Understanding baryons with DSEs and BSEs

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Bound States in Strongly coupled systems
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Contents

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

Motivation. First principles

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?)

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Immediate Goal:

- Form factors contain information about the internal structure of hadrons. They also tell us how the hadron couples to external 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.

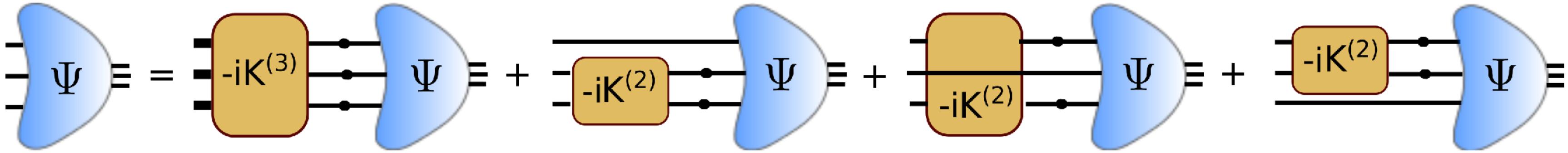
Framework (Covariant BSEs in a nutshell)

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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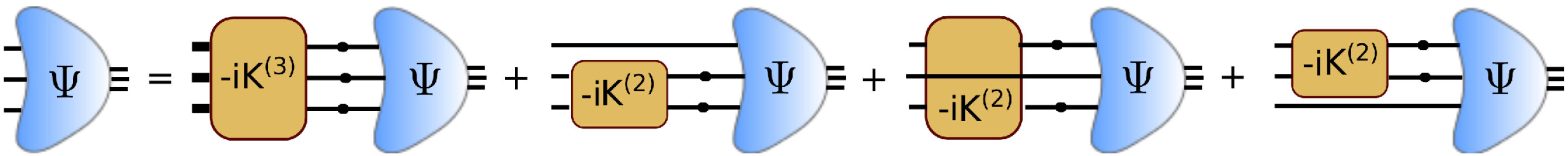
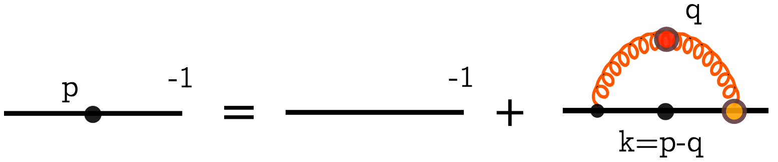


Elements needed:

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

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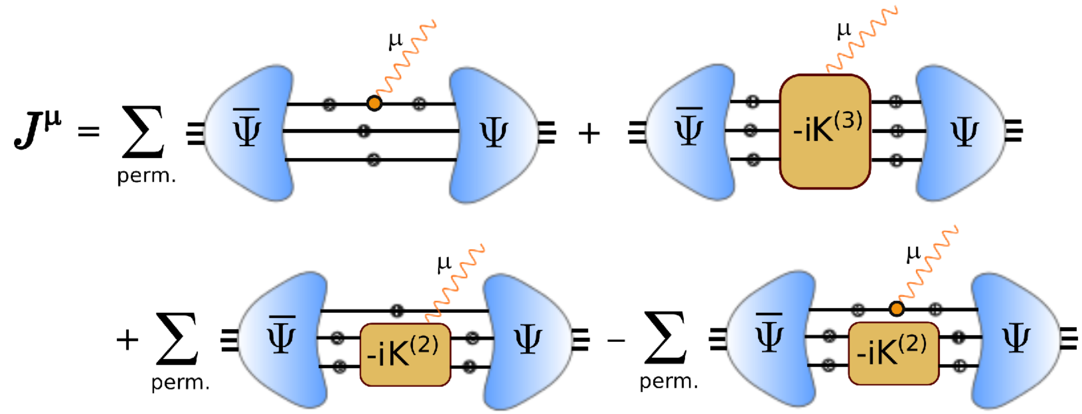
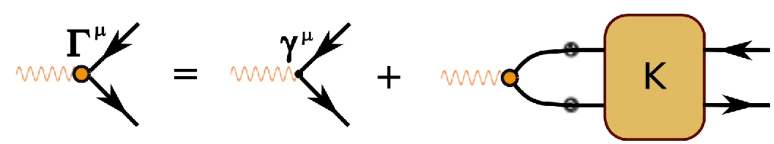
Framework (Covariant BSEs in a nutshell)

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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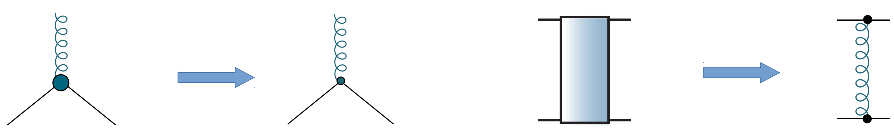
Truncation (see G. Eichmann and C. Fischer talks)

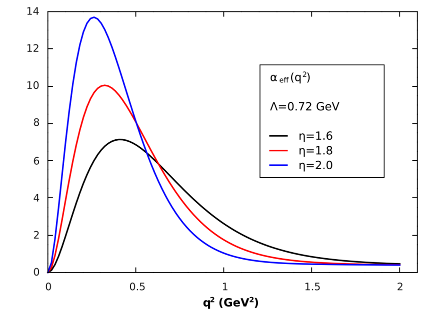
The results we will show in what follows are obtained using the **Rainbow-Ladder truncation** of the DSE/BSE system:



- Preserves AxVWTI
- Preserves VWTI

Effective coupling

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



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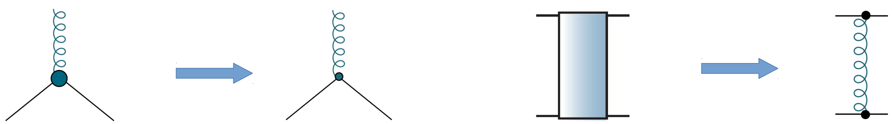

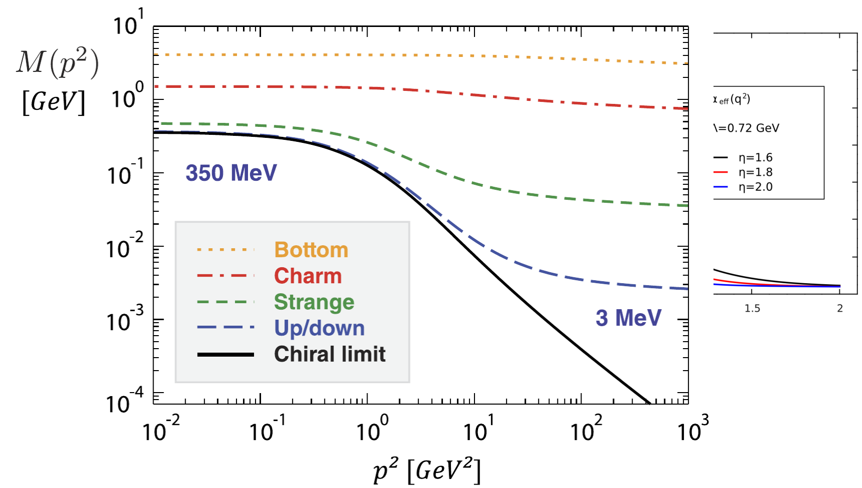

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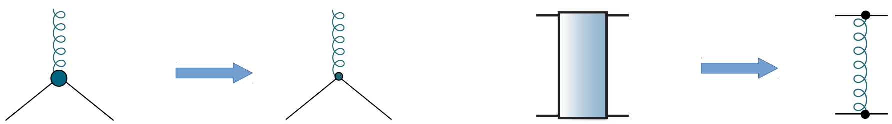
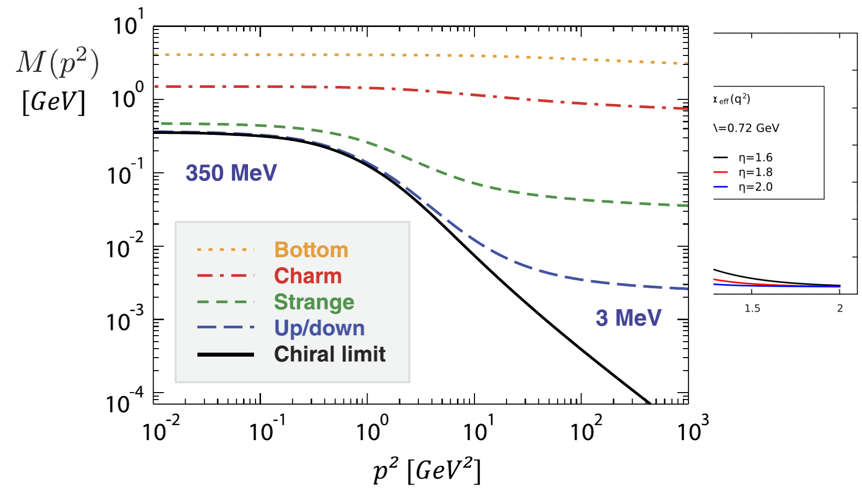




- Preserves AxVWTI
- Preserves VWTI

What are we missing?

- Fine details of the quark-gluon interaction (e.g. spin-orbit, quark-mass dependence, ...). Affect mostly excited states
- «Unquenching» effects, i.e. meson cloud effects (**will affect form factors; this talk**)
- ...

Technicalities. Covariant basis

What we have (for free!):

- Poincare covariance demands that **all possible «partial waves»** (quark-spin and orbital angular momentum) must be **present in the Bethe-Salpeter amplitude**
- The importance of each of them for each state is determined dynamically, **not fixed by hand**

nucleon

	s-wave	p-wave	d-wave	
S=1/2	8	24		64
S=3/2		12	20	

delta

	s-wave	p-wave	d-wave	f-wave	
S=1/2		24	40		128
S=3/2	4	12	20	28	

spin 5/2

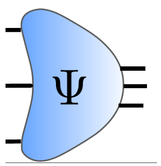
	p-wave	d-wave	f-wave	g-wave	
S=1/2		40	56		192
S=3/2	12	20	28	36	

spin 7/2

	d-wave	f-wave	g-wave	h-wave	
S=1/2		56	72		256
S=3/2	20	28	36	44	

spin 9/2

	f-wave	g-wave	h-wave	i-wave	
S=1/2		72	88		320
S=3/2	28	36	44	52	



$$= [Flavour] \otimes [Colour] \otimes [Spin - Momentum]$$

Figure: Richard Williams

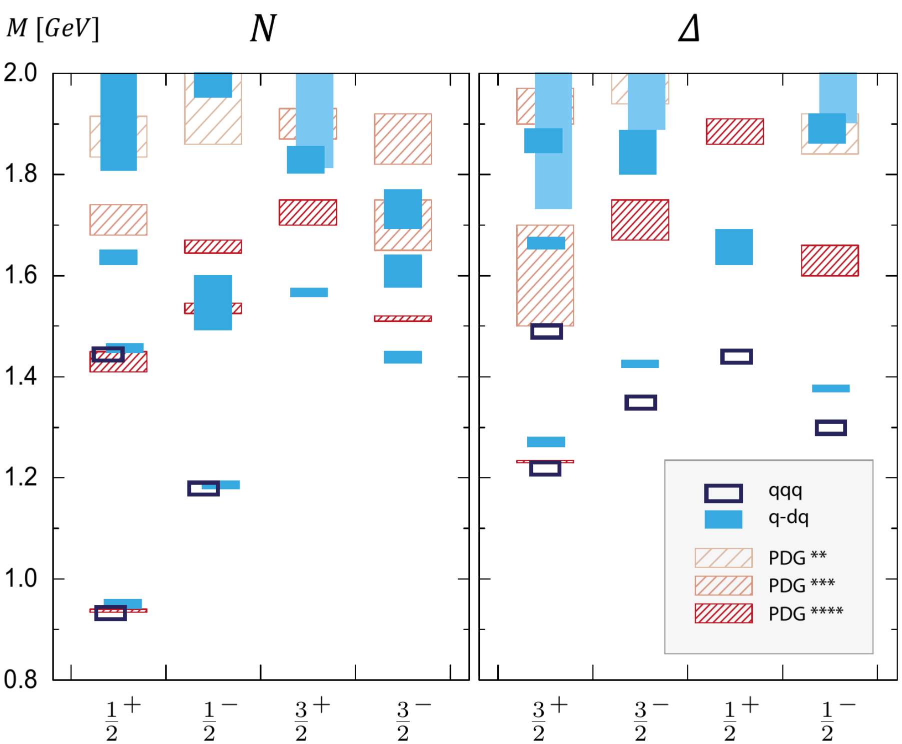
Selected RL results. Baryon spectrum

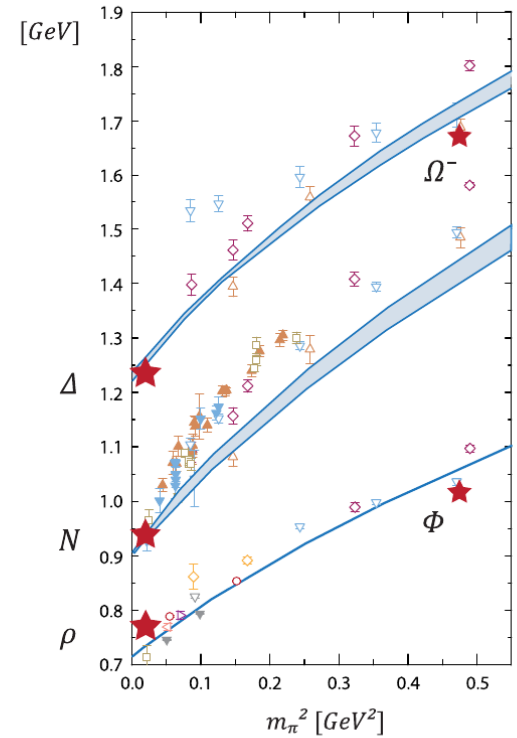
(LIGHT) BARYON MASSES

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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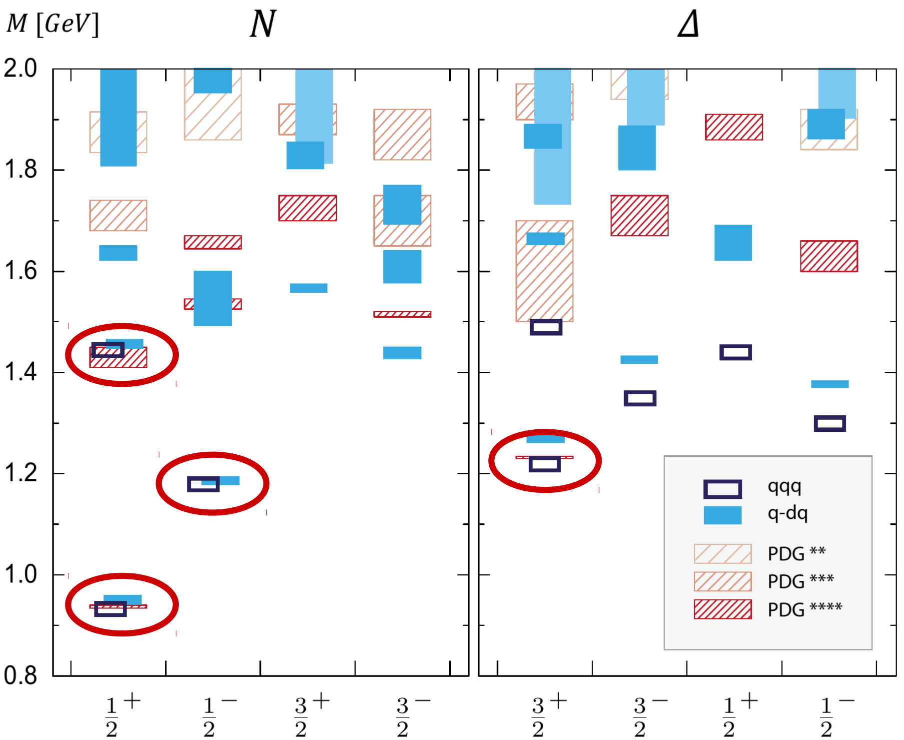
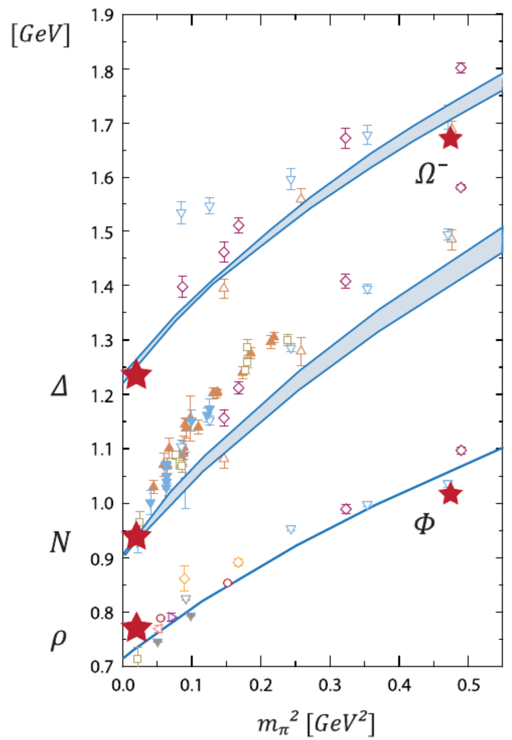




- Baryon-mass evolution with the quark mass allows to understand explicit chiral-symmetry breaking
- It also allows to compare with lattice QCD; there one can work with unphysical quark masses

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 will have to wait for more sophisticated truncations (see also Eichmann's talk)

BARYON FORM FACTORS

(spacelike) Electromagnetic FFs

(spacelike) Electromagnetic FFs

What about electromagnetic structure?

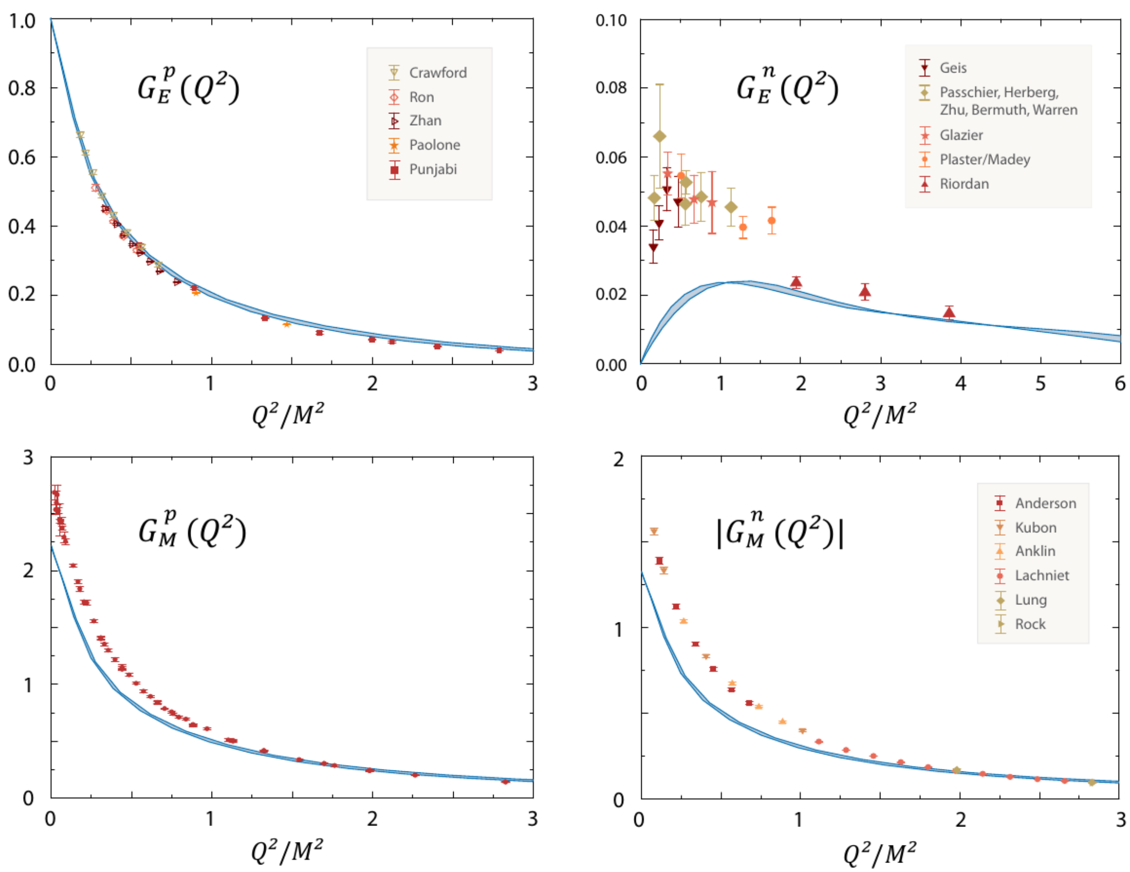
- Experiment: Nucleon elastic and Nucleon-Delta transition. (maybe more soon from JLAB? see talk by M. Battaglieri)
- Lattice QCD: Delta (at heavy pion mass) and Octet hyperons
- What can **we** do for phenomenology?

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

χ-PT calculation of meson-cloud (pion and kaon) effects on octet FFs:

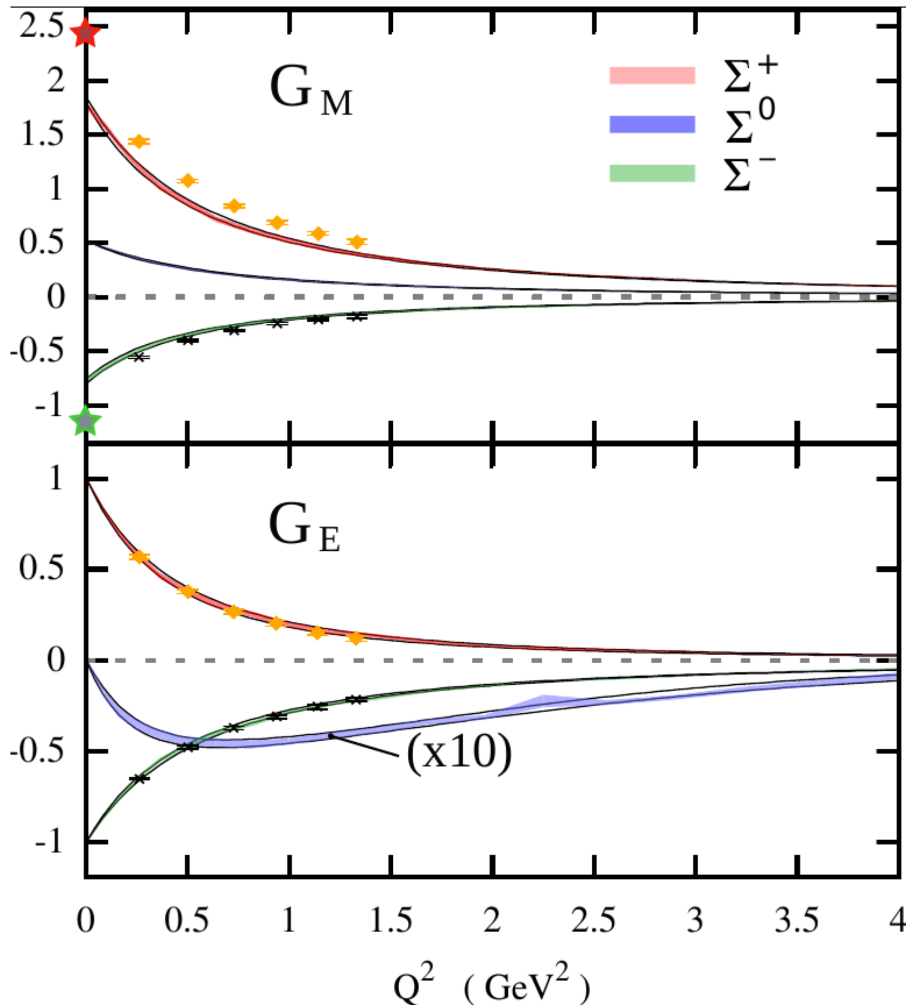
Boinepalli et al. Phys. Rev. D74 (2006)

Leinweber Phys. Rev. D69 (2004)

	Σ+	Σ0	Σ-
pi-cloud ↑ K-cloud ↑	↑↑↑ ↑↑↑	?	↑↑↑ ↑

Octet electromagnetic FFs. Sigma

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



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

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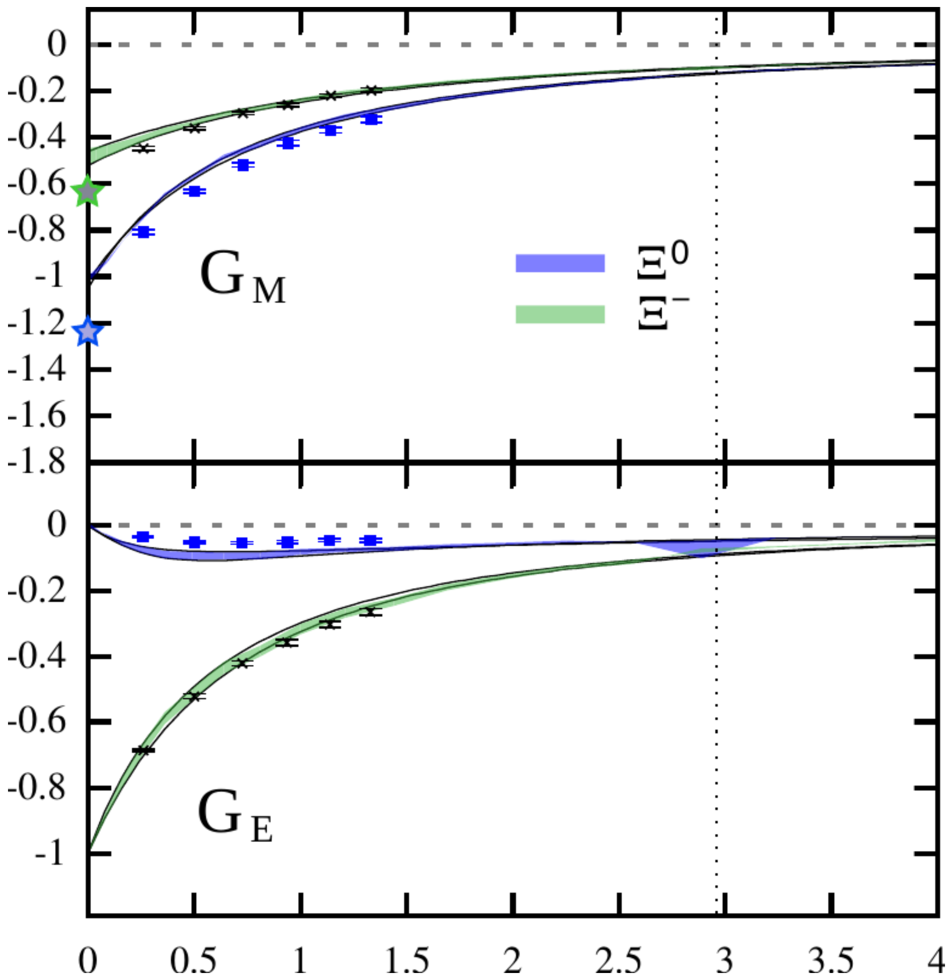
	Σ+	Σ0	Σ-
pi-cloud ↑ K-cloud ↑	↑↑↑ ↑↑↑	?	↑↑↑ ↑

- We see this trend at low-Q^2
- Electric FF (GE) in excellent agreement with lattice QCD. They are «protected» by charge conservation.

- No data at high Q^2. **Prediction**?
- No data for Σ0. **Prediction**?
- Static values (Q=0) always underestimated.

Octet electromagnetic FFs. Xi



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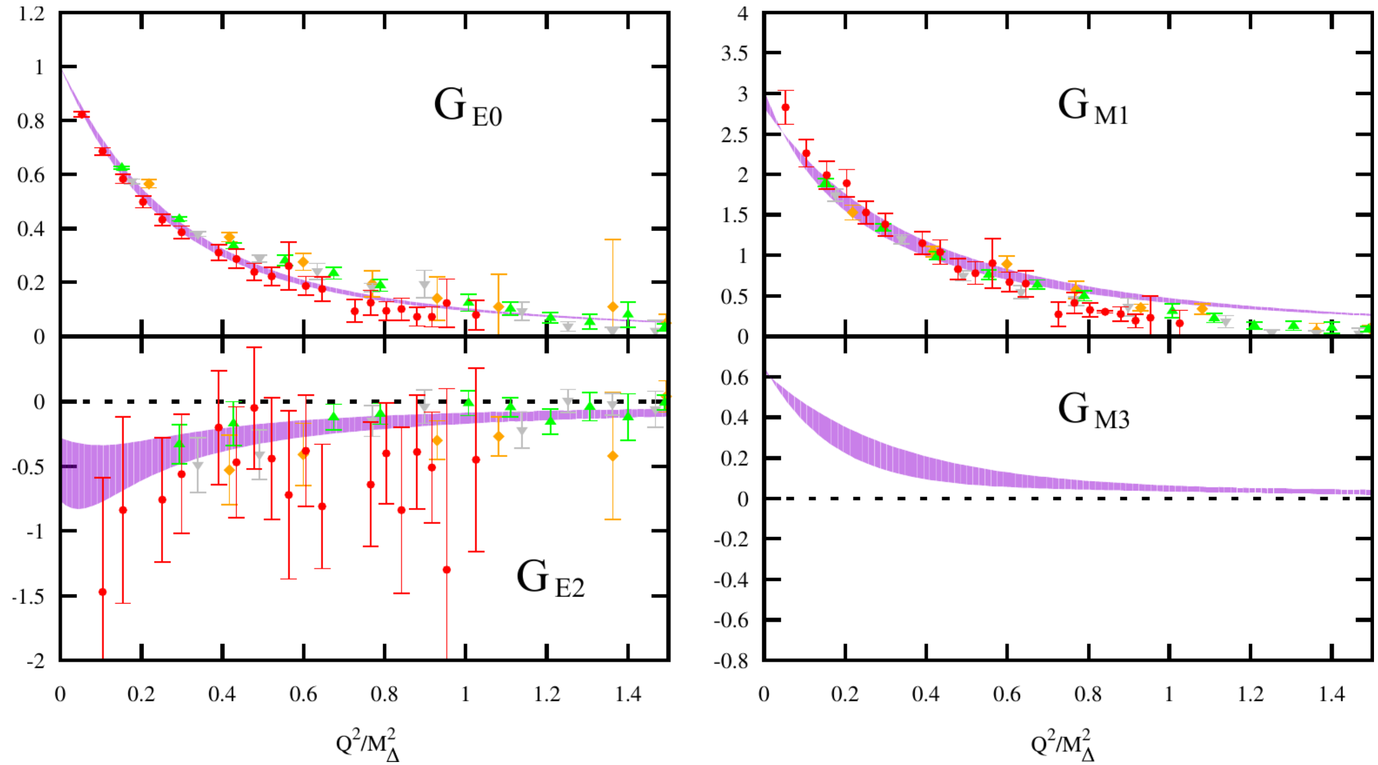
	Ξ0	Ξ-
pi-cloud ↑ K-cloud ↑	↑↑ ↑↑	↑↑ ↑

- 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

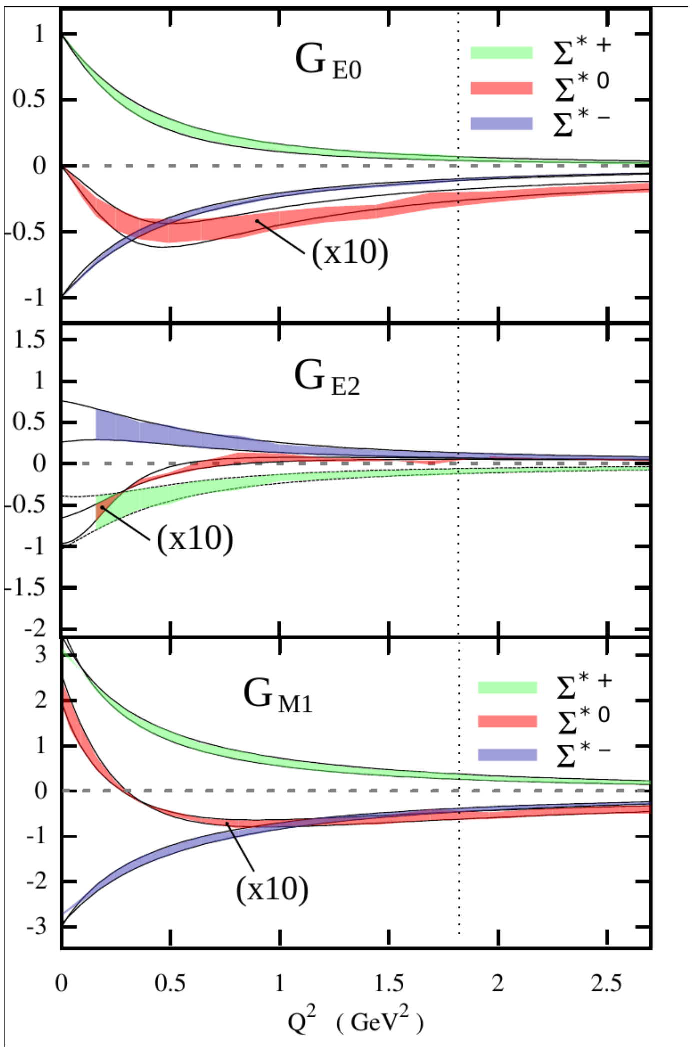
HSA, Williams, Alkofer   Phys.Rev. D87 (2013)



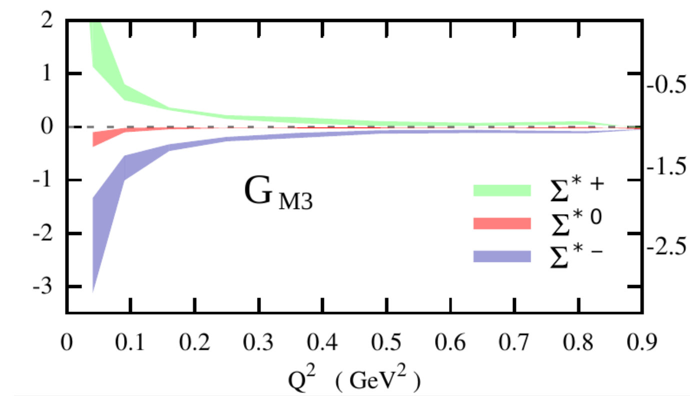
- **Similar pattern as with the octet FFs** (here compared with lattice data at unphysical pion mass. Thus, absence of meson cloud less apparent)
- For spin-3/2 baryons we have **direct access to** their **shape (here higher partial waves play a role)**:
  - Deformation of electric charge distribution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

+/- Oblate/ Prolate

Decuplet electromagnetic FFs. Sigma*



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



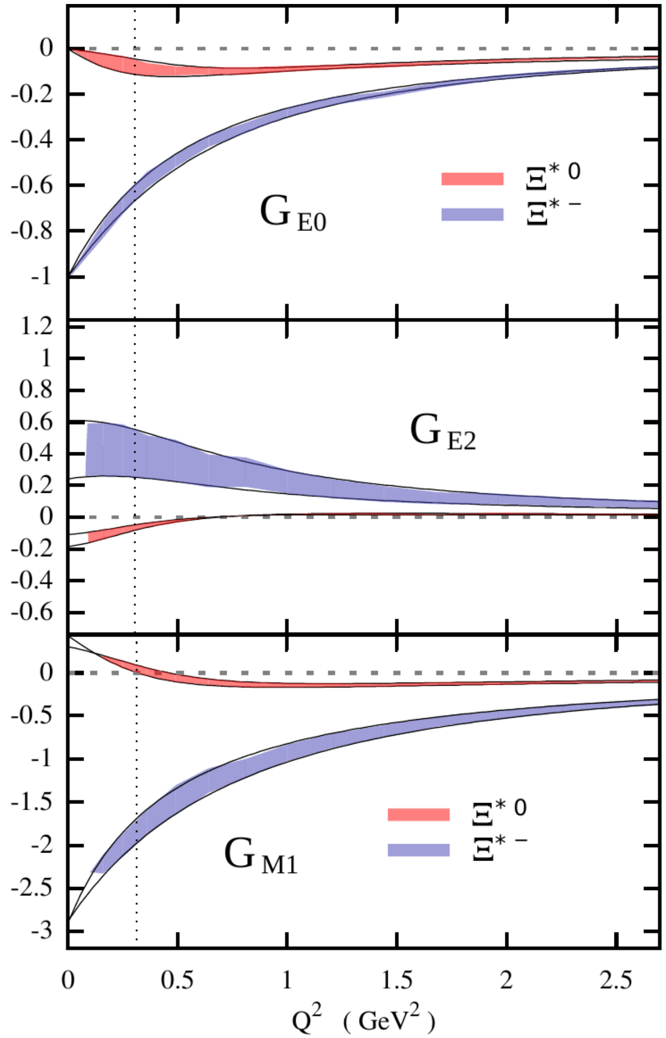
- No data at all, lattice or experiment.

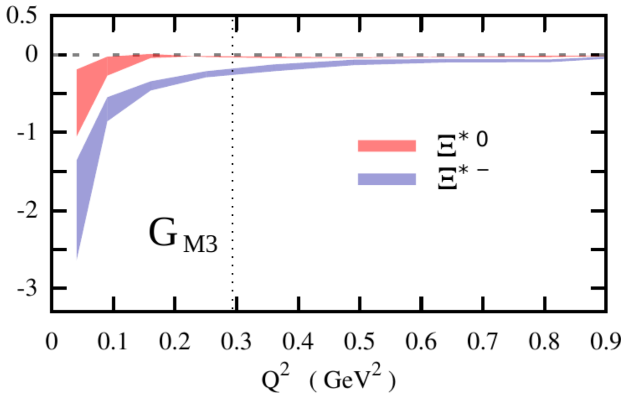
- Claim: our calculation gives a **qualitative description of Hyperon FFs at low Q^2 that becomes a quantitative prediction at high Q^2**.

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

Decuplet electromagnetic FFs. Xi*

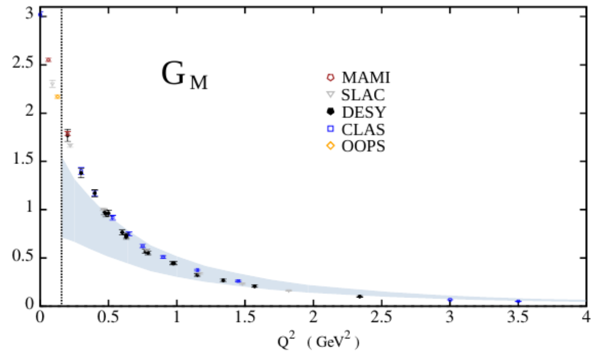
HSA, Fischer Eur.Phys.J. A52 (2016) no.2, 34

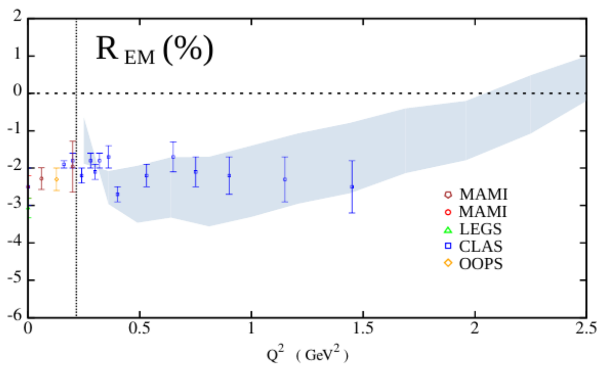


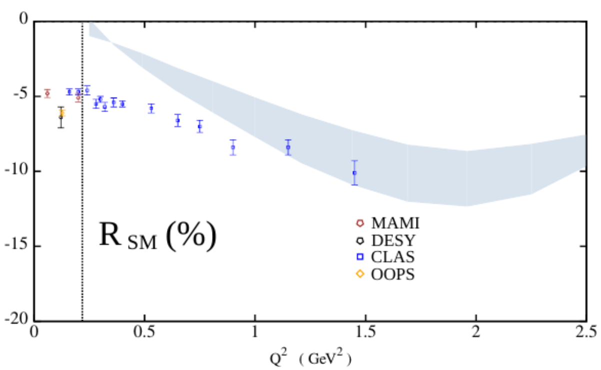


- Some things to note:
  - FFs for Ξ^{*0} not vanishing (they are for Δ^0)
  - Zero-crossing for GM1 in Ξ^{*0}: oblate prolate

Transition FFs. Nucleon-Delta





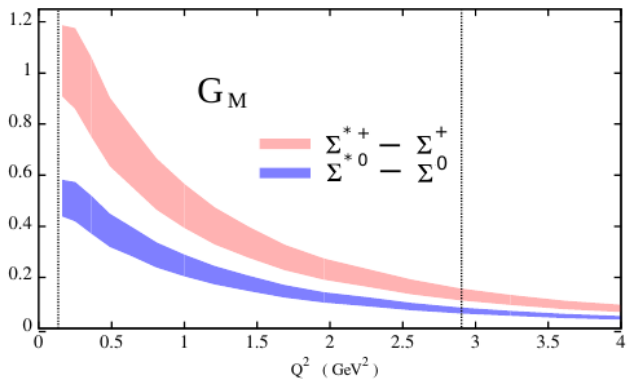


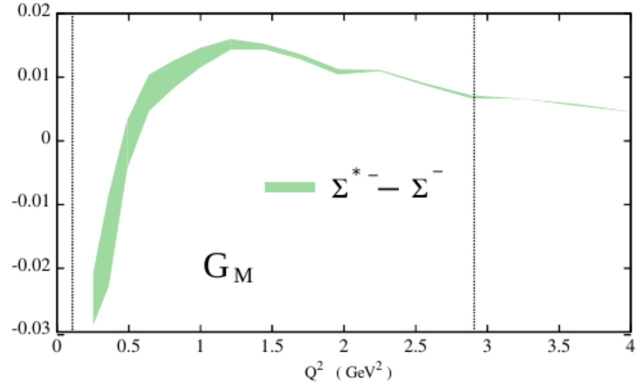
HSA, Alkofer, Fischer   EPJ-A 54 (2018) 3, 41

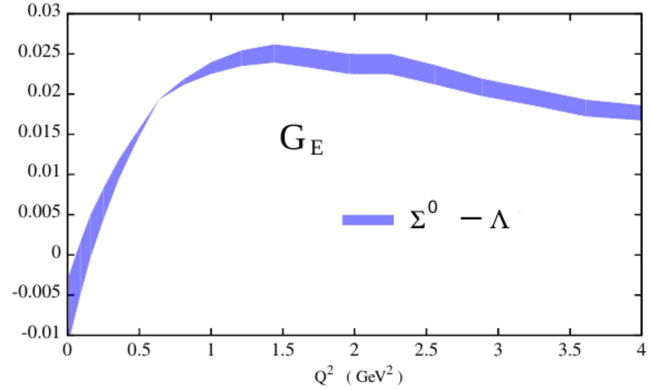
- Similar pattern: absence of pion cloud generates discrepancies.
- Currently, calculations of transition FFs are typically more noisy: for ratios, only qualitative features meaningful
- Agreement with experiment is reasonable
- Internal spin and angular momentum (higher partial waves) very important!

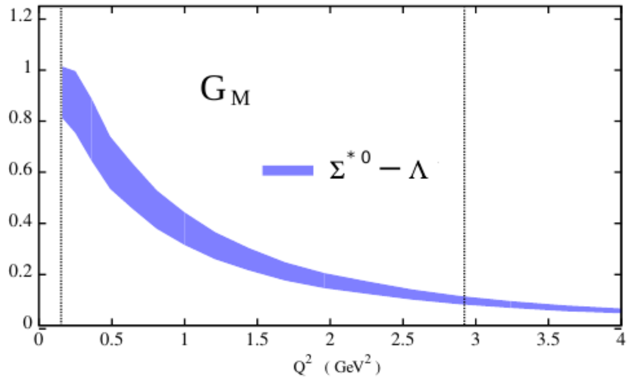
Transition FFs. Hyperons

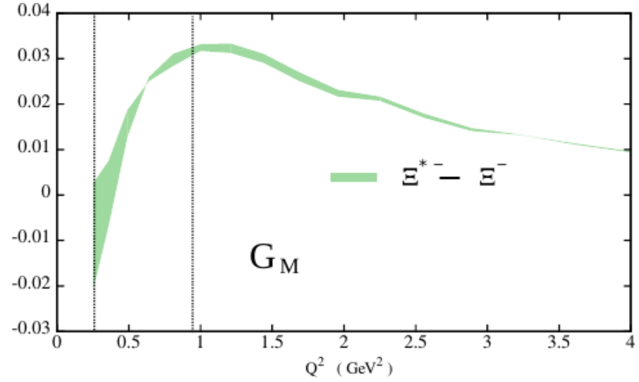
HSA, Alkofer, Fischer EPJ-A 54 (2018) 3, 41

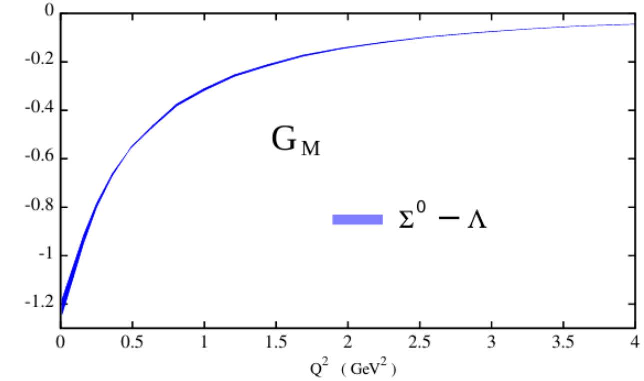


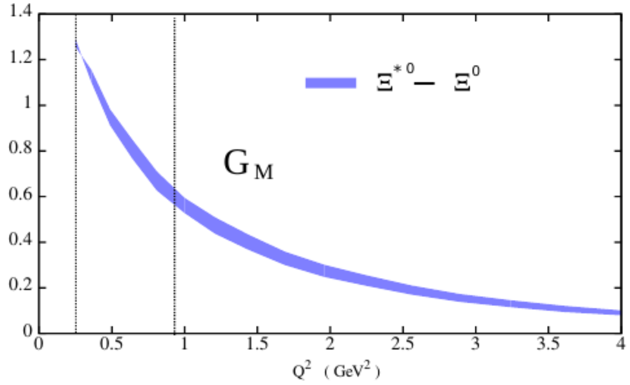








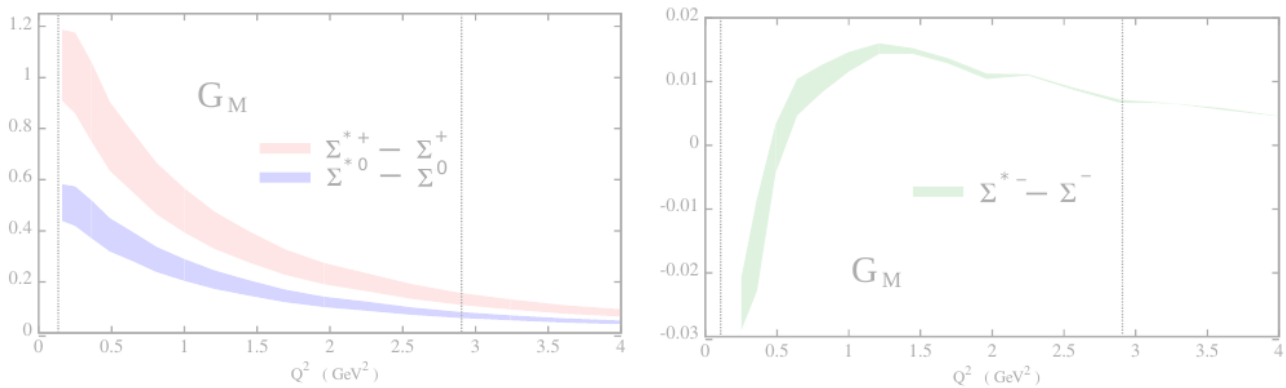


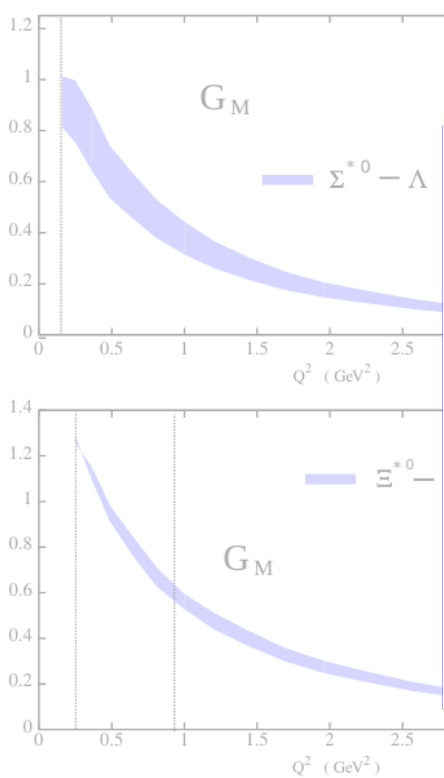


transition	ΔN	$\Sigma^{*\,+}\Sigma^{+}$	$\Sigma^{*\,0}\Sigma^{0}$	$\Sigma^{*\,0}\Lambda$	$\Xi^{*\,0}\Xi^{*\,0}$	$\Sigma^{*\,-}\Sigma^{-}$	$\Xi^{*\,-}\Xi^{*\,-}$
$G_M(0)(\eta = 2.0)$	2.0	1.1	0.5	1.0	1.8	-0.05	-0.07
$G_M(0)(\eta = 1.6)$	0.8	1.3	0.6	1.1	1.5	-0.04	-0.02
exp.	3.04 (11)	4.10 (57)		3.35 (57)		<0.8	

Transition FFs. Hyperons

HSA, Alkofer, Fischer EPJ-A 54 (2018) 3, 41

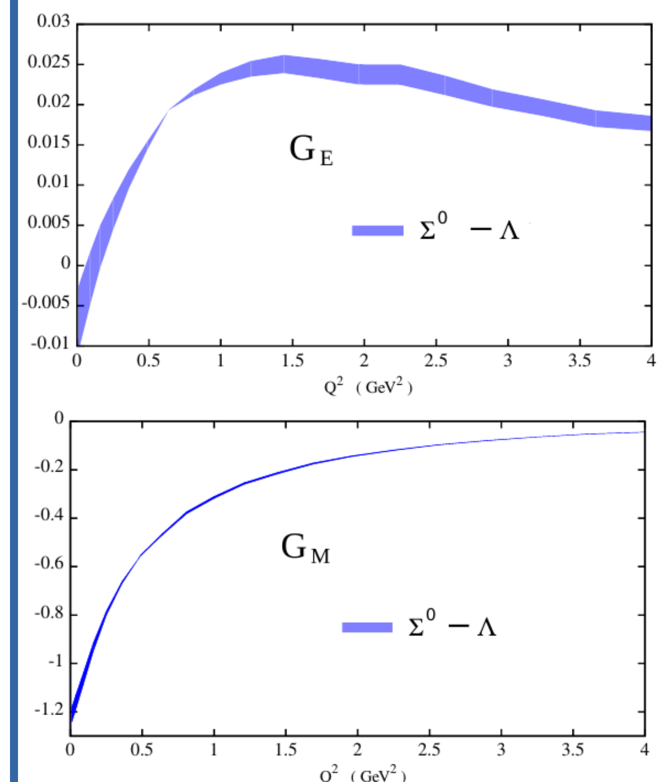




- The only electromagnetic transition allowed among octet members.

- CQM get GE=0 without meson cloud effects

- For us it appears as an effect of higher partial waves!



			$\Sigma^{*0}\Sigma^0$	$\Sigma^{*0}\Lambda$	$\Xi^{*0}\Xi^{*0}$	$\Sigma^{*-}\Sigma^-$	$\Xi^{*-}\Xi^{*-}$
			0.5	1.0	1.8	-0.05	-0.07
$G_M(0)(\eta = 1.6)$	0.8	1.3	0.6	1.1	1.5	-0.04	-0.02
exp.	3.04 (11)	4.10 (57)		3.35 (57)		<0.8	

Selected RL results. Baryon structure

Take-away message

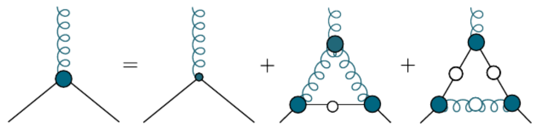
- At the present stage, gives a **qualitative description of baryon FFs at low Q^2 that becomes a quantitative prediction at high Q^2**.
- Qualitative features can (most probably) be taken seriously, even at the present level of truncation.
- **For quantitative predictions**, we have to wait at least until **pion effects** have been included (technically hard, but possible)

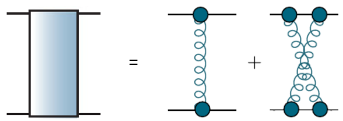
Future

Outlook

(A Glimpse into the Future)

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**

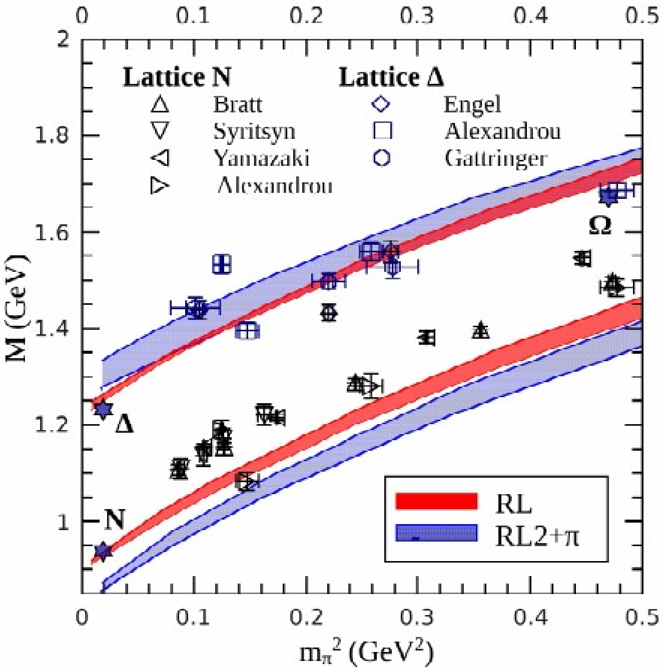
Meson cloud effects

- One can more easily study mesonic effects on hadrons in a BSE approach by including them as additional degrees of freedom in the interaction kernel (in addition to quarks and gluons)

- Meson and baryon spectrum calculated in this way.

Fischer, Williams, PRD78 (2008)

- **HSA, Fischer, Kubrak, PLB733 (2014)**



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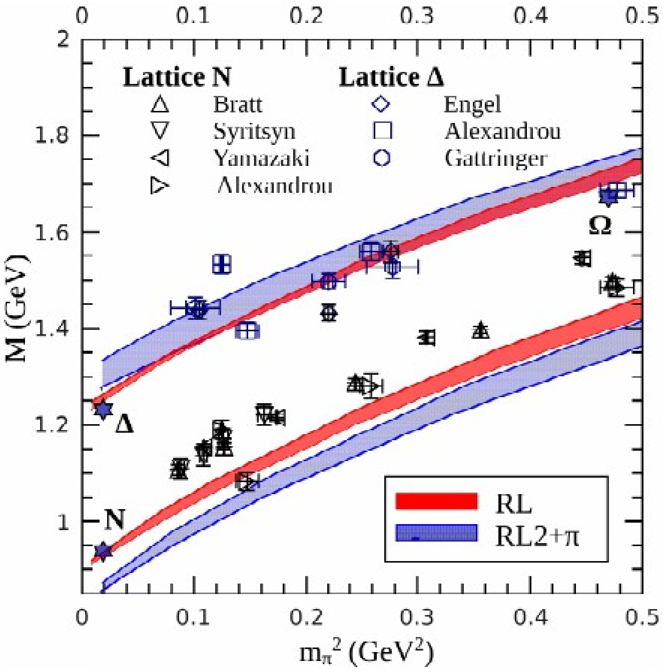
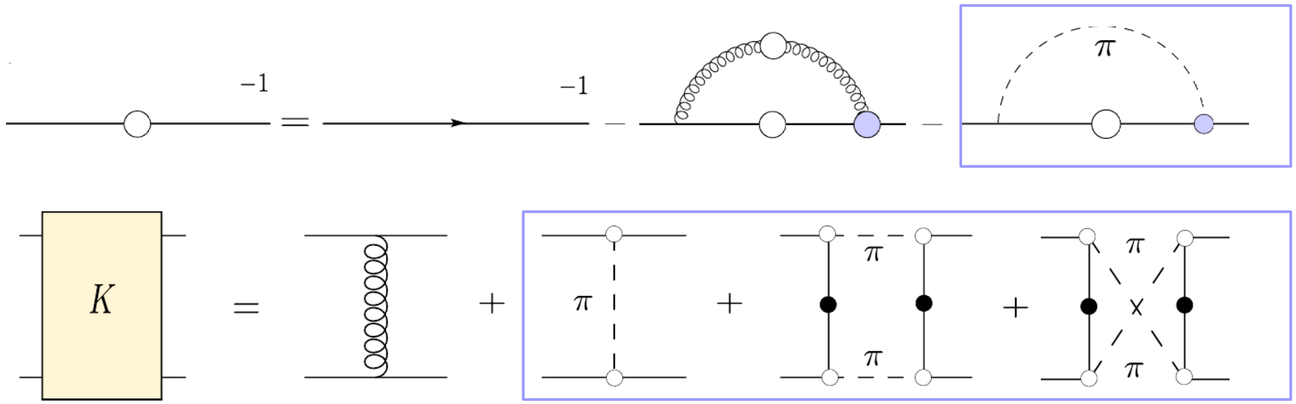


What about FFs? We contemplate two options:

1. Play the same game. Introduce mesonic d.o.f. ; couple the external photon to them too; calculate FFs.

2. Do a χ-PT like calculation, but with BSE meson and baryon amplitudes as input, to estimate the effect of meson cloud **within our approximation scheme (WIP).**

Decays mechanisms in kernels $\rho \to \pi\pi$



- The decay kernels contain a host of of cuts/poles (e.g. pion production threshold) that one has to deal with in a BSE.

Once we have control over the singularities:

- Solve the rho-meson BSE. Can we observe non-analyticities in the rho mass as a function of the quark mass, when the 2-pion channel opens?
- Solve the quark-photon vertex. Do we see «bumps» instead of poles in the timelike region.
- Attempt to solve (meson) form factors in the timelike region.

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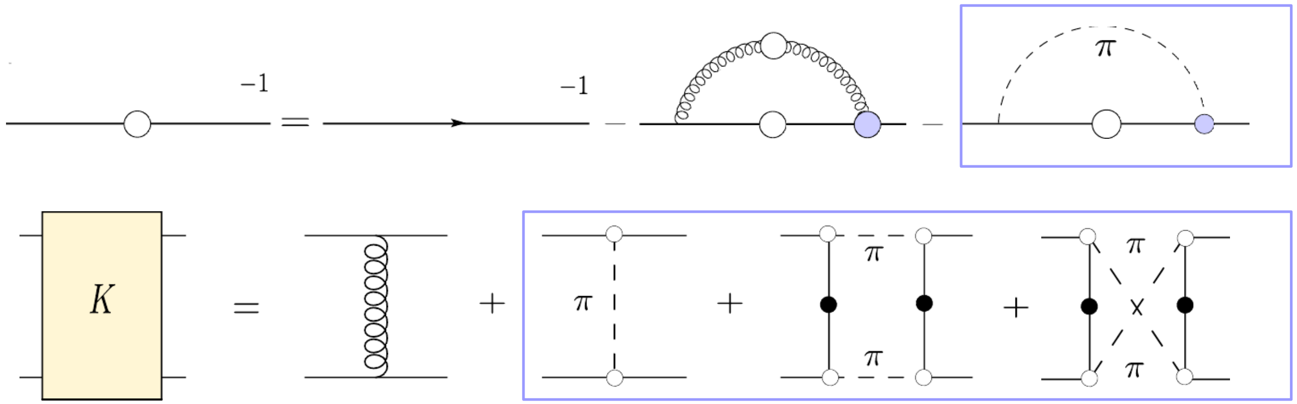

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THANK YOU!