Baryon spectrum and (transition) form factors from QCD’s Faddeev equation

Christian S. Fischer

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with Gernot Eichmann, Helios Sanchis-Alepuz and Richard Williams

Review: Eichmann, Sanchis-Alepuz, Williams, Alkofer, CF, PPNP 91, 1-100 [1606.09602]
Eichmann, CF, Sanchis-Alepuz, PRD 94 (2016) [1607.05748]
Take home messages

• Light baryon spectrum:

![Graph showing the light baryon spectrum with various states labeled and their corresponding masses in MeV.](image)

Eichmann, CF, Sanchis-Alepuz, PRD 94 (2016) [1607.05748]

• Space- and time-like form factors: pion TFF as test-case

![Graph showing space- and time-like form factors with various data points and error bars.](image)

Weil, Eichmann, CF, Williams, arXiv:1704.05774

Eichmann, CF, Weil, Williams, arXiv:1704.06046
Overview

1. Introduction - quarks, gluons and mesons

2. Baryon spectrum - light and strange

3. Pion TFF, baryon form factors and decays
Baryons as relativistic three-quark bound states

- Underlying QCD forces
  - two-body vs. three-body
  - confinement
  - spin structure
  - meson cloud effects
  - heavy/heavy-light systems
- ‘Missing resonances’
- Coupled-channel effects

→ Δ vs Y - configuration
→ Regge trajectories ?!
→ (Hyper)-Fine structure
→ GB-exchange vs QCD
→ Flavor dependence
→ 3-quark vs. quark-diquark

Strategies to deal with this situation:

Nonperturbative QCD: Lattice, Functional methods

Effective theories with hadronic dof
Light baryon spectrum - quark model

- ‘missing resonances’ - three-body vs. quark-diquark
- level ordering: $N^{1\pm}_2$ vs. $\Lambda^{1\pm}_2$
Strange baryon spectrum quark model

- Light, strange and heavy spectrum probe QCD physics at different scales
- Need flavor dependent QCD forces to explain spectrum
- Models: parametrization via exchange of Goldstone-bosons

Ronniger, Metsch, EPJA 47 (2011) 162
See also Glozmann, Riska, Plessars et al.

- Flavor dependent forces should be determined from QCD
Extracting spectra from correlators

BSE for baryons (derived from equation of motion for G)

\[ p^2 = -m_{\lambda}^2 \]

- exact equation for baryon ‘wave function’
Diquark-Quark approximation

BSE for baryons (derived from equation of motion for G)

\[ \text{BSE for baryons} \]
Diquark-Quark approximation

BSE for baryons (derived from equation of motion for G)
Diquark-Quark approximation

BSE for baryons (derived from equation of motion for G)

\[ \Gamma_i = \Gamma_j + \Gamma_k + \text{no three-body forces} \]

Faddeev equation (no three-body forces)

\[ \Gamma_i = T_i \Gamma_j + T_i \Gamma_k \]

Diquark-quark
Diquark-Quark approximation

**BSE for baryons** (derived from equation of motion for $G$)

\[ \Gamma_{i}^{k} = \Gamma_{j}^{i} \Gamma_{j}^{k} + \Gamma_{j}^{i} \Gamma_{k}^{i} \]

**Faddeev equation** (no three-body forces)

\[ \Gamma_{i}^{k} = \Gamma_{j}^{i} \Gamma_{j}^{k} + \Gamma_{j}^{i} \Gamma_{k}^{i} \]

**Diquark-quark**

\[ \phi = \Gamma_{j}^{i} \Gamma_{j}^{k} \]

- Input in both cases: quark propagator and interaction

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Baryons as relativistic three-quark bound states

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The DSE for the quark propagator

-1 = -1 +

Approximations:

I) NJL/contact model:

-1 = 1 +

II) Quark-diquark model: Ansatz for quark prop (and diquark wave function)

III) Rainbow-ladder:

-1 = 1 +

IV) Beyond rainbow-ladder: solve DSEs for quarks, gluons and quark-gluon vertex

Sanchis-Alepuz, Williams, PLB 749 (2015) 592
Williams, CF, Heupel, PRD93 (2016) 034026, and refs. therein
Binosi, Chang, Papavassiliou, Qin, Roberts PRD95 (2017) 031501 and refs. therein
## DSE/Faddeev landscape

<table>
<thead>
<tr>
<th>I) Contact interaction</th>
<th>II) QCD-based model</th>
<th>III) DSE (RL)</th>
<th>III) RL</th>
<th>IV) bRL</th>
<th>IV) bRL + 3q</th>
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<tbody>
<tr>
<td>(N, \Delta) masses</td>
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<td>(N, \Delta) em. FFs</td>
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<td>(N \rightarrow \Delta\gamma)</td>
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- \(N, \Delta\) masses: \(Eichmann, Alkofer, Nicmorus, Krassnigg\)
- \(N, \Delta\) em. FFs: \(Eichmann, Alkofer, Sanchis-Alepuz, CF Williams\)
- **Roper**: \(Roberts et al\)
- \(N \rightarrow N^*\gamma\): \(Oettel, Alkofer, Bloch Segovia et al\).

**see talk of Ralf Gothe**
### DSE/Faddeev landscape

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- Roberts et al
- Oettel, Alkofer, Bloch, Segovia et al.
- Eichmann, Alkofer, Nicmorus, Krassnigg
- Eichmann, Alkofer, Sanchis-Alepuz, CF Williams

**See talk of Ralf Gothe**

Eichmann, N*-Workshop, Trento 2015
Rainbow-ladder model for quark-gluon interaction

Combine **gluon** with quark-gluon vertex:

**Effective coupling**

\[
\alpha(k^2) = \pi \eta^7 \left( \frac{k^2}{\Lambda^2} \right) e^{-\eta^2 \left( \frac{k^2}{\Lambda^2} \right)} + \alpha_{UV}(k^2)
\]

- **Scale** \( \Lambda \) from \( f_\pi \), masses \( m_u = m_d, m_s \) from \( m_\pi, m_K \)
- \( \alpha_{UV} \) from perturbation theory
- Parameter \( \eta \): band of results

Rainbow-ladder model for quark-gluon interaction

Combine *gluon* with *quark-gluon vertex*:

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Rainbow-ladder model for quark-gluon interaction

Combine gluon with quark-gluon vertex:

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- \( \Lambda \) from \( f_\pi \), masses \( m_u = m_d, m_s \) from \( m_\pi, m_K \)
- \( \alpha_{UV} \) from perturbation theory
- Parameter \( \eta \) : band of results

Quark mass: flavor dependence

Typical solution:

\[ [S(p)]^{-1} = \left[ -ip + M(p^2) \right] / Z_f(p^2) \]

- **\( M(p^2) \): momentum dependent!**
- **Dynamical mass:** \( M_{\text{strong}} \approx 350 \text{ MeV} \)
- **Flavour dependence because of** \( m_{\text{weak}} \)
- **Chiral condensate:** \( \langle \bar{\Psi} \Psi \rangle \approx (250 \text{ MeV})^3 \)
Quark mass: flavor dependence

Typical solution:

\[ S(p) = \left\{ \begin{array}{ll} \frac{1}{i\not{p} + M(p^2)Z_f(p^2)} & \text{for } \not{p} > 0 \\ \frac{1}{i\not{p} + M(p^2)} & \text{for } \not{p} < 0 \end{array} \right. \]

- **M(p^2):** momentum dependent!
- **Dynamical mass:** \( M_{\text{strong}} \approx 350 \text{ MeV} \)
- **Flavour dependence** because of \( m_{\text{weak}} \)
- **Chiral condensate:** \( \langle \bar{\Psi} \Psi \rangle \approx (250 \text{ MeV})^3 \)
good channels: 1--, 2++, 3--, ...  
acceptable channels: 0--  
clear deficiencies in other channels: missing spin-structure  
excited states fine! (in good channels)
Charmonium spectrum

- good channels: $1^{--}, 2^{++}, 3^{--}, ...$
- acceptable channels: $0^{-+}$
- clear deficiencies in other channels: missing spin-structure
- excited states fine! (in good channels)

---

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Baryons as relativistic three-quark bound states
Light meson spectrum

- **good channels (ground state):** $0^+, 1^-$
- **acceptable channels (ground state):** $2^{++}, 3^-$,
- **clear deficiencies in other channels and excited states**
good channels (ground state): 0\(^{-+}\), 1\(^{--}\)
acceptable channels (ground state): 2\(^{++}\), 3\(^{--}\),...
clear deficiencies in other channels and excited states
Light meson spectrum

- good channels (ground state): $0^-, 1^-$
- acceptable channels (ground state): $2^{++}, 3^-, ...$
- clear deficiencies in other channels and excited states
- drastic improvement beyond rainbow-ladder!

**Notes:**
- Christian Fischer (University of Gießen)
- Baryons as relativistic three-quark bound states
1. Introduction - quarks, gluons and mesons

\[ -1 = -1 - \]

2. Baryon spectrum - light and strange

\[ = + + + \]

3. Pion TFF, baryon form factors and decays
relativistic bound state:
- 64 tensor structures for octet: s, p, d - waves
- 128 tensor structures for decuplett: s, p, d, f - waves

\[
\Gamma(P, p, q) = \sum_l \tau_l F_l(P, p, q) \times (\text{flavour} \times \text{colour})
\]

\[
D_i \gamma_5 C \otimes D_j \Lambda_+(P), \quad \gamma_5 D_i \gamma_5 C \otimes \gamma_5 D_j \Lambda_+(P),
\]

\[
D_i = \{1, \varphi, q, \bar{p}, [\varphi, \bar{p}], [q, \bar{p}], [\varphi, q, \bar{p}]\}, \quad \Lambda_{\pm}(P) = \frac{1}{2} (1 \pm \hat{P}),
\]
nucleon and delta - channels: good results
but: severe problems in all other channels
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but: severe problems in all other channels
**Light baryon spectrum: diquarks**

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- nucleon and delta - channels: good results
- but: severe problems in all other channels
- artifact of rainbow-ladder: ps and v too strongly bound!
Light baryon spectrum: diquarks

- Nucleon and delta - channels: good results
- But: severe problems in all other channels
- Artifact of rainbow-ladder: ps and v too strongly bound!

Reduce binding in ps and v diquark channels, adjust to ρ-a₁-splitting
Light baryon spectrum: diquarks

- Spectrum in one to one agreement with experiment
- Correct level ordering (without coupled channel effects!)

Eichmann, CF, Sanchis-Alepuz, PRD 94 (2016) [1607.05748]

M [GeV]

\[
\begin{array}{cccccccc}
\text{N(1440)} & \text{N(1535)} & \text{N(1650)} & \text{N(1710)} & \text{N(1720)} & \text{N(1700)} & \text{N(1875)} & \text{N(1900)} \\
\frac{1}{2}^+ & \frac{1}{2}^- & \frac{3}{2}^+ & \frac{3}{2}^- & \frac{3}{2}^+ & \frac{3}{2}^- & \frac{1}{2}^+ & \frac{1}{2}^- \\
\end{array}
\]

\[\text{sc}+\text{av} \quad \text{ps}+\text{v}\]
Light baryon spectrum: diquarks

M [GeV]

- N(1440)
- N(1520)
- N(1535)
- N(1650)
- N(1710)
- N(1720)
- N(1880)
- N(1895)
- N(1900)
- N(1875)
- N(1920)
- N(1940)
- Δ(1232)
- Δ(1600)
- Δ(1700)
- Δ(1620)
- Δ(1900)
- Δ(1910)
- Δ(1920)

\[
\begin{align*}
\text{sc+av} & \quad \text{ps+v} \\
\frac{1}{2}^+ & \quad \frac{1}{2}^- \\
\frac{3}{2}^+ & \quad \frac{3}{2}^- \\
\frac{3}{2}^+ & \quad \frac{1}{2}^+ \\
\frac{1}{2}^- & \quad \frac{1}{2}^- 
\end{align*}
\]

- spectrum in one to one agreement with experiment
- correct level ordering (without coupled channel effects !)
- three-body agrees with diquark-quark where applicable

Eichmann, CF, Sanchis-Alepuz, PRD 94 (2016) [1607.05748]
Properties of the Roper

Angular mom. decomposition

<table>
<thead>
<tr>
<th>%</th>
<th>N</th>
<th>N* (1440)</th>
<th>Δ</th>
<th>Δ* (1600)</th>
</tr>
</thead>
<tbody>
<tr>
<td>s wave</td>
<td>66</td>
<td>15</td>
<td>56</td>
<td>10</td>
</tr>
<tr>
<td>p wave</td>
<td>33</td>
<td>61</td>
<td>40</td>
<td>33</td>
</tr>
<tr>
<td>d wave</td>
<td>1</td>
<td>24</td>
<td>3</td>
<td>41</td>
</tr>
<tr>
<td>f wave</td>
<td>−</td>
<td>−</td>
<td>&lt;0.5</td>
<td>16</td>
</tr>
</tbody>
</table>

- Zero crossing of wave function: 2s-state
- Every state is mixture of several partial waves!
- Different internal structure of radial excitations

Leading amplitude
Several q-values (relative momentum)

Eichmann, CF, Sanchis-Alepuz, PRD 94 (2016)
Eichmann, Sanchis-Alepuz, Williams, Alkofer, CF, PPNP 91 (2016)

Tension with simpler calculations ('contact interaction', 'QCD based model'):
Wilson, Cloet, Chang and Roberts, PRC 85 (2012) 025205,
Segovia, El-Bennich, Rojas, Cloet, Roberts, Xu and Zong, PRL 115 (2015) 17
Excited spectrum: Omega

Same level ordering as quark model, but larger masses

Exp. quantum numbers ?

Assignment according to: Gamermann, Garcia-Recio, Nieves and Salcedo, PRD 84 (2011) 056017
1. Introduction - quarks, gluons and mesons

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Extracting form factors from correlators

Form factor from BSEs (derived from equation of motion for G and ‘gauging’)

\[ J^\mu = \]

- exact equation for baryon form factors (similar for mesons)
Quark-photon vertex and pion form factors

Pion form factor:

Vector meson poles dynamically generated!

Maris, Tandy NPPS 161, 2006
**Pion transition form factor**

- **Large space-like momenta:**

  \[
  \eta^+ = \frac{Q^2 + Q'^2}{2}
  \]

  \[\tilde{F}(Q^2, Q'^2)\]

- **Small time-like momenta:**

  \[
  \Gamma(\pi^0 \rightarrow e^+ e^- \gamma) = 9.11(4) \times 10^{-11} \text{ GeV}
  \]

  \[
  \Gamma(\pi^0 \rightarrow e^+ e^- e^+ e^-) = 2.63(1) \times 10^{-13} \text{ GeV}
  \]

  \[
  B(\pi^0 \rightarrow e^+ e^-) = 6.21(3) \times 10^{-8}
  \]

  \[\text{PDG}\]

  \[
  \Gamma(\pi^0 \rightarrow e^+ e^- \gamma) = 9.06(18) \times 10^{-11} \text{ GeV}
  \]

  \[
  \Gamma(\pi^0 \rightarrow e^+ e^- e^+ e^-) = 2.58(12) \times 10^{-13} \text{ GeV}
  \]

  \[
  B(\pi^0 \rightarrow e^+ e^-) = 6.87(36) \times 10^{-8}
  \]

  [Eichmann, CF, Weil, Williams, arXiv:1704.06046]

  [Weil, Eichmann, CF, Williams, arXiv:1704.05774]
Nucleon form factors and magnetic moments

- **missing pion cloud effects**: Eichmann, PRD 84 (2011)
- **similar for axial form factors**: Eichmann and CF, EPJ A48 (2012) 9
\textbf{Δ-form factors}

- \(G_{E0}(Q^2)\) vs \(Q^2/M^2_\Delta\)
- \(G_{M1}(Q^2)\) vs \(Q^2/M^2_\Delta\)
- \(G_{E2}(Q^2)\) vs \(Q^2/M^2_\Delta\)
- \(G_{M3}(Q^2)\) vs \(Q^2/M^2_\Delta\)

\(\Delta\)-form factors may serve to distinguish between qqq and q-dq!

- Sanchis-Alepuz, Williams, Alkofer, PRD87 (2013)
- Nicmorus, Eichmann, Alkofer, PRD82 (2010)
Strange form factors: octet and decuplet

- Decuplet: prediction

DSE: Sanchis-Alepuz, CF, EPJA 52 (2016)
Transition form factor: $\mathcal{N}\Delta\gamma$

\[ R_{\text{EM}} = -\frac{G_E^{\ast}}{G_M^{\ast}}, \quad R_{\text{SM}} = -\frac{|\vec{Q}|}{2M\Delta} \frac{G_C^{\ast}}{G_M^{\ast}} \]

![Diagram showing $G_M^{\ast}(Q^2)$ and transition form factors $R_{\text{EM}}$ and $R_{\text{SM}}$](image)

- $R_{\text{EM}}$ highly dominated by p-waves!

Eichmann, Nicmorus, PRD 87 (2012)
Decays: $\rho\pi\pi$ and $\Delta N\pi$

- Decay constants can be calculated in rainbow-ladder (although bound states have no width)
- Good agreement with lattice and experiment

\[
g_{\Delta N\pi} = G_{\Delta N\pi}(Q^2 = -m_{\pi}^2)
\]

Mader, Eichmann, Blank, Krassnigg PRD84 (2011)
Decays: $\rho\pi\pi$ and $\Delta N\pi$

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Mader, Eichmann, Blank, Krassnigg PRD84 (2011)
Summary and outlook

- Goal: get control over microscopic QCD forces
- Light baryon spectrum in good agreement with experiment
  - No tightly bound diquarks, correct level ordering
- Baryon form factors determined in rainbow-ladder
  - missing pion cloud effects, good results at intermediate $Q^2$
- pion-TFF: connecting space- and time-like FF

Outlook

- QCD forces beyond rainbow ladder
- Details of strange spectrum
- Transition form factors of strange baryons

Review: Eichmann, Sanchis-Alepuz, Williams, Alkofer, CF, PPNP 91, 1-100 [1606.09602]
Partial wave content:

- N and Δ ground states dominated by s waves, negative-parity states typically by p waves (as expected)
- But ‘quark-model forbidden’ contributions are always present, e.g. Roper: dominated by p waves ⇒ relativity is important!
Mass evolution

Eichmann, CF, Sanchis-Alepuz, PRD 94 (2016)
Eichmann, Sanchis-Alepuz, Williams, Alkofer, CF, PPNP 91 (2016)
Mass evolution as expected for three-body state…
pion TFF - general idea

\[ \eta_+ = \frac{Q^2 + Q'^2}{2} \]
\[ \omega = \frac{Q^2 - Q'^2}{2} \]
\[ \eta_- = Q \cdot Q' \]

Idea:
- calculate FF inside cone
- interpolate to physical plane using VM pole as constraint
- can be done for arbitrary \( Q^2 \)
Diquarks with modified rainbow-ladder

\[ \alpha \text{ multiplied with } 0.35 \text{ in ‘bad’ channels} \]
3PI-truncation

propagators

vertices

\[ -1 \cdot -1 = \frac{1}{2} \cdot -1 \]

\[ -1 \cdot -1 = \frac{1}{2} \cdot -1 = -1 \]

\[ -1 + \frac{1}{2} + \frac{1}{2} = -1 \]

\[ -1 = \frac{1}{2} \cdot -1 \]

\[ -2 \cdot -1 = -2 \]

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Pion cloud effects

- Hadron level: \( \pi N \)-contributions to nucleon self-energy
- Quark-level: \( \pi \)-contributions to quark self-energy and interactions
Pion cloud effects

- Hadron level: $\pi N$-contributions to nucleon self-energy
- Quark-level: $\pi$-contributions to quark self-energy and interactions

Pion not an elementary field!
Derived from DSE for quark-gluon interaction!

CF, Nickel and Wambach, PRD 76 (2007) 094009
Baryon masses- including pion cloud

- fix $\Lambda$ by $f_{\pi\pi}$, vary $\eta$ s.t. $f_{\pi\pi}$ still ok
- effects of the order of 50-100 MeV
- missing: gluon self-interaction effects

$$\alpha(k^2) = \pi \eta^7 \left( \frac{k^2}{\Lambda^2} \right) e^{-\eta^2 \left( \frac{k^2}{\Lambda^2} \right)} + \alpha_{UV}(k^2)$$
### Pion cloud effects in baryons: structure

<table>
<thead>
<tr>
<th></th>
<th>Nucleon</th>
<th></th>
<th>Delta</th>
<th></th>
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<td>s-wave</td>
<td>p-wave</td>
<td>d-wave</td>
<td>s-wave</td>
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<td>quark core</td>
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<td>24</td>
<td>1</td>
<td>61</td>
</tr>
<tr>
<td>quark core +</td>
<td>75</td>
<td>24</td>
<td>1</td>
<td>60</td>
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<tr>
<td>pion cloud</td>
<td></td>
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</tbody>
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\[
\sigma_{\pi N} = 30(3) \text{ MeV (quark core only)}
\]

\[
\sigma_{\pi N} = 31(3) \text{ MeV (quark core + pion cloud)}
\]

- Pion cloud does not change shape of nucleon: uniform skin
- Sigma-term small...

Sanchis-Alepuz, CF; Kubrak, PLB 733 (2014) [1401.3183]