model (IFSM) 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

$$\left\langle p_1', \sigma_1' \right| \hat{J}^{\mu}_{\mathrm{spec}} \left| p_1, \sigma_1 \right\rangle =$$

$$e_1 \bar{u}\left(p_1', \sigma_1'\right) \left[f_1(\bar{Q}^2)\gamma^{\mu} + \frac{i}{2m_1} f_2(\bar{Q}^2)\sigma^{\mu\nu}\bar{q}_{\nu} \right] u\left(p_1, \sigma_1\right)$$

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

$$\left\langle p_1', \sigma_1' \right| \hat{A}^{\mu}_{a,\mathrm{spec}} \left| p_1, \sigma_1 \right\rangle =$$

$$\bar{u}\left(p_1', \sigma_1'\right) \left[g_A^q \gamma^{\mu} + \frac{2f_{\pi}}{\bar{Q}^2 + m_{\pi}^2} g_{qq\pi} \bar{q}^{\mu} \right] \gamma_5 \frac{1}{2} \tau_a u\left(p_1, \sigma_1\right)$$

Peculiarities of the IF Spectator Model

Point-like constituent quarks:

$$f_1(\bar{Q}^2) = 1\,, \qquad f_2(\bar{Q}^2) = 0$$

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

with

$$\vec{p}_i' - \vec{p}_i = \vec{\bar{q}} = \vec{Q} = \vec{P}' - \vec{P}$$

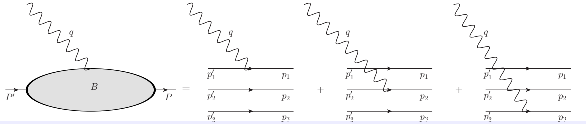
but

$$p_i'^0 - p_i^0 = \bar{q}^0 \neq Q^0 = P'^0 - P^0\,; \qquad \bar{q}^0 = \zeta Q^0$$

Since in the **IF** the 3-momenta are interaction-free, while the Hamiltonian P^0 is dynamical!

The whole 3-momentum $\vec{Q}$ carried by the photon is transferred to quark 1 but only part of its energy Q^0.

$\bar{q}^0$, however, is uniquely determined by overall momentum conservation.



Peculiarities of the FF Spectator Model

?

Elastic Sachs Form Factors

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

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

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

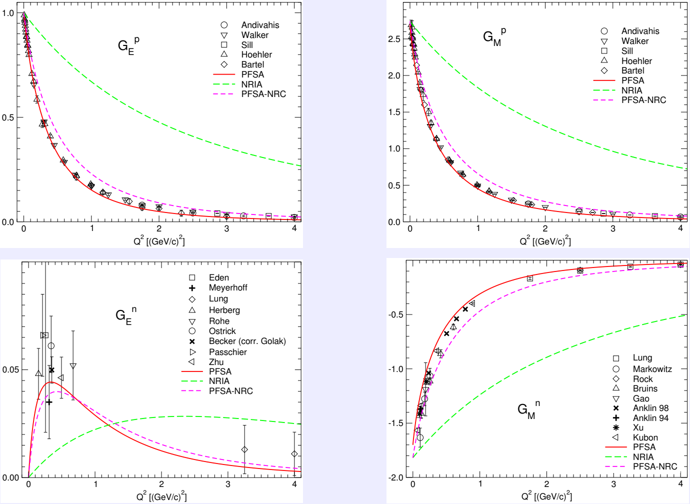
Spin-$\frac{3}{2}$ baryons:

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

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

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**, 33 (2001)

Nucleon Electric Radii and Magnetic Moments

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)

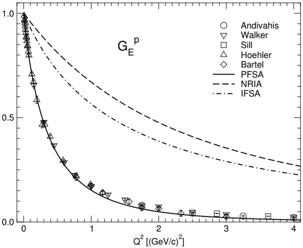
Comparison of PFSM to IFSM

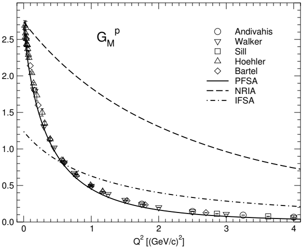
Point Form vs. **Instant Form** Calculations

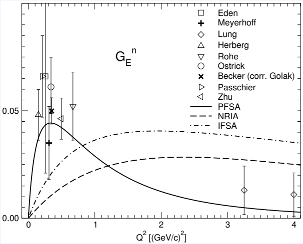
of

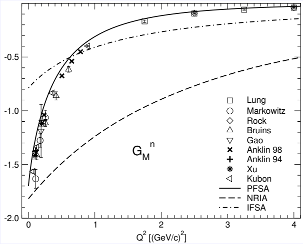
Nucleon Electromagnetic Form Factors

Point-Form vs. Instant-Form Spectator Model:









Comparison of Different RCQM Predictions

GBE RCQM vs. **OGE RCQM**

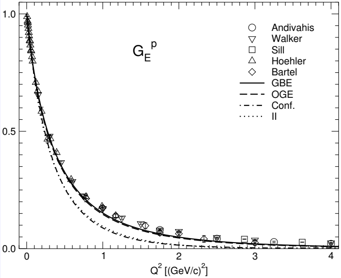
vs.

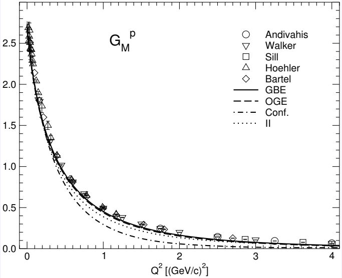
Instanton-Induced RCQM

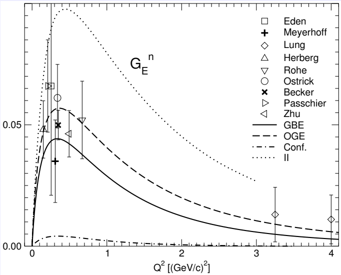
(Salpeter Equation - Bonn Group)

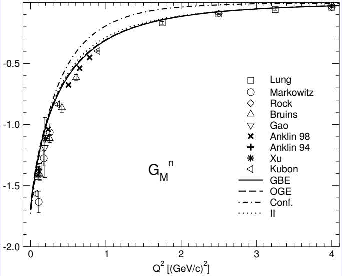
Electromagnetic Form Factors of the Nucleons

Different Quark-Model Predictions:

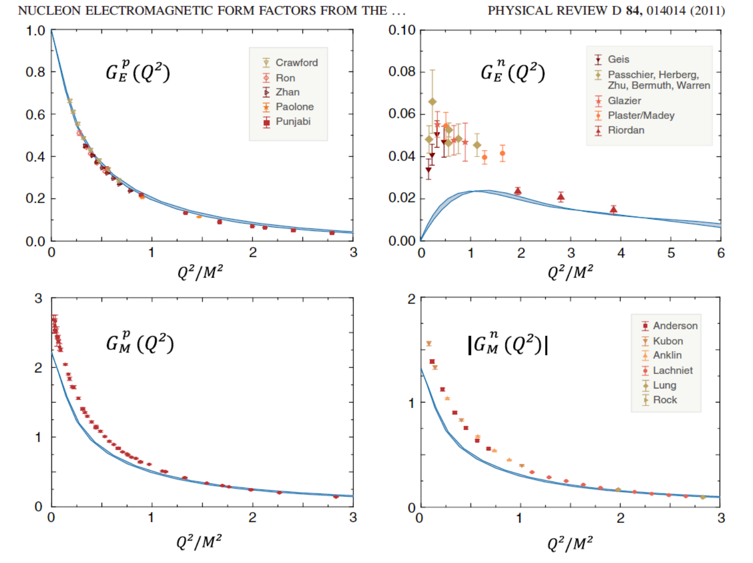






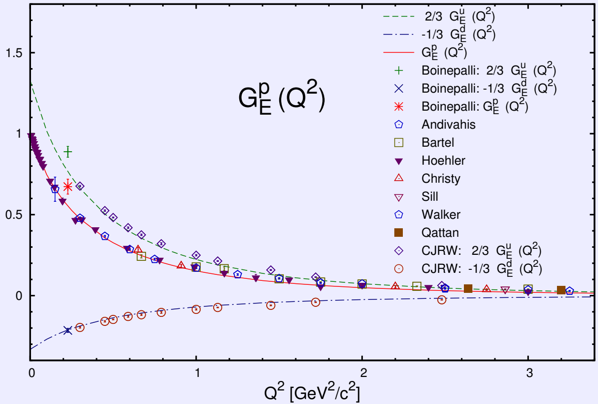


DSE/Faddeev Result from Graz (G. Eichmann)



Proton Electric Form Factor

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



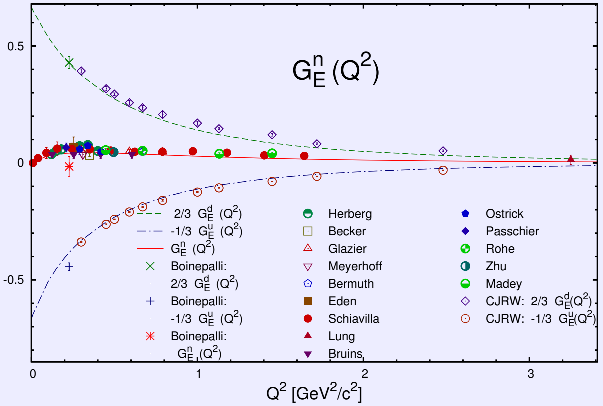
GBE RCQM prediction: M. Rohrmoser, Ki-Seok Choi, and W. Plessas: arXiv:1110.3665

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

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

Neutron Electric Form Factor

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



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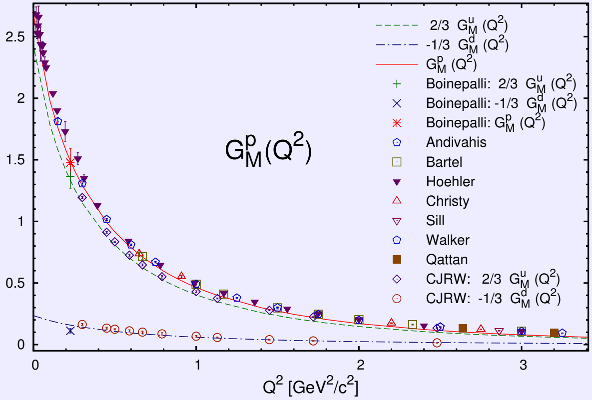
Proton Magnetic Form Factor

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



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Neutron Magnetic Form Factor

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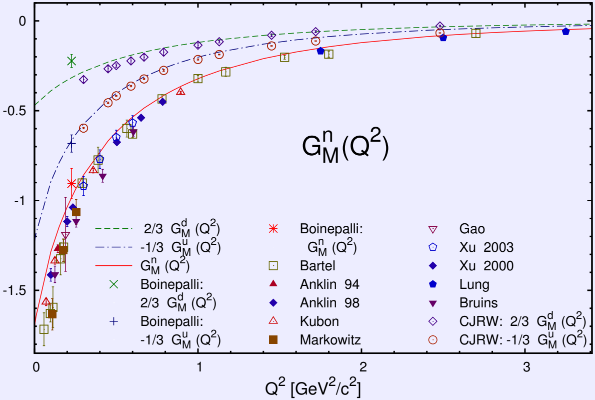

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Wish List

- Results from **different relativistic** approaches differ to a lesser or larger extent.
- It is not all **completely transparent**, how relativity is included in different approaches.
- Certainly, **Lorentz invariance** is of utmost importance.
- **Suggestion** (at least for Hamiltonian approaches): Take the same rest frame-wave function (e.g., of the GBE RCQM) and go ahead with calculating a certain reaction (e.g., elastic e^- scattering on the nucleon) along the spectator-model construction of the e.m. current operator.

Collaborators

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Thank you very much

for

your attention!