Baryon-photon interaction in a covariant Faddeev approach

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Workshop

Outline

- Motivation:
  baryonic structure $\longrightarrow$ experimental advances.

- Back to fundaments: Poincare invariant Faddeev equations.

  Ingredients: Quark propagator, gluon propagator, quark-gluon vertex ... DSEs.

  Diquarks... BSEs.

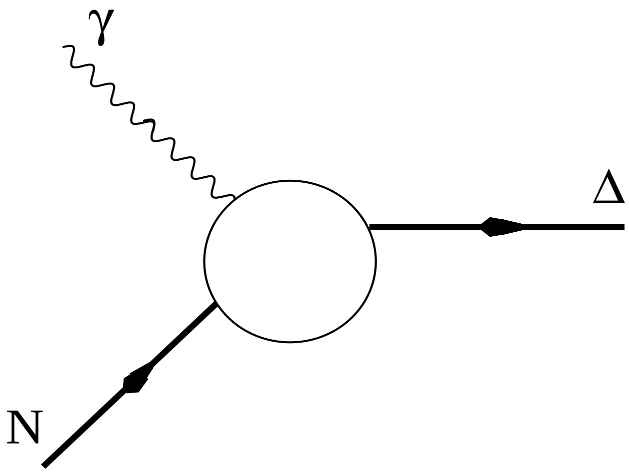
  Nucleon quark-core: solve a quark-diquark system.

- Calculated by now: M_N, nucleon FF, elmag. radii...

- Summary and Outlook (M_Δ, $N \rightarrow \Delta\gamma$, $\Sigma \rightarrow \Lambda\gamma$, π corrections).

Experimental advances

- Baryons are composite objects.
- Electromagnetic interaction:
  present precise tests of the structure.
- Nucleon electromagnetic form factors, polarizabilities, strangeness content ($e^- p$ scattering).
- Electro- and photoproduction:
  the proton and its lightest resonance $\Delta(1232)$.



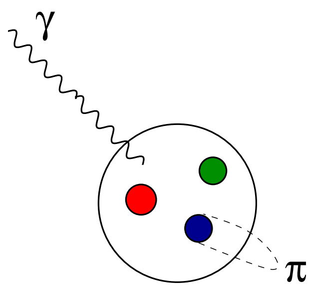
- JLab-CEBAF, MIT-BATES, Mainz-MAMI, Brookhaven-LEGS.

Theoretical efforts

$EMR(\%) = \frac{E2}{M1} = -2.5 \pm 0.5$ (MAMI) $CMR(\%) = \frac{C2}{M1} = -4.81 \pm 0.27$ (LEGS)

Models

- Constituent quark models, pion cloud models....



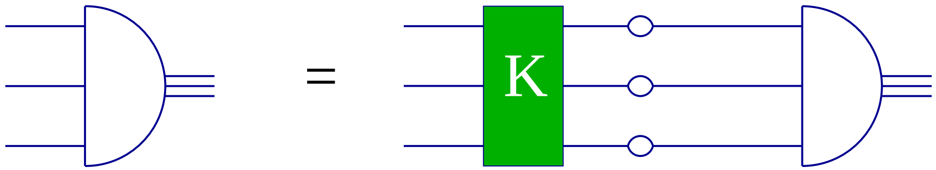
- Covariance, link to effective theories.

Do we understand the nucleon?

- Models offer a good description of data in low-energy regime.
- Baryon-quark vertex not trivial.
- Desired QCD-based solution.
- Confinement, DCSB, relativistic bound states ...

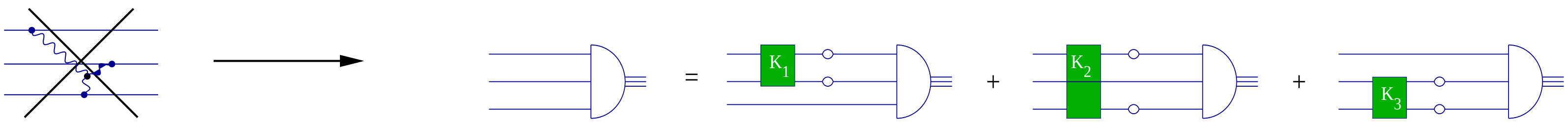
Faddeev Equations

- Baryons as composite objects of confined quarks and nonpointlike diquarks.
- Bound state poles in the 6-point Green-functions
  $\longrightarrow$ homogenous integral equations for the baryon amplitudes.
- Solve iteratively if ingredients are known:
  quark propagator, three-quark interaction kernel.



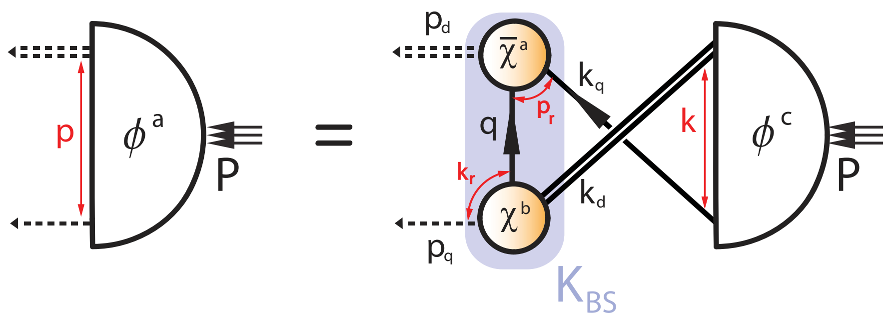
- Faddeev approximation:
  retain only 2-particle interaction kernels (dominant structure in nucleon).

$$K = \sum_{i=1}^{3} K_i \otimes S_i^{-1}$$



Faddeev equations

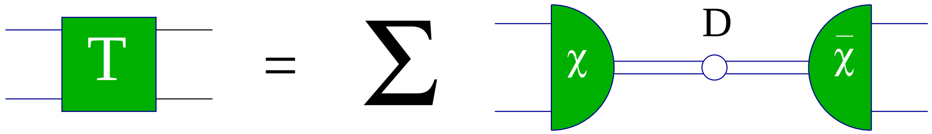
- Exploit the same attractive interaction for $1_c^{q\bar{q}}$ and $\bar{3}_c^{qq}$.
- Construct nucleon: $\bar{3}_c^{qq} \times 3_c^q \to$ color-singlet.
- Binding in the nucleon:
  quark exchange between the dormant quark and diquark.
- Solve numerically a quark-diquark BSE.



- Ingredients: quark propagator, 2-particle interaction kernel.

Diquarks

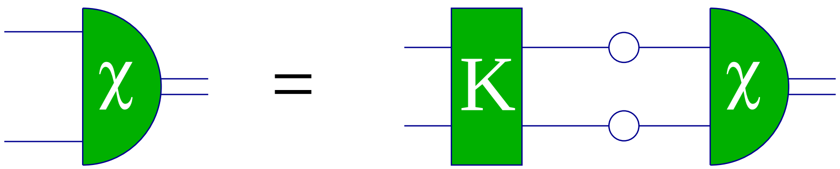
- q-q correlations dominant structure in the nucleon (supported by lattice).
- Approximation: two-quark separable correlations.



- Scalar and axial-vector correlations.

$$T_{qq}(p_1, p_2, P) \sim \chi(p_1)D(P)\bar{\chi}(p_2) + \chi^{\mu}(p_1)D^{\mu\nu}(P)\bar{\chi}^{\nu}(p_2)$$

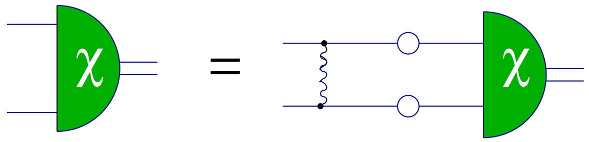
- Diquark homogenous Bethe-Salpeter equation.



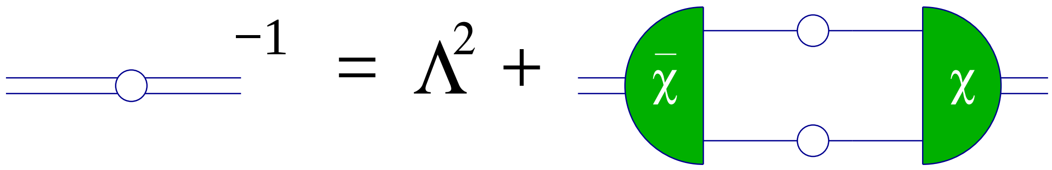
- Determines diquark amplitude on the mass-shell: $\chi = K\,G_0\,\chi$

Diquark ingredients

- Solve using rainbow-ladder truncation:
  one gluon exchange $+$ vector-like quark-gluon vertex.



- Diquark propagator in ladder approximation.



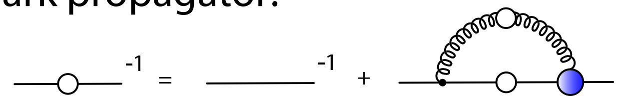
$$D^{-1} = \bar{\chi}\,(K^{-1} - G_0)\,\chi$$

- Diquark propagator: calculated on-shell behavior,
  parametrized off-shell behavior.

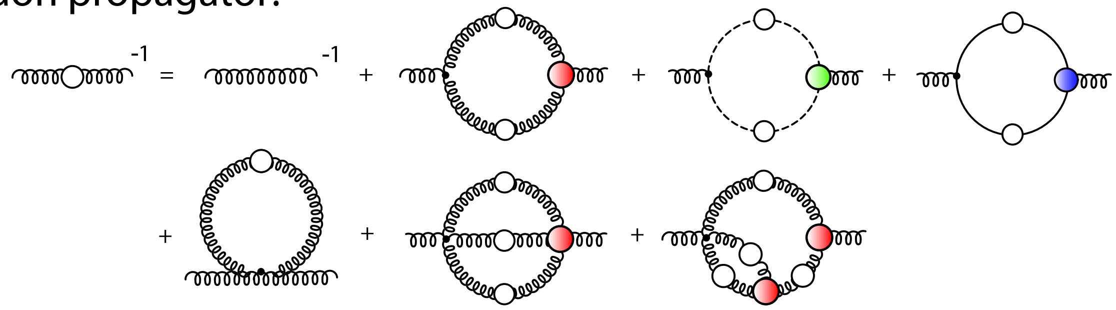
Quark ingredients

- Infinite coupled system of DSEs.

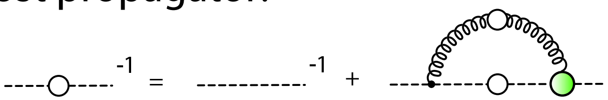
Quark propagator:



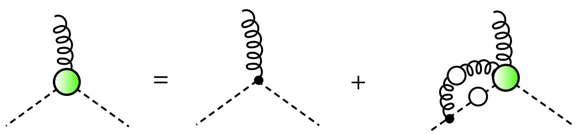
Gluon propagator:



Ghost propagator:



Ghost-gluon vertex:



Quark propagator

- Dressed quark propagator: solution of the DSE.

- General form: $S(p) = i \; \not p \, \sigma_v(p^2) - \sigma_s(p^2) = -\frac{1}{iA(p^2)+B(p^2)}$

- Gluon dressing reflected in the quark mass function $M(p^2) = \frac{B(p^2)}{A(p^2)}$

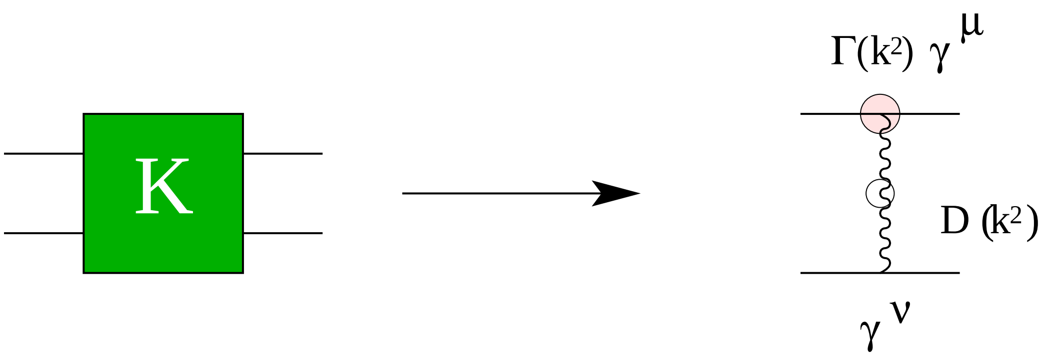
- Asymptotic freedom: $M(p^2) \rightarrow m_q$ perturbative quark propagator.

Rainbow-ladder truncation

- Solve quark DSE using rainbow truncation:

  Quark gluon vertex ansatz $i\Gamma_\mu = i\gamma_\mu \quad \times \Gamma(k^2)$

  Note: consistent BSE q-q kernel.



- Advantage: simple truncation, quark DSE and q-q BSE kernel fulfil AV-WTI.

Gluon propagator, running α

- Dressed gluon propagator.

$$D_{\mu\nu}(k) = D(k^2) D^{free}_{\mu\nu}(k^2)$$

- Dressings $D(k^2)$ and $\Gamma(k^2)$ absorbed in the running coupling:

$$\alpha_{eff}(k^2) \sim D(k^2)\ \Gamma(k^2)$$

constraint by the correct UV behaviour $\rightarrow \frac{\pi\, \gamma_m}{ln \frac{k^2}{\Lambda^2_{QCD}}}$

and strong enough in IR to generate DχSB.

- Dressed quark propagator

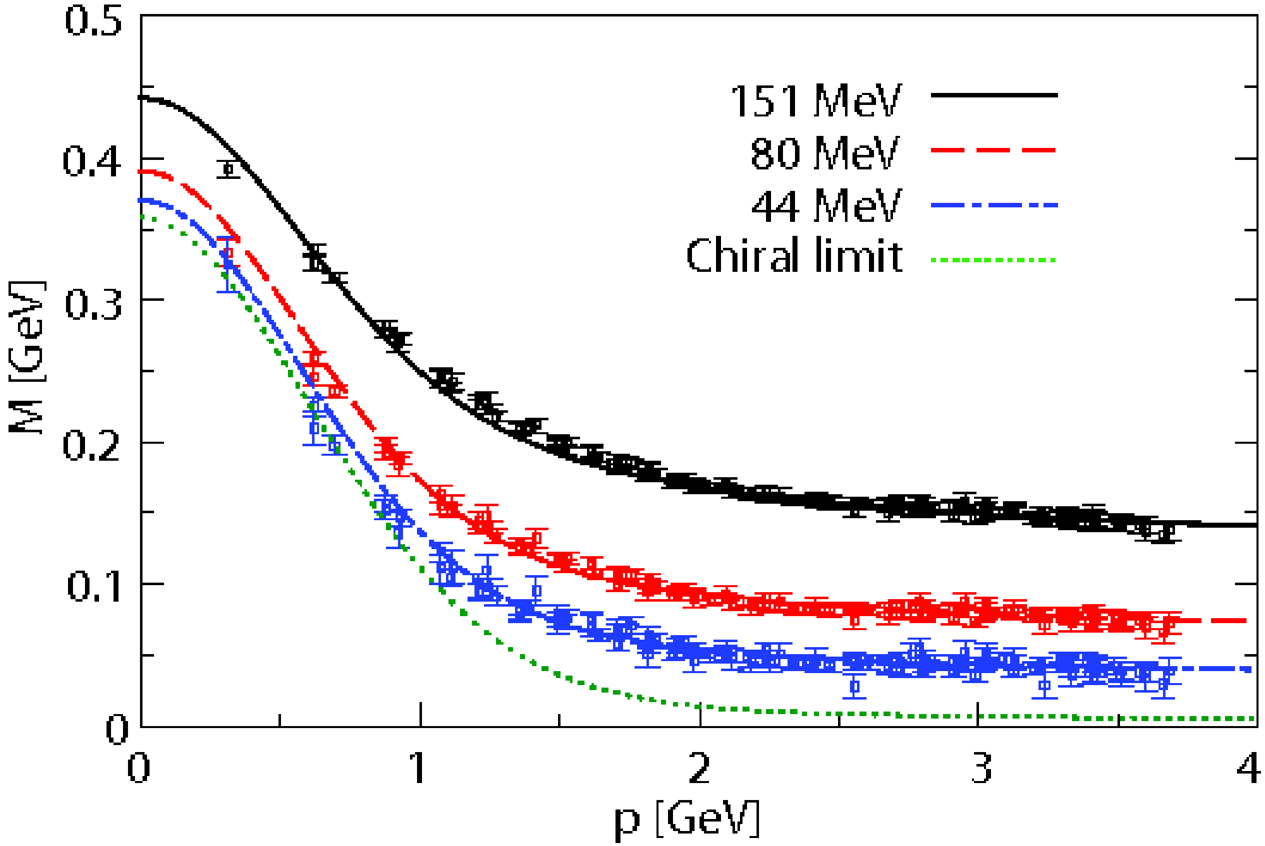
$$S^{-1}(p,\mu^2) \sim Z_2(\mu^2,\Lambda^2) S_0^{-1}(p,\Lambda^2) - Z_2(\mu^2,\Lambda^2) \int_q^\Lambda d^4q\ \alpha_{eff}(k^2) D^{free}_{\mu\nu} \gamma_\mu S(q,\mu^2) i\gamma_\nu$$

P. Maris, P.C. Tandy Phys. Rev. C 60, 055214 (1999).

$M(p)$ in rainbow-ladder

- Quark mass function fixed by lattice calculations

  P.O. Bowman *et al.* Phys. Rev. D 66, 014505 (2002).



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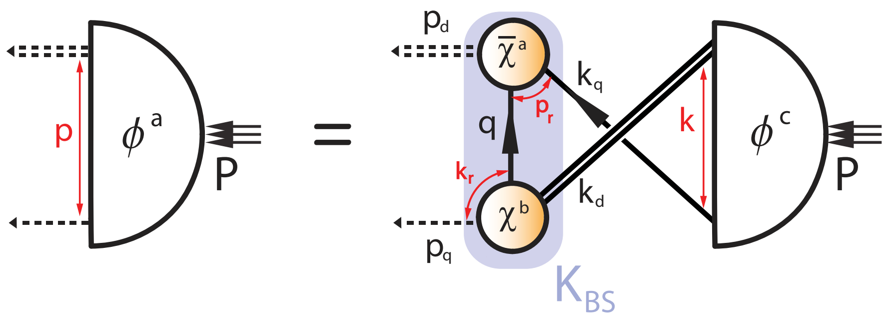
Nucleon BSE

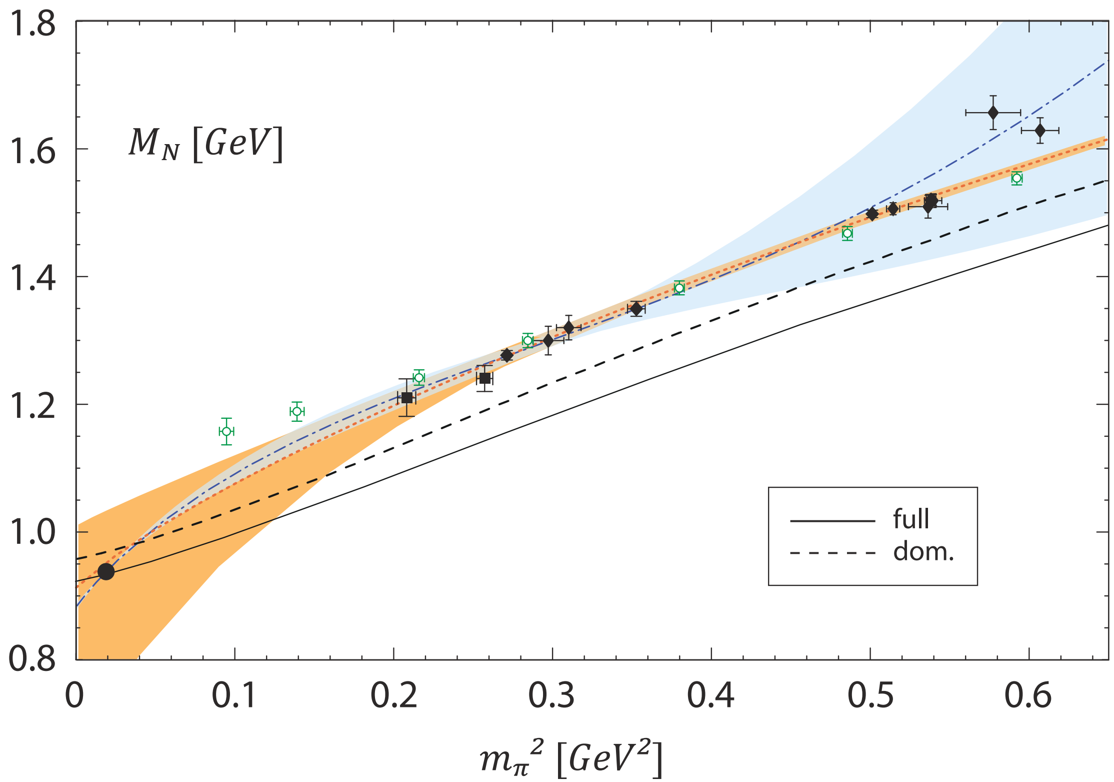
$$\Phi(p,P)^a = \sum_{b,c} \int \frac{d^4k}{(2\pi)^2}\, \chi^b(k_r,k_d)\, S^T(q)\, \bar{\chi}^{aT}(p_r,p_d)\, S(k_q)\, D^{bc}(k_d) \Phi(k,P)$$



- Decomposition of Faddeev amplitudes in Dirac space
  - in explicit calculations use full diquark amplitudes.

Nucleon mass

- $M_N = 0.93$ GeV at physical point $m_\pi = 138 MeV$
  $M_N^{exp} = 0.94$ GeV.



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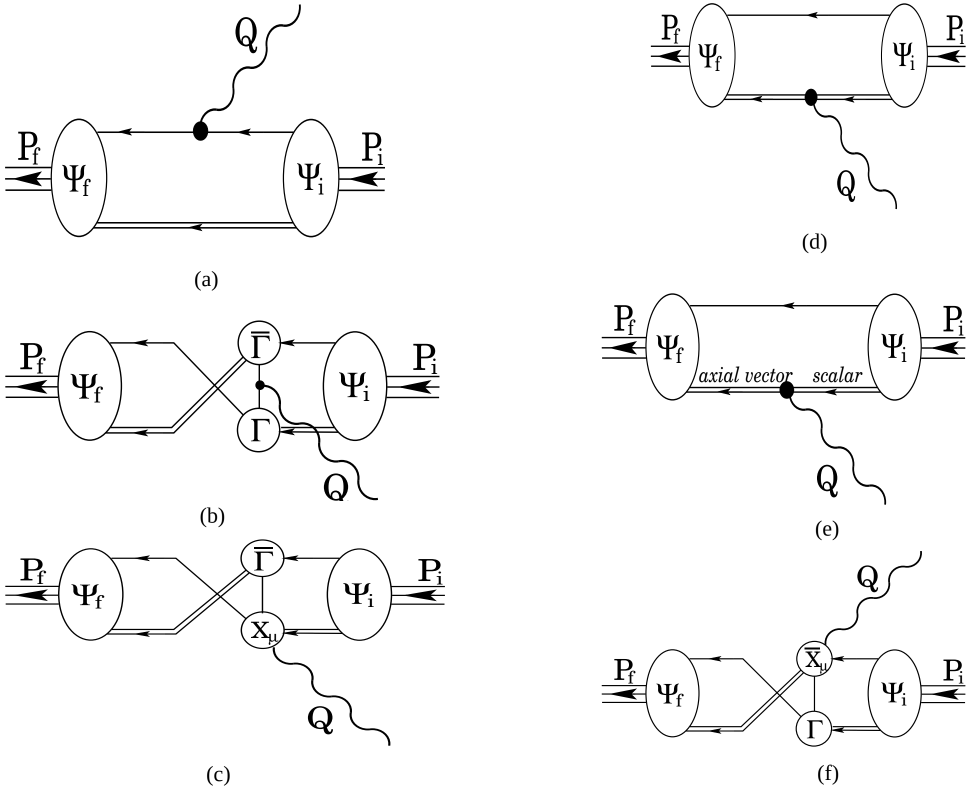
Lattice data; chiral extrapolation methods.

Electromagnetic interaction

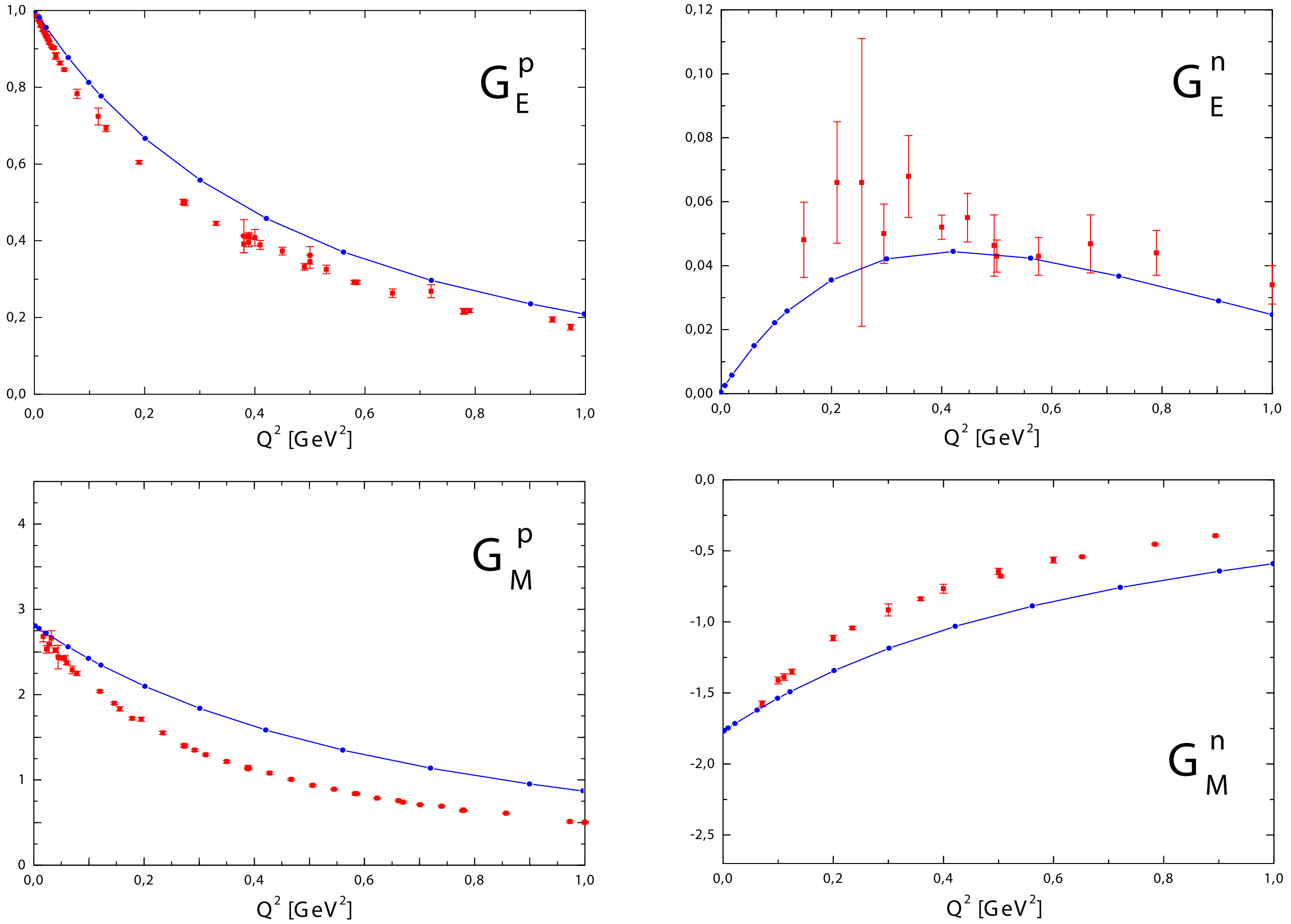
- Ward-Takahashi identity: more than impulse approx. is needed.
- Electromagnetic transition from Ax. to S diquark satisfies gauge invariance alone.



- General current:

$$< J^\mu >= \int \bar{\Phi}\{D\, S\, \Gamma^\mu_q\, S + D\, \Gamma^\mu_{diq.}\, D\, S + D\, S\, K^\mu\, S\, D\}\Phi$$

Results



Exp. data
by P. Grabmayr,
2005.

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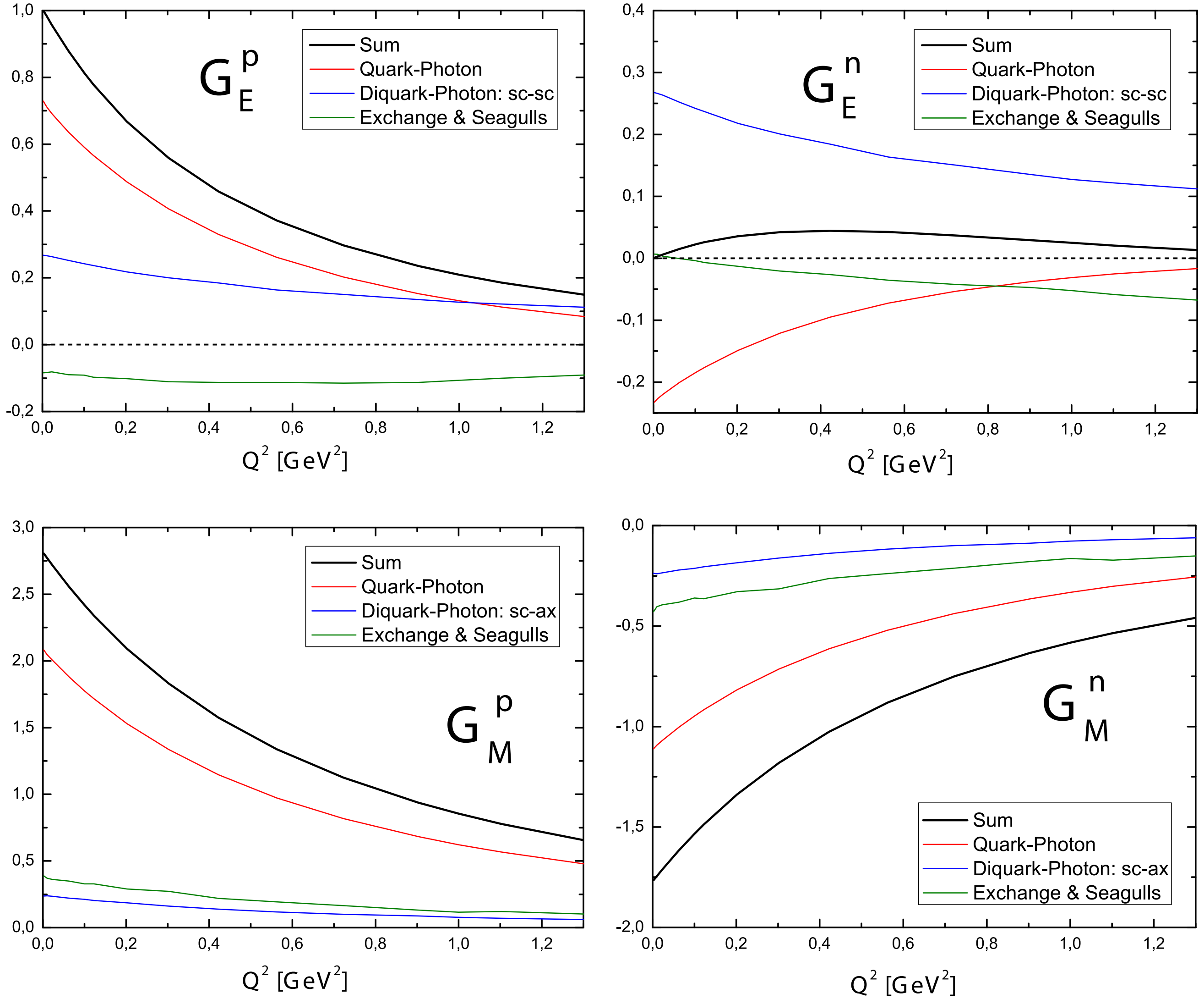
Results



$q - \gamma$ coupling is dominant

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Results

Electromagnetic radii of nucleon

	r_E^p	r_E^n	r_M^p	r_M^n	[fm]
exp	0.87	0.34	0.86	0.88	
calc.	0.67	0.13	0.58	0.57	

Magnetic moments of nucleon.

	μ_p	μ_n	[n.m]
exp	2.79	-1.91	
calc.	2.52	-1.55	

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Summary

- Main message: develop QCD - based understanding of the nucleon structure.
- Poincare covariant DSE-BSE approach to baryons.
- Relativistic bound states, dynamical chiral symmetry breaking...
- Quark-diquark picture describes well nucleon quark-core.
- Rainbow-ladder truncation: consistent resolvation of DSE and BSE.
  Calculation of nucleon static properties and FF.
- No baryon observables as input.

Outlook

- Study Δ (1232): spin$-\frac{3}{2}$ particle, fully flavour symmetric $\longrightarrow$ axial-vector diquarks only!
- By now, using specific ansätze for the quark propagator and the diquark correlations:
  $M_\Delta = 1.004 \div 1.007$ GeV
  M. Oettel, R. Alkofer, L. von Smekal, Eur. Phys. J. A8: 553-566 (2000)
- Extension to $N - \Delta\gamma$:

  - highly non-trivial!
  - long disputed electromagnetic ratios $\frac{E2}{M1}, \frac{C2}{M1}$ positive and few %
  - compare to the diagonal $\Sigma \longrightarrow \Lambda\gamma$: importance of axial-vector correlations.
- Consistently include $\pi-$clouds

  - expected to dominate low-energy obserbavles.

- $m_{sc} \simeq 0.67$ GeV
- $m_{av} \simeq 0.88$ GeV
- Chiral limit: $m_{av} - m_{sc} \simeq 0.21$ GeV

- Compared to the lattice values
  0.14 GeV - C. Alexandrou *et al.* Phys. Rev. Lett. 97, 222002 (2006)
  0.29 GeV - R. Babich *et al.* hep-lat/0701023

Few... technicalities

- Decompose nucleon Faddeev amplitudes in Dirac space.

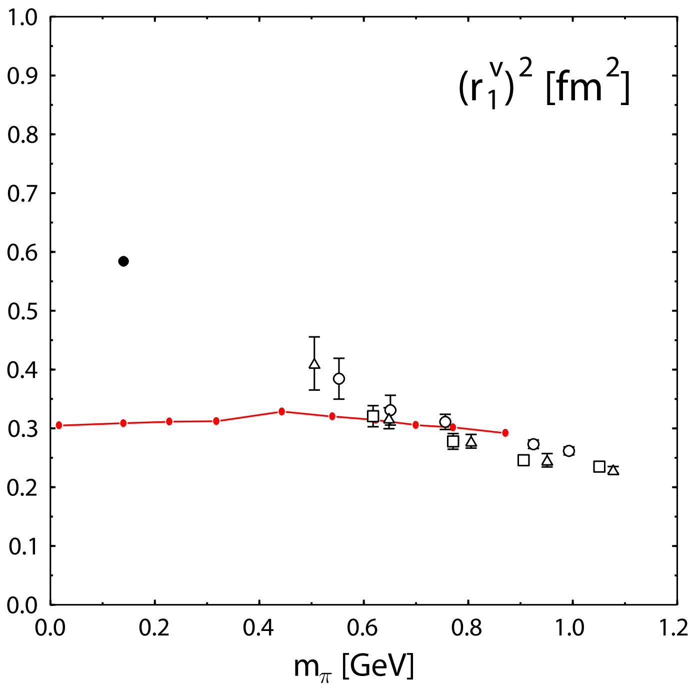
- Reduce the 4-dimensional eqs. to a coupled system of 1-dimensional eqs. via Chebyshev expansions of:

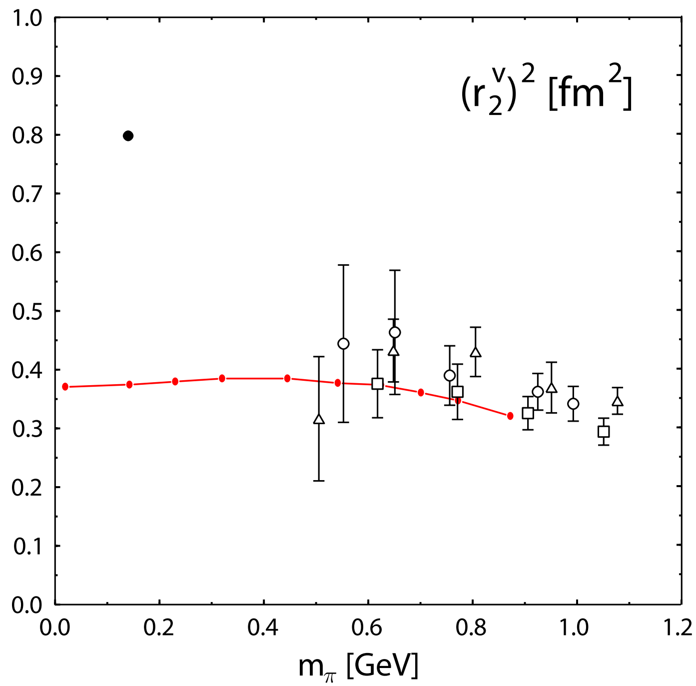
  - Dirac coefficients
  - propagator matrix: $S_q \; D_{diq}$
  - quark-exchange kernel.

- Solve quark-diquark BSE:
  obtain nucleon mass and quark-diquark amplitudes on the nucleon mass-shell.

Results

Isovector charge radii





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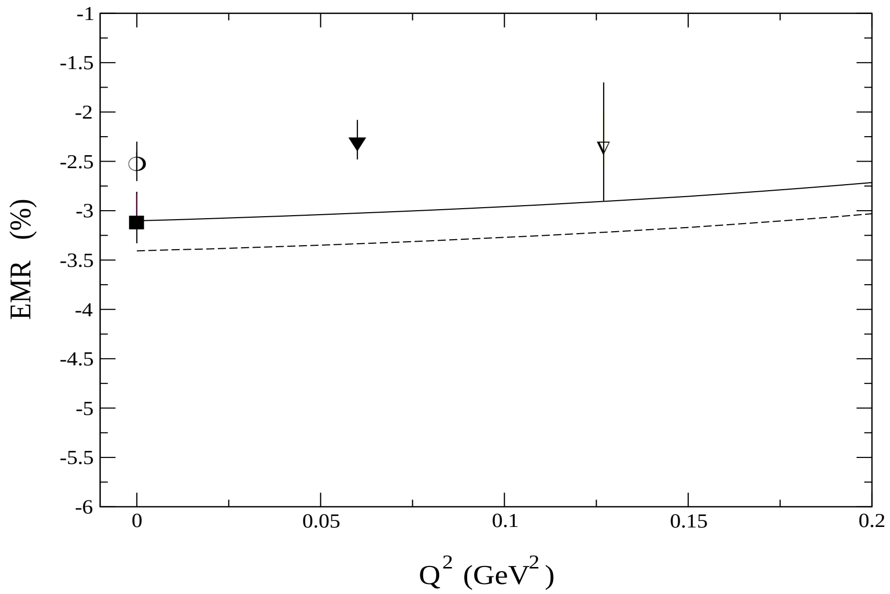
Lattice points Phys. Rev. D 71, 034508 (2005).

EMR and CMR



filled triangle - A1 Collab.
filled box - LEGS Collab.
opened circle - MAMI
opened triangle - OOPS Collab.

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