Baryon properties from DSEs/BSEs

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Contents

- The framework and its goals
- Spectrum
- Electromagnetic structure of baryons
- Future (Outlook)

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DISCLAIMER:

This talk reflects only part of the work of our group.

Many other groups useDSE/BSEs in different systems

and/or at different approximation levels

(e.g. El-Bennich's talk on Tuesday)

Motivation. First principles

- Strong interactions are described by QCD. QCD is a theory of **quarks** and **gluons.** But the **only observable** particles are **Hadrons** (quarks and gluons are confined within bound states). Can we understand their structure from QCD?

Ultimate Goal:

- Using only QCD input, (propagators, vertices, etc.) extract hadron properties, and do it directly in a **continuum QFT** formulation.
- In a DSE/BSE framework we could add/remove interaction terms and study their effect on hadron properties (example: what is the effect of the different components of the quark-gluon vertex in the spectrum?)

Motivation. Useful phenomenology

- The spectrum of hadrons is not completely understood.
- Perhaps **more interesting**: Form factors contain information about the internal structure of hadrons.
- They also tell us how the hadron couples to external fields (e.g. photons). Important for other research fields.
- Very little is known experimentally about hadron FFs, with the exception of pion and nucleon and some static properties of other hadrons.
- We aim at **providing reliable information on properties of hadrons**. How reliable they are, one infers from comparison with known data.

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In **this talk** I will focus on **baryons** (mostly as three-quark objects)

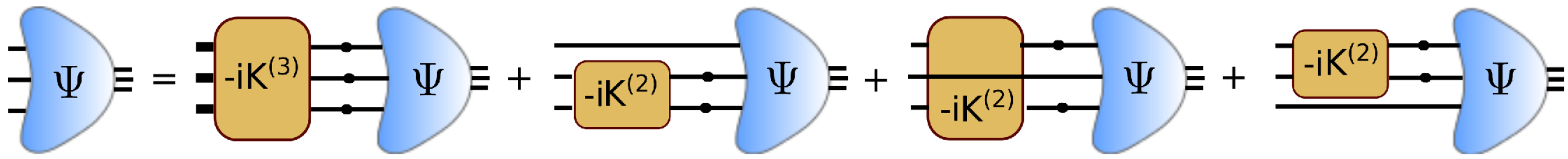
Framework (Covariant BSEs in a nutshell)

Further details:
Eichmann, HSA, Williams, Alkofer, Fischer -- PPNP 91 (2016) 1-100

HSA, Williams
To appear in Comp. Phys. Comm.

Framework (Covariant BSEs in a nutshell)

Baryon spectrum
(**Three-body Bethe-Salpeter eq.** $\sim$ Faddeev eq.):



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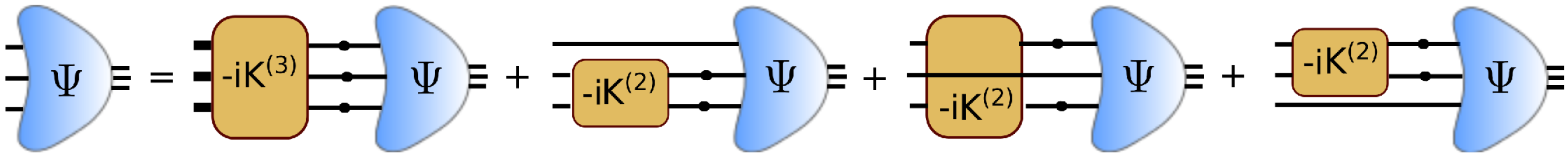
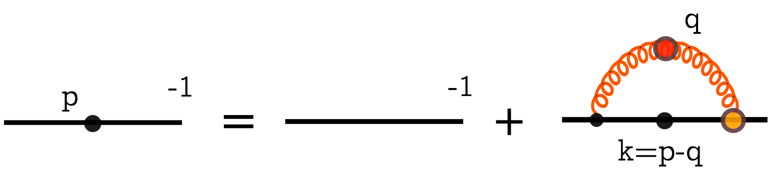


Elements needed:

- Interaction kernels K
- **Quark propagator. We obtain this by solving the quark Dyson-Schwinger eq.**



- i.e. additionally we need the quark-gluon vertex and the gluon propagator

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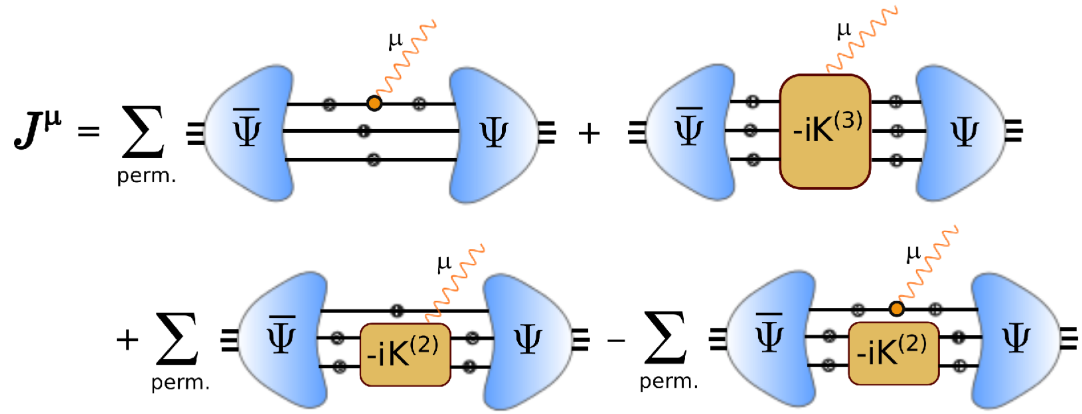
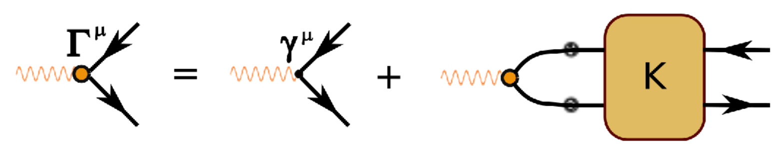
Framework (Covariant BSEs in a nutshell)

Coupling to external current:



Additional elements needed:

- **Quark-photon vertex. We obtain this by solving the vertex (inhomogeneous) BSE**



- Additionally, we need to know how does the current couple to the interaction kernels

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Symmetries and Truncations

Clearly, the equations are not exactly solvable, since the are an **infinite system** of coupled equation.

They must be **truncated to a finite system** (curse of DSEs/BSEs)

What do we demand to a «**good truncation**» **for** QCD **phenomenology**?

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What do we demand to a «**good truncation**» **for** QCD **phenomenology**?

- Preserve chiral symmetry in the chiral limit
- Implement a mechanism for dynamical chiral symmetry breaking

Those are essential features for hadron phenomenology

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What do we demand to a «**good truncation**» **for** QCD **phenomenology**?

- Preserve chiral symmetry in the chiral limit
- Implement a mechanism for dynamical chiral symmetry breaking

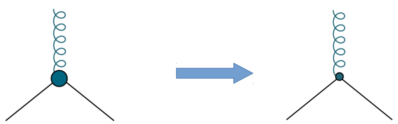
Those are essential features for hadron phenomenology

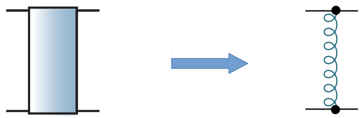
- Respect (eletromagnetic) charge conservation.

Obviously important for, e.g. , calculation of form factors

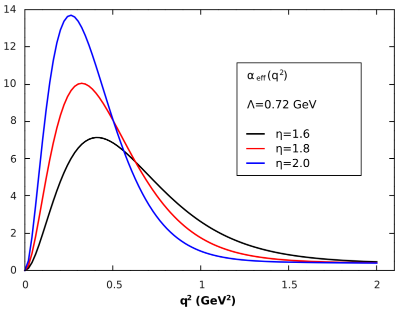
Symmetries and Truncations

The results we will show in what follows are obtained using the **Rainbow-Ladder truncation** of the DSE/BSE system:





Effective coupling



2-parameter model.
We fit to pion physics (pion mass and decay constant) **once and for all!**

Symmetries and Truncations

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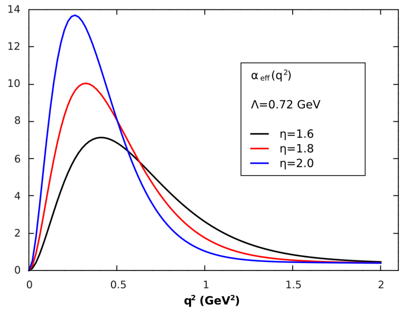
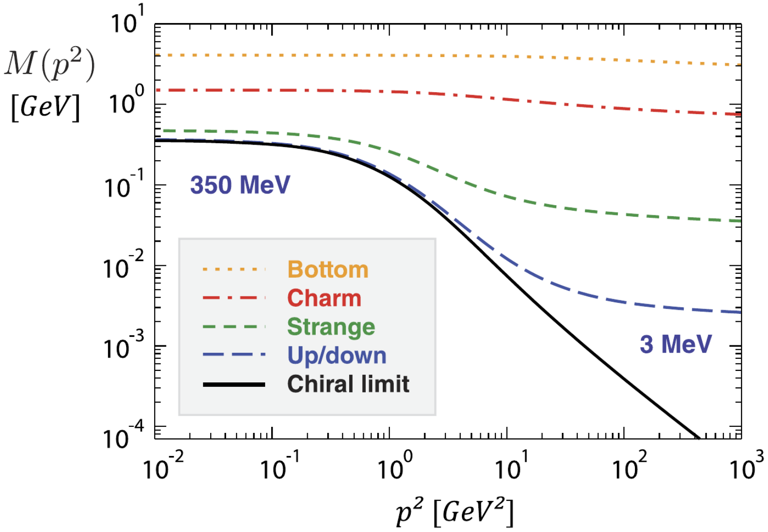




- Simplest truncation fulfilling the previous requirements
- As we will see, **performs surprisingly well for ground-state phenomenology**
- From symmetry requirements only, we cannot enlarge this truncation systematically (**more on truncations later**)

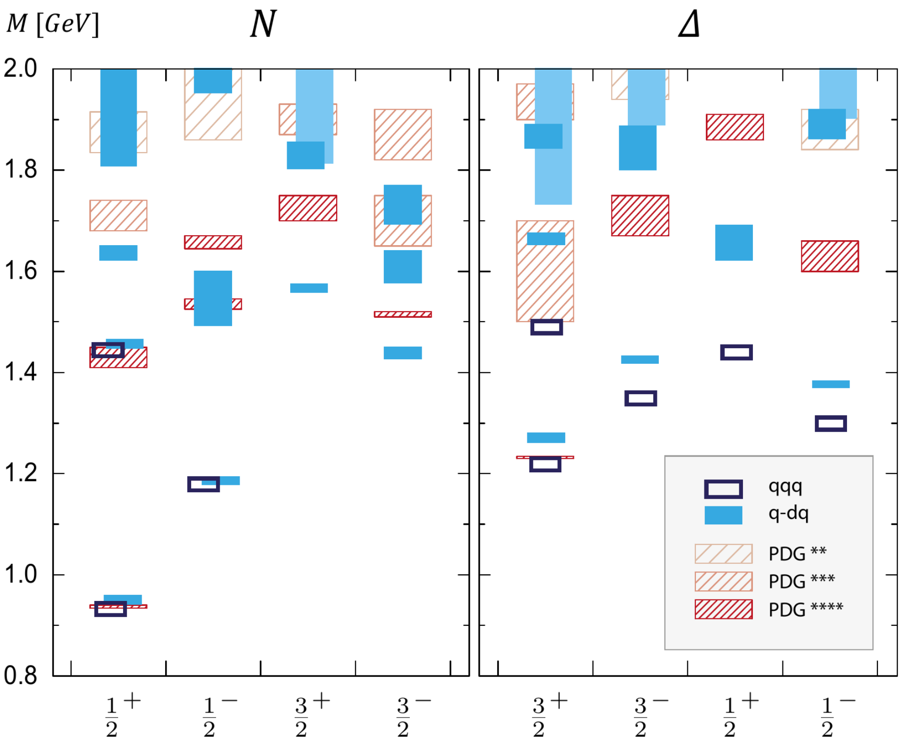
Selected RL results. Baryon spectrum

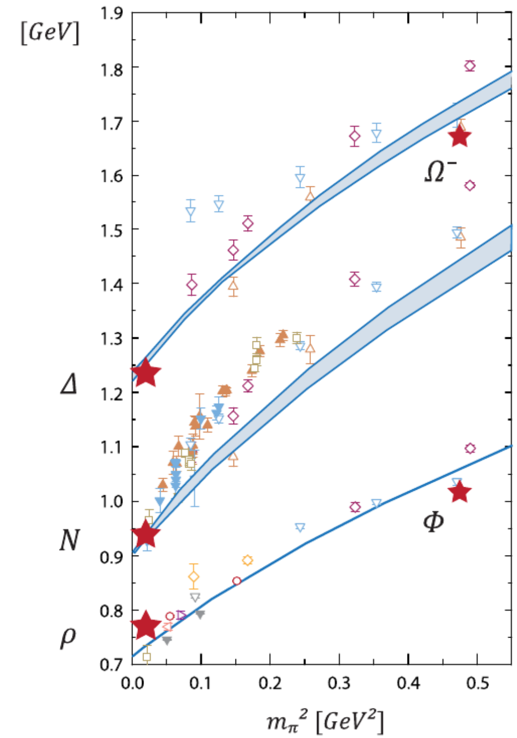
(LIGHT) BARYON MASSES

Selected RL results. Baryon spectrum

Eichmann, HSA, Fischer   Phys.Rev. D94 (2016)
Eichmann, HSA, Williams, Alkofer, Fischer   PPNP 91 (2016) 1-100

- Ground-state positive-parity masses well reproduced





- Baryon-mass evolution with the quark mass allows to understand explicit chiral-symmetry breaking
- It also allows to compare with lattice QCD; there one can work with unphysical quark masses

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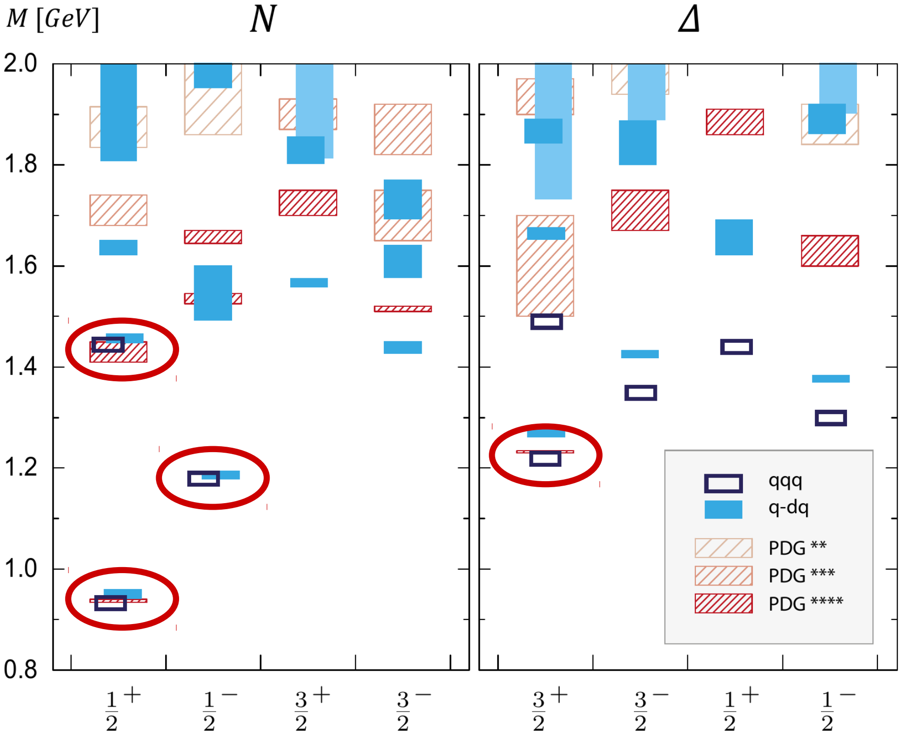

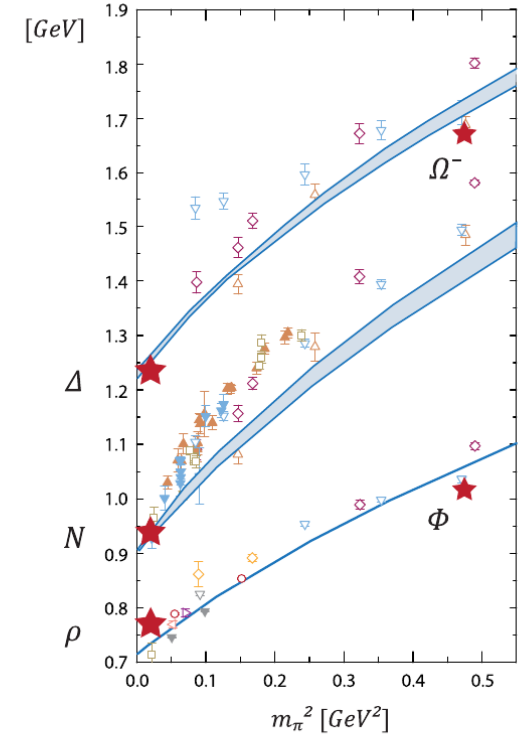

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Selected RL results. Baryon spectrum

HSA, Fischer Phys.Rev. D90 (2014)
Eichmann, HSA, Williams, Alkofer, Fischer PPNP 91 (2016) 1-100

- Ground-state strange baryons slightly underestimated. Reason: flavour independence of RL truncation
- Still, agreement reasonably good, given the simplicity of the model

$1/2^+$	N	Σ	Λ	Ξ
Faddeev	0.930 (3)	1.073 (1)	1.073 (1)	1.235 (5)
Experiment	0.938	1.189	1.116	1.315
Relative difference	< 1 %	10 %	4 %	6 %

$3/2^+$	Δ	Σ^*	Ξ^*	Ω
Faddeev	1.21 (2)	1.33 (2)	1.47 (3)	1.65 (4)
Experiment	1.232 (1)	1.385 (2)	1.533 (2)	1.672
Relative difference	2 %	4 %	4 %	1 %

Selected RL results. Baryon spectrum

Take-away message

- The simplest truncation possible is capable of reproducing positive-parity ground-state masses surprisingly well.
- Other parity channels and excited states have to wait for more sophisticated truncations (more on this later)

Selected RL results. Baryon structure

BARYON FORM FACTORS

(spacelike) Electromagnetic FFs

(spacelike) Electromagnetic FFs

What about electromagnetic structure?

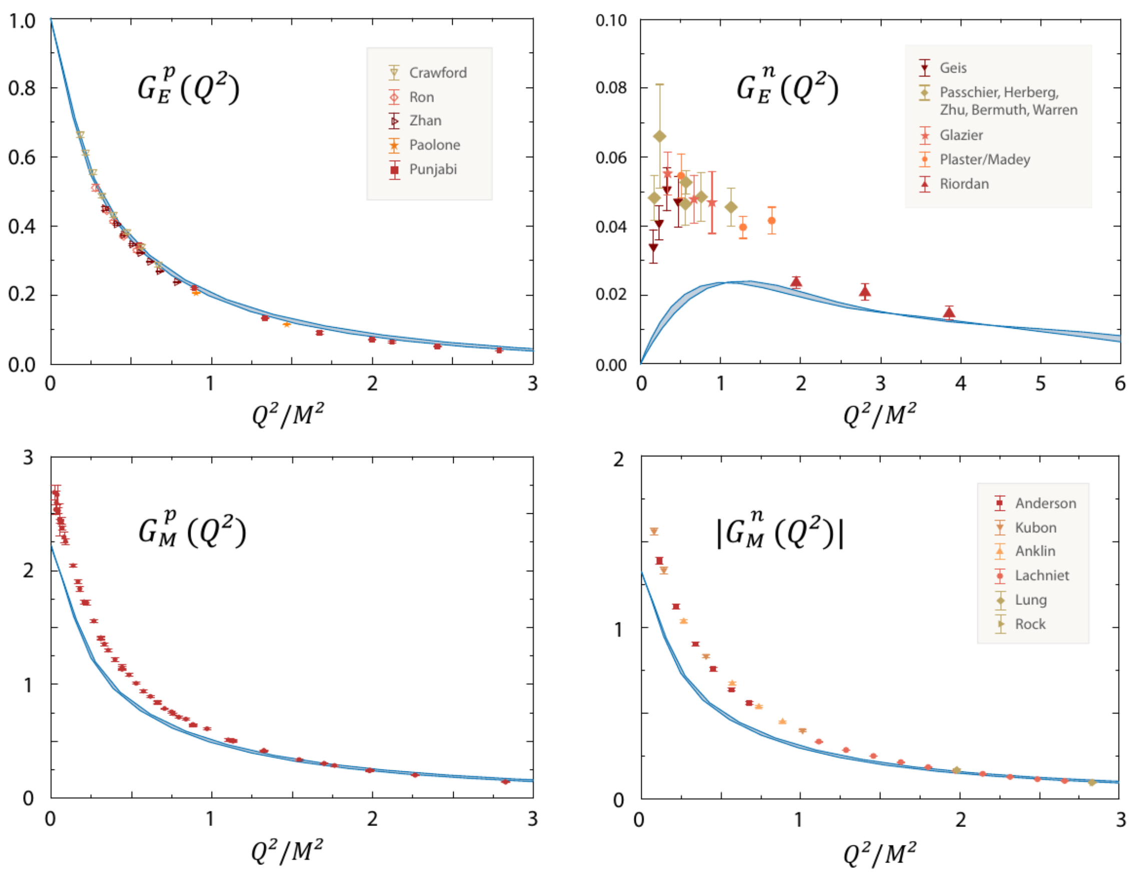
- Experiment: Nucleon elastic and Nucleon-Delta transition.
- Lattice QCD (first-principles computer simulation): Delta and Octet hyperons
- What can we do for phenomenology?

Strategy:

- Where experiment or lattice QCD data exists: compare and learn **where does our model show defficiencies and where is it reliable**.
- Where no data available: From what we learned above, we can make **predictions in some momentum regimes**.

Octet electromagnetic FFs. Nucleon

Nucleon electromagnetic form factors
Eichmann Phys.Rev. D84 (2011) 014014



- Effect of **pion cloud** expected to be **sizable at low photon momentum** (Q^2), especially for neutron.
- This appears as a discrepancy of our result with experiment at low-Q^2
- Where the influence of pion cloud is small (moderate to high Q^2), the calculation is in **excellent agreement with experiment.**

Also calculated (baryons):

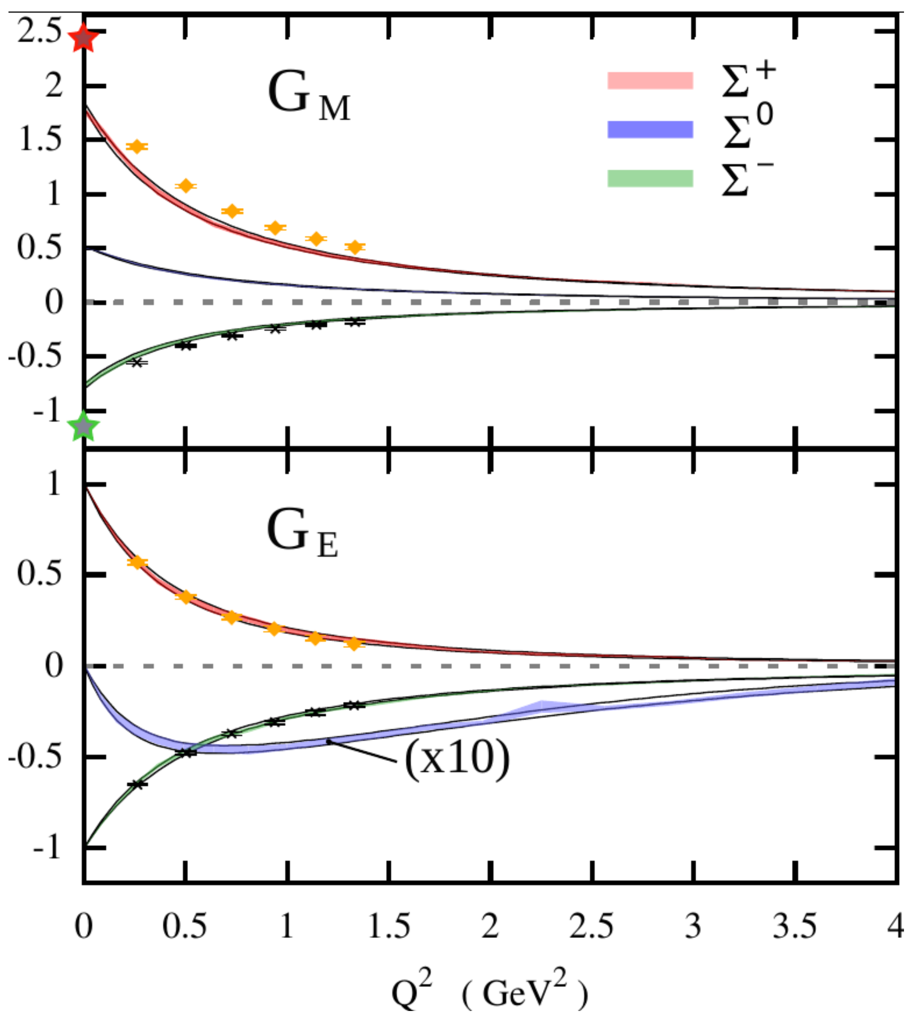
- Nucleon Axial FFs. **Eichmann, Fischer Eur.Phys.J. A48 (2012) 9**

  Same pattern

Octet electromagnetic FFs. Sigma

LATTICE: Shanahan et al. PRD89 (2014) PRD90 (2014)

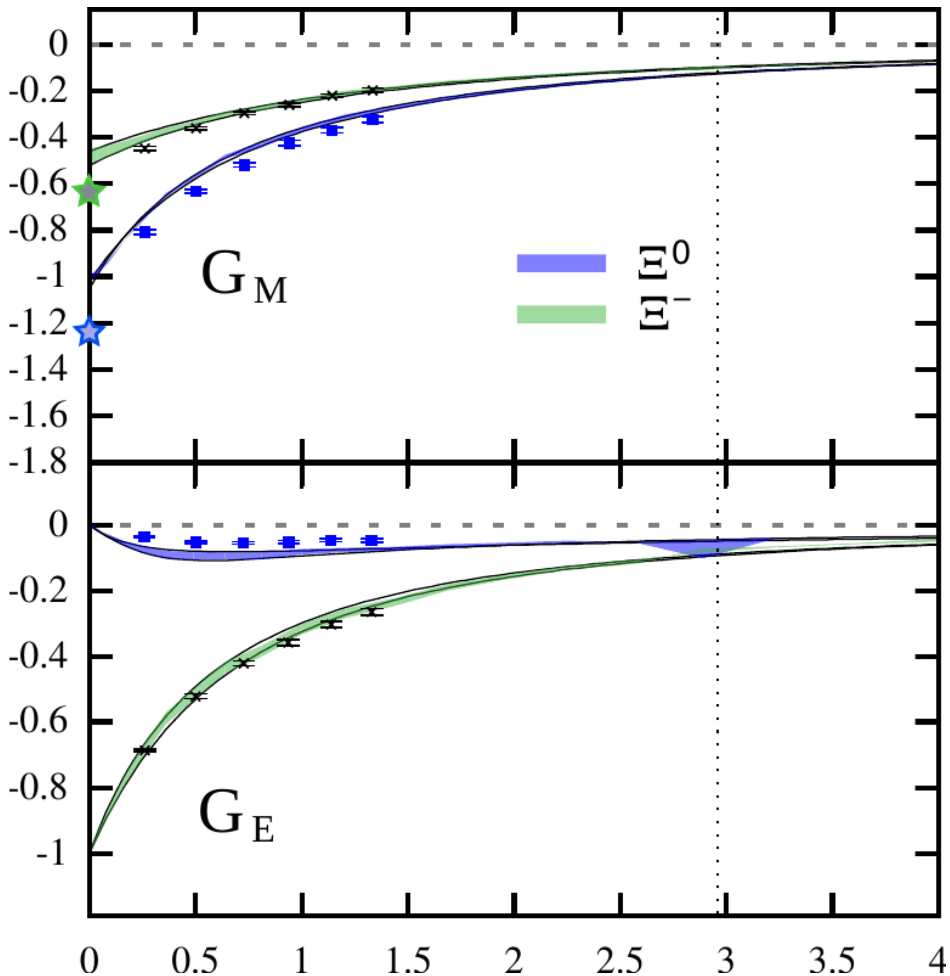
HSA, Fischer Eur.Phys.J. A52 (2016) no.2, 34



- Here, pion but also strange-meson cloud (e.g. Kaon cloud) play a role.
- Electric FF (GE) in excellent agreement with lattice QCD. They are «protected» by charge conservation.
- Kaon cloud stronger for Σ+ than for Σ- (see χ-PT calculation **Boinepalli et al. Phys. Rev. D74 (2006), Leinweber Phys. Rev. D69 (2004)**), thus better agreement for Σ+ at low Q^2
- No other data at high Q^2. **Prediction**?
- No other data for Σ0. **Prediction**?
- Static values (Q=0) always underestimated.

Octet electromagnetic FFs. Xi

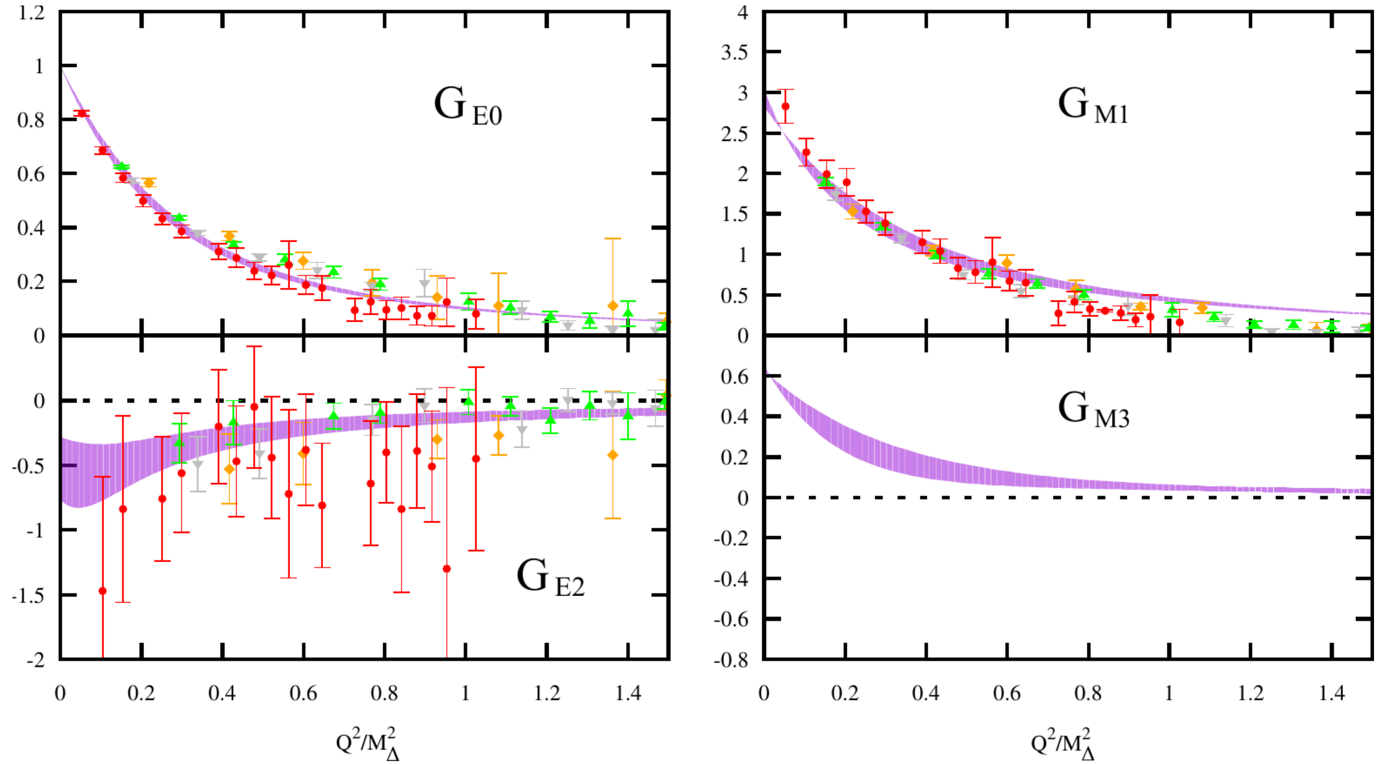
HSA, Fischer Eur.Phys.J. A52 (2016) no.2, 34



- Pion and Kaon cloud generally smaller than for Σ's (see again Boinepalli et al. Phys. Rev. D74 (2006), Leinweber Phys. Rev. D69 (2004)), and even smaller for Ξ-
- Agreement with lattice QCD improved wrt. Nucleon and Σ's.
- Again, no data at high Q^2. **Prediction**?
- Static values underestimated.

Decuplet electromagnetic FFs. Delta

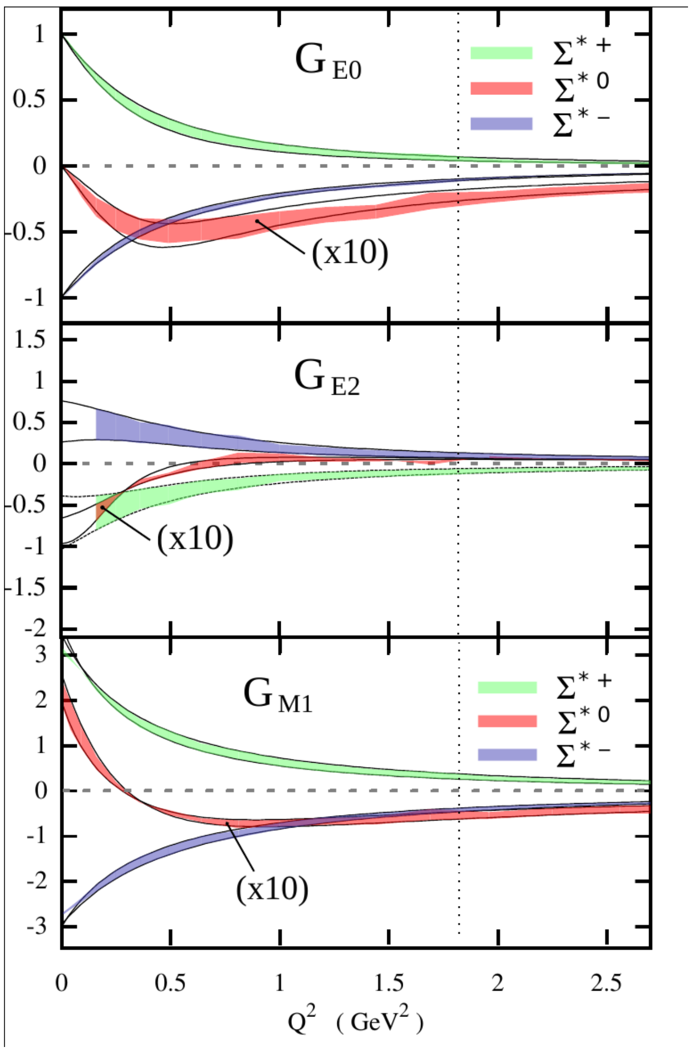
HSA, Williams, Alkofer Phys.Rev. D87 (2013)



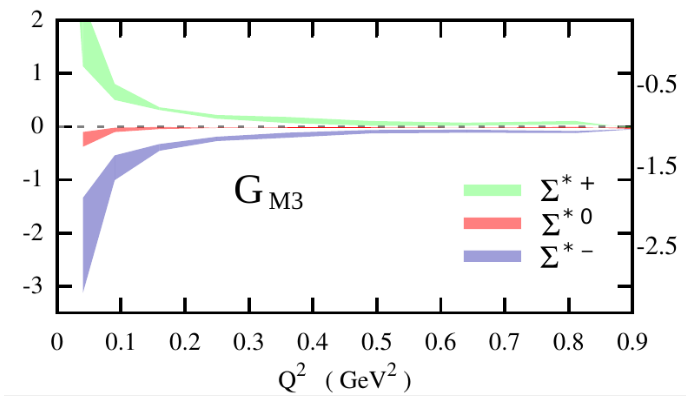
- **Similar pattern as with the octet FFs** (here compared with lattice data at unphysical pion mass. Thus, absence of meson cloud less apparent)
- For spin-3/2 baryons we have **direct access to** their **shape**:
  - Deformation of electric charge distribution GE2:
  - Deformation of magnetic moment distribution GM4:

+/- Oblate/ Prolate

Decuplet electromagnetic FFs. Sigma*



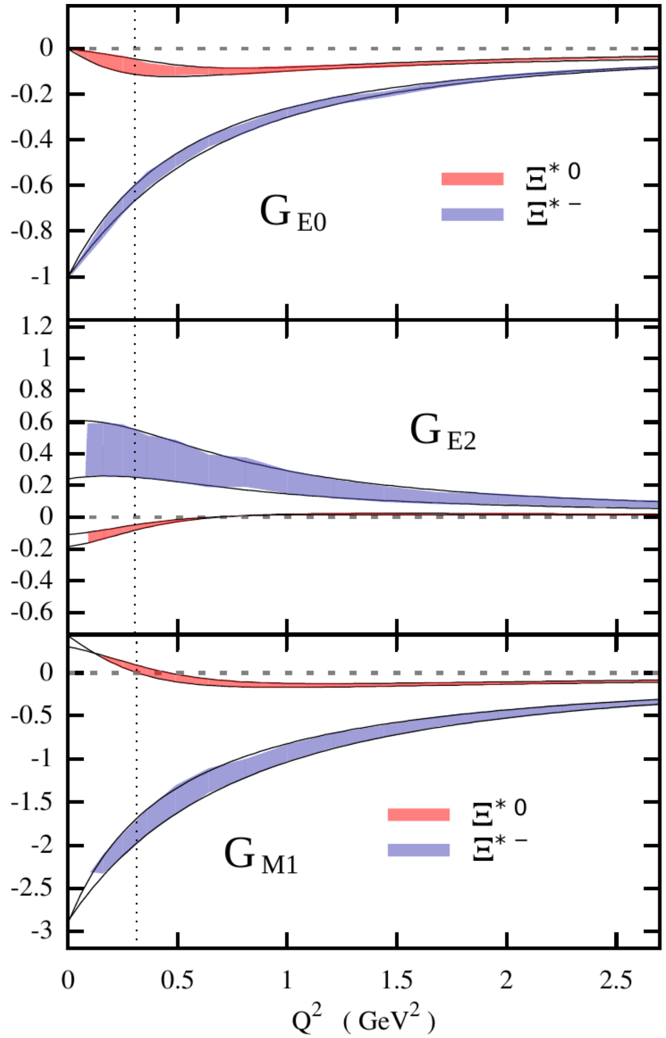
HSA, Fischer Eur.Phys.J. A52 (2016) no.2, 34

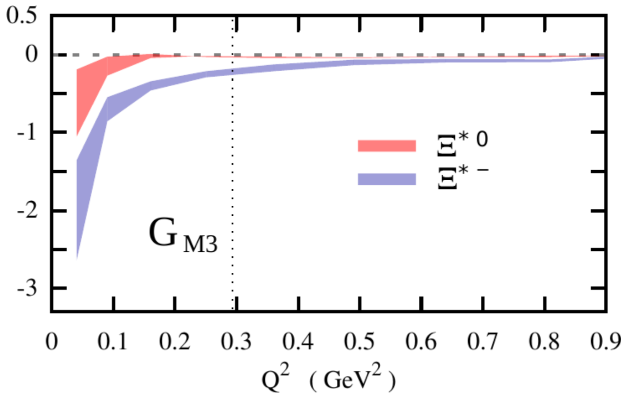


- No data at all, lattice or experiment.
- Claim: our calculation gives a **qualitative description of Hyperon FFs at low Q^2 that becomes a quantitative prediction at high Q^2**.
- Some things to note:
  - FFs for Σ^{*0} not vanishing (they are for Δ^0)
  - Zero-crossing for GM1 in Σ^{*0}: oblate ⟶ prolate

Decuplet electromagnetic FFs. Xi*

HSA, Fischer Eur.Phys.J. A52 (2016) no.2, 34





- Some things to note:
  - FFs for Ξ^{*0} not vanishing (they are for Δ^0)
  - Zero-crossing for GM1 in Ξ^{*0}: oblate prolate

Decuplet-Octet transition FFs:

HSA, Alkofer, Fischer arXiv:1707.08463 [hep-ph]

Selected RL results. Baryon structure

Take-away message

- At the present stage, gives a **qualitative description of baryon FFs at low Q^2 that becomes a quantitative prediction at high Q^2**.
- Qualitative features can (most probably) be taken seriously, even at the present level of truncation (more on this later)
- **For quantitative predictions**, we have to wait at least until **pion effects** have been included (technically hard, but possible: **HSA, Fischer Phys.Lett.B733 (2014) ; Eichmann,Fischer,Kubrak,Williams in preparation)**

Future

A Glimpse into the Future

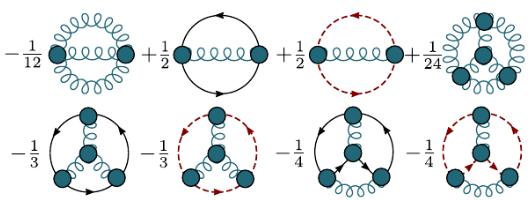
Truncations

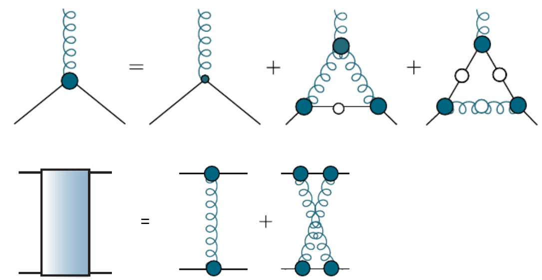
- A more systematic way of defining truncations is using effective action or **nPI techniques** (see, e.g. Berges et al. Phys. Rep. 363 (2002) 223–386)

- $\Gamma_{nPI}(\Phi, D, V, \ldots)$ is a generating functional for all the Green'S functions of the theory (QCD), where the Green's fucntions up to order n are considered independent.

$$\left.\frac{\delta \Gamma_{\mathrm{nPI}}}{\delta \tilde{\phi}}\right|_{\tilde{\phi}=0} = \left.\frac{\delta \Gamma_{\mathrm{nPI}}}{\delta D}\right|_{D=\overline{D}} = \left.\frac{\delta \Gamma_{\mathrm{nPI}}}{\delta U}\right|_{U=\overline{U}} = \cdots = 0 \quad \sim> \quad \text{DSEs} \quad ;$$

- A **loop expansion of** Γ_{nPI} is possible (it is an expansion in Planck's const.)
  - Interacting part to three-loop order

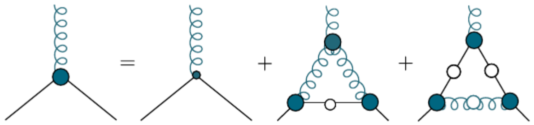


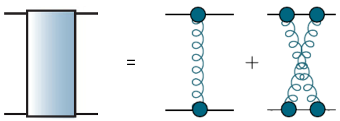


- The **expansion of the nPI** action is **systematic**, and it induces a **well-defined (truncated) BSE kernel** (Fukuda 1987 Prog.Theor.Phys. 78 | HSA, Williams, J.Phys.Conf.Ser.631(1) (2015) 012064)

- Such a scheme also preserves chiral symmetry and its breaking patterns

Truncations. 3PI masses





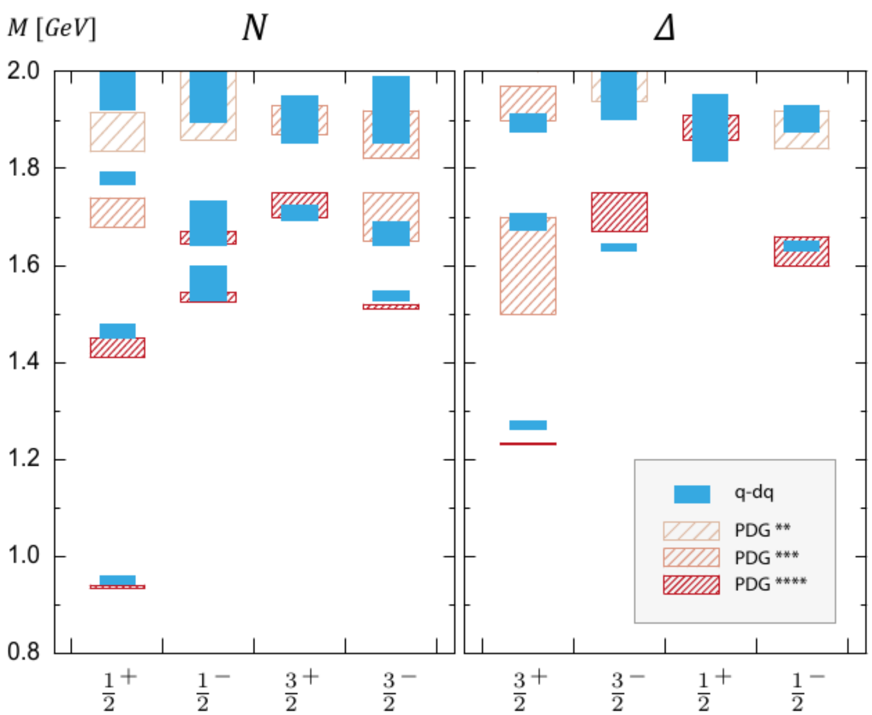
Williams, Fischer, Heupel, Phys.Rev. D93 (2016)

	RL	2PI-3L	3PI-3L	PDG
0^{-+} (π)	$0.14^{\dagger}$	$0.14^{\dagger}$	$0.14^{\dagger}$	0.14
0^{++} (σ)	0.64	0.52	1.1(1)	0.48(8)
1^{--} (ρ)	0.74	0.77	0.74	0.78
1^{++} (a_1)	0.97	0.96	1.3(1)	1.23(4)
1^{+-} (b_1)	0.85	1.1	1.3(1)	1.23

- Calculation done **without modelling**!! Propagators and vertices solved from their DSEs
- Meson spectrum in excellent agreement with experiment (scalar is expected to be heavy)
- **Baryons** in same truncation: **WIP**

Truncations. 3PI masses

Eichmann, Fischer, HSA PRD94 (2016)



- Without a full 3PI baryon calculation, we can «mimic» the result as follows:

  H. L. L. Roberts, L. Chang, I. C. Cloet, and C. D. Roberts, Few Body Syst. 51, 1 (2011), arXiv:1101.4244 [nucl-th].

  C. D. Roberts, I. C. Cloet, L. Chang, and H. L. L. Roberts, AIP Conf. Proc. 1432, 309 (2012), arXiv:1108.1327 [nucl-th]

  - Simplify the three-body problem to a quark-diquark problem
  - Artificially, make the pseudoscalar and vector diquarks heavier (analogous to scalar and axial-vector mesons being heavy in the 3PI truncation)

- **Baryons** spectrum shows very good agreement with experiment now, also in negative-parity channels and excited

Future

- The combined DSE/BSE framework is a powerful tool to calculate hadron properties. (spacelike) Electromagnetic form factors of all bayon octet and decuplet members are calculated or underway.
- We have quantitative predictions in some Q^2 regions and can make qualitative ones (e.g. shape, signs, etc.) for the rest
- Several technical and physical issues have to be tackled:

SHORT TERM / WIP

- Baryon masses without modelling (that is, 3PI kernel)
- Other FFs (e.g. axial)

MID TERM / MANPOWER-DEPENDENT

- Baryon FFs without modelling (that is, 3PI kernel)
- Inclusion of meson cloud (Doable.)

LONG TERM. EXPLORATORY

- Timelike FFs