From quarks and gluons to baryon form factors

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Erice, September 20, 2011

Hadron phenomenology:

- Mass spectrum
- Hadron deformation
- Charge and magnetization structure
- Quark and gluon distribution in hadrons, spin and OAM structure
- Chiral properties from pion cloud
- Transition between perturbative and non-perturbative regions

QCD:

- Dynamical chiral symmetry breaking
- Confinement
- UA(1) anomaly
- Infrared structure of Green functions

- **Experiment**
  (JLab, MAMI, MIT-Bates, RHIC, CERN-SPS, FAIR, ...)
- **Lattice QCD & ChPT**
- **Quark models**
- **Bridges between perturbative and non-perturbative QCD**
  (GPDs/TMDs, ...)

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Truncation of DSEs

↕

QCD:

- Dynamical chiral symmetry breaking
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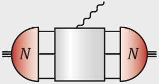
Covariant bound-state equations
for hadron wave functions / amplitudes

Dyson-Schwinger equations
for QCD's Green functions

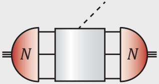
- **ab-initio**
- **non-perturbative**
- **covariant**
- **continuum**
- **light & heavy quarks**

Nucleon and Delta form factors:

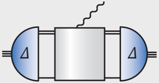
Nucleon em. FFs
GE, PRD 84 (2011)



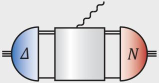
Nucleon axial & ps. FFs
GE & C. S. Fischer, in preparation



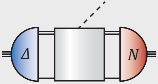
Delta em. FFs
D. Nicmorus, GE, R. Alkofer, PRD 82 (2010)



NΔγ (em. transition)
GE & D. Nicmorus, in preparation



NΔπ (ps. transition)
V. Mader, GE, M. Blank, A. Krassnigg, PRD 84 (2011)



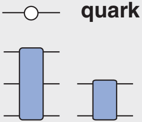
Building blocks

Truncation
of DSEs

DSE

Ansatz

quark propagator

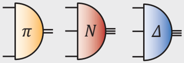


qqq, qq
kernels

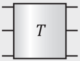
BSE & Faddeev equation

Scattering equation

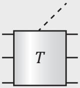
"Gauging" of T-matrix
Haberzettl, PRC 56 (1997)
Kvinikhidze, Blankleider, PRC 60 (1999)



hadron amplitudes
and masses

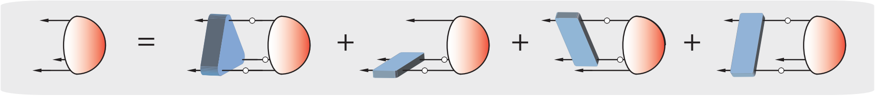


offshell
T-matrix



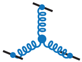
currents, form factors,
hadron structure

Three-body equation



Irreducible 3-body diagrams

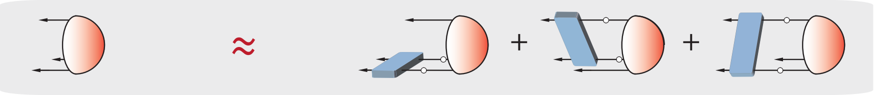
3-gluon coupling to each quark, ...



Quark-quark correlations

assumed as dominant structure in baryons.
Hints: lattice QCD, BSE, hadron spectrum, ...

Faddeev equation



Quark-quark correlations
assumed as dominant structure in baryons.
Hints: lattice QCD, BSE, hadron spectrum, ...

Same setup for **mesons and baryons:**
we need **quark propagator & qq / $q\bar{q}$ kernel**

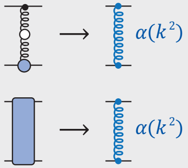
- **Dynamical chiral symmetry breaking**
  ⇒ **mass generation** at quark & hadron level

- **Poincaré covariance**
  ⇒ **orbital angular momentum** in the bound-state amplitudes:

  Nucleon: 64 basis elements **(s, p, d waves)**
  GE, Alkofer, Krassnigg, Nicmorus, PRL 104 (2010); GE, PRD 84 (2011)

  Delta: 128 basis elements **(s, p, d, f waves)**
  Sanchis-Alepuz, GE, Villalba-Chávez, Alkofer, 1109.0199 [hep-ph]

Rainbow-ladder truncation



in **quark DSE**

in **meson BSE** & **Faddeev equation**

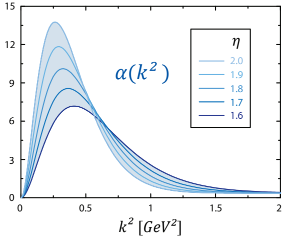
Satisfies Vector WTI (⇒ e.m. current conservation) and Axial WTI (⇒ Goldberger-Treiman, GMOR)

Effective coupling $\alpha(k^2)$ is (the only!) model input

Maris, Tandy: PRC 60 (1999)

$$\alpha(k^2) = \alpha_{\text{IR}}\left(\tfrac{k^2}{\Lambda^2}, \eta\right) + \alpha_{\text{UV}}(k^2)$$

Infrared scale Λ adjusted to f_π, width η kept as parameter



Beyond rainbow-ladder:

- **Pion cloud:** chiral region, low-Q^2 structure in FFs. Not included → **"Quark core"**
- **Decay channels** ($\rho\to\pi\pi$, $\Delta\to N\pi$): so far only bound states
- **"Non-resonant corrections":** cancel pion cloud in some channels (ρ, N?, Δ?), dominant in others (scalar, axialvector mesons)

Fischer, Williams, PRL 103 (2009), Chang, Liu, Roberts, PRL 103 (2009)

Mass results

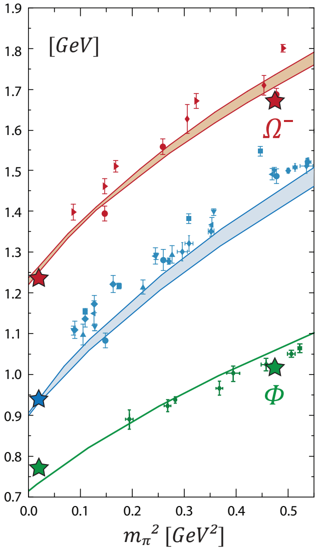
Consistent description
of π, ρ, N, Δ ground states
(dominated by **s waves**)

Only one input parameter:
scale Λ, adjusted to f_π

What **doesn't work** so well
in rainbow-ladder:

- scalar, axial-vector mesons
- excited mesons
- η–η'

Krassnigg, PRD 80 (2009)
Alkofer, Fischer, Williams, EPJ A38 (2008)
Fischer, Williams, PRL 103 (2009)
Chang, Roberts, PRL 103 (2009)



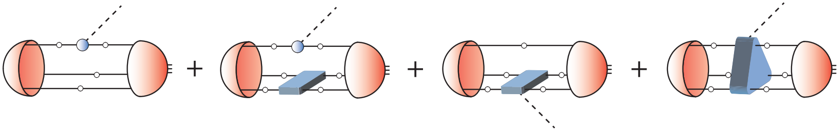
Delta mass:
Sanchis-Alepuz et al., 1109.0199 [hep-ph]

Nucleon mass:
GE, PRD 84 (2011)

ρ–meson mass:
Maris, Tandy, Nucl. Phys. Proc. Suppl. 161 (2006)

Hadron current

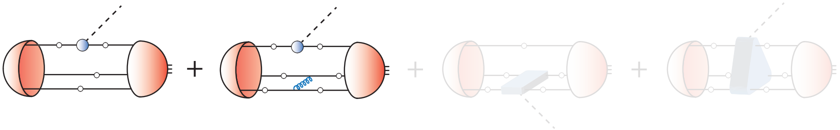
General expression for a baryon's **non-perturbative current:** GE, PRD 84 (2011)



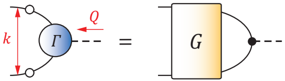
Impulse approximation + **2-quark kernel** + **Coupling to 2-quark kernel** + **Coupling to 3-quark kernel**

Hadron current

General expression for a baryon's **non-perturbative current:** GE, PRD 84 (2011)



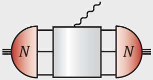
Form factors directly related to properties of pseudoscalar, vector, axial-vector **quark-antiquark vertices**:



- Baryon form factors inherit **meson bound-state poles:** "vector-meson dominance" for em. FFs
- Vector WTI ⇒ **em. current conservation**; AXWTI ⇒ **Goldberger-Treiman relation**

Nucleon em. FFs

GE, PRD 84 (2011)

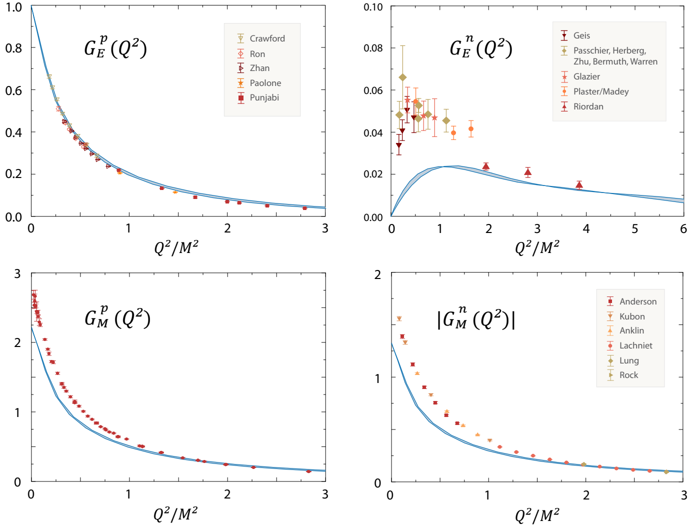


G_E, G_M for p, n

Sachs FFs

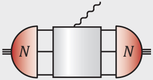
vs. momentum transfer

- match data at large Q^2, **missing pion cloud** below ~2 GeV^2
- agree with **lattice** at large quark mass and **ChPT quark core** in chiral region
- same shape up to strange-quark: **~30% p-waves** in amplitude

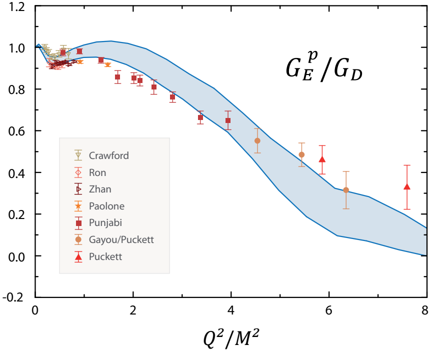


Nucleon em. FFs

GE, PRD 84 (2011)



G_E, G_M for p, n



Faddeev result consistent with data,
suggests zero crossing at larger photon momentum
$\Rightarrow$ **OAM in nucleon amplitude!**

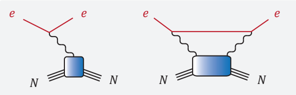
Electric proton form factor

at large momenta:

- **Rosenbluth method** suggested $G_E/G_M = \text{const.}$, in agreement with perturbative scaling

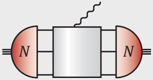
  Polarization experiments at JLAB showed **falloff** in G_E/G_M, with possible **zero crossing**

- Difference likely due to **two-photon corrections**
  Guichon, Vanderhaeghen, PRL 91 (2003)



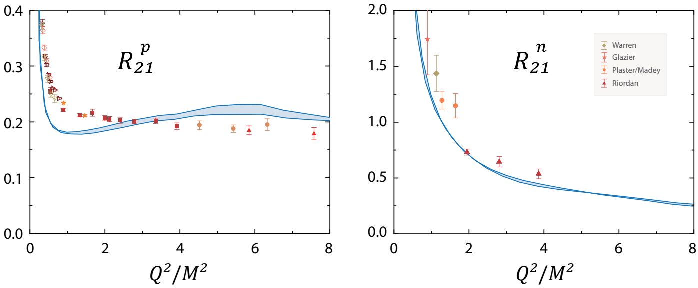
Nucleon em. FFs

GE, PRD 84 (2011)



G_E, G_M for p, n

Pauli-to-Dirac ratios
at large momenta:



- Updated scaling prediction for **Pauli-to-Dirac ratios:**
  Belitsky, Ji, Yuan, PRL 91 (2003)

  $$R_{21} \sim \frac{F_2}{F_1} \frac{Q^2}{ln^2(Q^2/\Lambda^2)} \xrightarrow{Q^2 \to \infty} \text{const.}$$

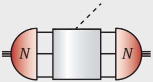
  ~ OAM

  Logarithmic scaling implies zero crossing in G_E/G_M.

- Faddeev result consistent with data. Perturbative behavior built in by **gluon exchange,** produces ~30% **OAM** in rest frame.

Nucleon axial & ps. FFs

GE & C. S. Fischer, in preparation



$G_A\,,\ G_L\,,\ G_{\pi NN}$

G_A ~ axial-transverse vertex, **axial-vector poles**

G_L ~ axial-longitudinal vertex, **pseudoscalar poles**

$G_{\pi NN}$ ~ pseudoscalar vertex, **pseudoscalar poles**

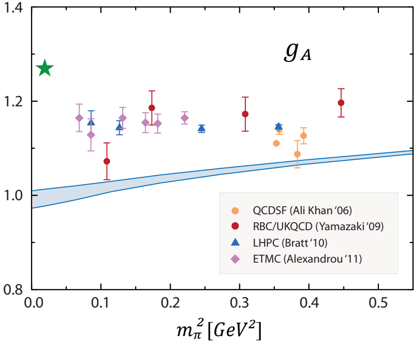
at $Q^2=0$: related by **analyticity**

related by **AXWTI**

- **Goldberger-Treiman** accurately reproduced for **all** quark masses:

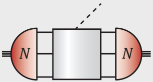
$$G_A(0) = \frac{f_\pi}{M_N}\,G_{\pi NN}(0)$$

- **Pion-cloud corrections?** lattice: large box sizes



Nucleon axial & ps. FFs

GE & C. S. Fischer, in preparation



G_A , G_L , $G_{\pi NN}$

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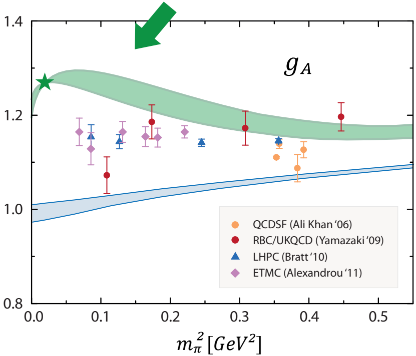
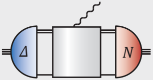
ChPT: Procura *et al.*, PRD 75 (2007)

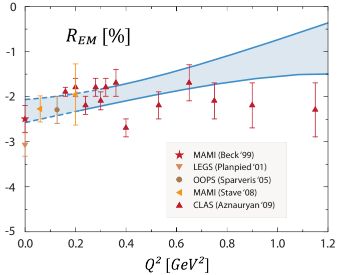


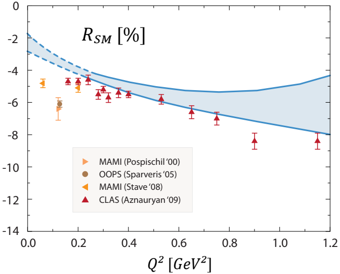
NΔγ (em. transition)

GE & D. Nicmorus, in preparation



$G_M^*,\ R_{EM},\ R_{SM}$





- G_M^* **(magnetic dipole transition)** dominant: quark spin flip (s wave).

- R_{EM} & R_{SM} **(electric & Coulomb quadrupole transitions)** small & negative. Encode **deformation**. Quark model: need **d-waves** in N or Δ amplitude, or **pion cloud**.

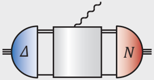
  ChPT: strong chiral non-analyticities due to open $\Delta \to N\pi$ decay channel
  Pascalutsa, Vanderhaeghen, Phys. Rept. 437 (2007)

  pQCD scaling predictions: $R_{EM} \to 1$, $R_{SM} \to$ const. **?**
  Carlson, PRD 34 (1986)

- **Faddeev result** (here: quark-diquark model) reproduces R_{EM} & R_{SM} even without pion cloud, and d-waves are typically small. **?**

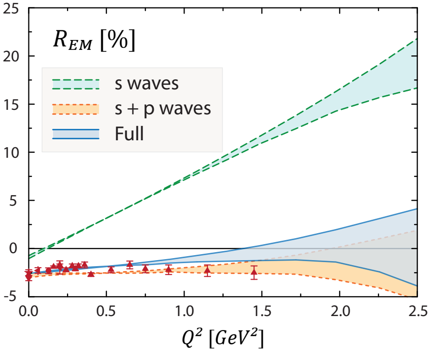
NΔγ (em. transition)

GE & D. Nicmorus, in preparation



$G_M^*,\ R_{EM},\ R_{SM}$

R_{EM} dominated by **p waves**!
Without OAM: R_{EM} small,
becomes positive and grows (⇒ pQCD!)



		$s=\frac{1}{2}$			$s=\frac{3}{2}$
N	$l=0$	τ_1	$\tau_1{}^\mu$	$\tau_3{}^\mu$	
	$l=1$	τ_2	$\tau_2{}^\mu$	$\tau_4{}^\mu$	$\tau_6{}^\mu$
	$l=2$				$\tau_5{}^\mu$
Δ	$l=0$				$\tau_1{}^{\mu\nu}$
	$l=1$		$\tau_4{}^{\mu\nu}$	$\tau_6{}^{\mu\nu}$	$\tau_2{}^{\mu\nu}$
	$l=2$		$\tau_3{}^{\mu\nu}$	$\tau_5{}^{\mu\nu}$	$\tau_7{}^{\mu\nu}$
	$l=3$				$\tau_8{}^{\mu\nu}$
		SC	AX		

Poincaré covariance ⇒
rich structure in N and Δ amplitudes,
already in the quark-diquark model.

Non-zero OAM appears naturally (p, d, f waves).
p waves much more important than d waves.

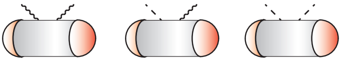
Summary

Groundwork for systematic description of **hadron properties in continuum QCD**.
Meson and baryon physics described by the same interaction.

- **Dynamical chiral symmetry breaking** generates (quark & hadron) masses.
- Nucleon and Delta 'quark core' dominated by **quark-quark correlations:** described by Faddeev equation; can be simplified to quark-diquark picture
- Even in s-wave dominated ground-state baryons, Poincaré covariance implies **orbital angular momentum (~ p waves)** in their wave functions.
  ⇒ hadron deformation, perturbative behavior in form factors
- Missing structure at low momentum & in chiral region due to **pion cloud**.

Outlook

- Excited baryons, Tetraquarks
- Hadronic four-point functions: Compton scattering; pion electroproduction; GPDs & nucleon structure ⟷ **Truncation beyond rainbow-ladder!!**



Thanks for your attention.

Cheers to my collaborators:

R. Alkofer, M. Blank, C. S. Fischer, W. Heupel,
A. Krassnigg, V. Mader, D. Nicmorus,
H. Sanchis-Alepuz, S. Villalba-Chávez