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KARL-FRANZENS-UNIVERSITÄT GRAZ

A Dyson-Schwinger equation study of the baryon-photon interaction.

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Jefferson Laboratory, March 24, 2010

What is the nucleon made of?

Mass? Spin?

Experiment: precise tests of nucleon structure
at JLab-CEBAF, MIT-BATES, Mainz-MAMI.

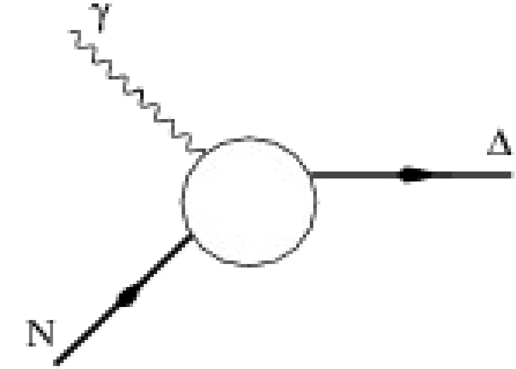
- electromagnetic formfactors, polarizabilities,
  transition form factors $N \to \Delta\gamma$ (shape of nucleon??)

Theory: good description of data

- constituent quark models, pion cloud models, EFTs,...

$$N \longrightarrow \Delta\gamma$$

Experimental Form Factor ratios



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

Theoretical predictions: zero in the naïve quark model!!

Improved models - correct sign and reasonable results.

Price to pay: overestimated or underestimated results for other transition observables!

Missing info - chiral symmetry and its dynamical breaking, relativistic effects, proper and complete partial wave decomposition.

Satisfied with only a description of the data?

A baryon-quark vertex is not trivial!

What about

- Chiral symmetry and DCSB?
- Quark and gluon confinement?

MUST

Do we really understand nucleon observables?

How are quarks and gluons distributed in hadrons?

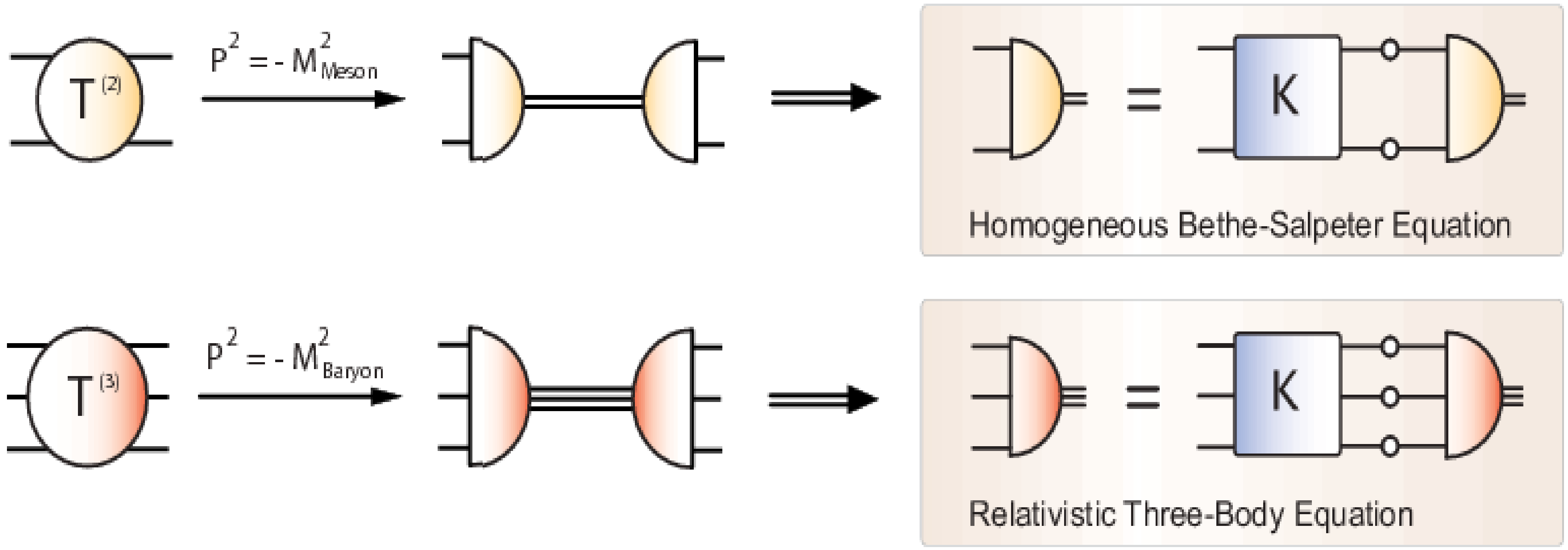
A Poincaré covariant hadron's amplitude in terms of QCD degrees of freedom is needed!

Dyson-Schwinger equation and bound-state equations enable a study of hadrons as composites of dressed-quarks and dressed-gluons.

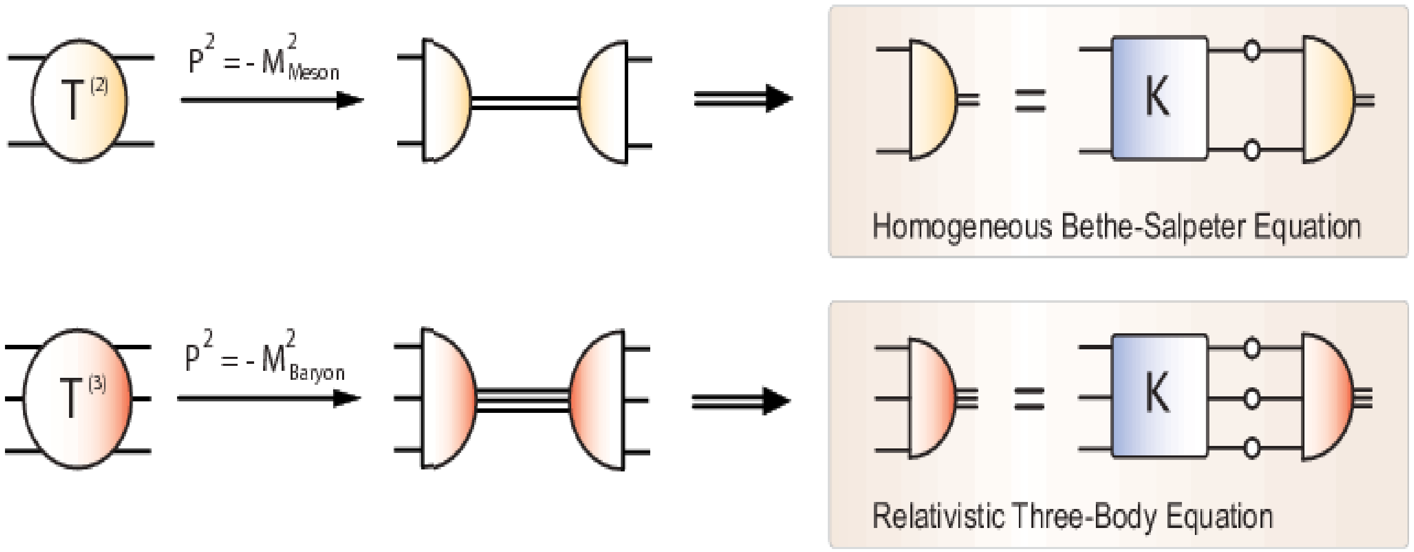
Review: C.D. Roberts et al. Eur. Phys. J. 2007.

Bound-state equations.

Bound-state poles in 4-point and 6-point Green functions lead to bound-state equations for mesons and baryons.



Bound-state equations.



Meson Bethe-Salpeter equations:
masses, FF,
leptonic decay constants.
Höll et al. PRC 71 2005
and PRC 70, 2004

Baryon Faddeev equations:
nucleon mass and FF,
recently delta mass and FF.

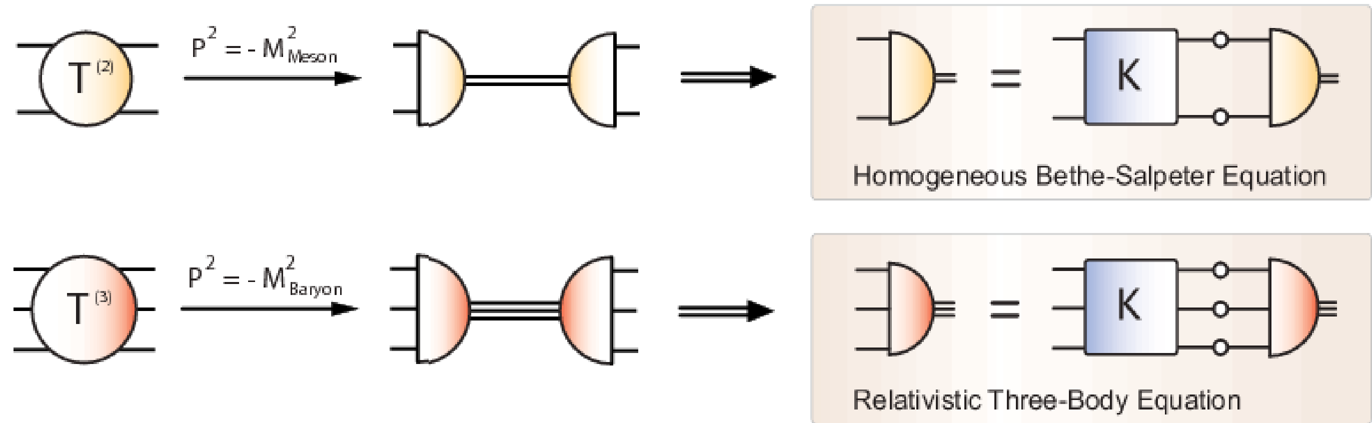
Quark-diquark: D.N. et al. PRD 80, 2009.
Eichmann et al. Ann.Phys. 323, 2008.
Oettel et al. EPJ A8, 2000.

Three-quark: Eichmann et al. arXiv:0912.2246

Recent!

Homogenous integral equations.
Resulting hadron amplitude and mass.

Bound-state equations.



Solution: * covariant hadron amplitude.

$$\Gamma(q,P) = \sum_i f_i(q^2, \hat{q}\cdot\hat{P})\tau_i(q,P)$$

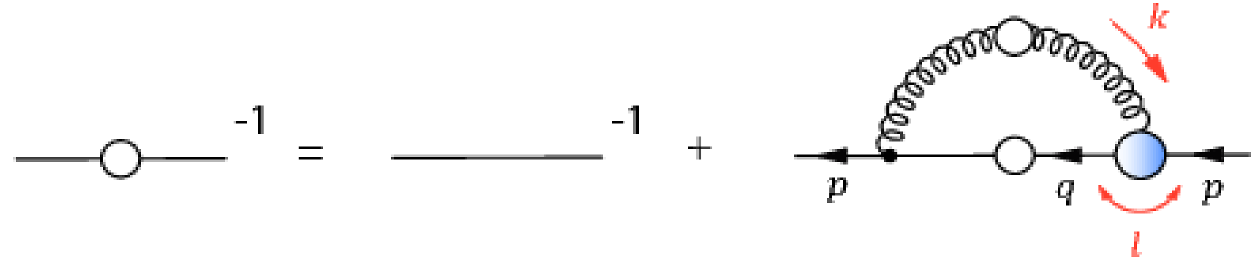
* depends on total hadron's momentum P and relative momentum q.

→ Pseudoscalar mesons: 4 covariants.

→ Nucleon: 64 covariants! Quark-diquark model: 8 covariants.

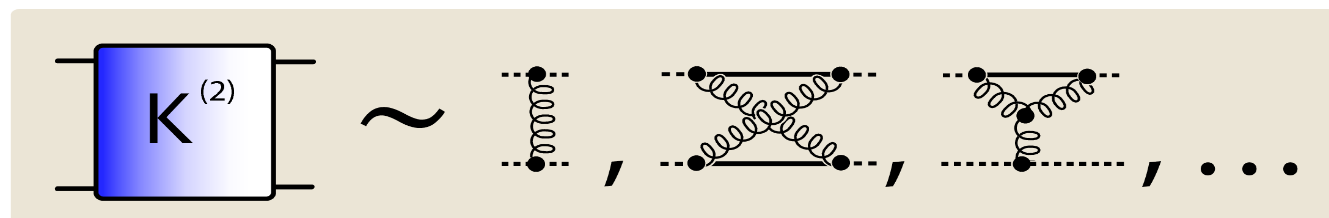
Bound-state equations ingredients.

Dressed-quark propagator

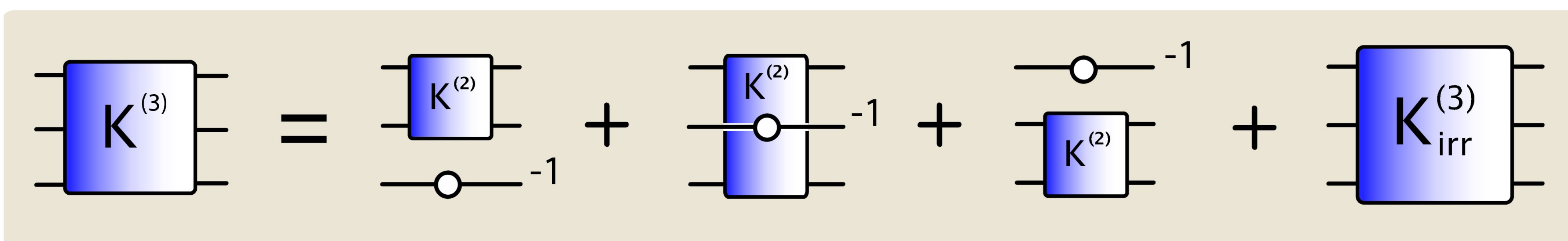


Interaction kernel

2-body:

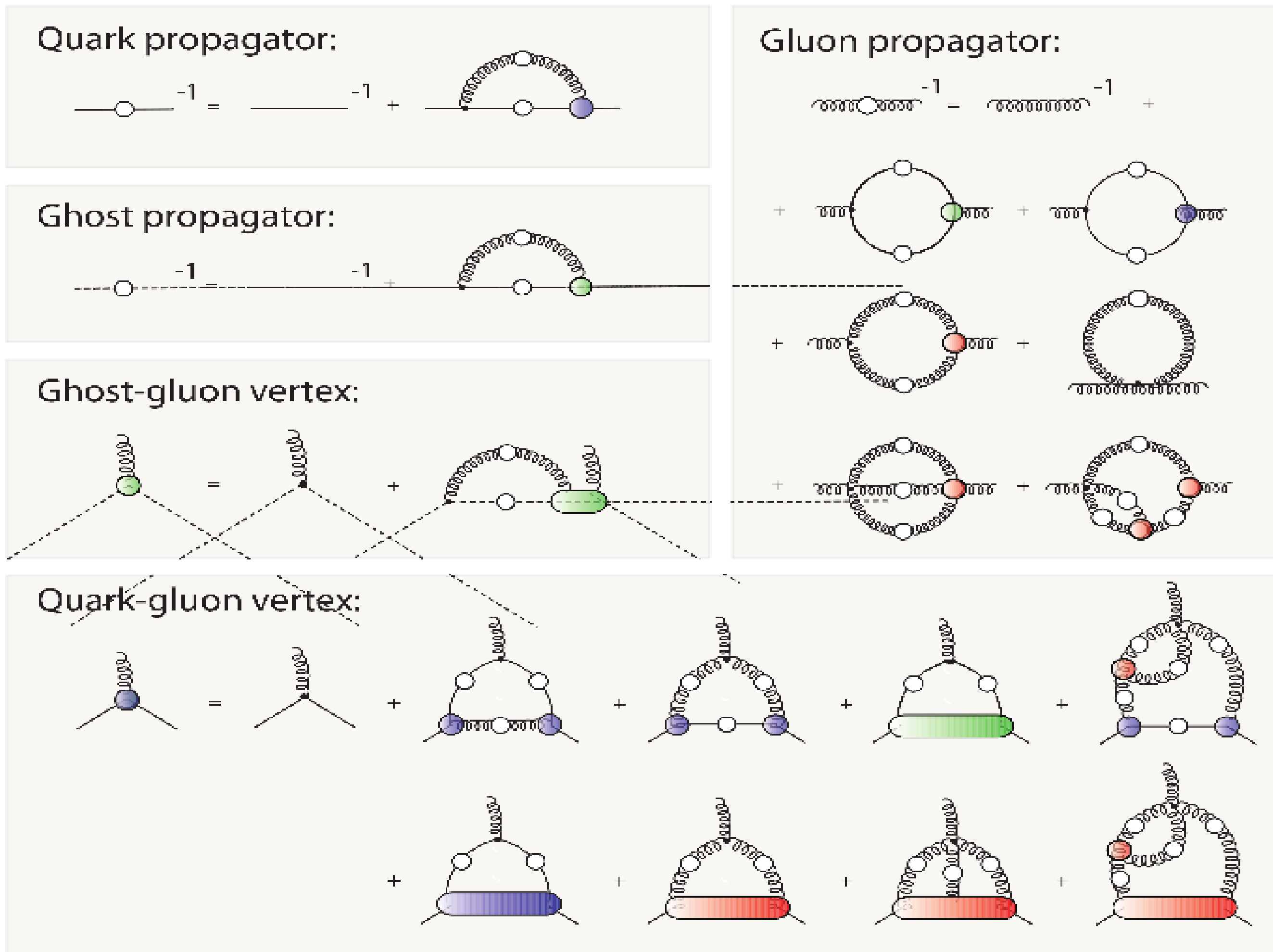


3-body:



Each ingredient obtained from its Dyson-Schwinger equation.

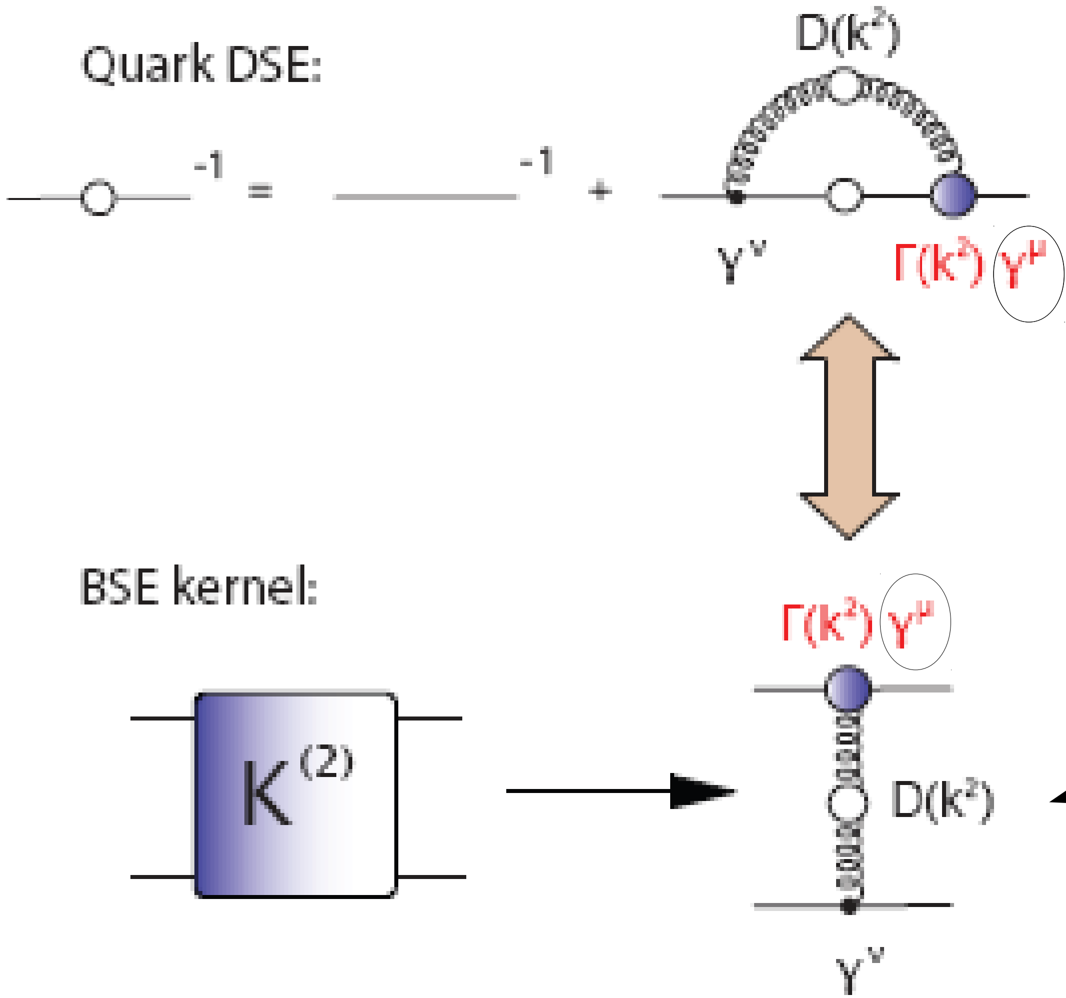
DSEs are equations of motions for QCD's Green functions.



Infinite set of coupled integral equations.

Truncations are needed (must satisfy QFT identities!).

Rainbow-ladder truncation.



Quark-gluon vertex consists of 12 tensor structures. Rainbow truncation retains only the vector part.

Ladder exchange of one dressed-gluon.

Dressings of the quark-gluon vertex and gluon propagator absorbed in an effective coupling $\alpha_{eff}(k^2) \sim D(k^2)\,\Gamma(k^2)$.

Rainbow-ladder truncation.

→ Simple, nonperturbative truncation of DSEs.

→ Satisfies Axial-Vector WTI.

→ Correctly implements chiral symmetry and its dynamical breaking: # massless pion in chiral limit
generalized GMOR at finite current quark mass.

Behavior of the effective coupling $\alpha_{eff}(k^2)$:

* Deep infrared → confinement
* Infrared → enhancement → DCSB, mass generation
* Ultraviolet → perturbation theory $\alpha_{eff}(k^2) \xrightarrow{1-loop} \dfrac{\pi\gamma_m}{ln\, k^2\ \Lambda^2_{QCD}}$

Modeling the effective coupling.

Based on P. Maris, P.C. Tandy PRC 60, 1999

$$\alpha_{eff}(k^2,\hat{m},\omega) = C\ \ \alpha_{IR}(k^2,\hat{m},\omega)\ \ +\ \ \alpha_{UV}(k^2)$$

Previous works:

coupling strength C fit to reproduce $f_\pi = 92MeV$

results independent of the coupling width ω

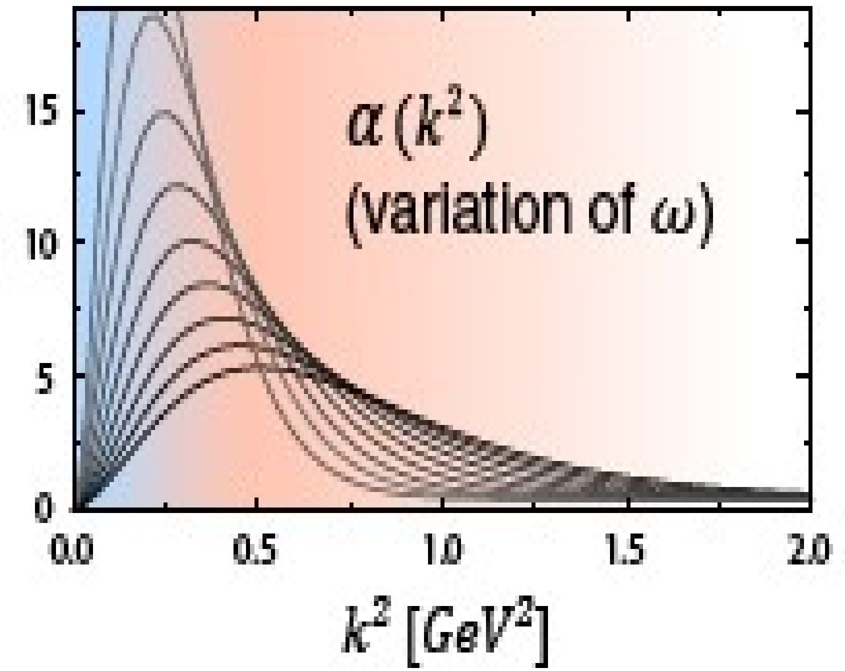
good description of basic meson observables

This work:

assume RL results describe quark-core contributions.

Rainbow-ladder truncation & quark-core contributions.

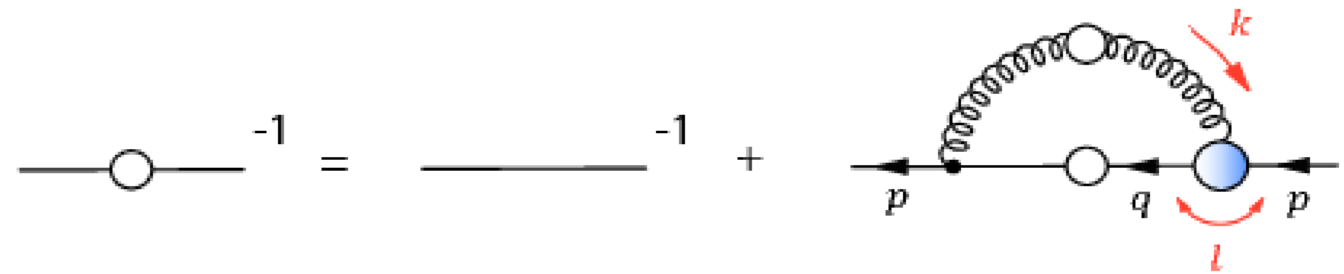
→ Adjust $\alpha_{IR}(k^2, \hat{m}, \omega)$ to estimated $m_\rho^{core}(m_\pi)$
Eichmann et al. PRC 77, 2008.
→ In chiral region $\left[m_\rho^{core} \sim 0.99_{\hat{m}=0}\ \mathrm{GeV}\right]$ this leads to:
* overestimated quark condensate,
hadron masses, decay constants.
* underestimated charge radii.



Estimates:
Pichowsky et al. PRD 60, 1999.
Bhagwat et al. PRC 70, 2004.
Matevosyan et al. PRC 75, 2007.

Rainbow-ladder truncation.

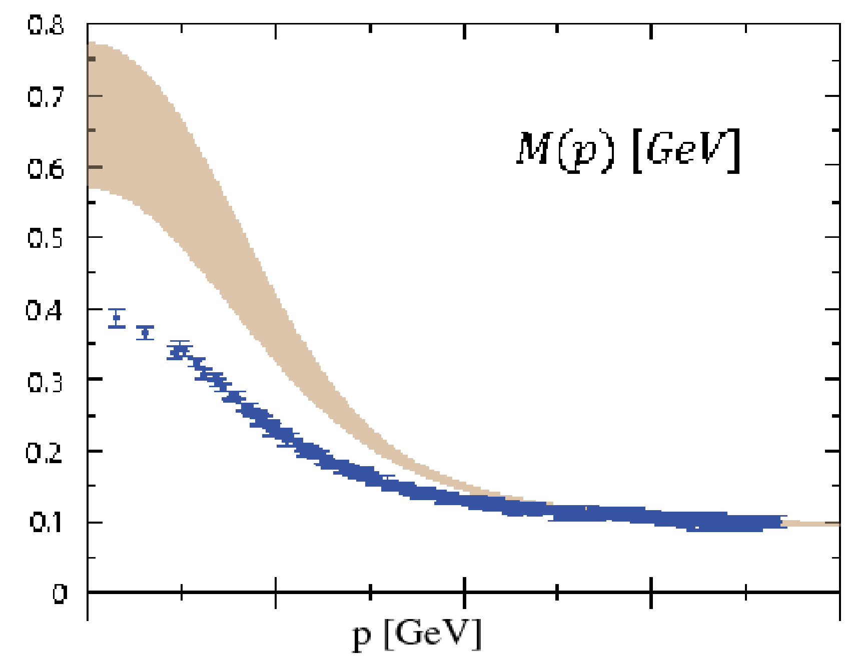
Dressed-quark DSE



$$S^{-1}(p) = S_0^{-1}(p) + \int_q \alpha_{eff}(k^2)\,\gamma_\mu\, D_{\mu\nu}^{free}(k)\,\gamma_\nu\, S(q)$$

Solution of general form

$$S(p) = \frac{1}{A(p^2)\;(i\,\not{p} + M(p^2))}$$

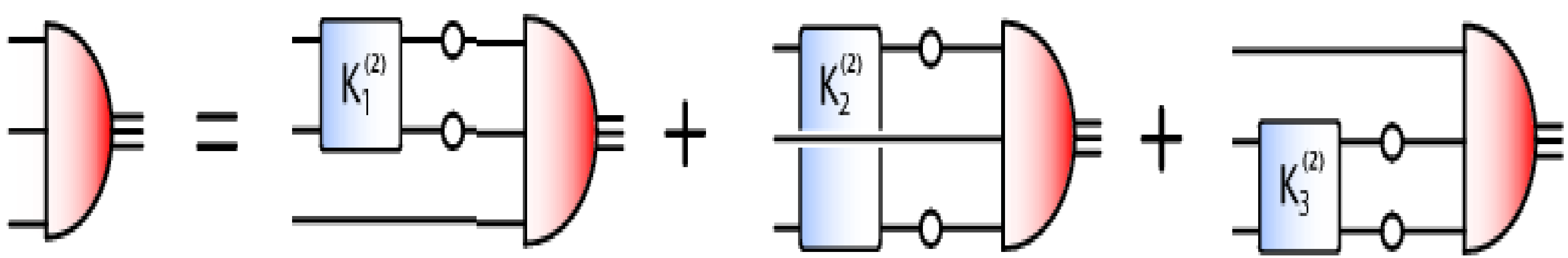


Quark mass function M(p) reflects quark dressing by gluons.
Dynamically generated enhancement at small momenta.

Baryons as quark-diquark bound-states.

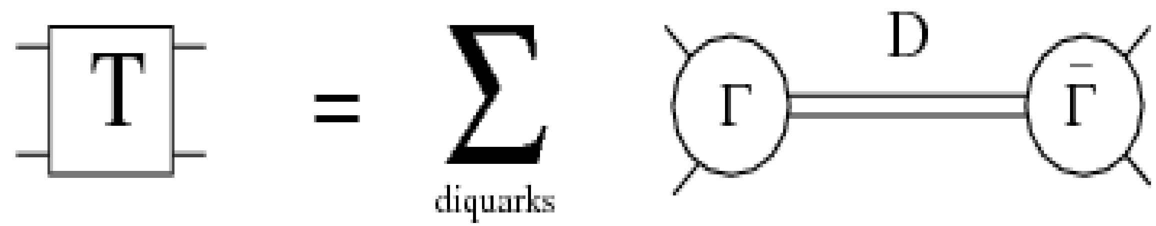
Attractive kernel in $1_c^{q\bar{q}}$ bound states.
Attractive kernel in $\bar{3}_c^{qq}$ channel (color singlet baryon $\bar{3}_c^{qq} \times 3_c^{q}$).
Binding in the nucleon: quark exchange between quark and diquark.

Faddeev truncation of the three-body problem:
qq correlations dominant structure in baryons.



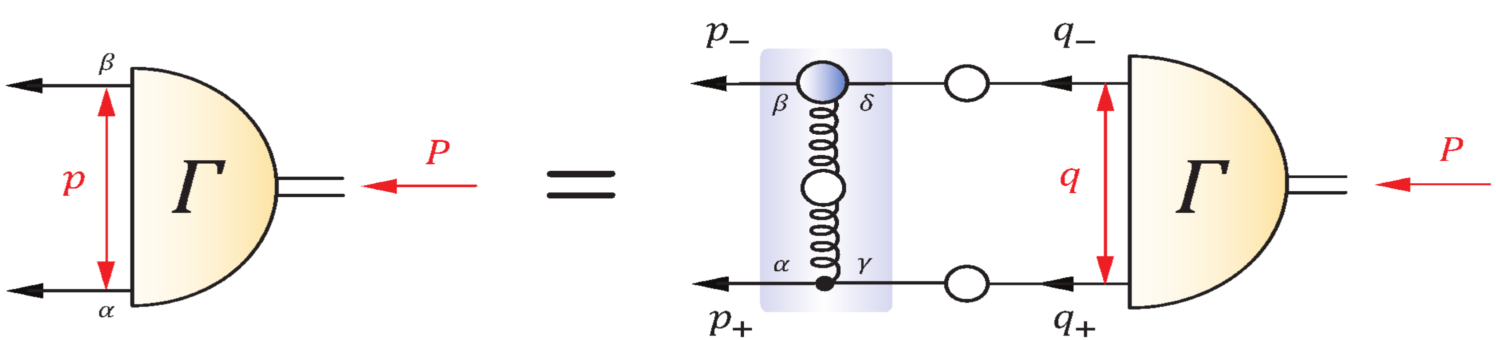
Diquarks.

* separable pole ansatz in qq scattering matrix

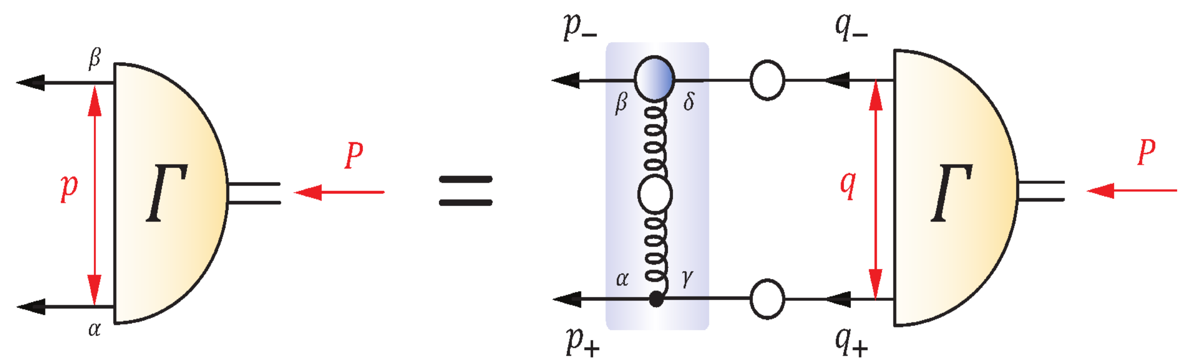


* non-pointlike
* rainbow-ladder artifacts
  (do not survive as asymptotic states)

Rainbow-ladder diquark BSE (analogy to meson sector).



Diquark BSE.



On mass-shell:

$$(P^2 = -M^2)$$

* diquark amplitudes

$$\Gamma(p,P) = \int_q K(p,q,P)\ \left[S(q_1)\,\Gamma(q,P)\,S^T(q_2)\right]$$

$$K(p,q,P) = \alpha(k^2)\,D_{free}(k)^{\mu\nu}\ \left(i\,\gamma^\mu \frac{\lambda^a}{2}\right)\left(i\,\gamma^\nu \frac{\lambda^a}{2}\right)$$

* diquark propagator

$$D(P^2) \longrightarrow \frac{1}{P^2 + M^2}$$

Off-shell diquark amplitudes parametrized as imposed by the asymptotic power behavior in UV of qq scattering matrix.

Diquark masses.

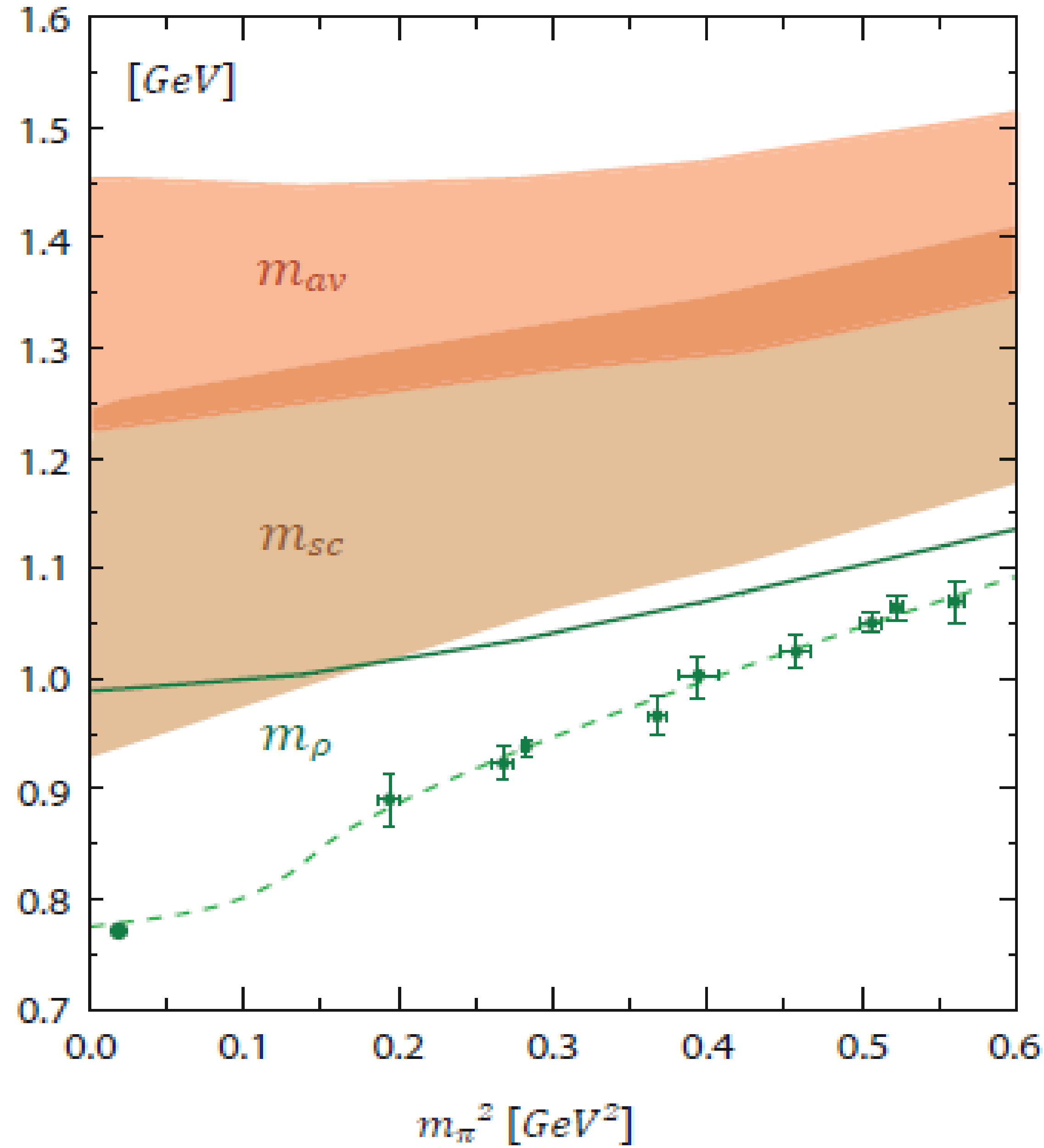
Diquark mass splitting:

decreases with increasing current quark mass.

several hundred MeV in chiral limit.

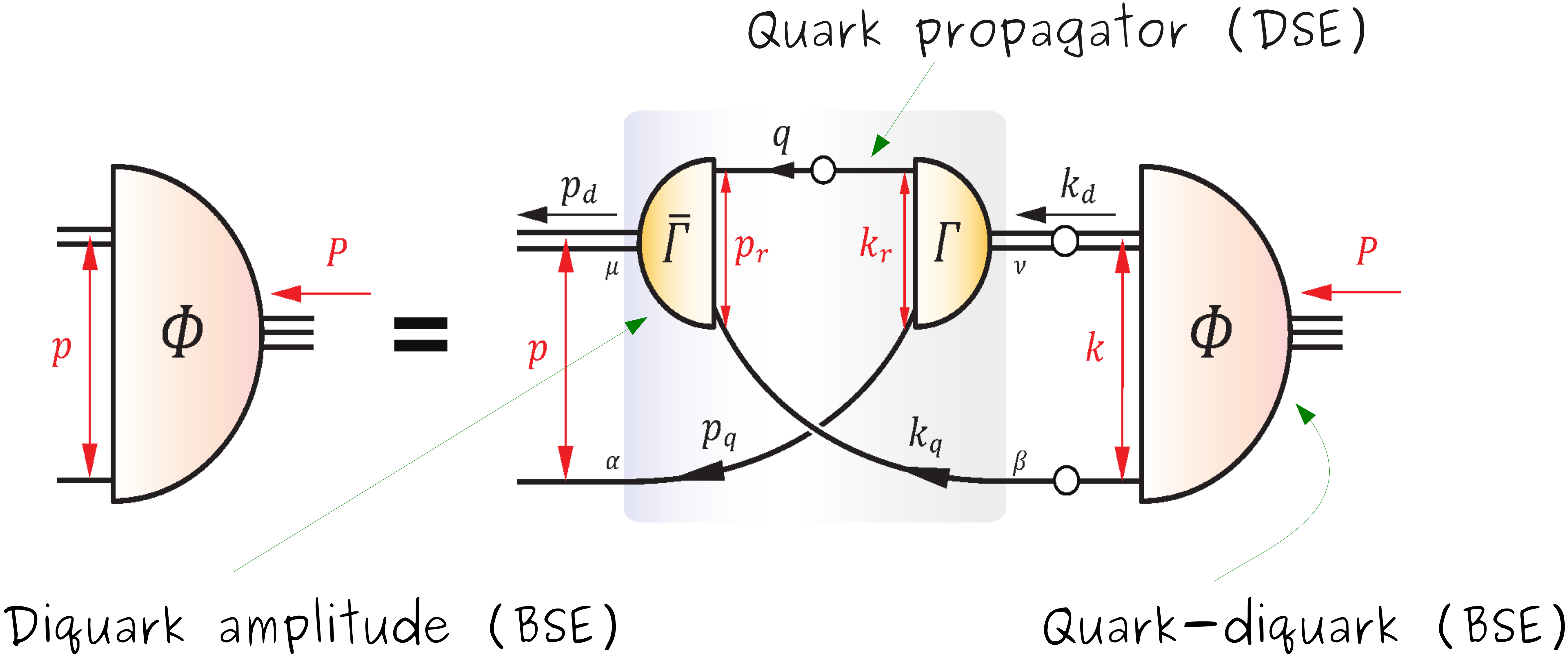
m_{sc} = 1.08 GeV

m_{av} = 1.35 Gev



Largely sensitive to the width parameter!!

Quark-diquark Bethe-Salpeter equation.



$$\Phi(p,P) = \int_k K(p,k,P)\, S(k_q)\, \Phi(k,P)\, D(k_d)$$

Quark-diquark core contributions to Nucleon and Delta masses

At physical point M_{pion} = 140 MeV :

Bands: core-version;

C fixed to reproduce hadron's core.

M_{Delta}^{core} = 1.73 GeV D.N. et al. PRD 80 (2009)

$M_{Nucleon}^{core}$ = 1.26 GeV G. Eichmann et al. PRC79 (2009)

M_{rho} = 990 MeV

Dashed lines: Maris-Tandy model;

C fixed to reproduce the pion.

Points: lattice data,

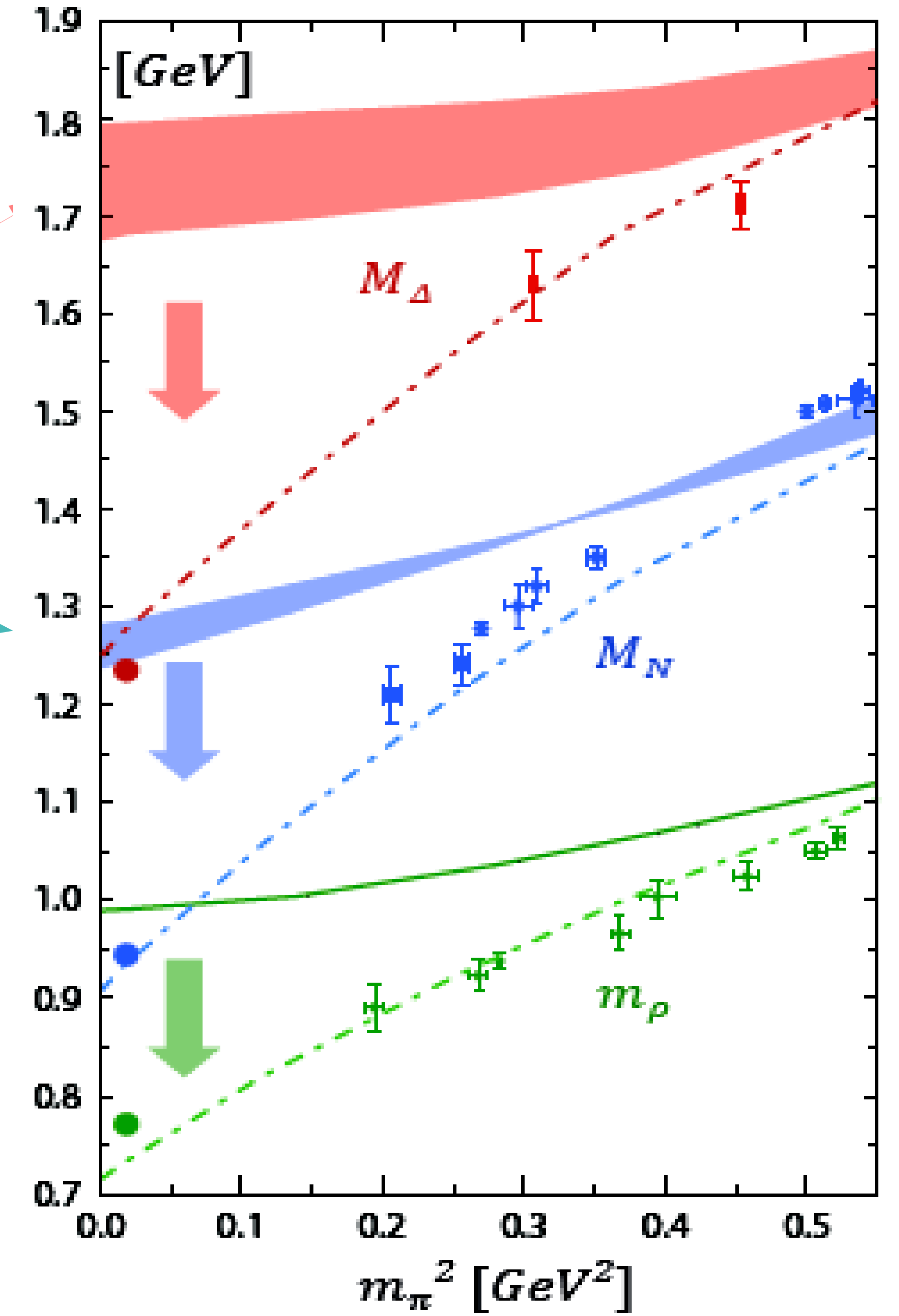
chiral extrapolation methods; experiment.

Zanotti et al. PRD 68 (2003)

Ali Khan et al. Nucl.Phys.B 689 (2004)

Allton et al. PLB 628 (2005)

Frigori et al. PoS(LAT2007)

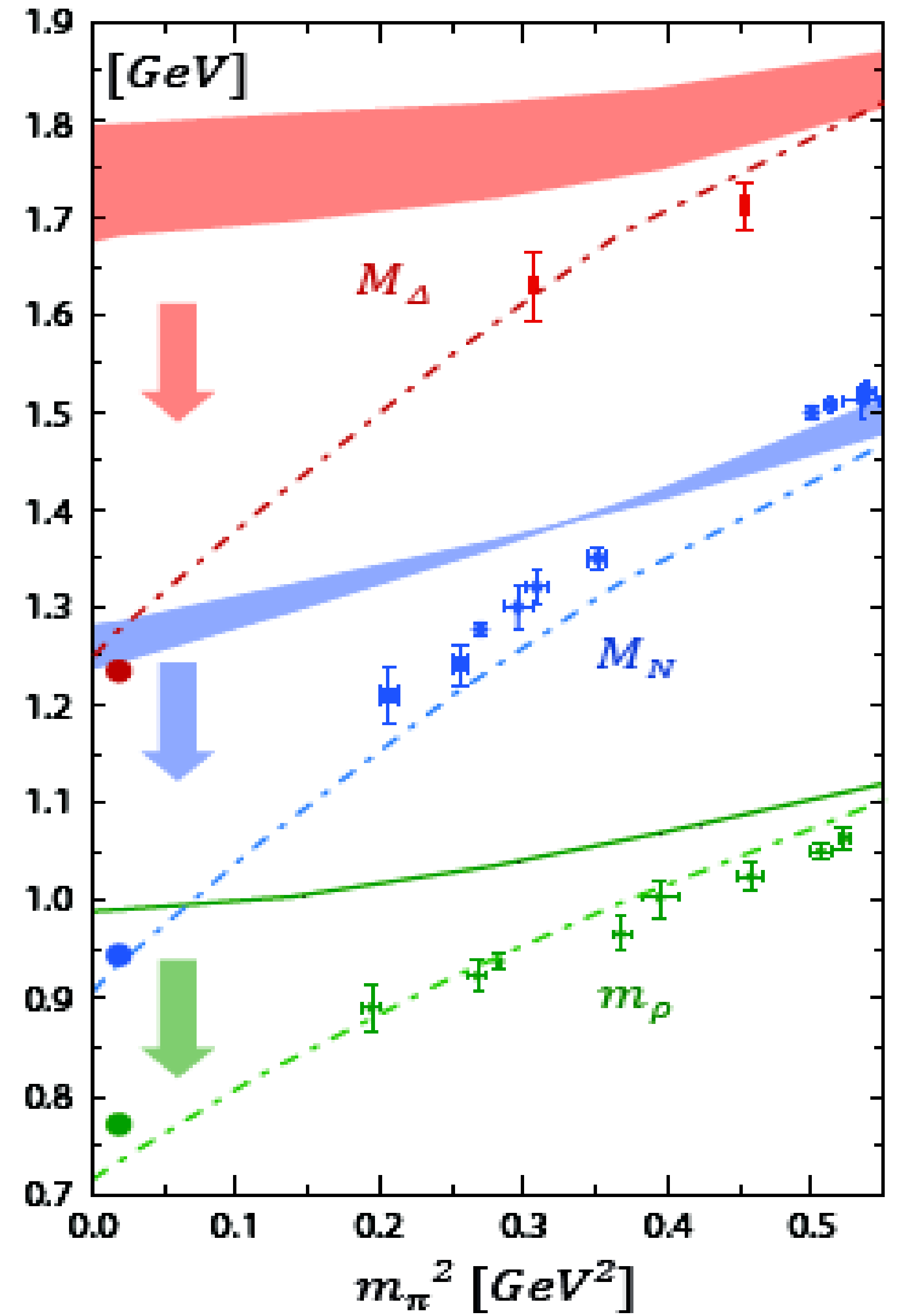


Quark-diquark core contributions to Nucleon and Delta masses.

* Both curves approach full lattice QCD predictions in the heavy-quark limit.

* At small current quark masses corrections to RL truncation are expected to be large.
Approx. 200-300 MeV for Nucleon, more for Delta!!
More diquarks needed?
Quark-diquark picture? RL truncation?

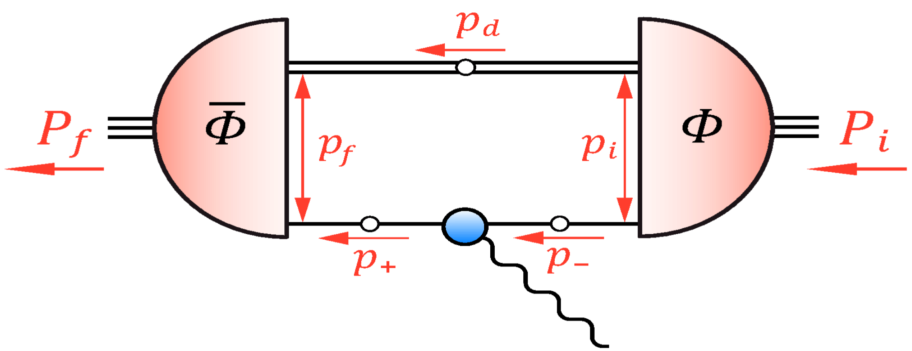
* Expected that missing contributions will bend the curves closer to data.



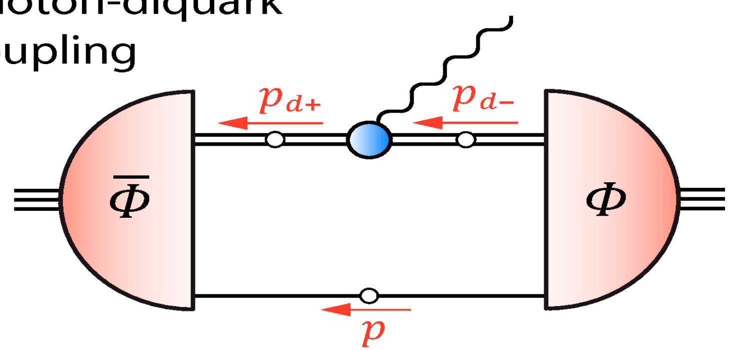
Baryon-photon coupling.

Current conservation requires the following diagrams.

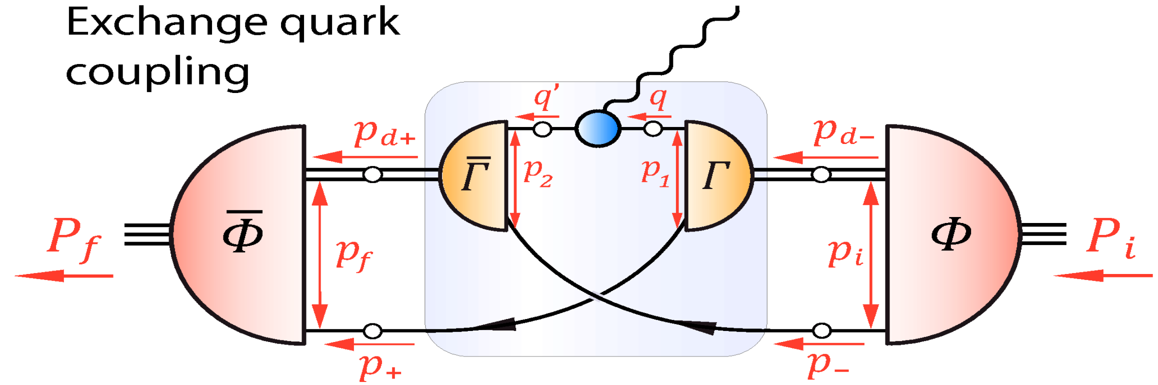
Photon-quark coupling



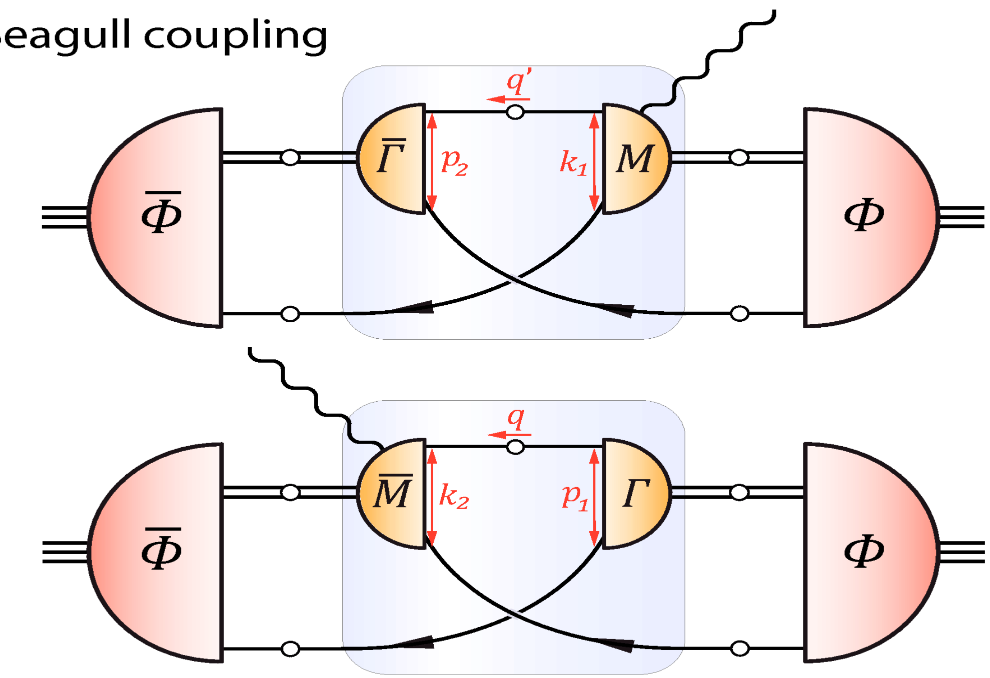
Photon-diquark coupling



Exchange quark coupling

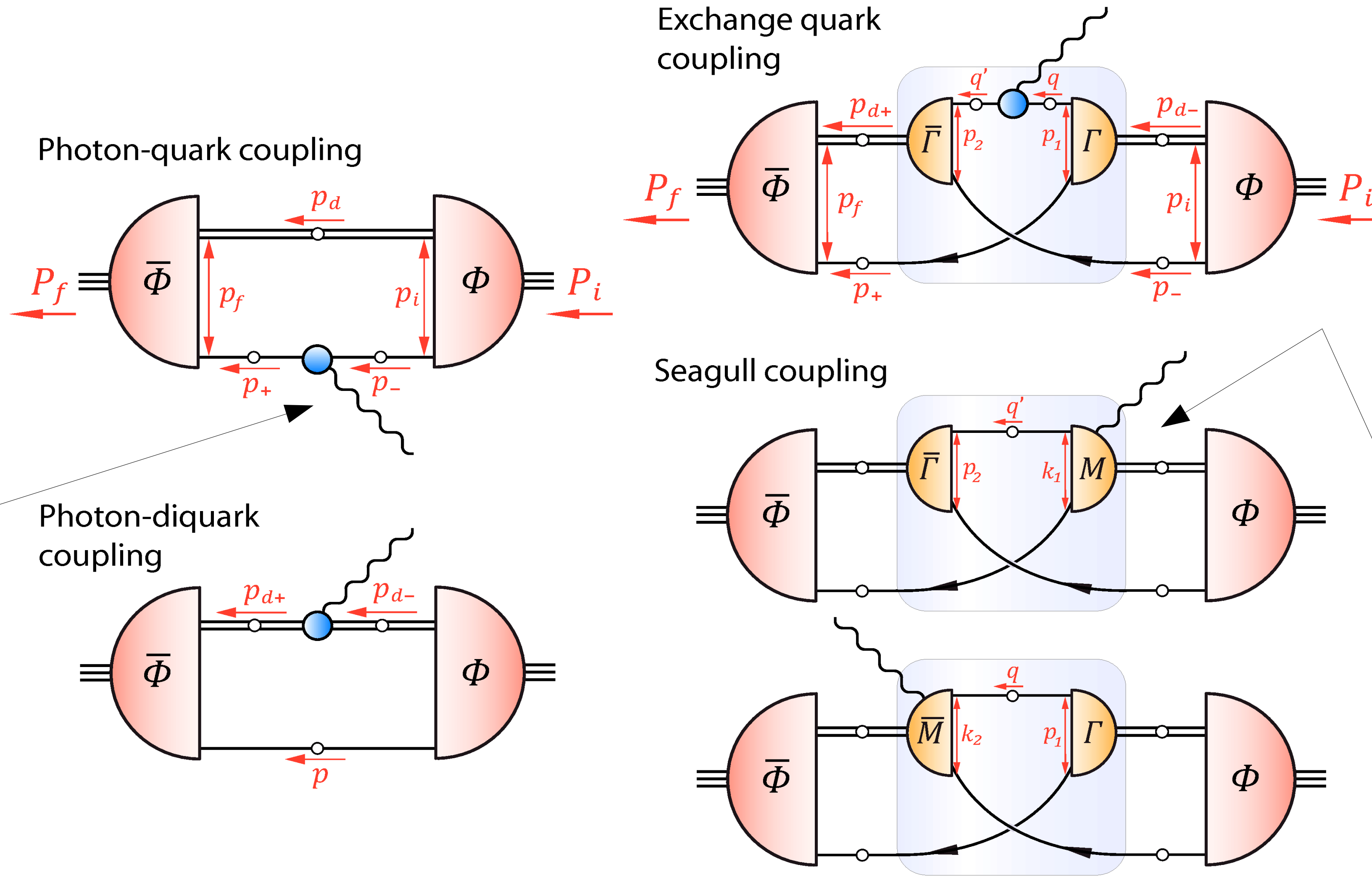


Seagull coupling



Oettel, Pichowsky, von Smekal, EPJ A 8, 2000.

Baryon-photon coupling.



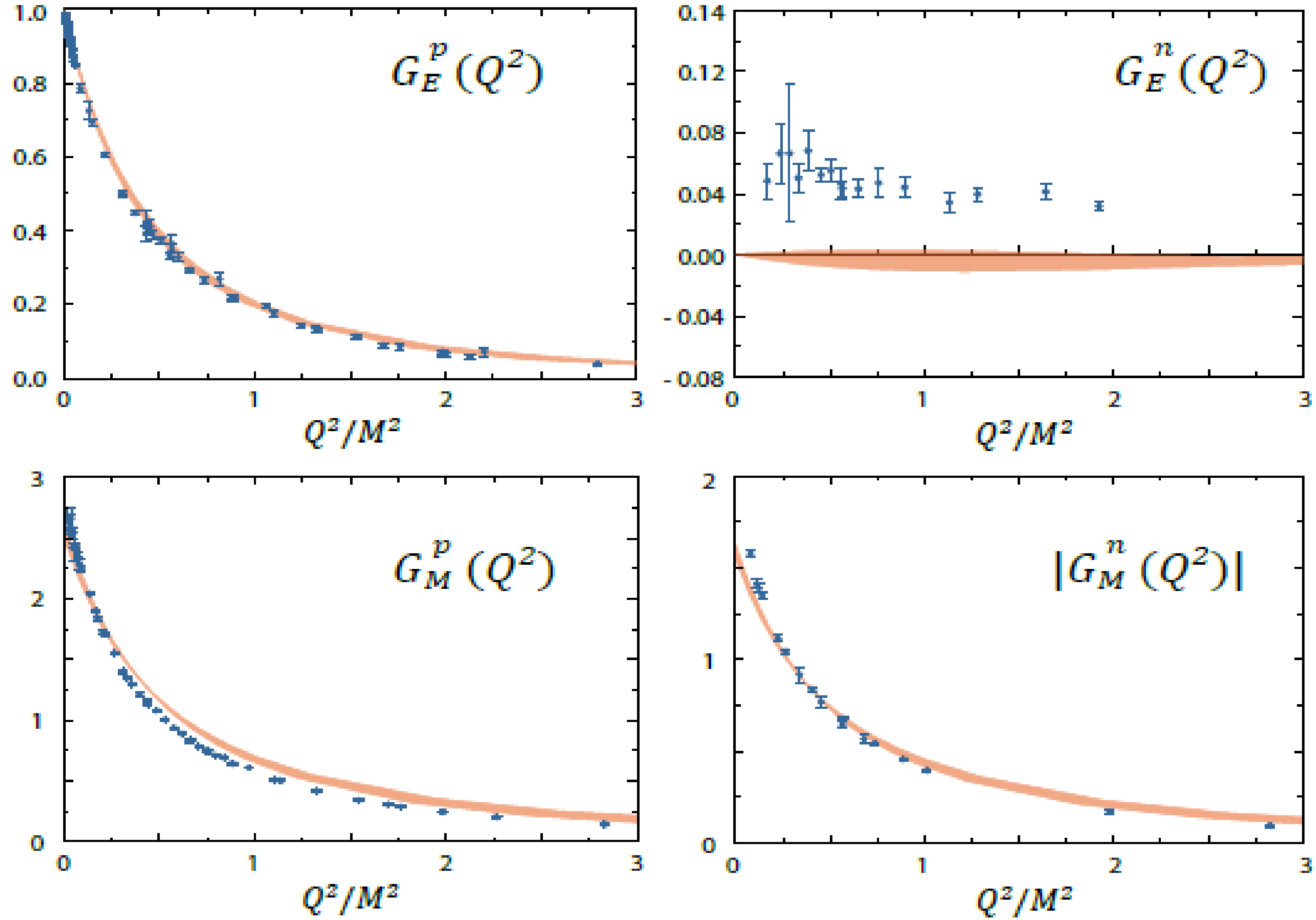
Ball−Chiu
vertex
+
rho−meson
mass pole
in the transverse part

ansatz
satisfying
WTIs

All vertices depend on dressed-quark propagators.

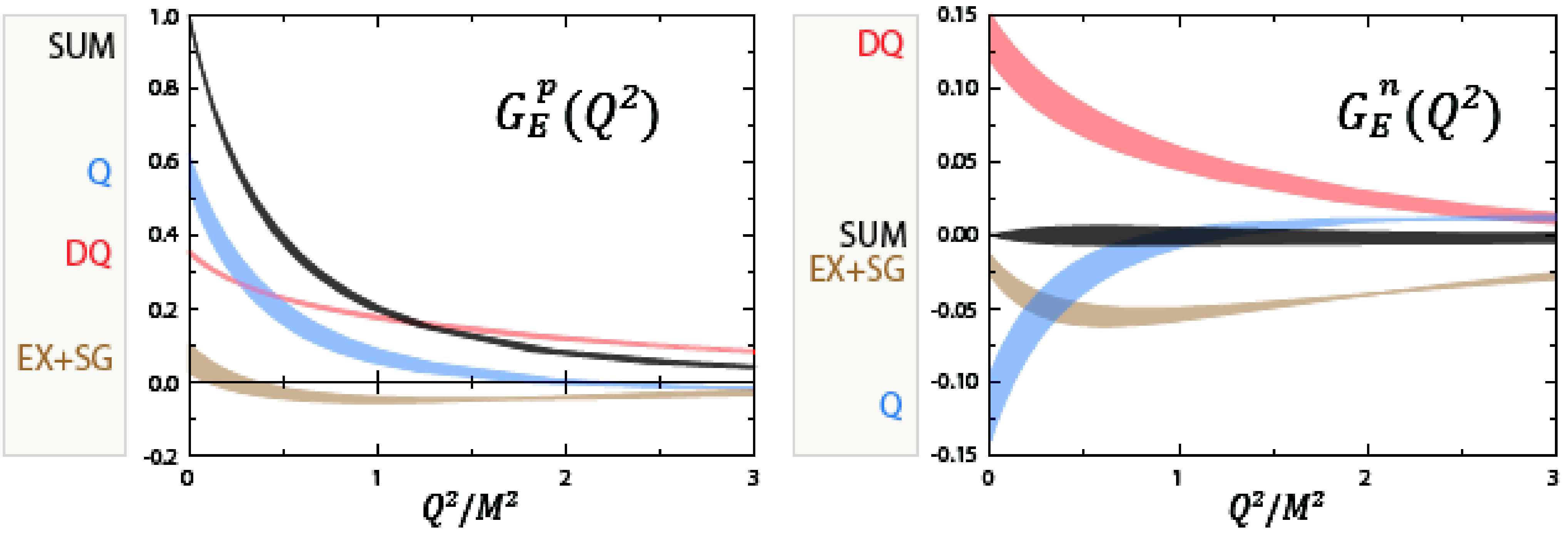
All longitudinal parts are ansätze fixed by WTIs.

Nucleon electromagnetic form factors.

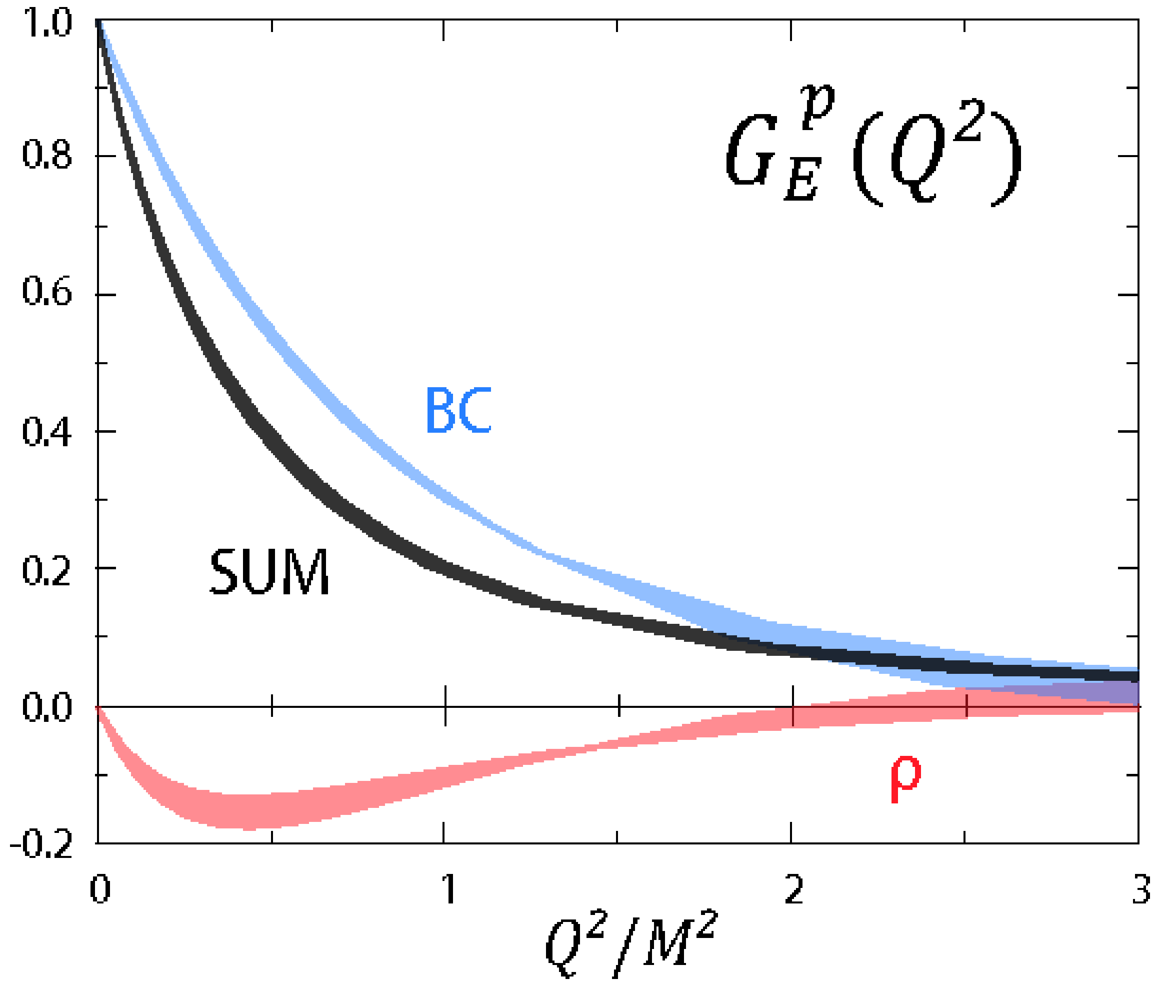


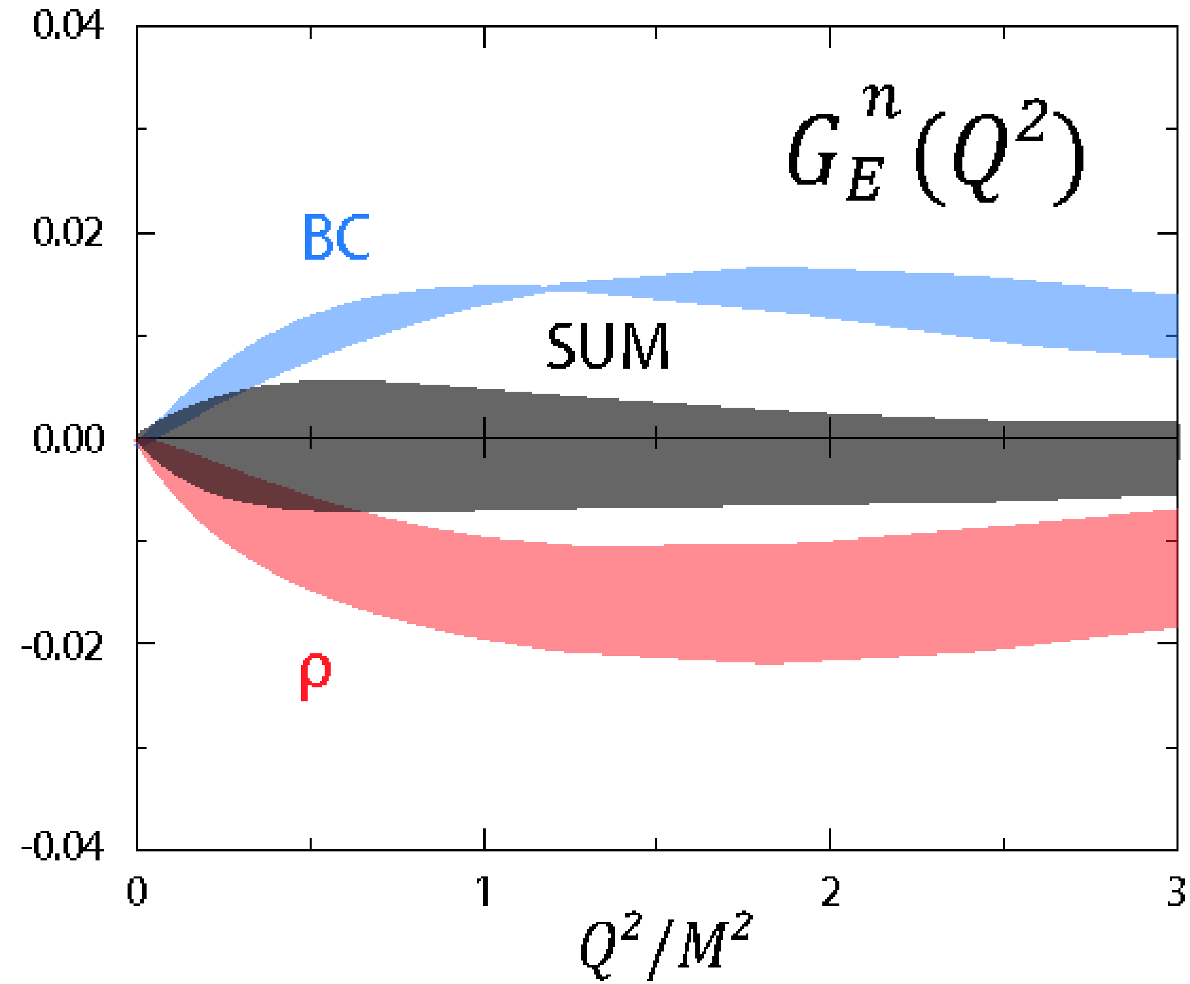
Comparison to a selection of experimental data (P. Grabmayr, Univ. Tuebingen). Bands represent the variation with the width parameter.

Quark-photon, diquark-photon, exchange and seagull contributions to electric form factors.



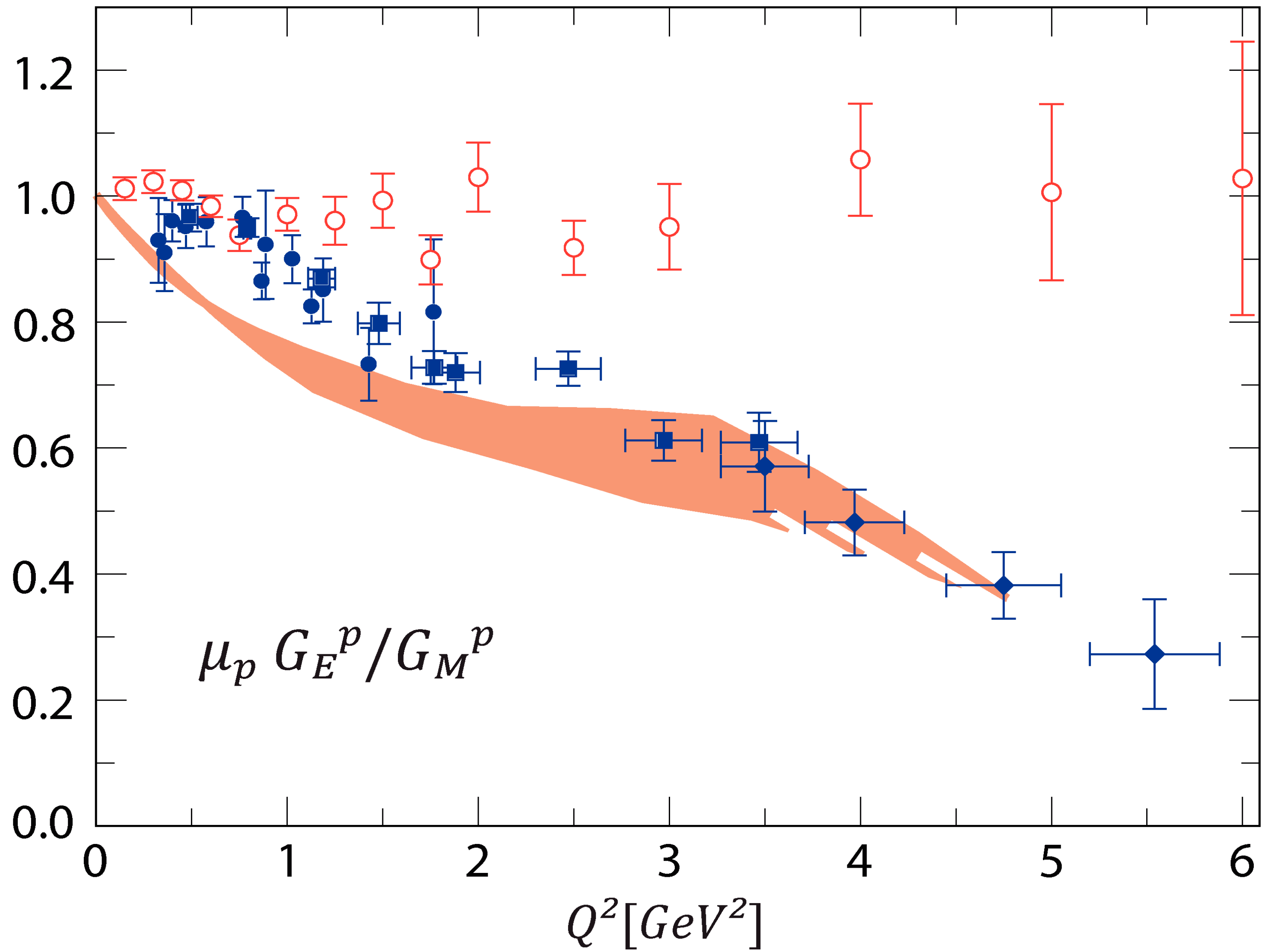
Ball-Chiu and vector-meson quark-photon vertex contributions to electric form factors.



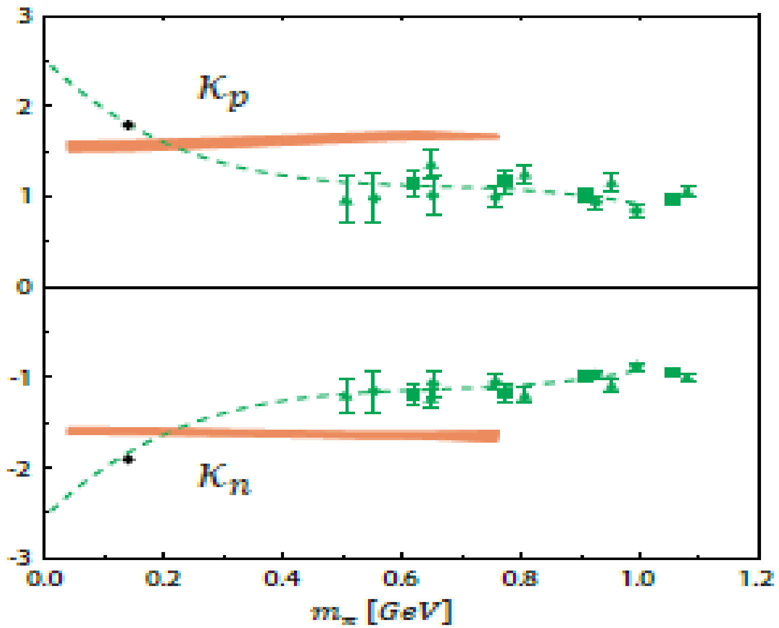


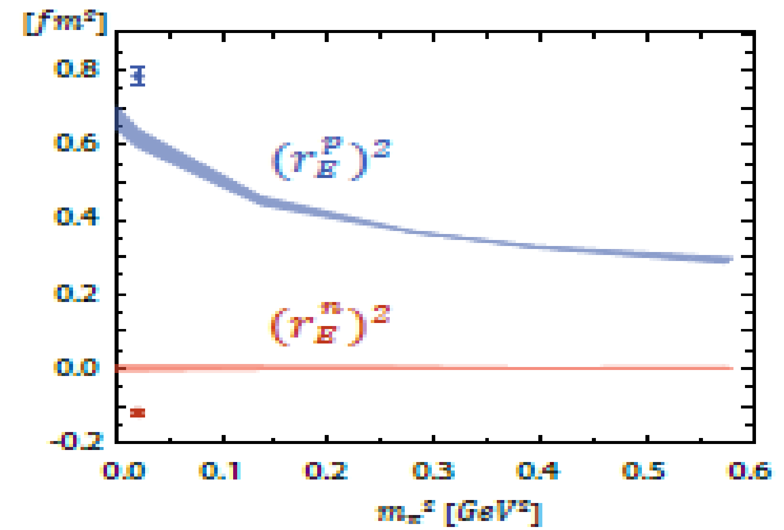
Sensitivity of proton form factor ratio with variation of the width parameter in the quark-diquark core model.

Data: Rosenbluth-separation and polarization-transfer measurements.



Nucleon electromagnetic static properties.





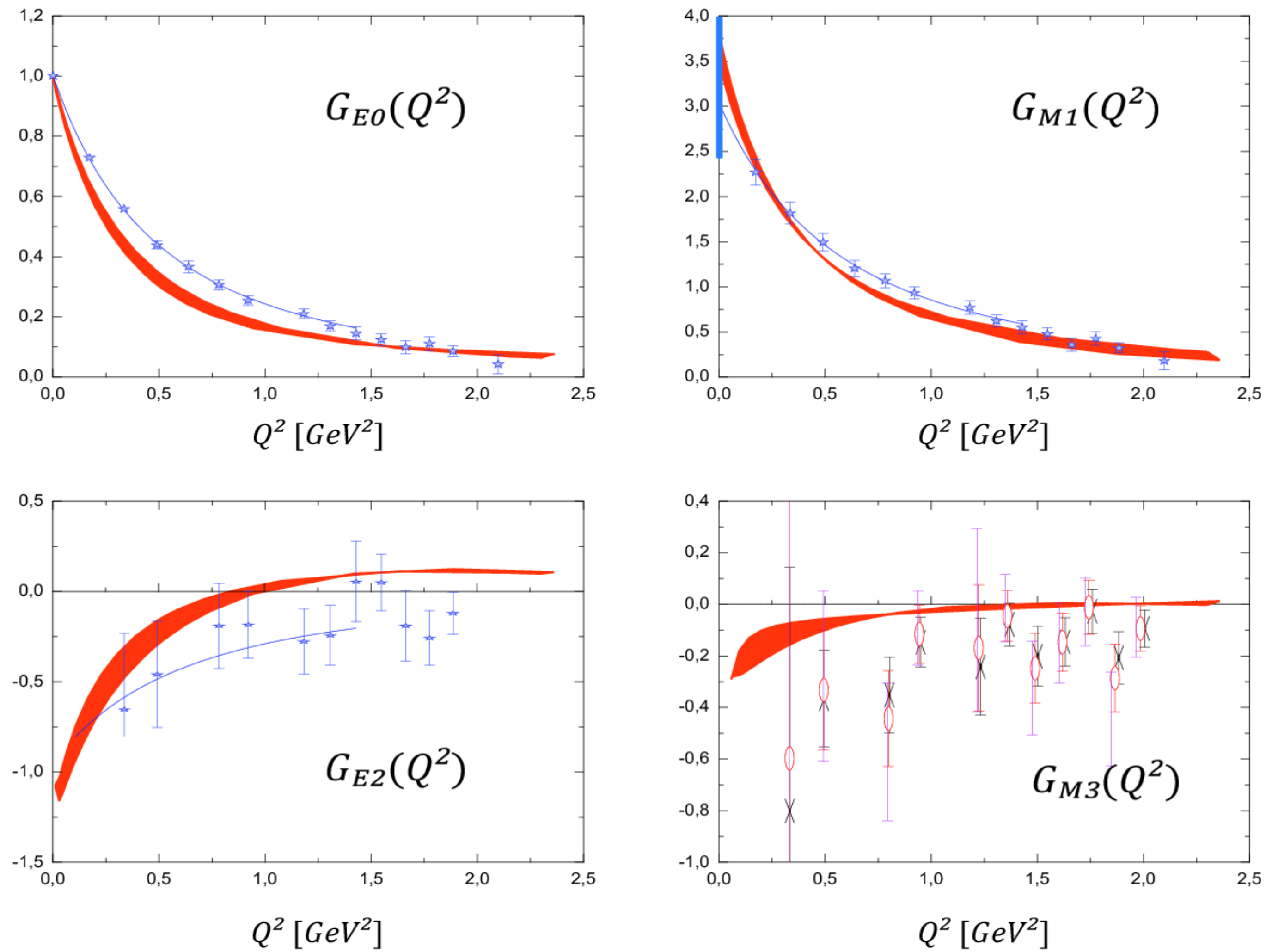
	μ_p	μ_n	r_E^p	$(r_E^n)^2$	r_M^p	r_M^n
Core	2.56(5)	−1.58(3)	0.79(2)	0.00(1)	0.73(2)	0.72(2)
Exp.	2.79	−1.91	0.89	−0.12	0.86	0.87

Preliminary!!

Delta electromagnetic form factors.

Here quark–diquark core version!!
Bands represent variation with the width parameter.

Data: lattice calculations of Alexandrou et al. PoSLAT2007, 149,2007



Summary.

Baryon observvbles: core + chiral clouds.

Baryon quark-core: quark + diquark in
a covariant Faddeev framework.

RL truncation: overestimated constituent mass scales, baryon masses... and underestimated static electromagnetic properties.

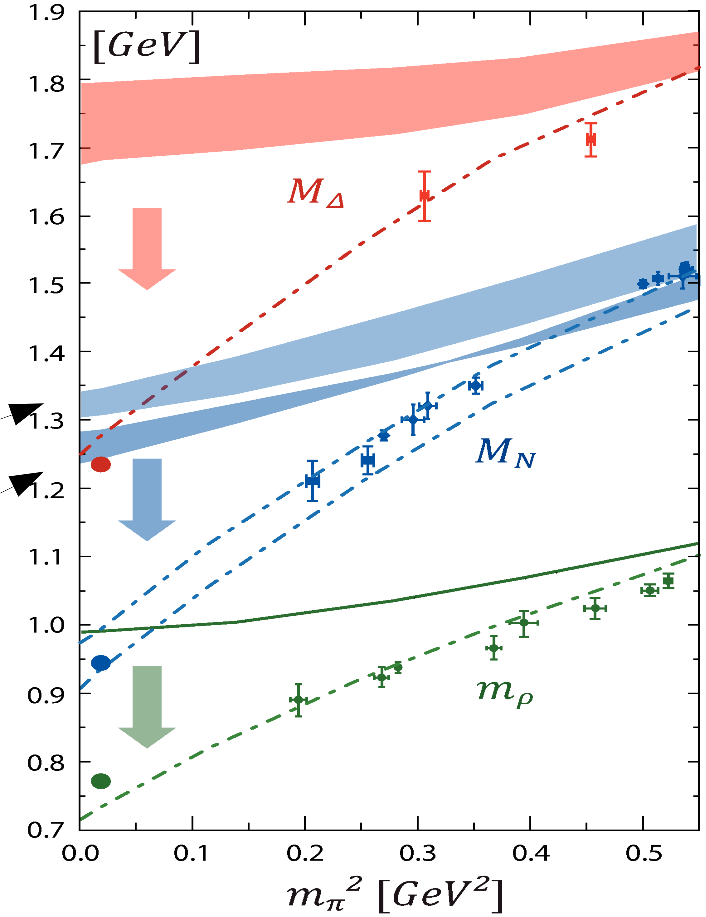
Clouds: approx. 200-300 MeV for nucleon mass.
ChEFT: Young et al. PRD 66 (2002).
ChEFFT and DSE: Thomas et al. PRC 66 (2002).

No baryon observables as input!!

Improvements/Outlook

Nucleon mass in a three-body Faddeev approach given by a consistent rainbow-ladder gluon exchange between any two quarks. Diquark pole ansatz is abandoned in favor of the full qq scattering kernel.

Done! See arXiv:0912.2876



Three-body core

Quark-diquark core

\# $N \longrightarrow \Delta\gamma$ transition form factors.

\# Delta mass, Nucleon and Delta FF in a three-body Faddeev approach.

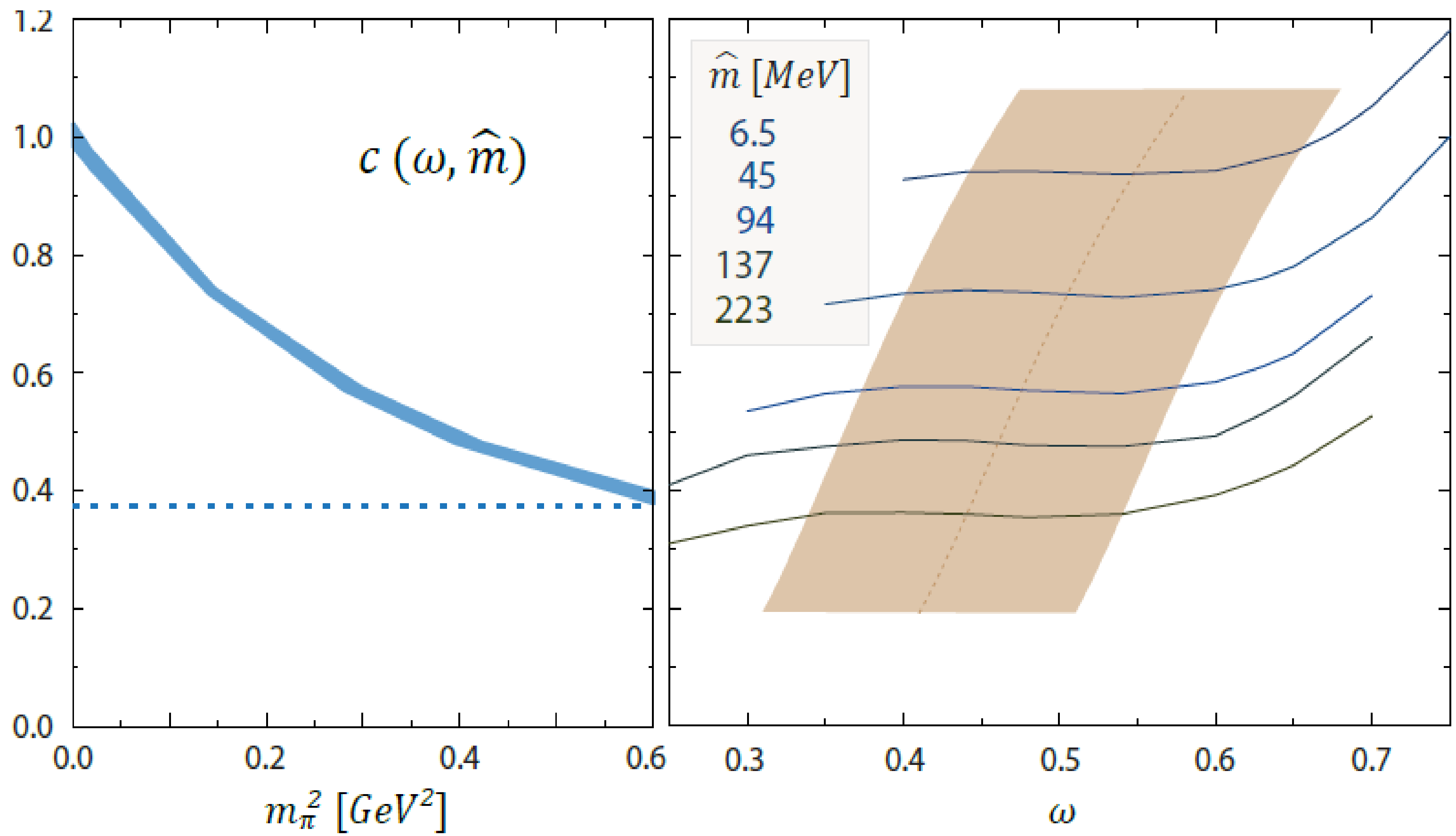
\# Excited states!!

\# Beyond RL truncation: chiral corrections, scalar part of quark-gluon vertex...

So ja... lots of work :)

Thank you for your attention!

Coupling strength C in the Maris-Tandy model (dashed line) and core-version (solid band). The current-mass evolution is expressed in terms of the squared pion mass obtained from the pseudoscalar-meson BSE.



Coupling strength in the core-version as a function of the width parameter for different current-quark masses. The dotted vertical line corresponds to a central value of the width parameter.