Relativistic Coupled-Channels Constituent-Quark Model for Baryon Ground and Resonant States

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7th International Conference on New Frontiers in Physics

OAC, Kolymbari, July 5th, 2018

Aims and Challenges

- **Comprehensive framework** for treating hadrons ...
- To approach / solve / understand **QCD** ...
- To have a **universally working theory/model** ...

Some basic requirements:

- incorporate the notions we have about QCD
- include the essential degrees of freedom
- meet the symmetries of Lorentz invariance
- ...

Deal with:

- **hadron spectra**: ground states & excitations
- **hadron structure**: r_E, μ, g_A ; G_E, G_M, G_A, G_P, ...
- **resonance excitations**: $\gamma N \to N^*$, $e^- N \to N^*$, ...
- **resonance decays**: $\rho \to \pi\pi$, $N^* \to N\pi$, $\Lambda^* \to KN$, ...

Baryons as $\{QQQ\}$ Systems

For baryons viewed as $\{QQQ\}$ systems:

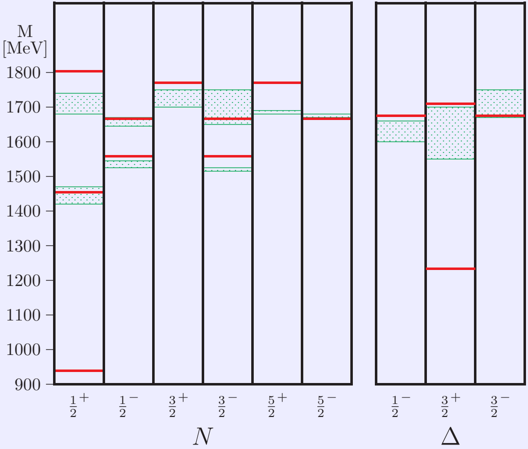
- Baryon spectroscopy ☺
  - ↪ Universal relativistic constituent-quark model ⇝ fig.
  - ↪ Lattice QCD (with physical π mass)
- Electroweak structures of baryon ground states ☺
  - ↪ Elastic electromagnetic form factors (N, Δ, ...) ⇝ fig.
  - ↪ Axial charges and weak form factors ⇝ fig.
- Problems for reactions involving resonances ☹
  - ↪ Resonance excitations and decays ⇝ tab.

Baryon Spectroscopy

of

Light Flavors

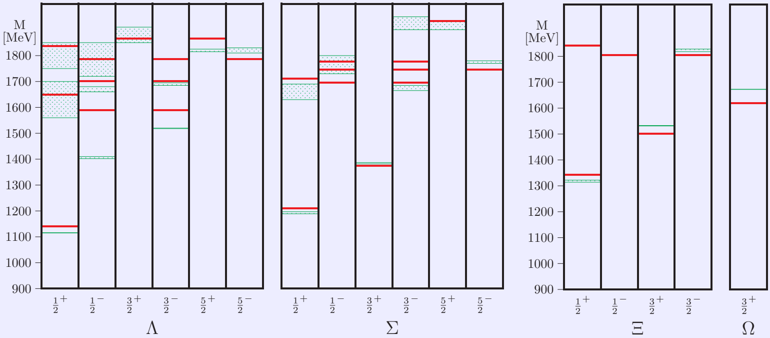
Baryon Spectroscopy: *u*, *d* Flavors



red Universal GBE RCQM

green Particle Data Group (experimental values and their uncertainties)

Baryon Spectroscopy: u, d, s Flavors



red — Universal GBE RCQM

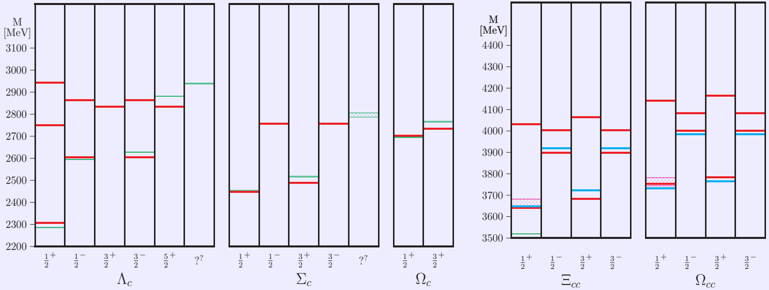
green — Particle Data Group (experimental values and their uncertainties)

Baryon Spectroscopy

of

Heavy Flavors

Baryon Spectroscopy: Single/Double Charm



↑ our value $m(\Xi_{cc}) = 3642$ MeV

Left panel – single charm:

red Universal GBE RCQM prediction

green Particle Data Group (experimental values + uncertainties)

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)

Universal GBE RCQM predictions

Baryon	J^P	URCQM
Ξ_{cc}	$\frac{1}{2}^+$	3642
Ξ_{cc}	$\frac{3}{2}^+$	3683
Ξ_{cc}	$\frac{1}{2}^-$	3899
Ξ_{cc}	$\frac{3}{2}^-$	3899
Ξ_{cc}	$\frac{1}{2}^-$	4004
Ξ_{cc}	$\frac{3}{2}^-$	4004
Ξ_{cc}	$\frac{1}{2}^+$	4032
Ξ_{cc}	$\frac{3}{2}^+$	4064

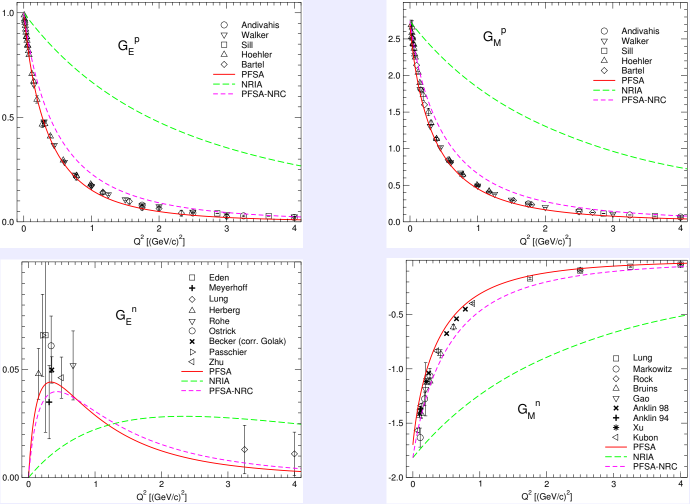
Electroweak Structures

of the

Nucleons and Other Baryon Ground States

Electromagnetic Nucleon Form Factors

Covariant predictions of the GBE RCQM:

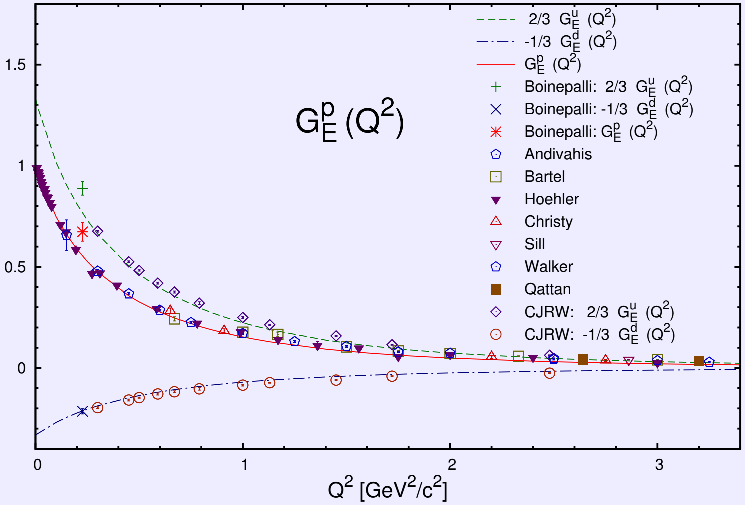


R.F. Wagenbrunn, S. Boffi, W. Klink, W. Plessas, and M. Radici: Phys. Lett. **B511** (2001) 33

Flavor Analysis: Proton Electric Form Factor

Intro
Spectroscopy
E.w. structure
Decays
CC Theory
$\tilde{N}$, $\tilde{\Delta}$ dressing
N and Δ masses
CC Quark Model
Vertex FFs
Quark model N, Δ
Summary
Addenda
Low-energy QCD
RCQM
URCQM
Baryon states
Baryon structures

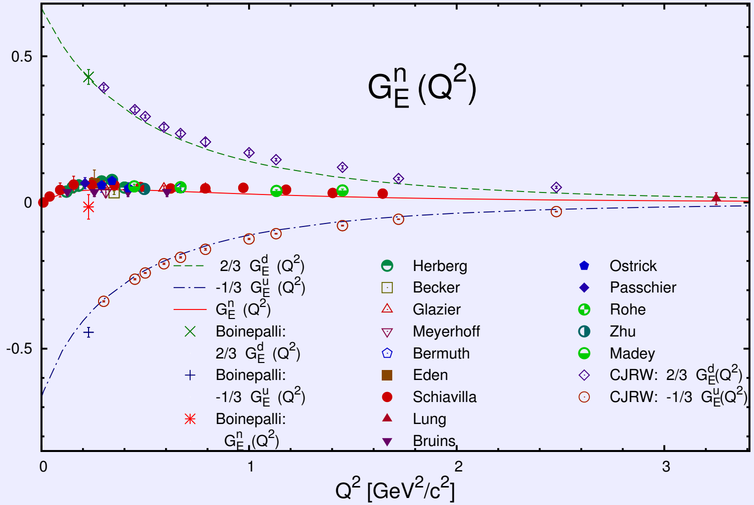
$$G_E^p = \frac{2}{3} G_E^u - \frac{1}{3} G_E^d$$



M. Rohrmoser, Ki-Seok Choi, and W. Plessas: Few-Body Syst. **58**, 83 (2017)

Flavor Analysis: Neutron Electric Form Factor

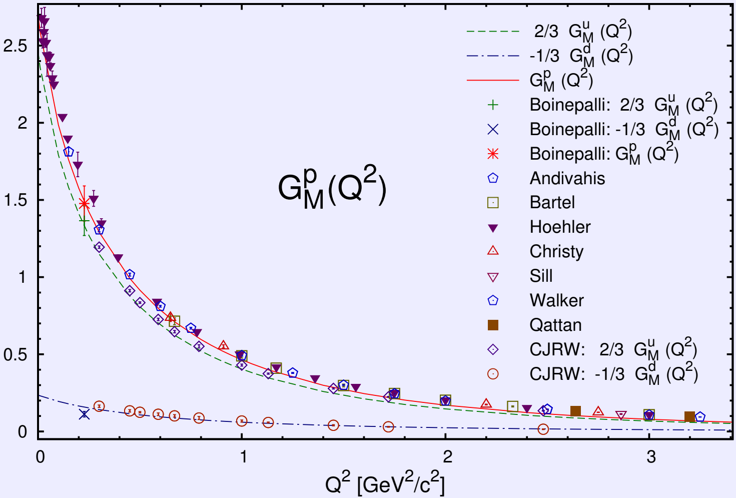
$$G_E^n = \frac{2}{3} G_E^d - \frac{1}{3} G_E^u$$



M. Rohrmoser, Ki-Seok Choi, and W. Plessas: Few-Body Syst. **58**, 83 (2017)

Flavor Analysis: Proton Magnetic Form Factor

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



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Flavor Analysis: Neutron Magnetic Form Factor

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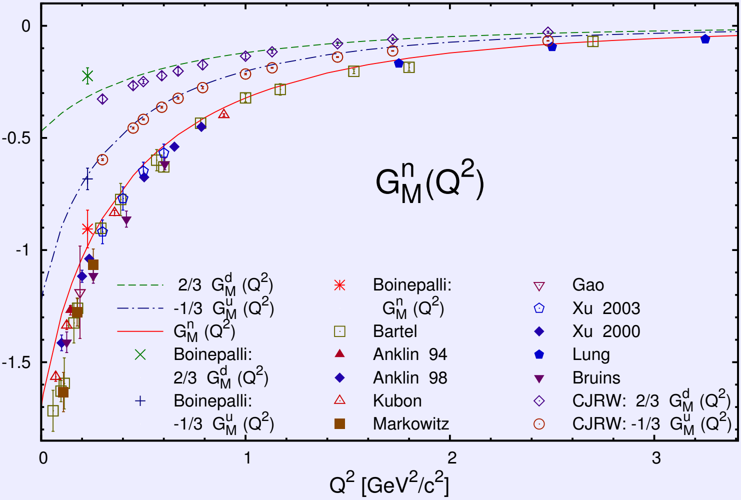
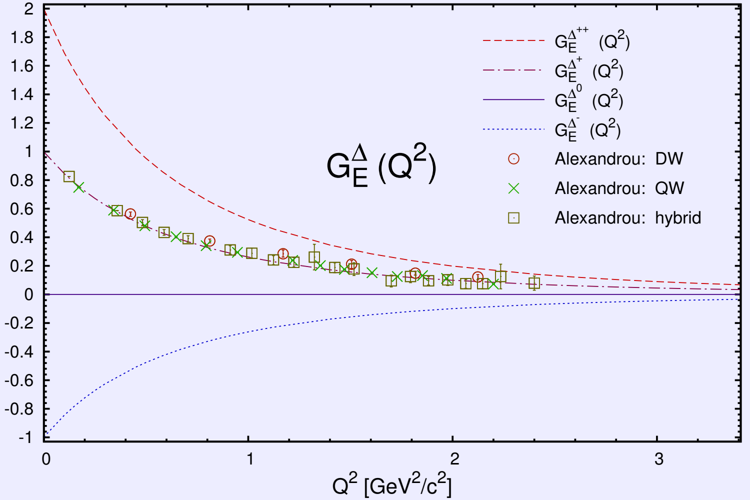


M. Rohrmoser, Ki-Seok Choi, and W. Plessas: Few-Body Syst. **58**, 83 (2017)

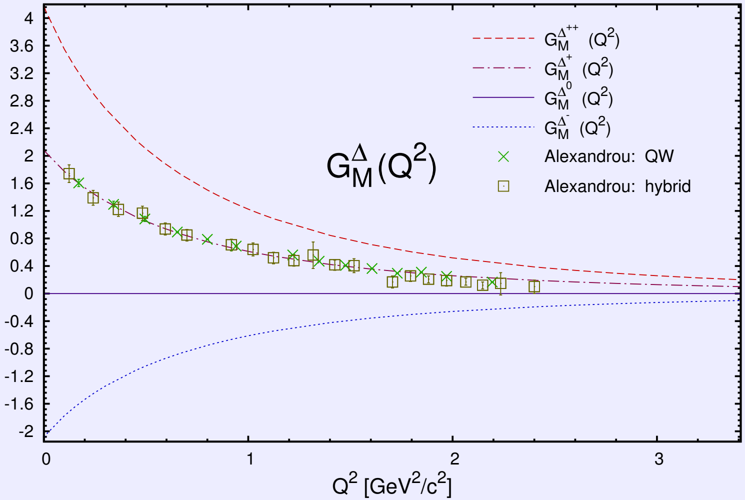
Electric Δ Form Factors



GBE RCQM: M. Rohrmoser, Ki-Seok Choi, and W. Plessas: Few-Body Syst. **58**, 83 (2017)

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

Magnetic Δ Form Factors



GBE RCQM: M. Rohrmoser, Ki-Seok Choi, and W. Plessas: Few-Body Syst. **58**, 83 (2017)

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

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

of

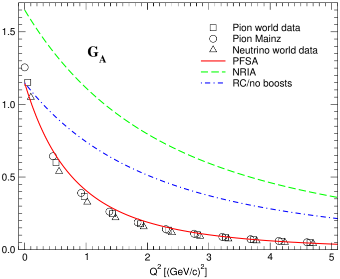
N Ground State and N^* Resonances

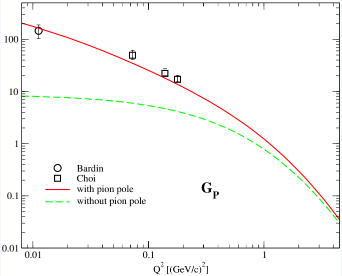
as well as

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

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)

More in Constituent-Quark-Model Review

W. Plessas:
Int. J. Mod. Phys. A30 (2015) 02, 1530013

also in:

"50 Years of Quarks"

ed. by M. Gell-Mann and H. Fritzsch

(World Scientific, Singapore, 2015)

π, η, and K Decay Modes

of

N^*, Δ^*, Λ^*, Σ^*, Ξ^* Resonances

Strong π Decays of Baryon Resonances

	Decay	Experiment (MeV)	Relativistic GBE (MeV)	Relativistic OGE (MeV)
$\Delta(1232)$	$\to N\pi$	$(119 \pm 1)^{+5}_{-5}$	35	31
$N(1440)$	$\to N\pi$	$(195 \pm 30)^{+113}_{-55}$	30	59
$\Lambda(1600)$	$\to \Sigma\pi$	$(53 \pm 38)^{+60}_{-10}$	3	33
$\Sigma(1660)$	$\to \Sigma\pi$	$\Gamma_{tot} = 40 - 200$	10	24
$\Sigma(1660)$	$\to \Lambda\pi$	$\Gamma_{tot} = 40 - 200$	8	5
$\Xi(1690)$	$\to \Xi\pi$	$\Gamma_{tot} < 30$	0.8	1.8

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

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

Similar characteristics obtained for η and K decays

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

Lesson from $\{QQQ\}$ Constituent-Quark Model

- **Baryon spectroscopy of all flavors** consistently described in a universal RCQM based on GBE dynamics
- The **covariant structures** of the ground states (N, Δ, Λ, ...) in good agreement with experiment (wherever such data are available)
- Predictions by the GBE RCQM reasonable consistent with (reliable) **lattice-QCD** results.
- **Disturbing shortcomings** of the $\{QQQ\}$ quark model for hadronic decays
- Obviously certain observables require **more than $\{QQQ\}$** degrees of freedom

Outline

Achievements, Problems, Challenges

Baryon spectroscopy
Nucleon and baryon electroweak structure
Reactions involving baryon resonances (decays)

Coupled-Channels Theory - Including Meson Channels

Dressing bare $\widetilde{N}$ and $\widetilde{\Delta}$ with pions / hadronic level
$\hookrightarrow$ N and Δ masses and Δ decay width

Relativistic Coupled-Channels Quark Model

Strong vertex form factors $\mathcal{F}_{\pi\widetilde{N}\widetilde{N}}, \mathcal{F}_{\pi\widetilde{N}\widetilde{\Delta}}, \mathcal{F}_{\pi\widetilde{\Delta}\widetilde{N}}\mathcal{F}_{\pi\widetilde{\Delta}\widetilde{\Delta}}$
π-dressed N and Δ from (miscroscopic) quark model

Conclusions and Outlook

Introducing

explicit mesonic degrees of freedom

$\hookrightarrow$ macroscopic / hadronic level

$\hookrightarrow$ microscopic / quark level

by a relativistic CC constituent-quark model

Theoretical Framework

- **Coupled-channels mass-operator eigenvalue equation**
  to include explicit mesonic degrees of freedom

$$\begin{pmatrix} M_{\widetilde{11}} & K_{12} & \cdots \\ K_{12}^{\dagger} & M_{\widetilde{22}} & \cdots \\ \vdots & \vdots & \ddots \end{pmatrix} \begin{pmatrix} \Psi_1 \\ \Psi_2 \\ \vdots \end{pmatrix} = m \begin{pmatrix} \Psi_1 \\ \Psi_2 \\ \vdots \end{pmatrix}$$

- $M_{\widetilde{11}}$ bare hadron mass operator of, e.g., $\widetilde{N}$, $\widetilde{\Delta}$,
  but also $\{QQQ\}_{\widetilde{N}}$, $\{QQQ\}_{\widetilde{\Delta}}$ etc.
- $M_{\widetilde{22}}$ free mass operator of, e.g., $\widetilde{N}+\pi$, $\widetilde{\Delta}+\pi$ channels,
  but also $\{QQQ\}_{\widetilde{N}}+\pi$ channels etc.
- K_{12} channel-coupling interaction
- m mass eigenvalue

Dressing

the bare nucleon $\widetilde{N}$ with π's

on the macroscopic (hadronic) level

The Nucleon with Explicit Pions

Coupled-channels mass-operator eigenvalue equation
for π-dressing of the bare nucleon $\widetilde{N}$

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

where m is now a real mass eigenvalue (of the π-dressed N).

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

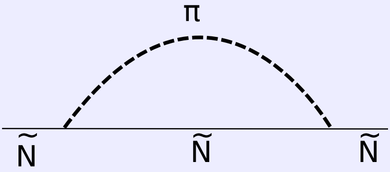
$$[M_{\widetilde{N}} + \underbrace{K_{\pi\widetilde{N}\widetilde{N}}(m - M_{\widetilde{N}+\pi})^{-1}K^{\dagger}_{\pi\widetilde{N}\widetilde{N}}}_{V_{opt}}]|\psi_N\rangle = m|\psi_N\rangle.$$

It is an exact eigenvalue equation of a two-channel problem, yielding m and $|\psi_N\rangle$ of the dressed (i.e. realistic) N.

πNN Eigenvalue Equation

$$\left\langle \widetilde{N} : v \mid [M_{\widetilde{N}} + \underbrace{K_{\pi\widetilde{N}\widetilde{N}} \mathbb{1}_{\widetilde{N}+\pi} (m - M_{\widetilde{N}+\pi})^{-1} \mathbb{1}_{\widetilde{N}+\pi} K^{\dagger}_{\pi\widetilde{N}\widetilde{N}}}] \mid \psi_N \right\rangle =$$

$$= m \left\langle \widetilde{N} : v \mid \psi_N \right\rangle$$



Transition interaction $K_{\pi\widetilde{N}\widetilde{N}}$ from pseudovector Lagrangian density:

$$\mathcal{L}^{PV}_{\pi\widetilde{N}\widetilde{N}}(x) = -\frac{f_{\pi\widetilde{N}\widetilde{N}}}{m_\pi} \bar{\psi}(x)\gamma^\mu\gamma_5\vec{\tau}\psi(x) \cdot \partial_\mu\vec{\phi}(x)$$

πNN Eigenvalue Equation ctd.

$$
\begin{aligned}
&\Bigg[m_{\widetilde{N}} + \int \frac{d^3k_\pi}{(2\pi)^3}\frac{1}{2\omega_\pi 2\omega_{\widetilde{N}} 2m_{\widetilde{N}}} \mathcal{F}_{\pi\widetilde{N}\widetilde{N}}(\vec{k}_\pi^2)\left\langle \widetilde{N} \mid \mathcal{L}_{\pi\widetilde{N}\widetilde{N}}(0) \mid \widetilde{N}, \pi : \vec{k}_\pi \right\rangle \\
\times \quad & \left(m - \sqrt{m_{\widetilde{N}}^2 + \vec{k}_\pi^2} - \sqrt{m_\pi^2 + \vec{k}_\pi^2}\right)^{-1} \\
\times \quad & \mathcal{F}^*_{\pi\widetilde{N}\widetilde{N}}(\vec{k}_\pi^2)\left\langle \widetilde{N}, \pi : \vec{k}_\pi \mid \mathcal{L}^\dagger_{\pi\widetilde{N}\widetilde{N}}(0) \mid \widetilde{N}\right\rangle\Bigg]\left\langle \widetilde{N} \mid \psi_N \right\rangle \\
= \quad & m\left\langle \widetilde{N} \mid \psi_N \right\rangle ,
\end{aligned}
$$

where the form factors $\mathcal{F}_{\pi\widetilde{N}\widetilde{N}}(\vec{k}_\pi^2)$ take into account the extended structures of the interaction vertices.

In the actual calculations we employed form factors from four different approaches in the literature.

Meson-Baryon Interaction Vertices (FF's)

Form factors $\mathcal{F}_{\pi\widetilde{N}\widetilde{N}}(\vec{k}_\pi^2)$ from

- Relativistic Constituent-Quark Model (RCQM) by the Graz group 2009
- Phenomenological meson-baryon model by Sato-Lee (SL)
- Meson-nucleon potential by Polinder-Rijken (PR Multipole)

$$\mathcal{F}_{\pi\widetilde{N}\widetilde{N}}(\vec{k}_\pi^2) = \frac{1}{1+\left(\frac{\vec{k}_\pi}{\Lambda_1}\right)^2+\left(\frac{\vec{k}_\pi}{\Lambda_2}\right)^4}$$

- Phenomenological meson-baryon model by Kamano, Nakamura, Lee, and Sato (KNLS)

$$\mathcal{F}_{\pi\widetilde{N}\widetilde{N}}(\vec{k}_\pi^2) = \left(\frac{\Lambda^2}{\vec{k}_\pi^2+\Lambda^2}\right)^2$$

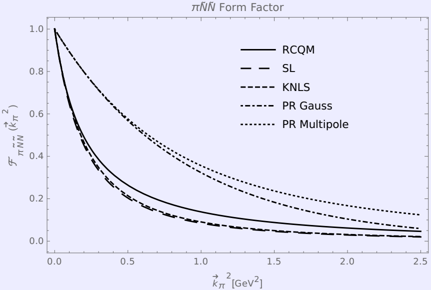
- Meson-nucleon potential by Polinder-Rijken (PR Gauss)

$$\mathcal{F}_{\pi\widetilde{N}\widetilde{N}}(\vec{k}_\pi^2) = \exp^{-\vec{k}_\pi^2/\Lambda^2}$$

π-Loop Effects on Nucleon Mass (hadronic)

	RCQM	SL	KNLS	PR Gauss	PR Multipole
m_N	939	939	939	939	939
$m_{\tilde{N}}$	1067	1031	1037	1025	1051
$m_N - m_{\tilde{N}}$	-128	-92	-98	-86	-112

(all values in MeV)



	$\frac{f^2_{\pi\tilde{N}\tilde{N}}}{4\pi}$
RCQM	0.0691
SL	0.08
KNLS	0.08
PR Gauss	0.013
PR Multipole	0.013

Dressing

the bare $\widetilde{\Delta}$ with π's

on the macroscopic (hadronic) level

The Δ with Explicit Pions

Coupled-channels mass-operator eigenvalue equation
for π-dressing of the bare Δ

$$\begin{pmatrix} M_{\tilde{\Delta}} & K_{\pi\tilde{N}\tilde{\Delta}} \\ K^{\dagger}_{\pi\tilde{N}\tilde{\Delta}} & M_{\tilde{N}+\pi} \end{pmatrix} \begin{pmatrix} |\psi_{\Delta}\rangle \\ |\psi_{N+\pi}\rangle \end{pmatrix} = m \begin{pmatrix} |\psi_{\Delta}\rangle \\ |\psi_{N+\pi}\rangle \end{pmatrix} .$$

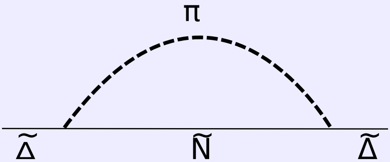
After Feshbach elimination of the $|\psi_{N+\pi}\rangle$ channel:

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

It is an exact eigenvalue equation for $|\psi_{\Delta}\rangle$,
yielding (above the πN threshold) in general
a complex mass m of the dressed (i.e. realistic) Δ.

$\pi N\Delta$ Eigenvalue Equation

$$\left\langle \widetilde{\Delta} : v \mid [M_{\widetilde{\Delta}} + \underbrace{K_{\pi\widetilde{N}\widetilde{\Delta}} \mathbb{1}_{\widetilde{N}+\pi} (m - M_{\widetilde{N}+\pi})^{-1} \mathbb{1}_{\widetilde{N}+\pi} K^{\dagger}_{\pi\widetilde{N}\widetilde{\Delta}}}] \mid \psi_{\Delta} \right\rangle = m \left\langle \widetilde{\Delta} : v | \psi_{\Delta} \right\rangle$$



Transition interaction $K_{\pi\widetilde{N}\widetilde{\Delta}}$ from pseudovector Lagrangian density:

$$\mathcal{L}^{PV}_{\pi\widetilde{N}\widetilde{\Delta}} = -\frac{f_{\pi\widetilde{N}\widetilde{\Delta}}}{m_{\pi}} \bar{\psi}(x) \vec{T} \cdot \partial_{\mu} \vec{\phi}(x) \psi^{\mu}(x) + h.c.$$

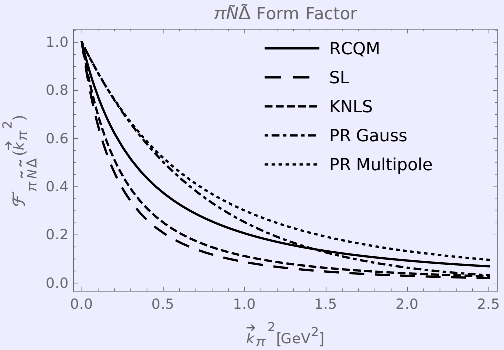
$\pi N \Delta$ Eigenvalue Equation ctd.

$$
\begin{aligned}
&\left[m_{\widetilde{\Delta}} + \int \frac{d^3 k_\pi}{(2\pi)^3} \frac{1}{2\omega_\pi 2\omega_{\widetilde{N}} 2 m_{\widetilde{\Delta}}} \mathcal{F}_{\pi\widetilde{N}\widetilde{\Delta}}(\vec{k}_\pi^2) \left\langle \widetilde{\Delta} \,\middle|\, \mathcal{L}_{\pi\widetilde{N}\widetilde{\Delta}}(0) \,\middle|\, \widetilde{N}, \pi : \vec{k}_\pi \right\rangle \right.\\
&\times \quad \left(m - \sqrt{m_{\widetilde{N}}^2 + \vec{k}_\pi^2} - \sqrt{m_\pi^2 + \vec{k}_\pi^2} \right)^{-1}\\
&\times \quad \left. \mathcal{F}^*_{\pi\widetilde{N}\widetilde{\Delta}}(\vec{k}_\pi^2) \left\langle \widetilde{N}, \pi : \vec{k}_\pi \,\middle|\, \mathcal{L}^\dagger_{\pi\widetilde{N}\widetilde{\Delta}}(0) \,\middle|\, \widetilde{\Delta} \right\rangle \right] \left\langle \widetilde{\Delta} \,\middle|\, \psi_\Delta \right\rangle\\
&= \quad m \left\langle \widetilde{\Delta} \,\middle|\, \psi_\Delta \right\rangle ,
\end{aligned}
$$

where the form factors $\mathcal{F}_{\pi\widetilde{N}\widetilde{\Delta}}(\vec{k}_\pi^2)$ take into account the extended structures of the interaction vertices.

In the actual calculations we employed form factors again from four different approaches in the literature.

Momentum Dependences of $\mathcal{F}_{\pi\tilde{N}\tilde{\Delta}}(\vec{k}_\pi^2)$



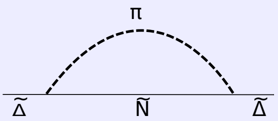
	RCQM	SL	KNLS	PR Gauss	PR Multipole
$\frac{f^2_{\pi\tilde{N}\tilde{\Delta}}}{4\pi}$	0.188	0.334	0.126	0.167	0.167

π-Loop Effects on Δ Mass and Width (hadr.)

	RCQM	SL	KNLS	PR Gauss	PR Multipole
$m_{\widetilde{N}}$	1067	1031	1037	1025	1051
$Re[m_\Delta]$	1232	1232	1232	1232	1232
$m_{\widetilde{\Delta}}$	1300	1290	1259	1321	1335
$Re[m_\Delta] - m_{\widetilde{\Delta}}$	-68	-58	-27	-89	-103
$2\ Im[m_\Delta] = \Gamma$	4	23	7	16	8
$\Gamma_{exp}(\Delta \to \pi N)$			~ 117		

(all values in MeV)

Decay to bare $\widetilde{N}$:



π-Loop Effects on Δ Mass and Width (hadr.)

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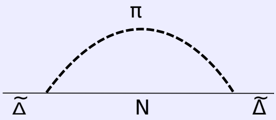
$Re[m_\Delta]$	1232	1232	1232	1232	1232
$m_{\tilde{\Delta}}$	1309	1288	1261	1328	1347
$Re[m_\Delta] - m_{\tilde{\Delta}}$	-77	-56	-29	-96	-114
$2\ Im[m_\Delta] = \Gamma$	47	64	27	51	52
$\Gamma_{exp}(\Delta \to \pi N)$			~ 117		

(all values in MeV)

Decay to physical N:



Summary on Dressing $\widetilde{N}$ and $\widetilde{\Delta}$ with π's

Investigated on the macroscopic/hadronic level:

- Dressing effect on N (ground-state) mass
- Dressing effect on Δ (resonance) mass and width
- Tested different models for πNN and $\pi N\Delta$ vertex form factors
- Higher-order π effects have been studied

  $\rightarrow$ minor corrections.

Microscopic picture:

Development of a coupled-channels RCQM

to include explicit π's on the microscopic level

$\{QQQ\}$ Cluster with Explicit Pions

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.

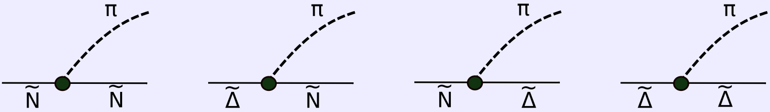
Strong $\pi\widetilde{N}\widetilde{N}$, $\pi\widetilde{N}\widetilde{\Delta}$, $\pi\widetilde{\Delta}\widetilde{N}$, and $\pi\widetilde{\Delta}\widetilde{\Delta}$ FFs

Equating the microscopic optical potential with the hadronic one (including vertex FF's)

$$\int K_{\pi\widetilde{QQQ}}(m - M_{\widetilde{QQQ}+\pi})^{-1} K^{\dagger}_{\pi\widetilde{QQQ}}$$

$$\sim \int \mathcal{F}_{\pi\widetilde{B}\widetilde{B}}(\vec{k}_\pi^2) K_{\pi\widetilde{B}\widetilde{B}}(m - M_{\widetilde{B}+\pi})^{-1} K^{\dagger}_{\pi\widetilde{B}\widetilde{B}} \mathcal{F}^{*}_{\pi\widetilde{B}\widetilde{B}}(\vec{k}_\pi^2)$$

allows to determine the various strong $\pi\widetilde{B}\widetilde{B}$ form factors $\mathcal{F}_{\pi\widetilde{B}\widetilde{B}}(\vec{k}_\pi^2)$ at the followingvertices:



Consistent Solution of the CC RCQM for N

$$\Bigg[m_{\tilde{N}} + \int \frac{d^3k_\pi}{(2\pi)^3} \frac{1}{2\omega_\pi 2\omega_{\tilde{N}} 2m_{\tilde{N}}} \mathcal{F}_{\pi\tilde{N}\tilde{N}}(\vec{k}_\pi^2) \left\langle \tilde{N} \mid \mathcal{L}_{\pi\tilde{N}\tilde{N}}(0) \mid \tilde{N}, \pi : \vec{k}_\pi \right\rangle$$

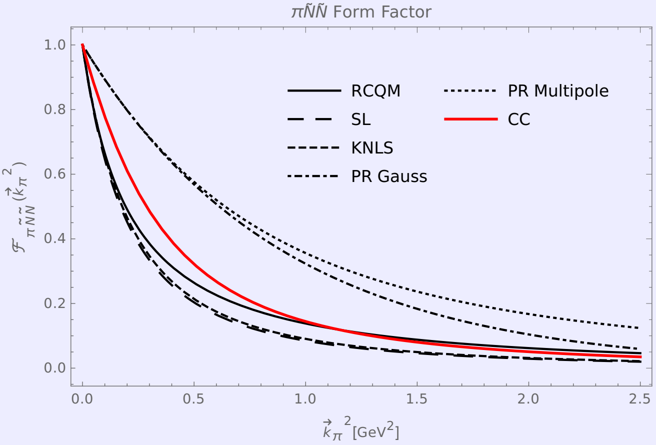
$$\times \quad \left(m - \sqrt{m_{\tilde{N}}{}^2 + \vec{k}_\pi^2} - \sqrt{m_\pi^2 + \vec{k}_\pi^2} \right)^{-1}$$

$$\times \quad \mathcal{F}^*_{\pi\tilde{N}\tilde{N}}(\vec{k}_\pi^2) \left\langle \tilde{N}, \pi : \vec{k}_\pi \mid \mathcal{L}^\dagger_{\pi\tilde{N}\tilde{N}}(0) \mid \tilde{N} \right\rangle \Bigg] \left\langle \tilde{N} \mid \psi_N \right\rangle = m \left\langle \tilde{N} \mid \psi_N \right\rangle$$

- Start with an arbitrary value $m_{\tilde{N}}^{(0)}$ for $m_{\tilde{N}}$ and calculate $\mathcal{F}^{(0)}_{\pi\tilde{N}\tilde{N}}(\vec{k}_\pi)$
- Use $\mathcal{F}^{(0)}_{\pi\tilde{N}\tilde{N}}(\vec{k}_\pi)$ in the eigenvalue equation to obtain $m = 939$ MeV and a corresponding bare mass $m_{\tilde{N}}^{(1)}$
- Take $m_{\tilde{N}}^{(1)}$ and calculate $\mathcal{F}^{(1)}_{\pi\tilde{N}\tilde{N}}(\vec{k}_\pi)$
- Repeat this iteration until a consistent solution is achieved

$\pi\widetilde{N}\widetilde{N}$ Form Factor from Microscopic Theory

Result of the **CC RCQM** compared to other models



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

(all values in MeV)

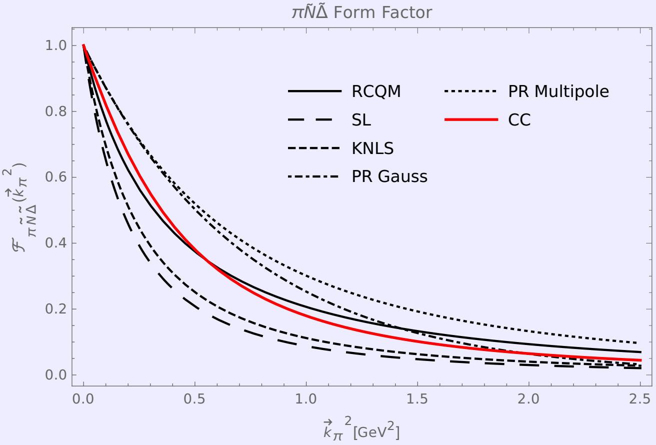
Consistent Solution of the CC RCQM for Δ

$$\Big[m_{\widetilde{\Delta}} + \int \frac{d^3k_\pi}{(2\pi)^3}\frac{1}{2\omega_\pi 2\omega_{\widetilde{N}} 2m_{\widetilde{\Delta}}} \mathcal{F}_{\pi\widetilde{N}\widetilde{\Delta}}(\vec{k}_\pi^2)\left\langle \widetilde{\Delta} \mid \mathcal{L}_{\pi\widetilde{N}\widetilde{\Delta}}(0) \mid \widetilde{N}, \pi : \vec{k}_\pi \right\rangle$$
$$\times \left(m - \sqrt{m_{\widetilde{N}}{}^2 + \vec{k}_\pi^2} - \sqrt{m_\pi^2 + \vec{k}_\pi^2} \right)^{-1}$$
$$\times \mathcal{F}^*_{\pi\widetilde{N}\widetilde{\Delta}}(\vec{k}_\pi^2)\left\langle \widetilde{N}, \pi : \vec{k}_\pi \mid \mathcal{L}^\dagger_{\pi\widetilde{N}\widetilde{\Delta}}(0) \mid \widetilde{\Delta} \right\rangle\Big]\left\langle \widetilde{\Delta} \mid \psi_\Delta \right\rangle = m \left\langle \widetilde{\Delta} \mid \psi_\Delta \right\rangle$$

- The bare N mass $m_{\widetilde{N}}$ is determined from above
- Assume an arbitrary value $m^{(0)}_{\widetilde{\Delta}}$ for $m_{\widetilde{\Delta}}$ and calculate $\mathcal{F}^{(0)}_{\pi\widetilde{N}\widetilde{\Delta}}(\vec{k}_\pi)$
- Use $\mathcal{F}^{(0)}_{\pi\widetilde{N}\widetilde{\Delta}}(\vec{k}_\pi)$ in the eigenvalue equation to obtain the physical Δ mass m and a corresponding bare mass $m^{(1)}_{\widetilde{\Delta}}$
- Take $m^{(1)}_{\widetilde{\Delta}}$ and calculate $\mathcal{F}^{(1)}_{\pi\widetilde{N}\widetilde{\Delta}}(\vec{k}_\pi)$
- Repeat this iteration until a consistent solution is achieved

$\pi\widetilde{N}\widetilde{\Delta}$ Form Factor from Microscopic Theory

Result of the **CC RCQM** compared to other models



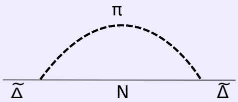
Pionic Effects on Δ Mass and Width

Predictions of the **CC RCQM**

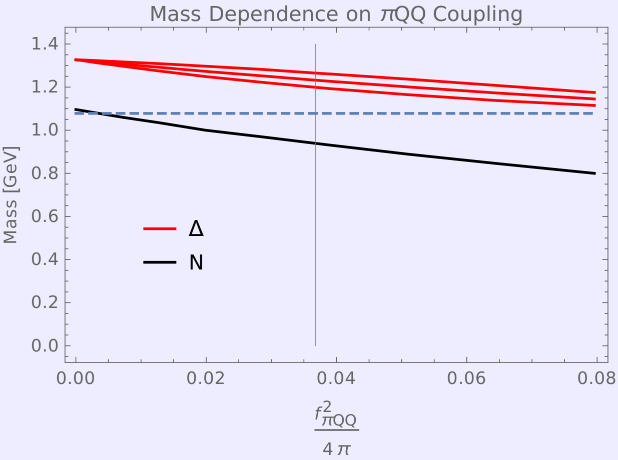
	CC	RCQM	SL	KNLS	PR Gauss	PR Multipole
$\frac{f^2_{\pi\tilde{N}\tilde{\Delta}}}{4\pi}$	0.239	0.188	0.334	0.126	0.167	0.167
m_N	939	939	939	939	939	939
$Re[m_\Delta]$	1232	1232	1232	1232	1232	1232
$m_{\tilde{\Delta}}$	1327	1309	1288	1261	1329	1347
$Re[m_\Delta] - m_{\tilde{\Delta}}$	-95	-77	-56	-29	-96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

(all values in MeV)

Δ decay to physical N:



Mass Dependence on Coupling Strength



Blue dotted line: decay threshold $m_N + m_\pi = 1078$ MeV

$(m_N = 939 \text{ MeV}, m_\pi = 139 \text{ MeV})$

Pionic Effects on Δ Mass and Width

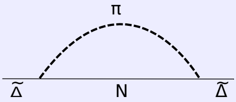
Predictions of the **CC RCQM**

with **dressed** coupling constant $f_{\pi N\Delta} = 1.3 \times f_{\pi\tilde{N}\tilde{\Delta}}$:

	CC	RCQM	SL	KNLS	PR Gauss	PR Multipole
$\frac{f^2_{\pi N\Delta}}{4\pi}$	0.403	0.318	0.564	0.213	0.282	0.282
m_N	939	939	939	939	939	939
$Re[m_\Delta]$	1232	1232	1232	1232	1232	1232
$m_{\tilde{\Delta}}$	1381	1356	1319	1279	1387	1418
$Re[m_\Delta] - m_{\tilde{\Delta}}$	-149	-124	-87	-47	-155	-186
$2\ Im[m_\Delta] = \Gamma$	118	83	106	45	94	97
$\Gamma_{exp}(\Delta \to \pi N)$			~ 117			

(all values in MeV)

Δ decay to physical N:



Conclusions and Outlook

- A $\{QQQ\}$ constituent-quark model **cannot provide** a comprehensive, simultaneous description of baryon ground **AND** resonant states
- A **coupled-channels theory** taking into account the π, as the Goldstone boson of spontaneous chiral-symmetry breaking of low-energy QCD, immediately offers new degrees of freedom
- A **consistent implementation** of pionic effects for the N and the Δ has now been achieved (in a relativistically-invariant framework)
- **Extensions to further resonances** are called for
- **Other** than just π couplings will presumably be needed

Thank you very much

for

your attention!