Quantum Chromodynamics and the Constituent-Quark Model

Workshop on "Half a Century of QCD"

13th Int. Conference on New Frontiers in Physics

Kolymbari, August 29th, 2024

Willibald Plessas

Institute of Physics, University of Graz

Contents

- QCD degrees of freedom at low energies
- Relativistic Hamiltonian dynamics for the constituent quark model
- Universal RCQM for all baryons
- Spectroscopy
- Electroweak structures (form factors) of nucleons, hyperons, … inlcuding their flavor decompositions
- Strong vertex form factors πNN, $\pi N\Delta$, $\pi\Delta\Delta$
- Hadronic resonance decays – failure of $\{QQQ\}$ configurations for resonances
- Coupled-channels RCQM with explicit meson degrees of freedom
- Summary and Outlook

Origin of Quantum Chromodynamics (QCD)

Volume 47B, number 4 PHYSICS LETTERS 26 November 1973

ADVANTAGES OF THE COLOR OCTET GLUON PICTURE ☆

H. FRITZSCH*, M. GELL-MANN and H. LEUTWYLER**
California Institute of Technology, Pasadena, Calif. 91109, USA

Received 1 October 1973

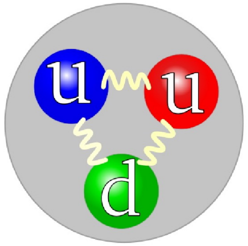
It is pointed out that there are several advantages in abstracting properties of hadrons and their currents from a Yang–Mills gauge model based on colored quarks and color octet gluons.

Phys. Lett. B 47 (1973) 365-368

~ 2600 citations as of today

Low-Energy QCD

- Hadrons consist of constituent quarks, e.g. baryons of $\{QQQ\}$, such as the (colorless) proton:



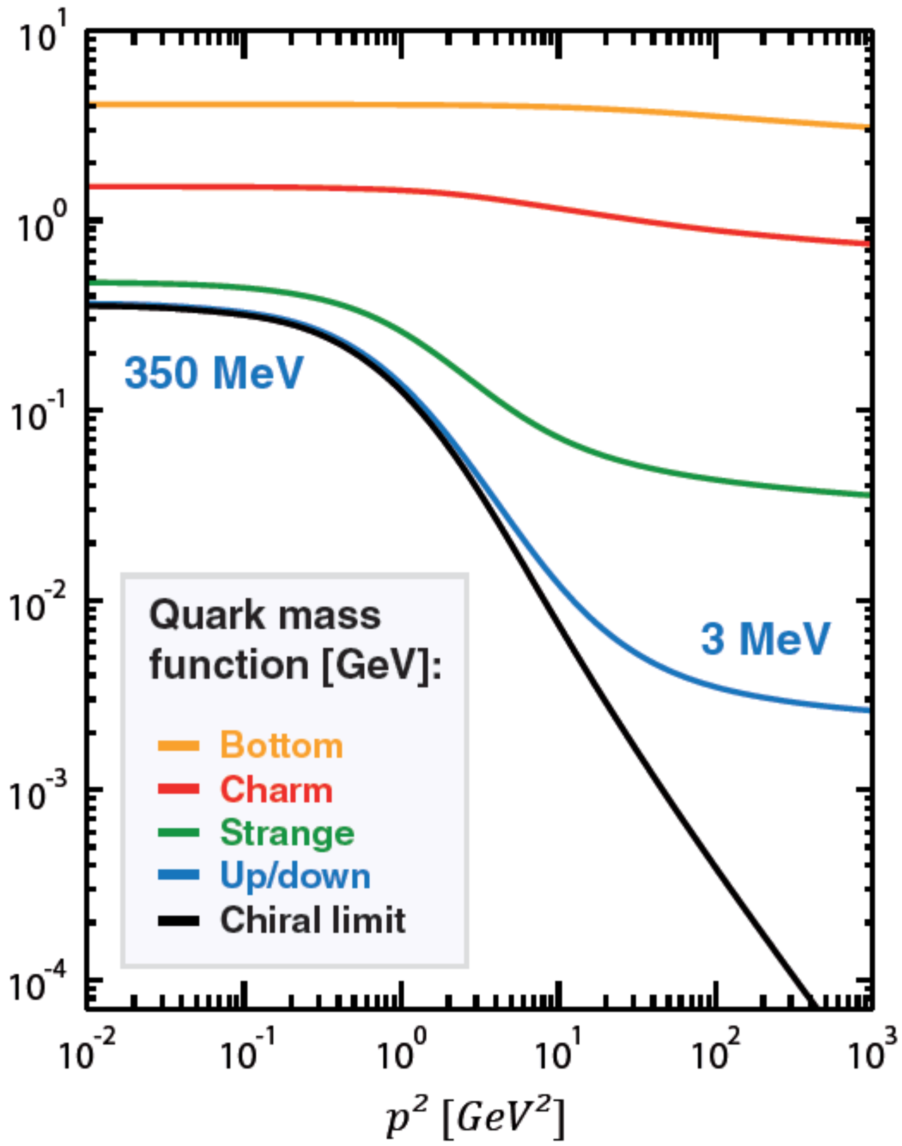
  $\{QQQ\}$ are considered as quasiparticles, confined inside hadrons.

- The $\{Q\text{–}Q\}$ interaction is furnished by the low-energy d.o.f. of QCD, resulting from the spontaneous breaking of chiral symmetry ($SB\chi S$), i.e. for N_F flavors $SU(N_F)_L \times SU(N_F)_R \rightarrow SU(N_F)_V$, leading to the appearance of Goldstone bosons.

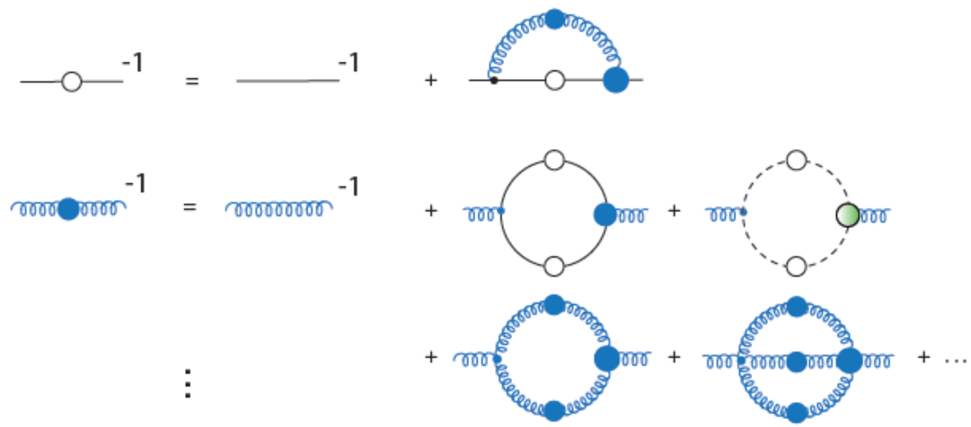
- Construct a Poincaré-invariant interacting mass operator based on

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

Dynamical Mass Generation



Dynamical quark masses generated by Dyson-Schwinger equations (DSE):



Slide by courtesy from G. Eichmann

Relativistic Quantum Mechanics

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

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

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

Relativistic Constituent Quark Model (RCQM)

Interacting mass operator

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

fulfilling the **Poincaré algebra**

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

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

Universal Goldstone-Boson-Exchange 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)

UGBE RCQM Parametrization

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

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

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

$B = -402$ 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

Solution of Mass-Operator Eigenvalue Problem

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

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

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

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

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

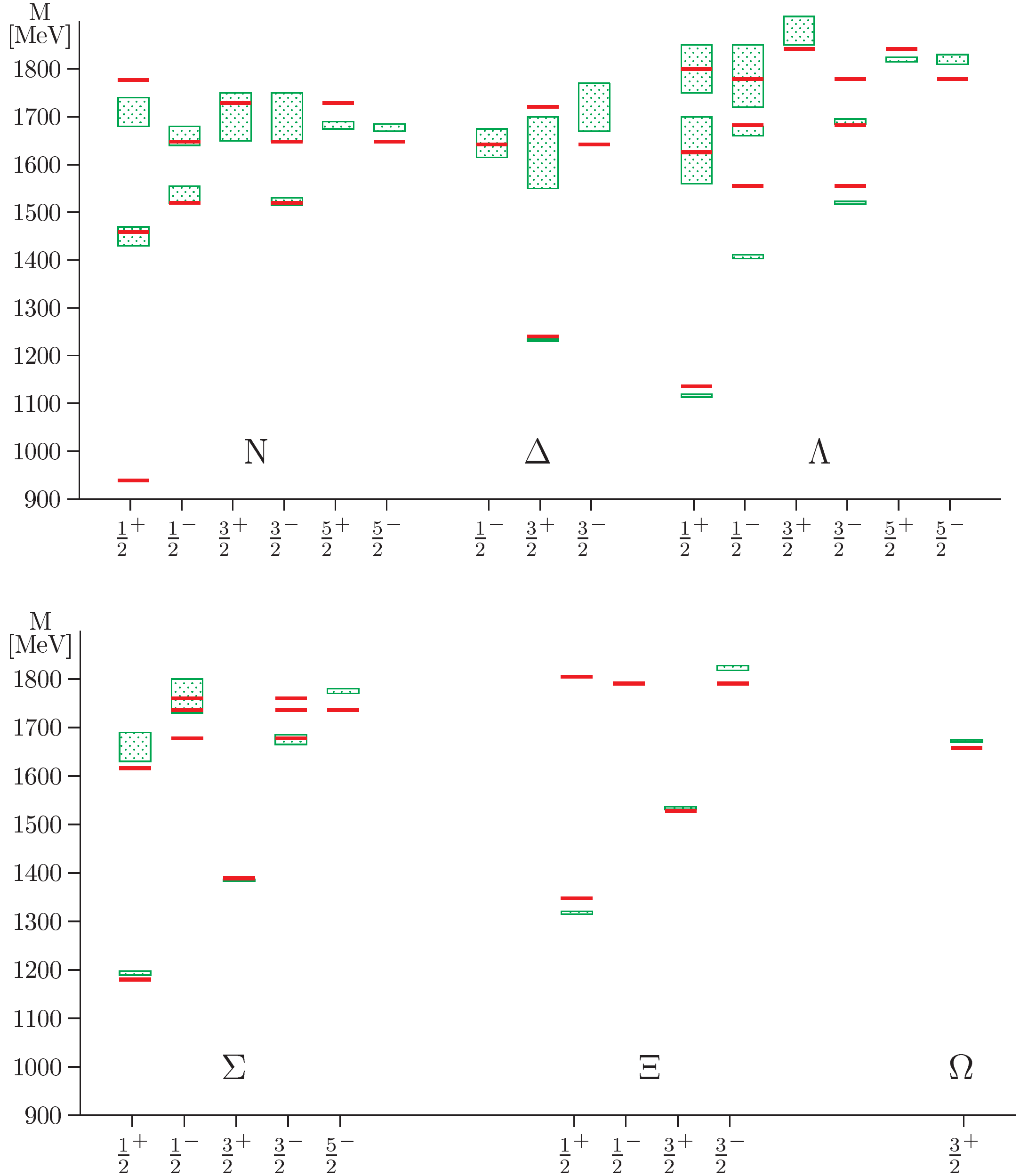
Spectroscopy of Baryons

Excitation Spectra

of Baryons with ALL Flavors

u, d, s, c, b

Excitation Spectra of Baryons with *u*, *d*, *s* Flavors



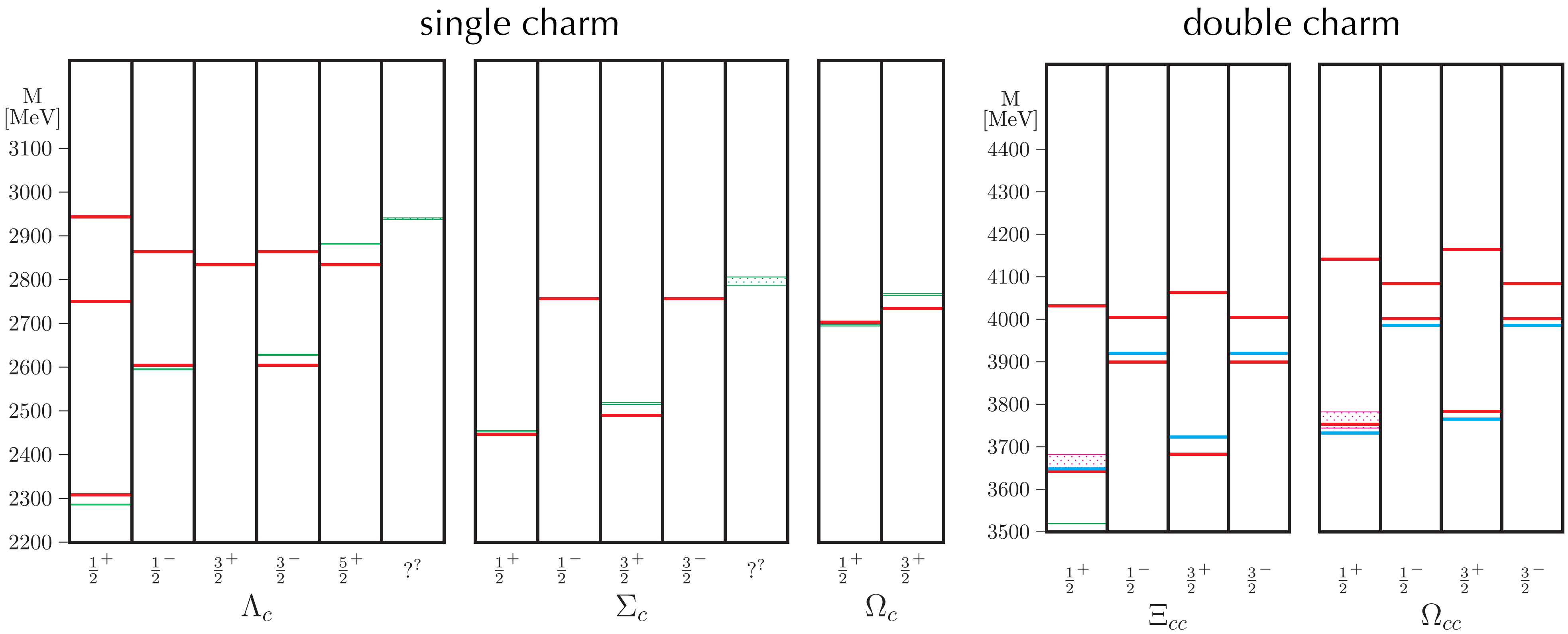
red levels = theoretical prediction

green boxes = exp. data with uncertainties

L.Ya. Glozman, W. Plessas, K. Varga, and R.F. Wagenbrunn:

Phys. Rev. D 58, 094030 (1999)

Excitation Spectra of Charm Baryons



Left panel – single charm:

↑ our value $m(\Xi_{cc}) = 3642$ MeV

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)

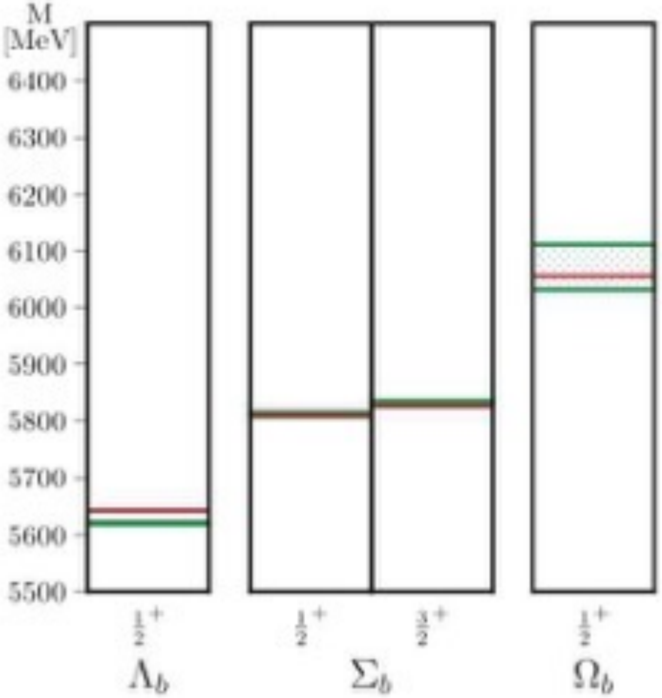
New datum from LHCb 2017: $m(\Xi_{cc})$= 3621.40±0.72(stat.)±0.27(syst.)±0.14(Λ_c) MeV

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

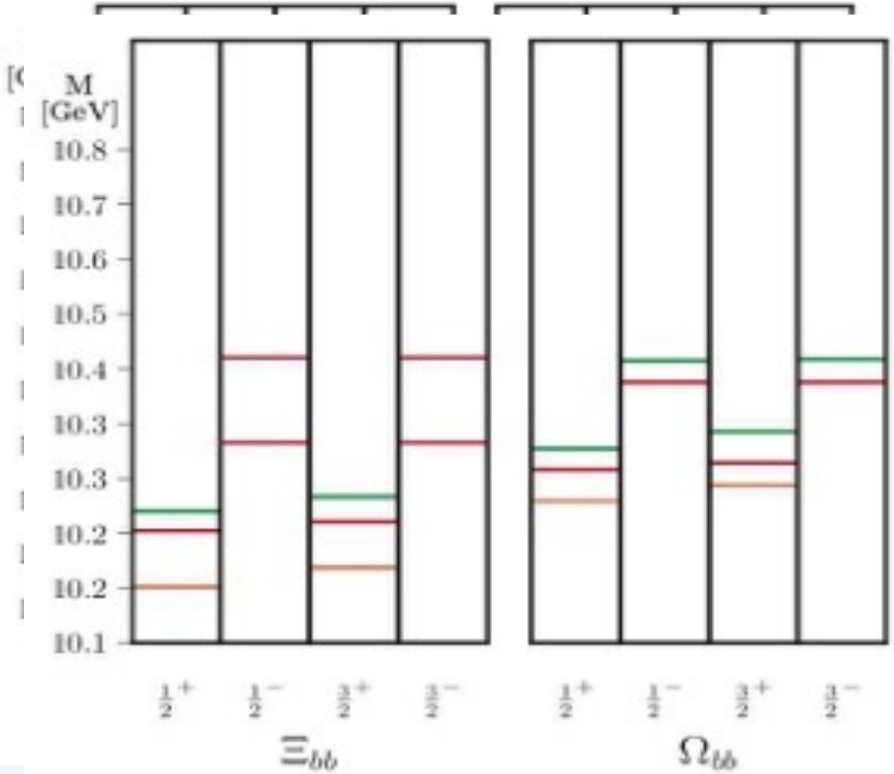
magenta — L. Liu et al.: Phys. Rev. D 81 (2010) 094505 (Lattice QCD)

Excitation Spectra of Bottom Baryons

single bottom



double bottom



Left panel – single bottom:

red Universal GBE RCQM prediction

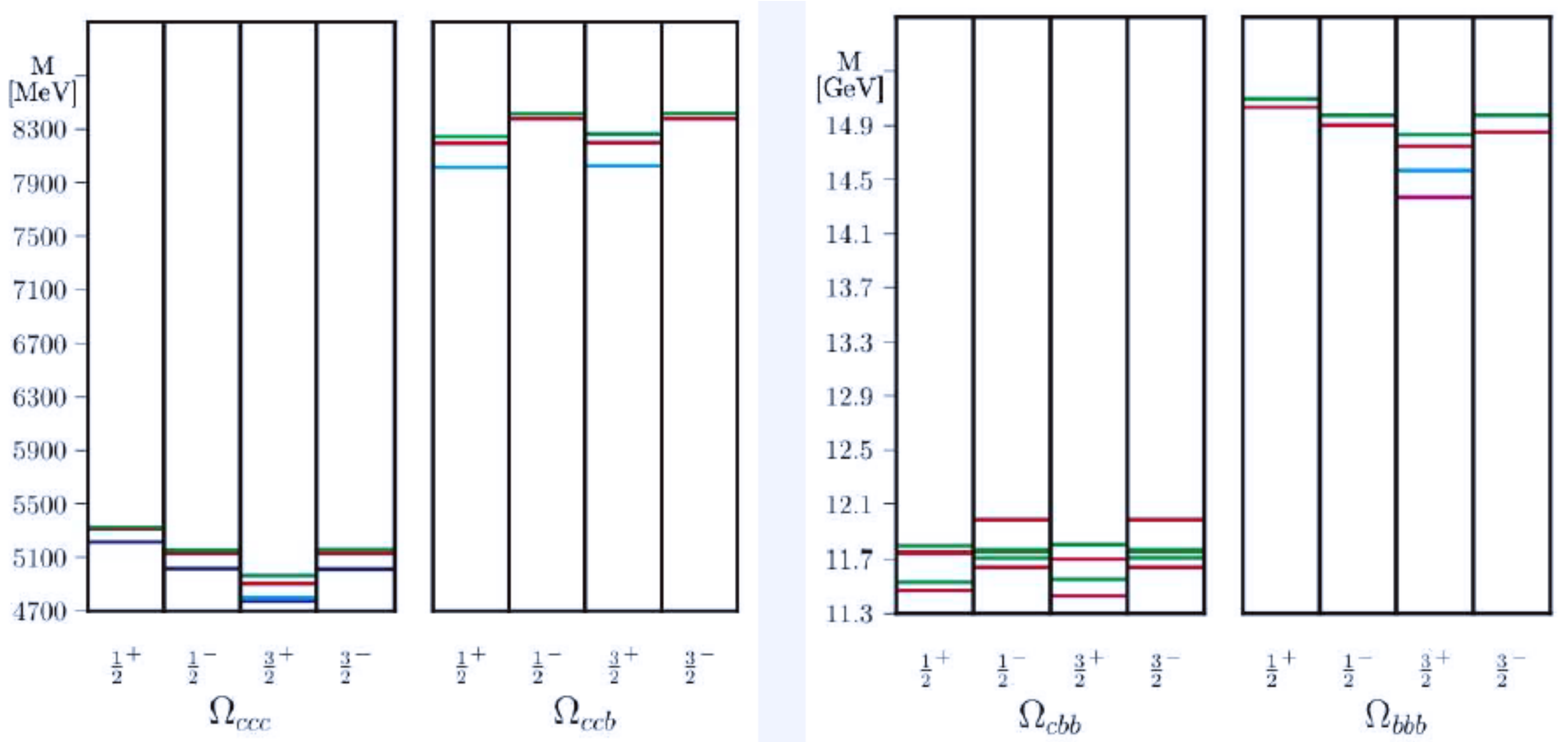
green PDG 2013 (experiment)

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

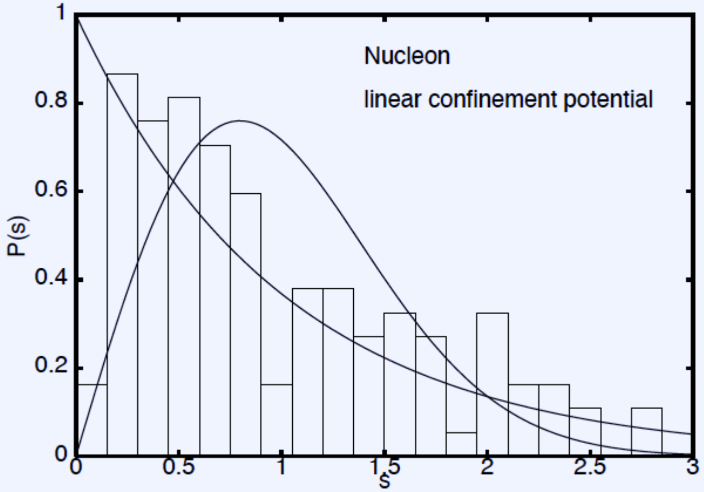


red	Universal GBE RCQM
green	W. Roberts and M. Pervin: Int. J. Mod. Phys. A 23 (2008) 2817 (nonrelativistic one-gluon-exchange CQM)
blue	S. Migura, D. Merten, B. Metsch, and H.-R. Petry: Eur. Phys. J. A 28 (2006) 41 (Bonn RCQM)
cyan	A.P. Martynenko: Phys. Lett. B 663 (2008) 317 (RCQM)
magenta	S. Meinel: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

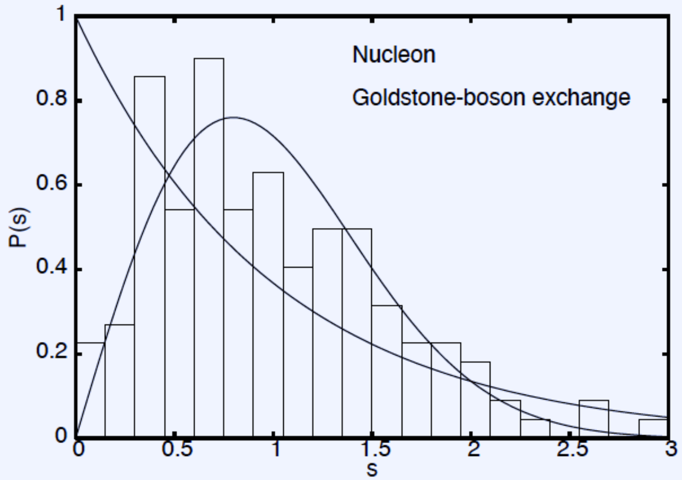
Quantum Chaos in *N* Spectra

Distribution of nearest-neighbour nucleon level spacings:

Only confinement interaction



Confinement + GBE hyperfine interaction



Histogramm of theoretical level spacings in comparison to Poisson and Wigner GOE distributions (solid lines)

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

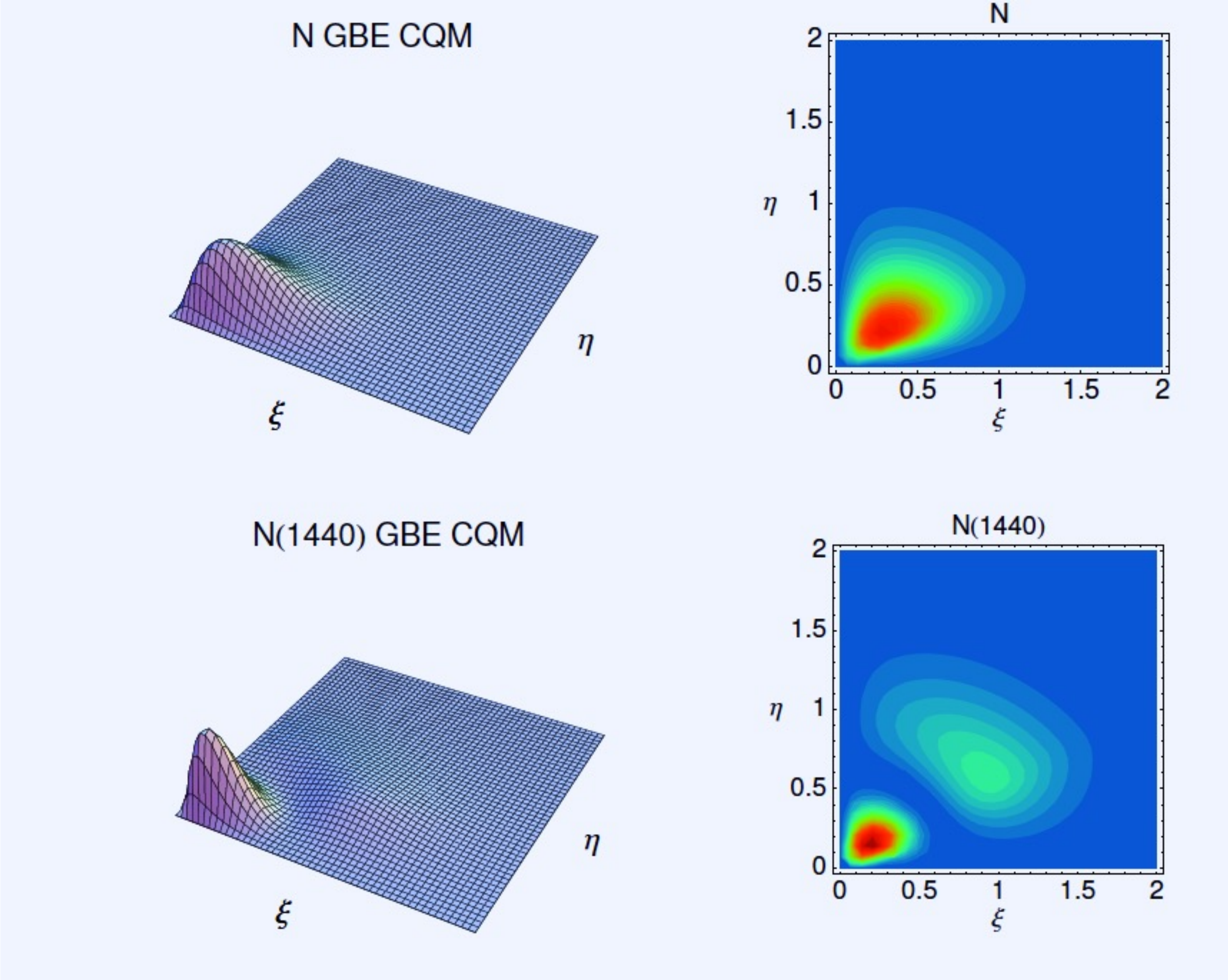
$$\left\langle \vec{\xi},\vec{\eta}\,\middle|\,P,J,\Sigma,T,M_T\right\rangle = \Psi_{PJ\Sigma TM_T}(\vec{\xi},\vec{\eta})$$

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

Picture the baryon wave functions through
spatial probability density distributions

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

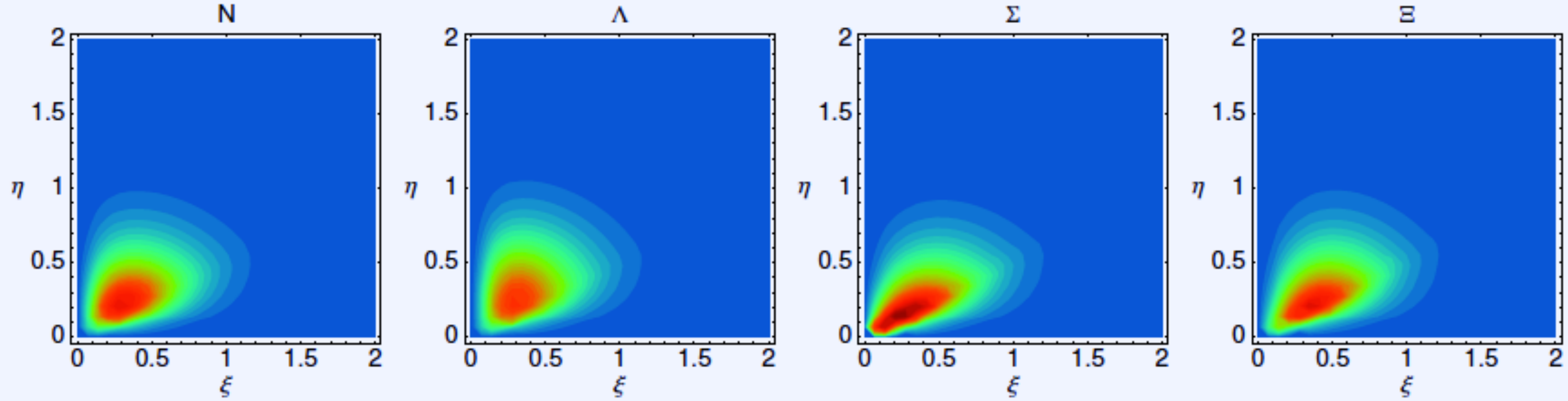
Spatial Probability Density Distributions



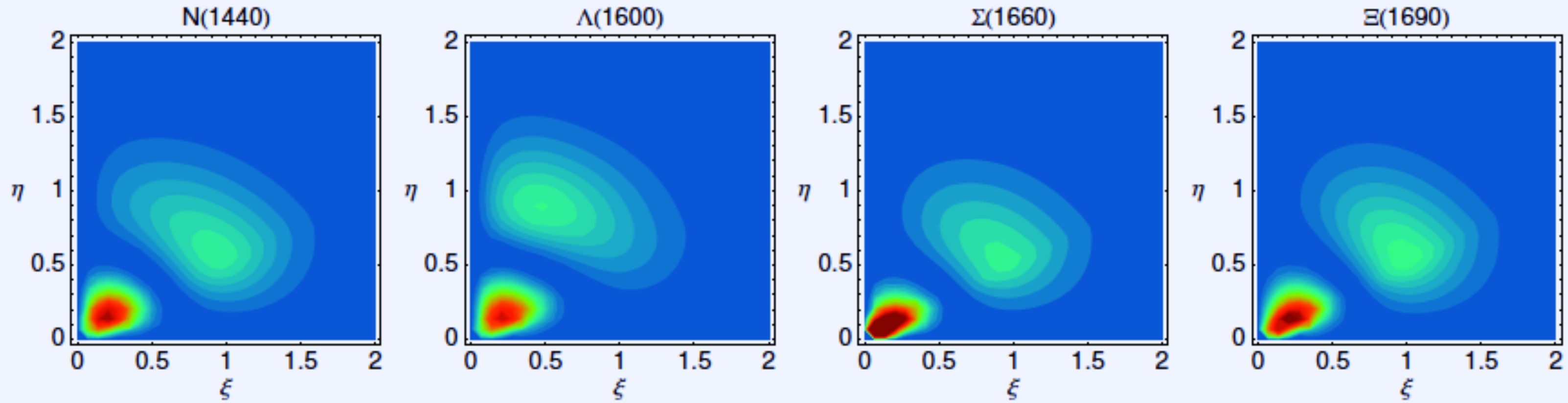
T. Melde, W. Plessas, and B. Sengl: Phys. Rev. D **77** (2008) 114002

Spatial Probability Density Distributions

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



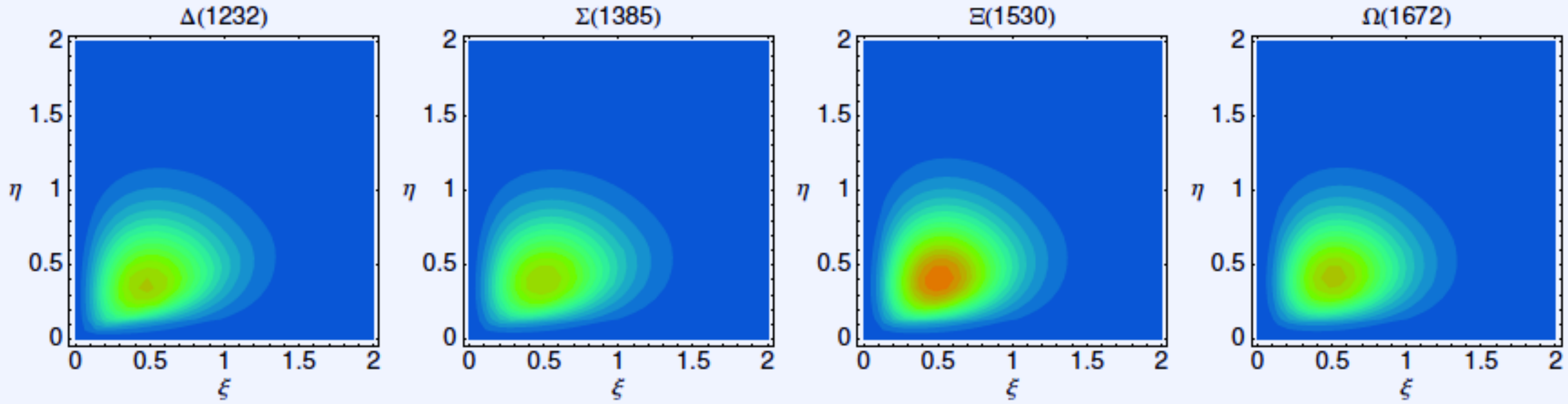
$\rho(\xi, \eta)$ for the $\frac{1}{2}^+$ **octet** baryon states $N(1440)$, $\Lambda(1600)$, $\Sigma(1660)$, $\Xi(1690)$:



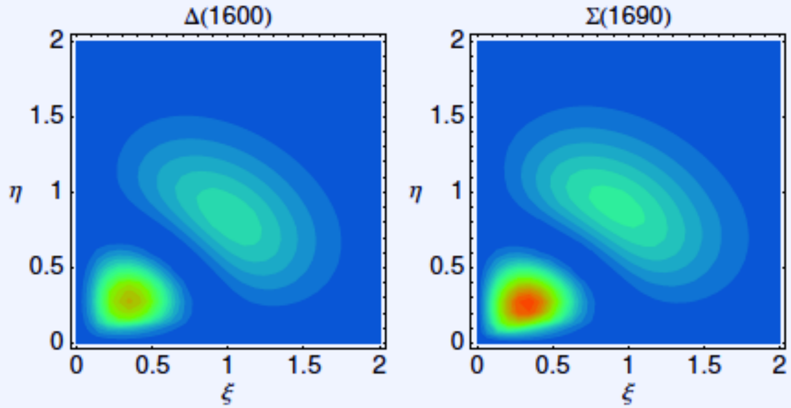
T. Melde, W. Plessas, and B. Sengl: Phys. Rev. D **77** (2008) 114002

Spatial Probability Density Distributions

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



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



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

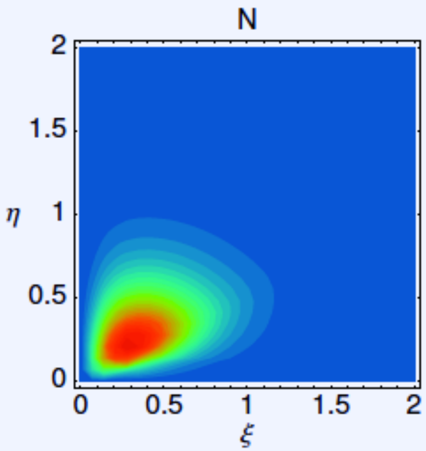
Electric Radii vs. Root-Mean-Square Radii

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**!

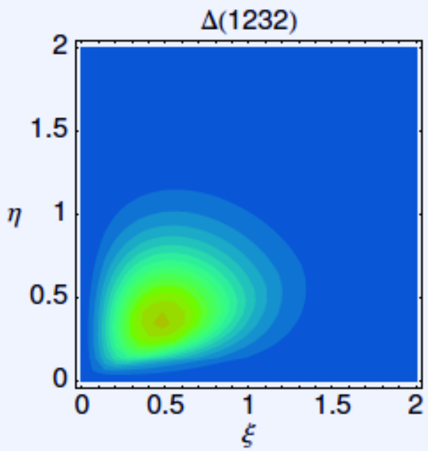
$\rightarrow$ Idea about the spatial distribution of constituent quarks.



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

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

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



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

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

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

Calculation of Covariant Observables

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

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

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

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

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

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

... $\hat{D}^{\mu}_{\lambda}$ $\rightarrow$ hadronic decays

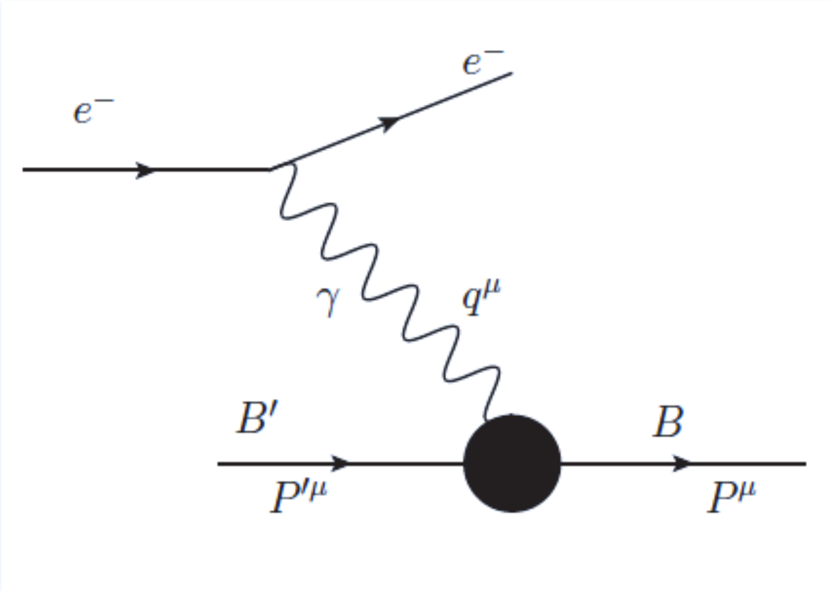
To be calculated from microscopic three-quark ME's

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

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

e^- Scattering – Electromagnetic Form Factors

Elastic electron scattering:

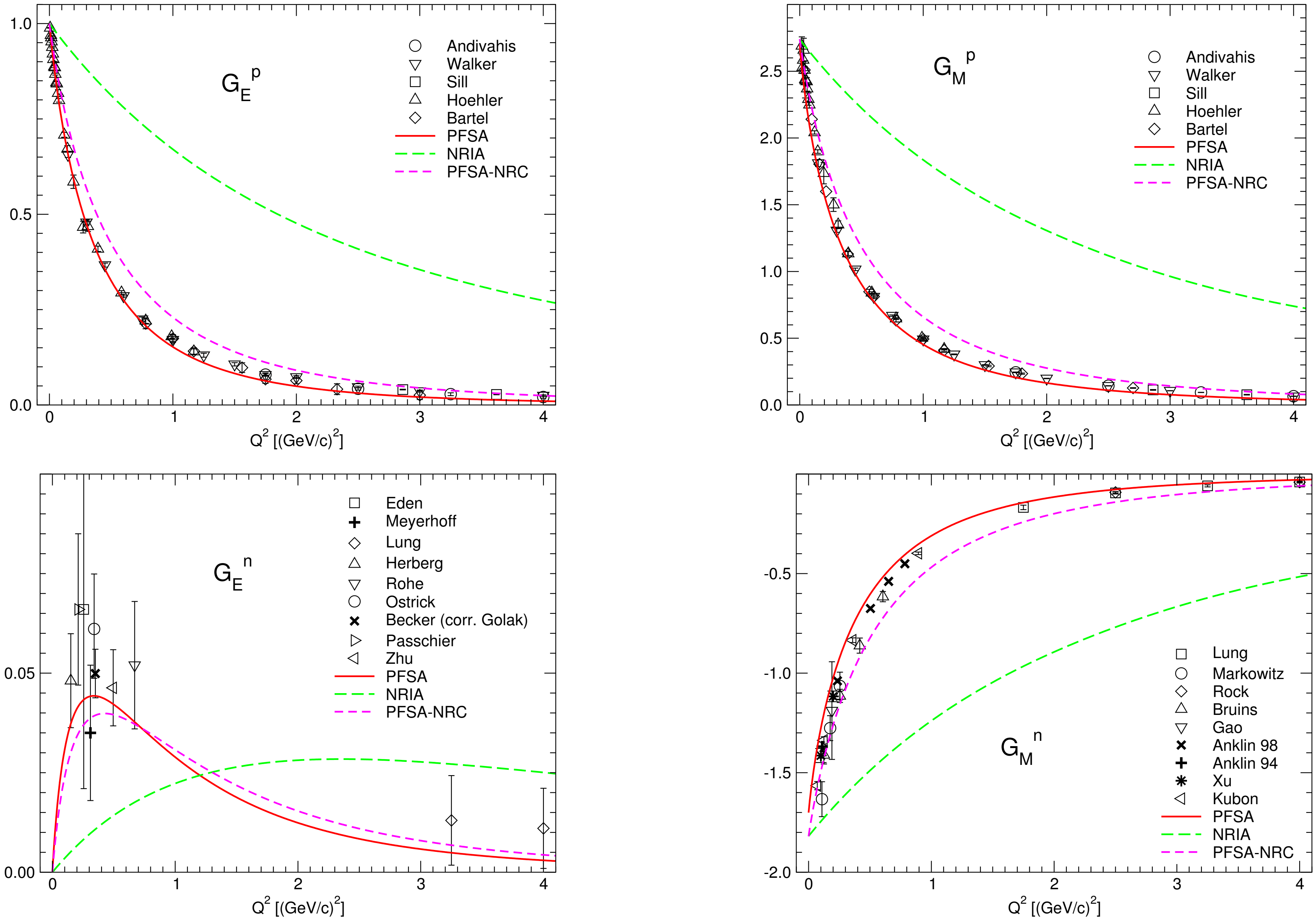


Invariant form factors:

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

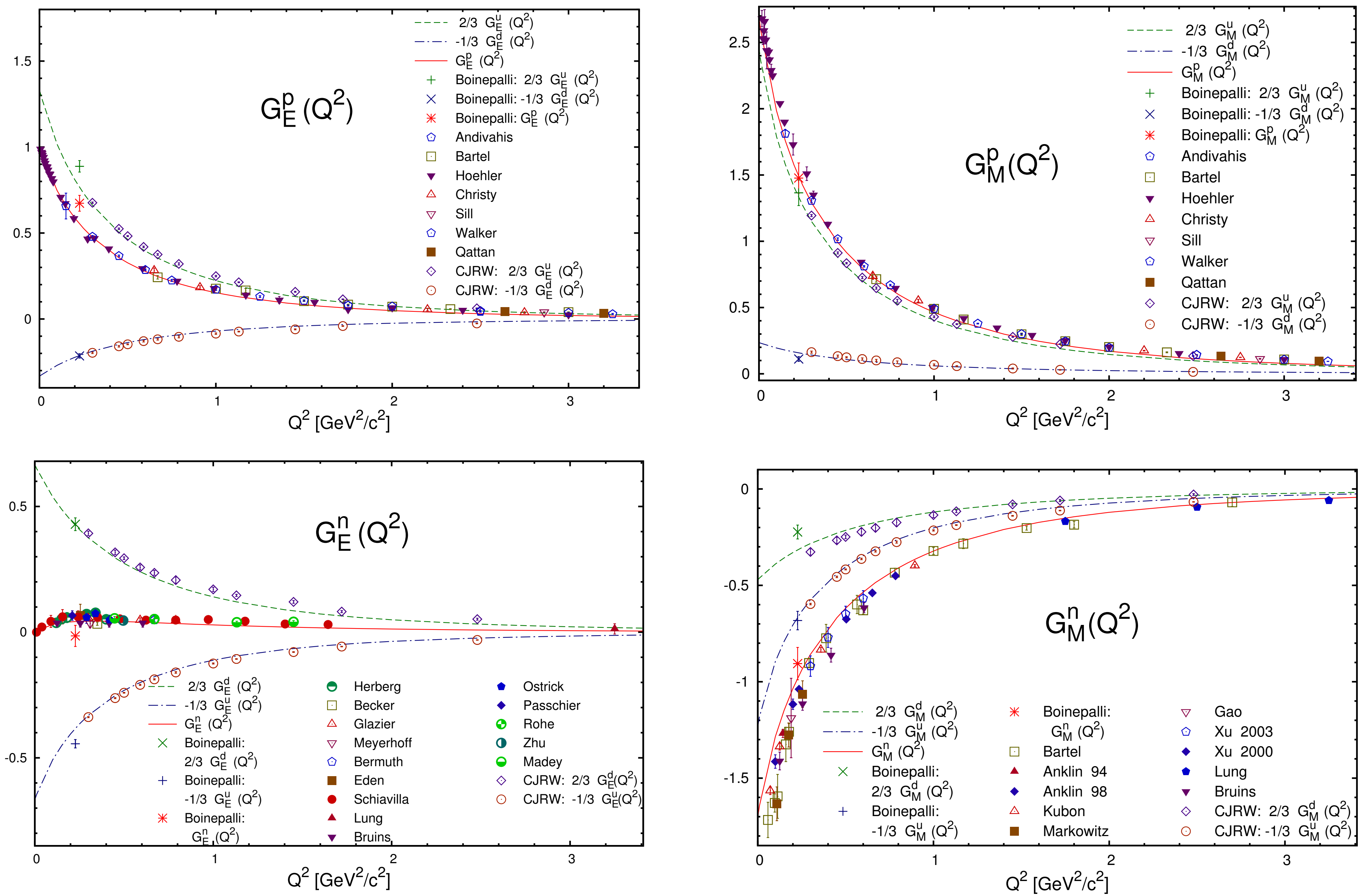
with $Q^2 = -q^2$; $\qquad q^\mu = P^\mu - P'^\mu$

Electromagnetic Nucleon Form Factors



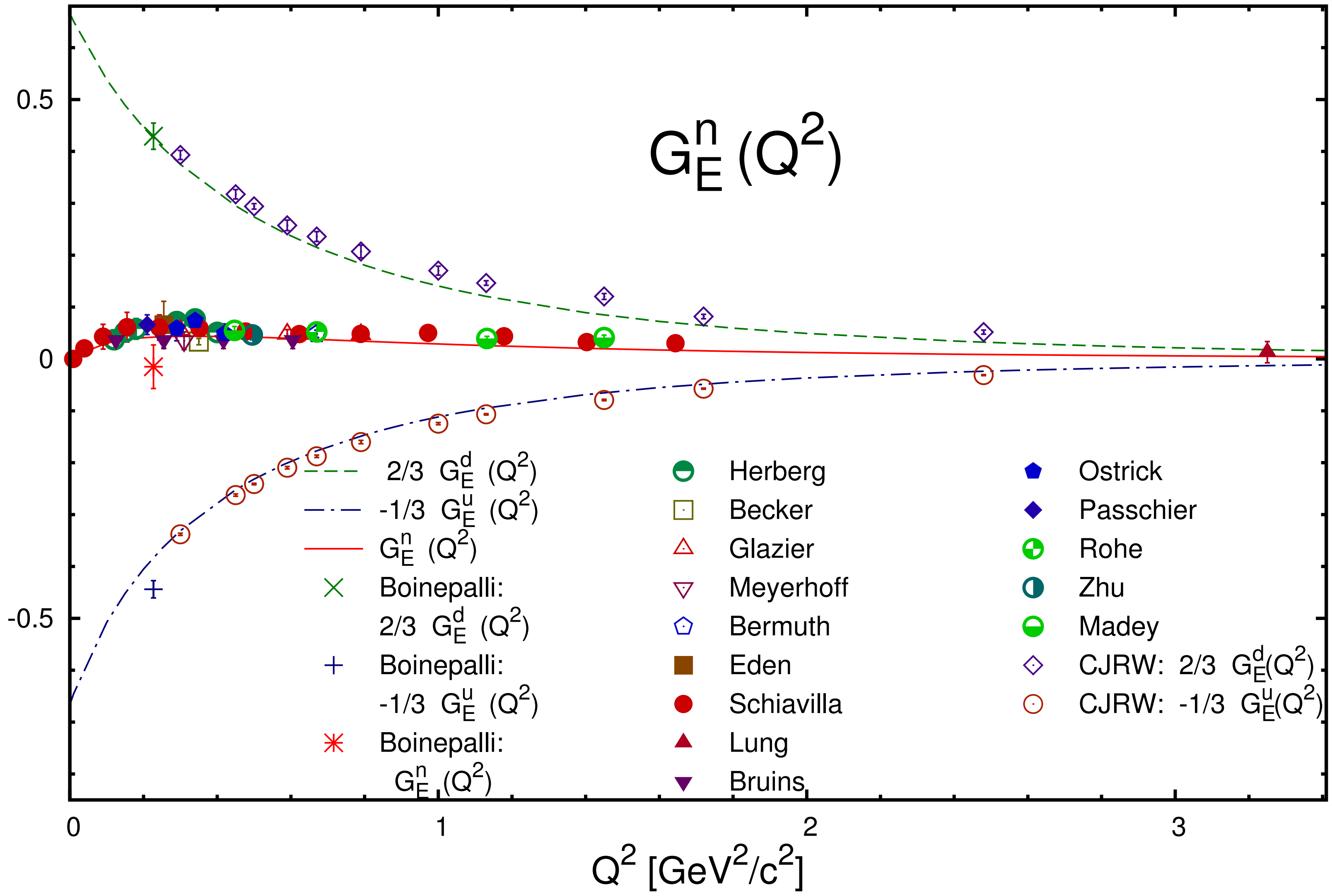
R.F. Wagenbrunn, S. Boffi, W. Klink, W. Plessas, and M. Radici: Phys. Lett. B511 (2001) 33

Flavor Decomposition of Nucleon Form Factors



M. Rohrmoser, K.-S. Choi, and W. Plessas: Few-Body Syst. 58 (2017) 83

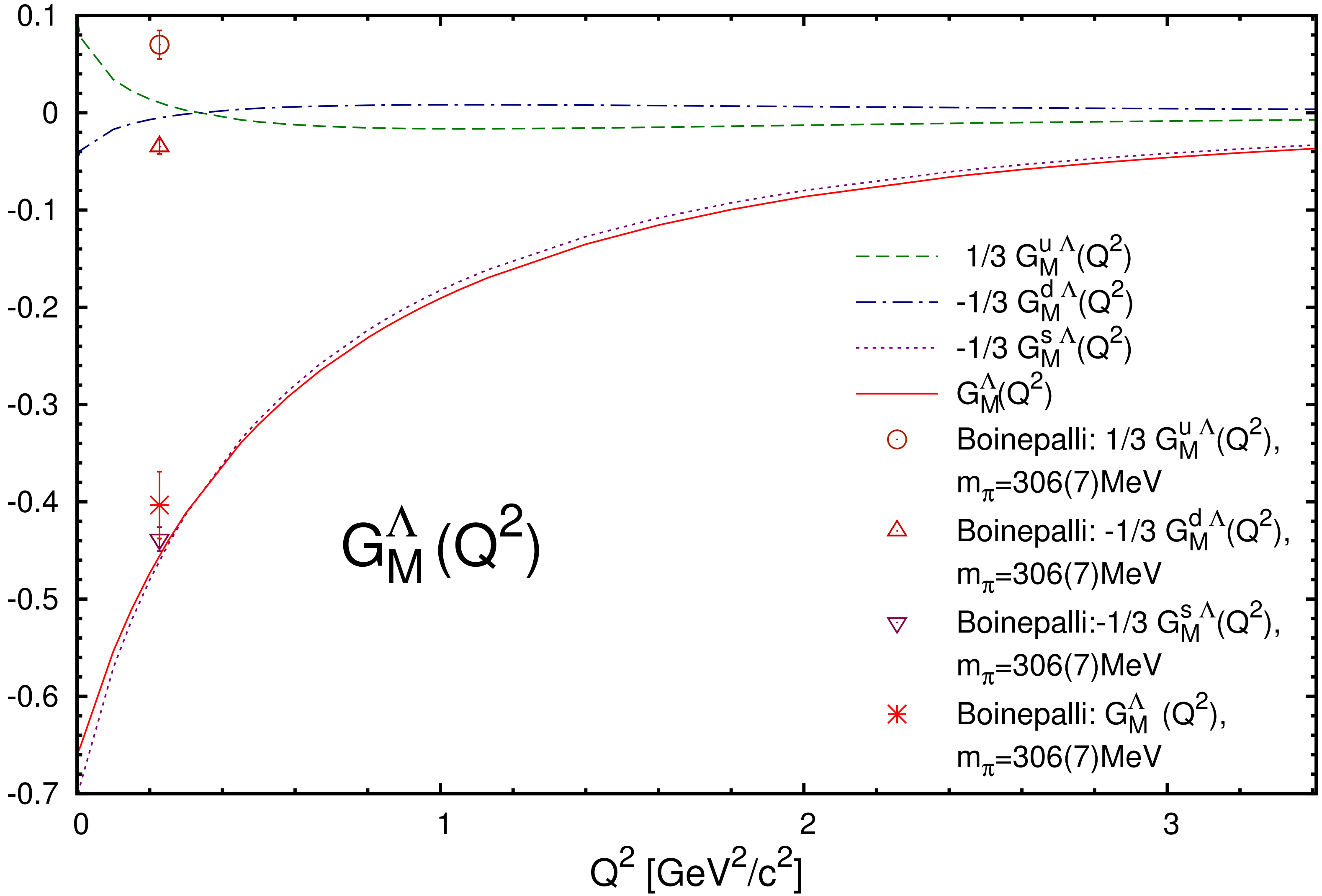
Flavor Decomposition of Neutron $G_E(Q^2)$



M. Rohrmoser, K.-S. Choi, and W. Plessas: Few-Body Syst. 58 (2017) 83

Lattice QCD: S. Boinepalli et al.: Phys. Rev. D74 (2006) 093005

Flavor Components in $\Lambda(1116)$ Magnetic FF $G_M(Q^2)$



M. Rohrmoser, K.-S. Choi, and W. Plessas: Few-Body Syst. 58 (2017) 83

Lattice QCD: S. Boinepalli et al.: Phys. Rev. D74 (2006) 093005

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)

Electric Radii and Magnetic Moments – 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)

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	$0.61 \pm 0.12 \pm 0.09$

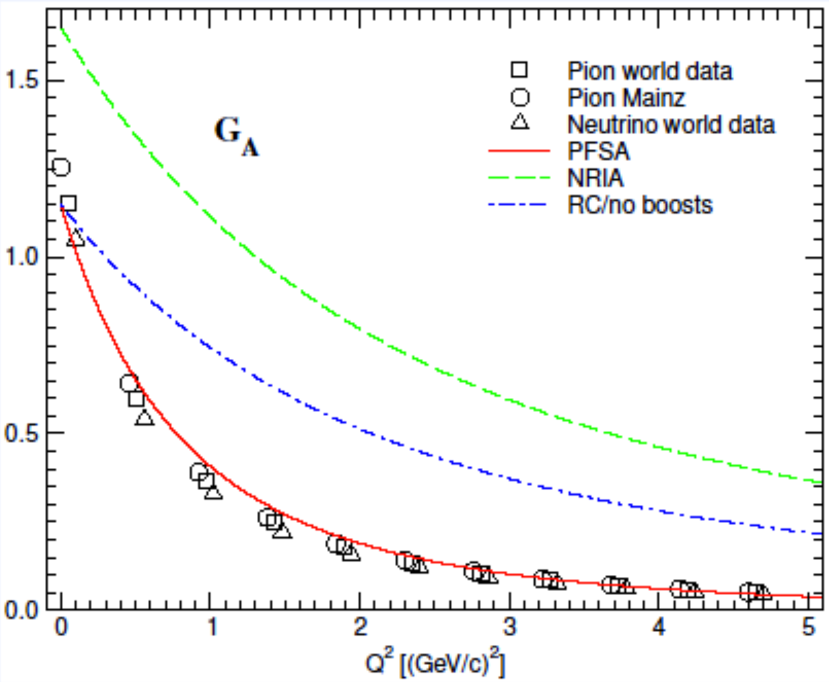
Magnetic moments μ [n.m.]

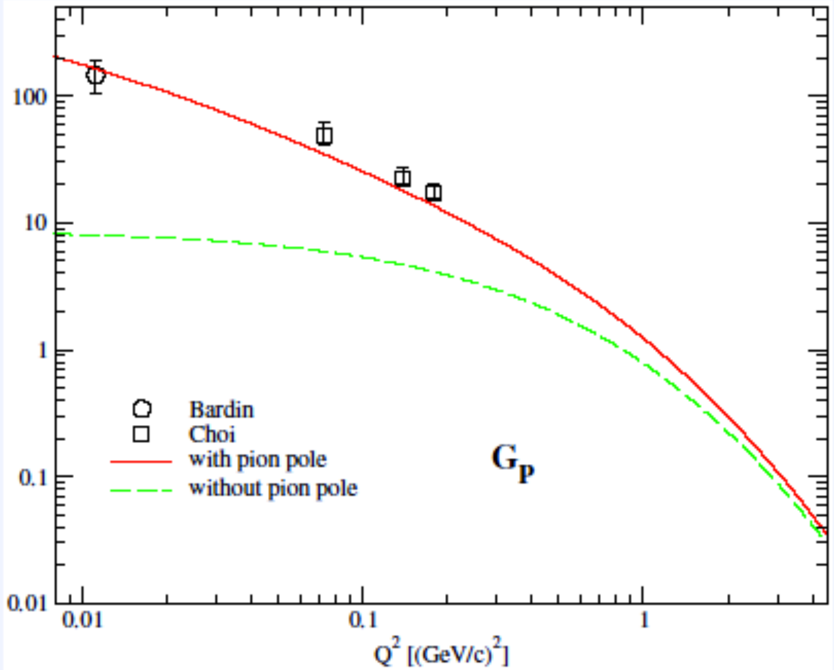
Baryon	GBE PFSM	Experiment
p	2.70	2.792847356
n	-1.70	-1.9130427
Λ	-0.64	-0.613 ± 0.004
Σ^+	2.38	2.458 ± 0.010
Σ^-	-0.93	-1.160 ± 0.025
Ξ^0	-1.25	-1.250 ± 0.014
Ξ^-	-0.70	-0.6507 ± 0.0025
Δ^+	2.08	$2.7^{+1.0}_{-1.3} \pm 1.5 \pm 3$
Δ^{++}	4.17	$3.7 - 7.5$
Ω^-	-1.59	-2.020 ± 0.05

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

Axial Nucleon Form Factors

Covariant predictions of the GBE RCQM:

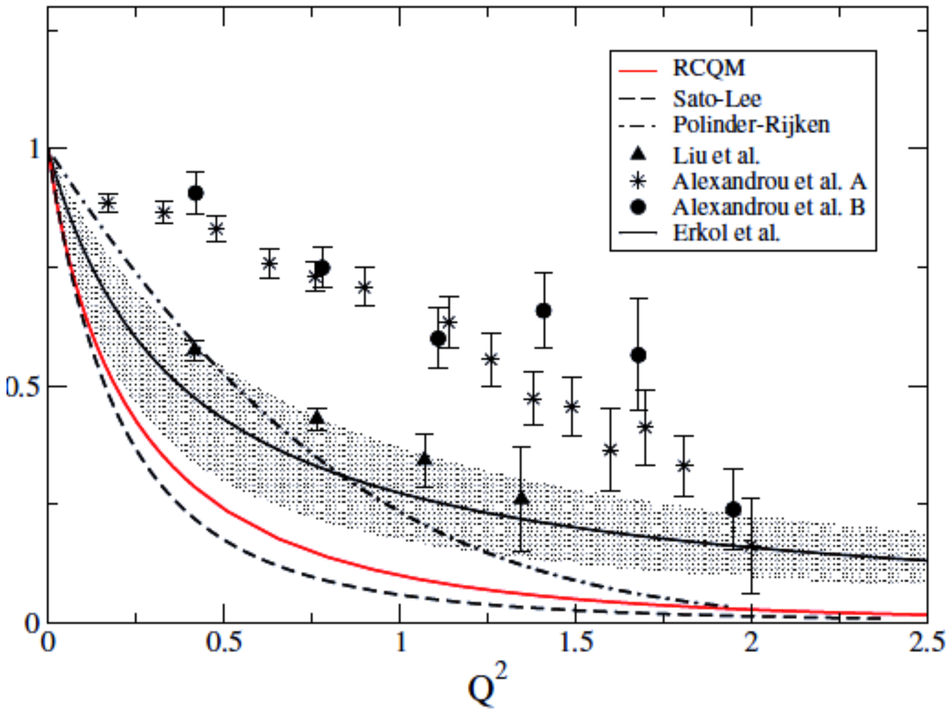




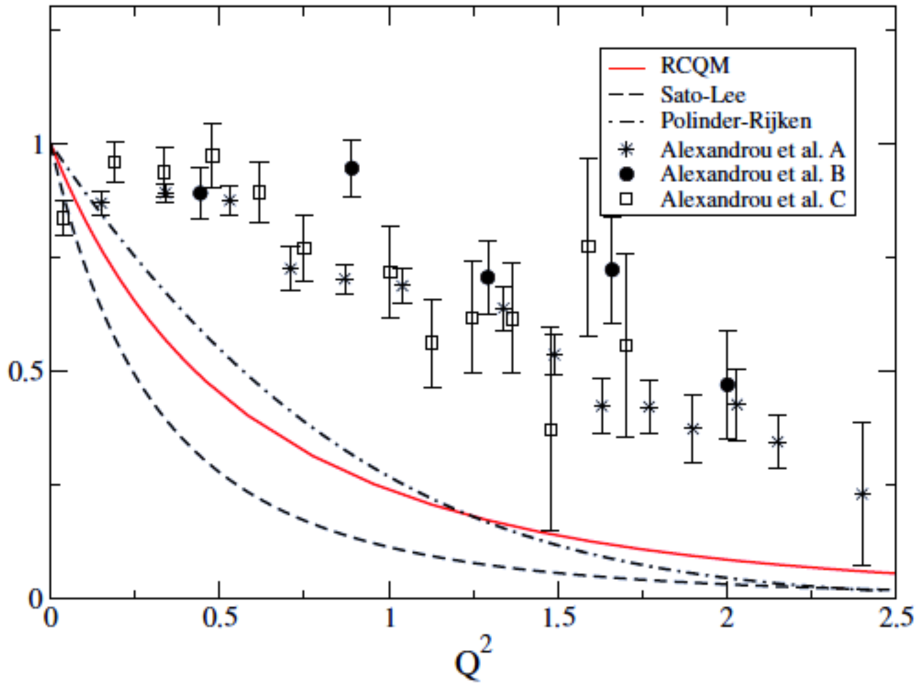
$$g_A^{GBE} = 1.15 \quad \text{vs.} \quad g_A^{exp} = 1.2695 \pm 0.0029$$

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

Meson-Baryon Vertices – Strong FFs



$G_{\pi NN}(Q^2)$

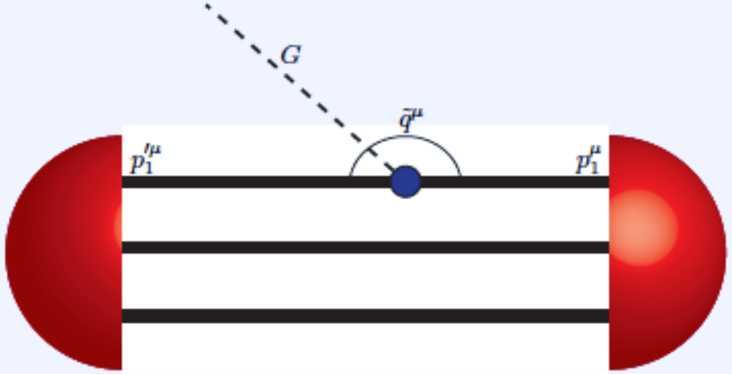


$G_{\pi N\Delta}(Q^2)$

First genuine microscopic predictions of the πNN and $\pi N\Delta$ strong-interaction vertices from the realtivistic Goldstone-boson-exchange constituent quark model

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

Gravitational Nucleon Form Factors

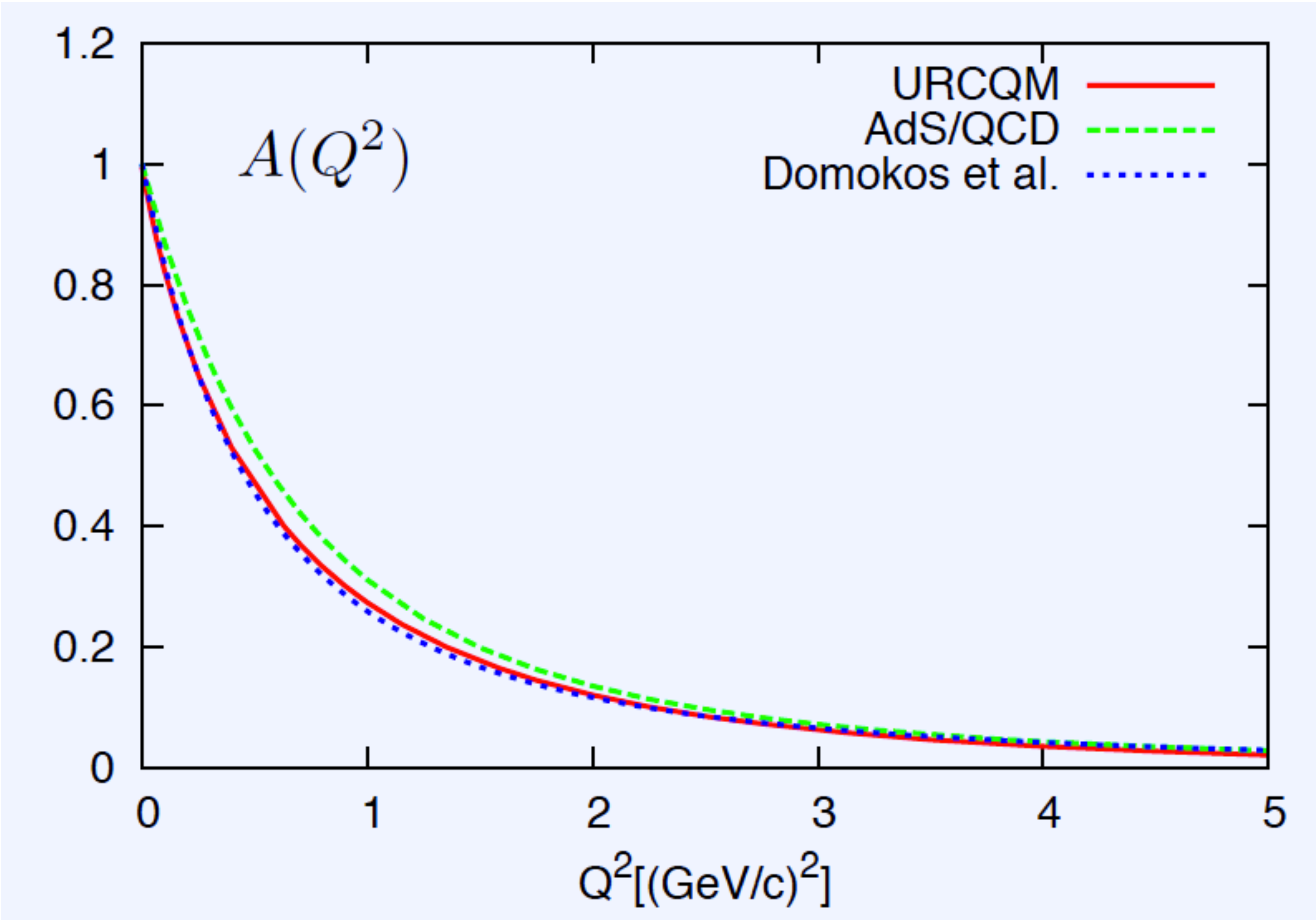


Invariant ME of **energy-momentum tensor** $\hat{\Theta}^{\mu\nu}$:

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

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

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



Hadronic Resonance Decays

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

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

With theoretical masses

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

Coupled-Channels RCQM with Explicit Mesons

Coupled-channels mass-operator eigenvalue equation
for π-dressing of a given bare $\{\widetilde{QQQ}\}$ cluster state

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

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

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

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

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

π-Dressing Effects on N and Δ

Predictions of the **CC RCQM**

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

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

(all values in MeV)

Summary and Some Open Problems

- Baryon spectroscopy of ALL flavors can be consistently described in a universal relativistic constituent quark model (URCQM), especially with respect to ground states
- The nonrelativistic constituent quark model must be discarded
- The covariant structures of the baryon ground states (N, Δ, Λ, Ξ, … form factors) at low momentum transfers result in agreement with experimental observables
- Beyond that the results agree with (reliable) lattice QCD data
- Strong baryon resonance decays fail with $\{QQQ\}$ d.o.f. only
- A realistic description of hadron resonances still represents a formidable challenge (for all QCD-based approaches)
- Inclusion of explicit meson d.o.f. can be achieved in a coupled-channels relativistic constituent quark model
- Calculation of baryon properties in a medium will be an interesting task

The End

Thank you very much for your attention!