Octet baryon double ratios $(G_E^*/G_M^*)/(G_E/G_M)$ in a nuclear medium

[Study of electromagnetic structure of baryons in-medium]

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ICTP-SAIFR/FAIR Workshop on Mass Generation in QCD,
IFT-UNESP, São Paulo, SP, Brazil
February 28, 2019

Plan of the talk

- Motivation ... to study the double ratios $(G_E^*/G_M^*)/(G_E/G_M)$
- Formalism (vacuum and medium)
- Octet baryon double ratios in nuclear medium

GR, JPBC de Melo and K Tsushima **arXiv:1902.04488 [hep-ph]**

X^* represent the variable X in nuclear medium

Motivation

$\vec{e}p \to e\vec{p}$

JLab 1999–...

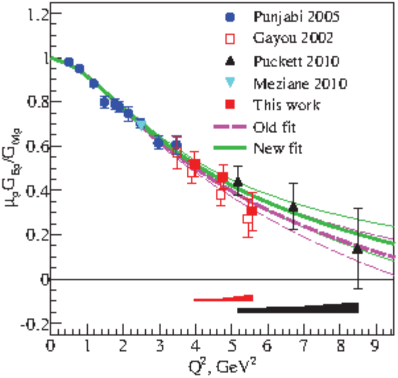
Polarization transfer method

$$\frac{G_E}{G_M} \propto -\frac{P_t}{P_l}$$

P_t = parallel
P_l = longitudinal

Jones PRL 84 (2000); Gayou PRL 88 (2002); Punjabi PRC 71 (2005); Puckett PRL 104 (2010)

$$\frac{G_E}{G_M} \times \mu_p$$



Motivation

$\vec{e}p \to e\vec{p}$

In Medium (bound p)

Polarization transfer method

$$\frac{G_E^*}{G_M^*} \propto -\frac{P_t}{P_l}$$

$P_t =$ parallel
$P_l =$ longitudinal

Dieterich, PLB 500 (2001);
Strauch, EPJA 19 S1 (2004);

Paolone, PRL 105 (2010)

Vacuum: G_E/G_M

Medium: G_E^*/G_M^*

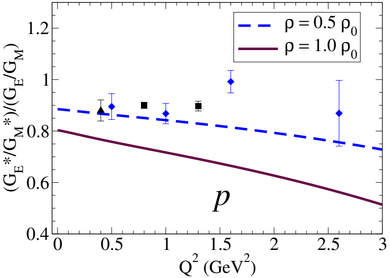
Define **Double Ratio**

$$\mathcal{R}_p \equiv \frac{G_E^*/G_M^*}{G_E/G_M} \neq 1$$

Measures modifications in-medium

Motivation

proton **In Medium**



$\rho_0 = 0.15$ fm^{-1}

normal nuclear density

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Strauch, EPJA 19 S1 (2004);

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Vacuum: G_E/G_M

Medium: G_E^*/G_M^*

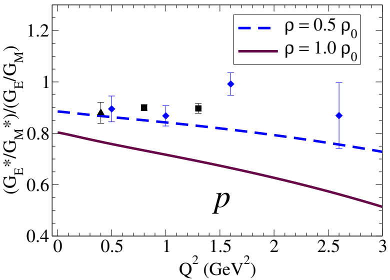
Define **Double Ratio**

$$\mathcal{R}_p \equiv \frac{G_E^*/G_M^*}{G_E/G_M} \neq 1$$

Measures modifications in-medium

Motivation

proton **In Medium**
suppression of G_E/G_M



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Vacuum: G_E/G_M

Medium: G^*_E/G^*_M

Define **Double Ratio**

$$\mathcal{R}_p \equiv \frac{G^*_E/G^*_M}{G_E/G_M} \neq 1$$

Measures modifications in-medium
Dependence on ρ

Motivation (2)

In Medium

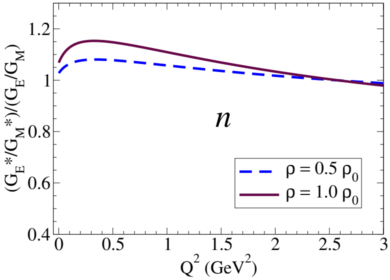
What about the neutron ?

Possible enhancement of G_E/G_M

- IC Cloet, GA Miller, E Piasetzky and G Ron, PRL 103, 082301 (2009)
- WRB de Araújo, JPCB de Melo and K Tsushima, NPA 970, 325 (2018)
- GR, K Tsushima and AW Thomas, JPG 40, 015102 (2013)

Model from:

GR, K Tsushima and AW Thomas, JPG 40, 015102 (2013)



Dependence on ρ

Motivation (3)

What about ?

- Σ^+ and Σ^-
- Λ and Σ^0 (neutral baryons)
- Ξ^- and Ξ^0 (two strange quarks)

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Motivation to this work:
Study electromagnetic structure of Octet Baryons in-medium

Model: GR, K Tsushima and AW Thomas, JPG 40, 015102 (2013)

- Use in-medium results (G_E^*, G_M^*)
- Estimate medium modifications G_E^*/G_M^*
- ...

Method

Calculation of **Octet baryon** electromagnetic form factors
in the **vacuum** and in the **nuclear medium**

- **Covariant Spectator Quark Model**
  Valence quark degrees of freedom
  $\oplus$ **pion cloud** effects
  $\Rightarrow$ **Model for the vacuum**
  calibrated by physical and lattice QCD data

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  Valence quark degrees of freedom
  $\oplus$ **pion cloud** effects
  $\Rightarrow$ **Model for the vacuum**
  calibrated by physical and lattice QCD data
- **Extension to the nuclear medium**
  Quark-Meson-Coupling model $\Leftarrow$ CBM
  Saito, Tsushima and Thomas, Prog. Part. Nucl. Phys. 58, 1 (2007)
  Baryons as on-mass-shell particles with effective mass M_B^*
  Modified masses and coupling constants ($g^*_{\pi BB'}$):
  $\Rightarrow$ Medium modifications: Valence quark $\oplus$ Pion cloud

In vacuum: GR, K Tsushima, PRD **84**, 054014 (2011)

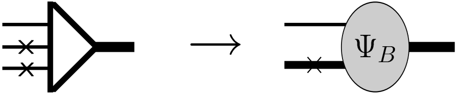
In nuclear medium: GR, K Tsushima, AW Thomas JPG **40**, 015102 (2013)

Formalism †

- **Covariant Spectator Quark Model**

  F Gross, GR and MT Peña, PRC 77, 015202 (2008); GR, FBS 59, 92 (2018)

  - Baryon as qqq systems – $SU(6) \otimes O(3)$ symmetry
  - Radial wave function adjusted phenomenologically (momentum scales)
  - Spectator formalism:



system with 2 on-shell quarks and an off-shell quark

$\Longrightarrow$ qq pair replaced by an *effective* diquark with mass m_D

F Gross, GR and MT Peña, PRD 85, 093005 (2012)

Ψ_B – effective quark-diquark wave function

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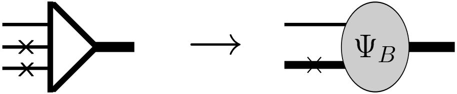

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- **Pion cloud excitations** ($q\bar{q}$ states)
  Phenomenological parametrization;
  using $SU(3)$ (baryon-meson) and χPT constraints

CSQM: **Octet** wave function (1)

S-state approximation (quark-diquark) P: Baryon; k: diquark

F Gross, GR and K Tsushima, PLB 690, 183 (2010):

$$\Psi_B(P,k) = \frac{1}{\sqrt{2}}\left[|M_S\rangle \Phi_S^0 + |M_A\rangle \Phi_S^1\right]\psi_B(P,k)$$

$|M_S\rangle, |M_A\rangle$: flavor states; $\Phi_S^{0,1}$: spin states

B	$\|M_S\rangle$	$\|M_A\rangle$
p	$\frac{1}{\sqrt{6}}\left[(ud+du)u - 2uud\right]$	$\frac{1}{\sqrt{2}}(ud-du)u$
n	$-\frac{1}{\sqrt{6}}\left[(ud+du)d - 2ddu\right]$	$\frac{1}{\sqrt{2}}(ud-du)d$
Λ^0	$\frac{1}{2}\left[(dsu-usd)+s(du-ud)\right]$	$\frac{1}{\sqrt{12}}\left[s(du-ud)-(dsu-usd)-2(du-ud)s\right]$
Σ^+	$\frac{1}{\sqrt{6}}\left[(us+su)u - 2uus\right]$	$\frac{1}{\sqrt{2}}(us-su)u$
Σ^0	$\frac{1}{\sqrt{12}}\left[s(du+ud)+(dsu+usd)-2(ud+du)s\right]$	$\frac{1}{2}\left[(dsu+usd)-s(ud+du)\right]$
Σ^-	$\frac{1}{\sqrt{6}}\left[(sd+ds)d - 2dds\right]$	$\frac{1}{\sqrt{2}}(ds-sd)d$
Ξ^0	$-\frac{1}{\sqrt{6}}\left[(ud+du)s - 2ssu\right]$	$\frac{1}{\sqrt{2}}(us-su)s$
Ξ^-	$-\frac{1}{\sqrt{6}}\left[(ds+sd)s - 2ssd\right]$	$\frac{1}{\sqrt{2}}(ds-sd)s$

CSQM: **Octet** wave function (2) $SU(3)$ breaking

Radial (scalar) wave functions: functions of $(P-k)^2$
Defined in terms of

$$\chi_B = \frac{(M_B - m_D)^2 - (P-k)^2}{M_B m_D}$$

$$\psi_N(P,k) = \frac{N_N}{m_D(\beta_1 + \chi_N)(\beta_2 + \chi_N)}$$

$$\psi_\Lambda(P,k) = \frac{N_\Lambda}{m_D(\beta_1 + \chi_\Lambda)(\beta_3 + \chi_\Lambda)}$$

$$\psi_\Sigma(P,k) = \frac{N_\Sigma}{m_D(\beta_1 + \chi_\Sigma)(\beta_3 + \chi_\Sigma)}$$

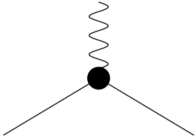
$$\psi_\Xi(P,k) = \frac{N_\Xi}{m_D(\beta_1 + \chi_\Xi)(\beta_4 + \chi_\Xi)}$$

β_i: momentum range parameters (m_D units); $\beta_4 > \beta_3 > \beta_2 > \beta_1$
long range: β_1 (all systems)
short range: β_2 (lll systems); β_3 (sll systems); β_4 (ssl systems)

CSQM: Photon-Quark coupling (1)

- Quark current – constituent quark form factors
  $SU_F(3)$ structure

$$j_q^\mu = \left[\frac{1}{6} f_{1+} \lambda_0 + \frac{1}{2} f_{1-} \lambda_3 + \frac{1}{6} f_{10} \lambda_s\right] \gamma^\mu + \left[\frac{1}{6} f_{2+} \lambda_0 + \frac{1}{2} f_{2-} \lambda_3 + \frac{1}{6} f_{20} \lambda_s\right] \frac{i\sigma^{\mu\nu} q_\nu}{2M_N}$$



quark-antiquark
$\oplus$ gluon dressing

$\lambda_0 = \text{diag}(1,1,0)$, $\lambda_3 = \text{diag}(1,-1,0)$, $\lambda_s = \text{diag}(0,0,2)$

Quarks with anomalous magnetic moments $\kappa_u, \kappa_d, \kappa_s$

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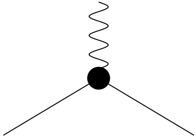

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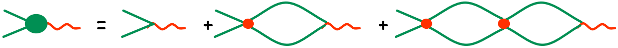
- Vector meson dominance parameterization:



CSQM: Photon-Quark coupling (2) ††

Vector meson dominance

- Quark form factors parameterization ($m_\omega \approx m_\rho$)
  Vector meson poles: m_ρ, m_ϕ ($\bar{s}s$) and $M_h = 2M_N$ (effective)

$$f_{1\pm} = \lambda_q + (1-\lambda_q)\frac{m_\rho^2}{m_\rho^2+Q^2} + c_\pm \frac{M_h^2 Q^2}{(M_h^2+Q^2)^2}$$

$$f_{2\pm} = \kappa_\pm \left\{ d_\pm \frac{m_\rho^2}{m_\rho^2+Q^2} + (1-d_\pm)\frac{M_h^2}{M_h^2+Q^2} \right\}$$

$$f_{10} = \lambda_q + (1-\lambda_q)\frac{m_\phi^2}{m_\phi^2+Q^2} + c_0 \frac{M_h^2 Q^2}{(M_h^2+Q^2)^2}$$

$$f_{20} = \kappa_s \left\{ d_0 \frac{m_\phi^2}{m_\phi^2+Q^2} + (1-d_\pm)\frac{M_h^2}{M_h^2+Q^2} \right\}$$

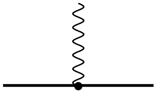
- Current parameters: λ_q, c_0, $c_\pm$, d_0 and $d_\pm$ determined in previous applications PRC 77, 015202 (2008); PRD 80, 033004 (2009) (nucleon $\oplus$ baryon decuplet)
- Anomalous magnetic moments: $\kappa_\pm$ **fitted to the data** ($\kappa_s \Leftarrow \mu_{\Omega^-}$)

Pion cloud: total electromagnetic current †

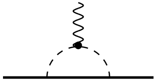
$$J^\mu = J^\mu_{0B} + J^\mu_{\pi B} + J^\mu_{\gamma B}$$

$J^\mu_{0B} \leftrightarrow$ QM

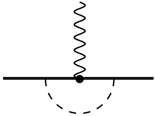
$$J^\mu_{0B} = Z_B \left[\tilde{e}_B \gamma^\mu + \tilde{\kappa}_B \frac{i\sigma^{\mu\nu} q_\nu}{2M_B} \right]$$



$$J^\mu_{\pi B} = Z_B \left[\tilde{B}_1 \gamma^\mu + \tilde{B}_2 \frac{i\sigma^{\mu\nu} q_\nu}{2M_B} \right] G_{\pi B}$$



$$J^\mu_{\gamma B} = Z_B \left[\tilde{C}_1 \gamma^\mu + \tilde{C}_2 \frac{i\sigma^{\mu\nu} q_\nu}{2M_B} \right] G_{eB} + Z_B \left[\tilde{D}_1 \gamma^\mu + \tilde{D}_2 \frac{i\sigma^{\mu\nu} q_\nu}{2M_B} \right] G_{\kappa B}$$



$\tilde{B}_i, \tilde{C}_i$ and $\tilde{D}_i$ octet functions $SU(3)$; $G_{\pi B}, G_{eB}$ and $G_{\kappa B}$ flavor deppendent;
GR and K Tsushima, PRD 84, 054014 (2011)

Pion cloud: adding PC effects †

- Projecting $G_{\pi B}, G_{eB}$ and $G_{\kappa B}$ $\Rightarrow$ coupling constants β_B

$$\beta_N = 1, \qquad \beta_\Lambda = \frac{4}{3}\alpha^2$$
$$\beta_\Sigma = 4(1-\alpha)^2, \qquad \beta_\Xi = (1-2\alpha)^2$$

$SU(6)$ limit: $\alpha = 0.6$; and $g = g_{\pi NN}$ $\longrightarrow$ included in $\tilde{B}_i$, $\tilde{C}_i$, $\tilde{D}_i$

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- Fit functions of Q^2: $\tilde{B}_i, \tilde{C}_i$, $\tilde{D}_i$ $\longrightarrow$ δG_{EB}, δG_{MB} **pion cloud**

GR and K Tsushima, PRD 84, 054014 (2011);

Bare: $\tilde{e}_B, \tilde{\kappa}_B$ F Gross, GR and MT Peña, PRC 77, 015202 (2008)

$$F_{1B} = Z_B\left[\tilde{e}_B + \delta F_{1B}\right], \qquad G_{EB} = Z_B\left[G_{E0B} + \delta G_{EB}\right]$$
$$F_{2B} = Z_B\left[\tilde{\kappa}_B + \delta F_{2B}\right], \qquad G_{MB} = Z_B\left[G_{M0B} + \delta G_{MB}\right]$$

Z_B is a normalization factor

Calibration of model in vacuum †

Information included in the fit

- **Lattice QCD data** – bare part $\tilde{e}_B, \tilde{\kappa}_B$
  Octet baryon form factors: $p, n, \Sigma^{\pm}, \Xi^{0,-}$ – **no pion cloud**
  H. W. Lin and K. Orginos, PRD 79, 074507 (2009)
  Lattice parametrization $\Longrightarrow$ Physical regime (bare part)
- **Physical data** – meson cloud part $\tilde{B}_i$, $\tilde{C}_i$, $\tilde{D}_i$
  - Nucleon form factor data (proton and neutron)
  - Octet magnetic moments $(\Lambda, \Sigma^{\pm}, \Xi^{0,-})$
  - Octet radii: r^2_{Ep}, r^2_{En}, r^2_{Mp}, r^2_{Mn} and $r^2_{E\Sigma^-}$

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  - Octet radii: r^2_{Ep}, r^2_{En}, r^2_{Mp}, r^2_{Mn} and $r^2_{E\Sigma^-}$
- **Parameters:**
  Bare: $\kappa_\pm$, $\beta_1, \beta_2, \beta_3, \beta_4$
  Pion cloud: B_1, D_1', B_2, C_2, D_2 and Λ_1, Λ_2

Extension to the nuclear medium – valence quark †

- Quark current (VMD): $j_q^\mu = j_1 \gamma^\mu + j_2 \frac{i\sigma^{\mu\nu} q_\nu}{2M_N}$

  $j_q^\mu(M_N; m_\rho, m_\phi, M_h = 2M_N) \to j_q^\mu(M_N^*; m_\rho^*, m_\phi^*, M_h^* = 2M_N^*)$

  [replace in-vacuum masses by in-medium masses]

- Radial wave functions:

  $\psi_B(P, k, M_B) \to \psi_B(P, k, M_B^*)$

  [replace baryon mass M_B by in-medium baryon mass M_B^*]

G_l^B bare contributions $\to G_l^{B*}$

Next slide: G_l^π pion cloud $\to G_l^{\pi *}$

Results in medium

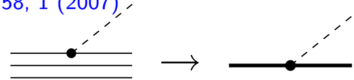
Use medium modifications of **masses** and **coupling constants** for

$\rho = 0.5\rho_0$ and $\rho = \rho_0$ ($\rho_0 = 0.15$ fm^{-3})

Parameters from Quark-Meson-Coupling model – masses **reduced** in medium

Saito, Tsushima and Thomas, Prog. Part. Nucl. Phys. 58, 1 (2007)

$$M_N^* = M_N - g_\sigma \sigma + \ldots$$



Goldberger-Treimann relation:

$$\frac{g^*_{\pi BB}}{g_{\pi BB}} \simeq \left(\frac{f_\pi}{f^*_\pi}\right)\left(\frac{g_A^{N*}}{g_A^N}\right)\left(\frac{M_B^*}{M_B}\right)$$

Goldberger and Treiman, PRC 110, 1178 (1958)

	$\rho = 0$	$\rho = 0.5\rho_0$	$\rho = \rho_0$
M_N	939.0	831.3	754.5
M_Λ	1116.0	1043.9	992.7
M_Σ	1192.0	1121.4	1070.4
M_Ξ	1318.0	1282.2	1256.7
m_ρ	779.0	706.1	653.7
m_ϕ	1019.5	1019.1	1018.9
m_π	138.0	138.0	138.0

	$\rho = 0$	$\rho = 0.5\rho_0$	$\rho = \rho_0$
$g^*_{\pi NN}/g_{\pi NN}$	1	0.921	0.899
$g^*_{\pi\Lambda\Sigma}/g_{\pi\Lambda\Sigma}$	1	0.973	0.996
$g^*_{\pi\Sigma\Sigma}/g_{\pi\Sigma\Sigma}$	1	0.977	1.004
$g^*_{\pi\Xi\Xi}/g_{\pi\Xi\Xi}$	1	1.012	1.067

Results: Form Factors – nucleon units ††

All G_{MB}/G^*_{MB} converted into **units** of the **nucleon in vacuum**

Vacuum: F_{1B}, F_{2B}

$$G_{EB}(Q^2) = F_{1B}(Q^2) - \frac{Q^2}{4M_B^2} F_{2B}(Q^2)$$

$$G_{MB}(Q^2) = \left[F_{1B}(Q^2) + F_{2B}(Q^2)\right] \frac{M_N}{M_B}$$

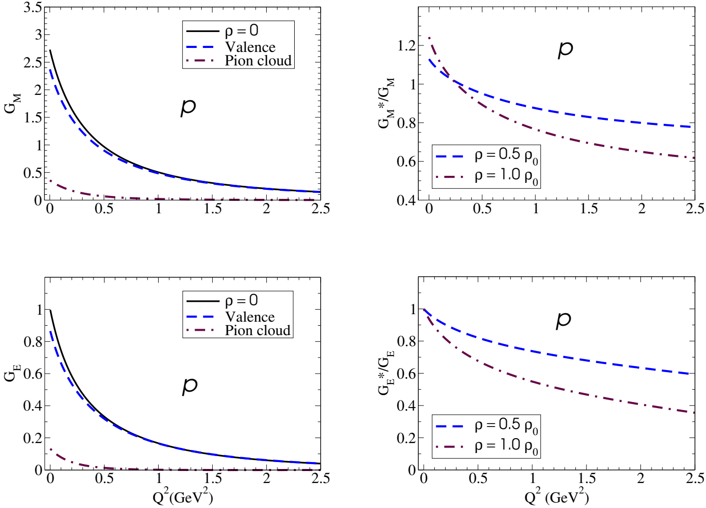
$\frac{M_N}{M_B}$: $G_{MB}(Q^2)$ in nucleon units; $\mu_B = G^0_{MB}(0)\frac{e}{2M_B} = \underbrace{G^0_{MB}(0)\frac{M_N}{M_B}}_{G_{MB}(0)} \frac{e}{2M_N}$

Medium: F^*_{1B}, F^*_{2B}

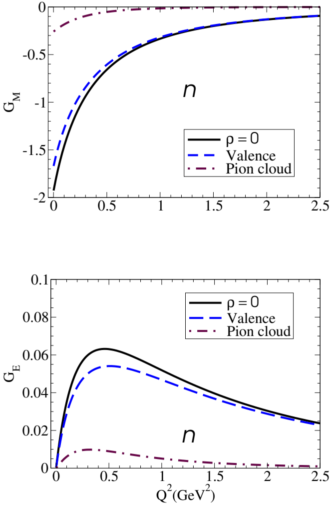
$$G^*_{EB}(Q^2) = F^*_{1B}(Q^2) - \frac{Q^2}{4{M^*_B}^2} F^*_{2B}(Q^2)$$

$$G^*_{MB}(Q^2) = \left[F^*_{1B}(Q^2) + F^*_{2B}(Q^2)\right] \frac{M_N}{M^*_B}$$

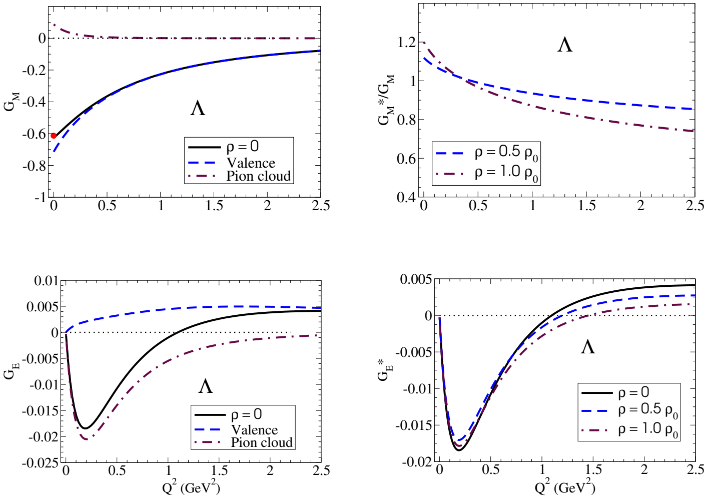
Results: Proton form factors in medium



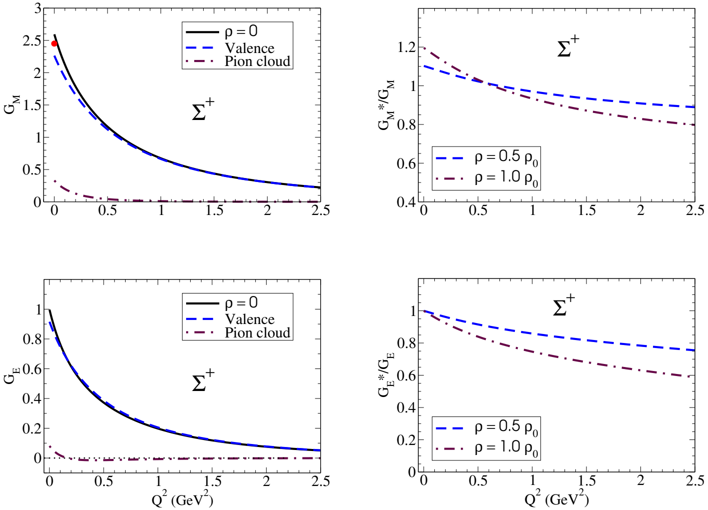
Results: Neutron form factors in medium



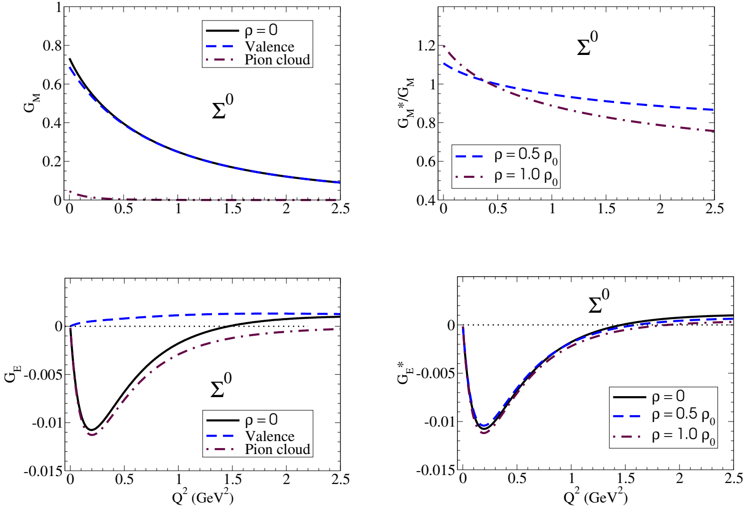
Results: Λ form factors in medium $- \cdot -$ $G_E \simeq G_E^\pi$



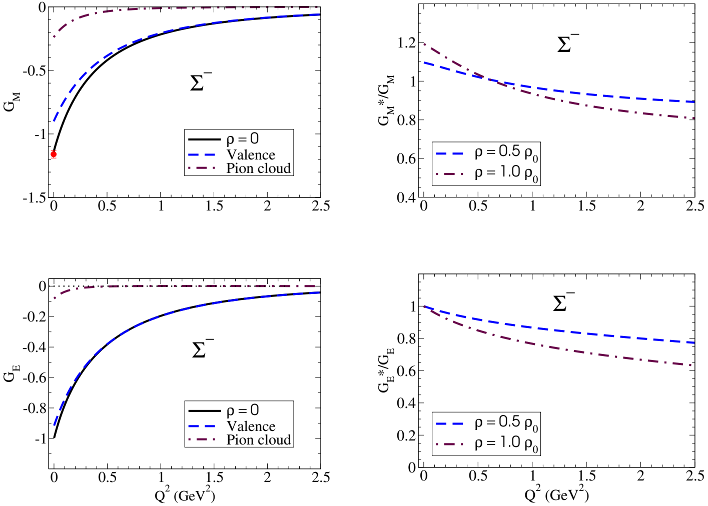
Results: Σ^+ form factors in medium



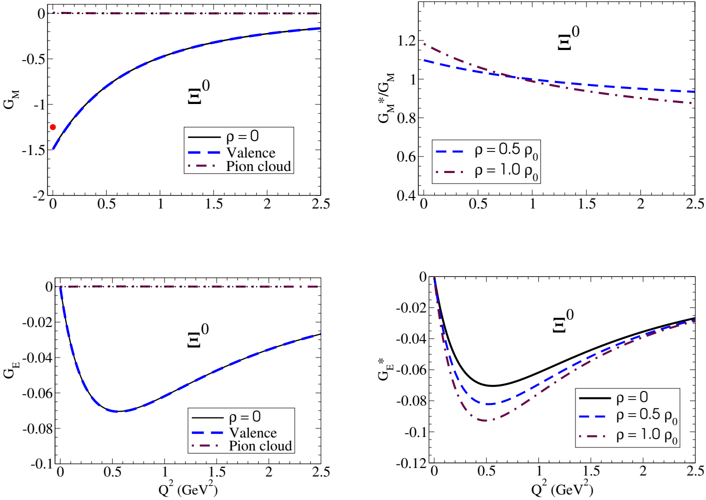
Results: Σ^0 form factors in medium $- \cdot -$ $G_E \simeq G_E^\pi$



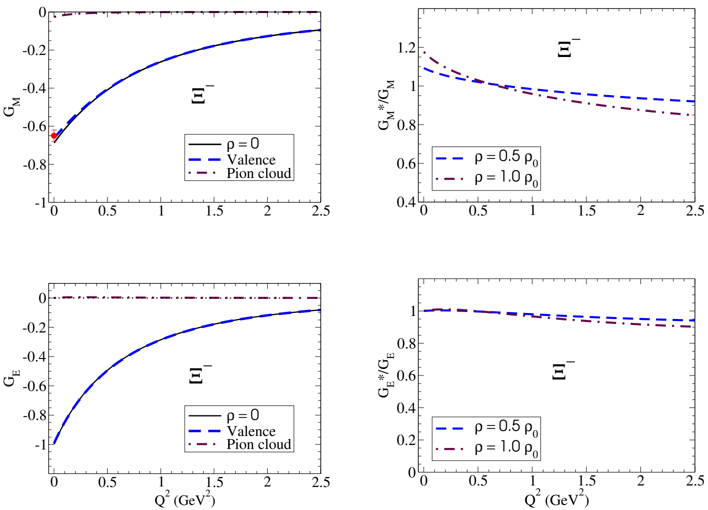
Results: Σ^- form factors in medium



Results: Ξ^0 form factors in medium



Results: Ξ^- form factors in medium



Results in vacuum/in medium – summary †

- **Vacuum** and **Medium**:
  Dominance of valence quark component
- Medium modifications **dominated** by valence quark component
- Variation on **pion cloud** component $\lesssim 4\%$
- Exception: **Electric** form factor of neutral particles:
  Λ, Σ^0 dominated by pion cloud part
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Next: results for the **Double Ratios**

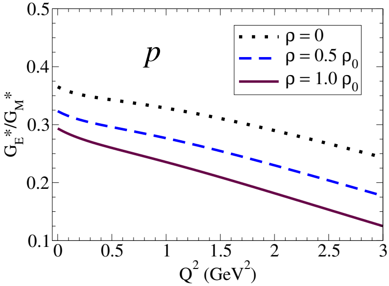
Medium: proton G_E^*/G_M^* **single ratio**

- $Q^2 = 0$: $G_E^*/G_M^* \propto M_N^*$
  suppression of small masses
  $\left(G_E^* = 1,\, G_M^* \propto 1/M_N^*\right)$
- Low-Q^2:

$$\frac{G_E^*}{G_M^*} \simeq \frac{1}{G_M^*(0)} \left[1 - (r_{EB}^{*\,2} - r_{MB}^{*\,2}) \frac{Q^2}{6}\right]$$

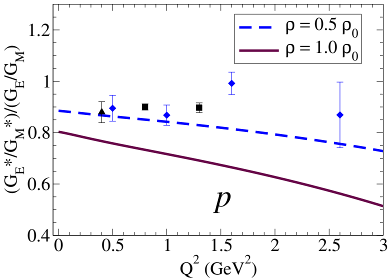
almost linear falloff

- Vacuum $(r_{EB}^2 - r_{MB}^2) \simeq (0.782 - 0.718)$ fm^2
  slow falloff
- In Medium:
  $r_{EB}^{*\,2} - r_{MB}^{*\,2}$ **enhanced**
  faster falloff
- $\frac{G_E^*}{G_M^*}$ more supressed in medium



Medium: proton G_E^*/G_M^* **double ratio**

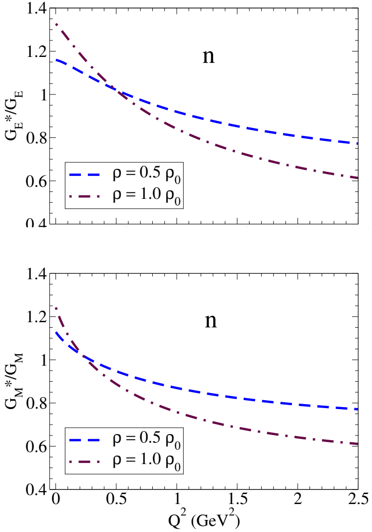
- G_E^*/G_M^* suppressed in medium
- **Larger** suppression for **larger** densities
- Available data (^{4}He) closer to estimate $\rho = 0.5\rho_0$



Dieterich, PLB 500 (2001);
Strauch, EPJA 19 S1 (2004);

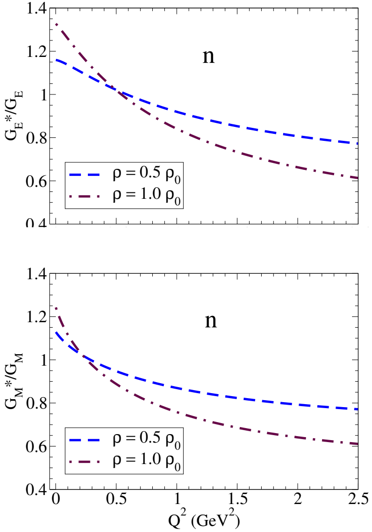
Paolone, PRL 105 (2010)

Medium: neutron G^*_E/G^*_M **double ratio** (1)



- $Q^2 \approx 0$:
  G^*_{En} enhanced
  G^*_{Mn} enhanced
  Enhancement increases with ρ

Medium: neutron G_E^*/G_M^* **double ratio** (1)



- $Q^2 \approx 0$:
  G_{En}^* enhanced
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  Enhancement increases with ρ
- Low-Q^2: $G_{En}^* \simeq -\frac{1}{6} r_{En}^{*\,2} Q^2$
  $-r_{En}^{*\,2}$ enhanced in medium
  $\frac{G_{En}^*}{G_{En}} \approx \frac{r_{En}^{*\,2}}{r_{En}^2} > 1$

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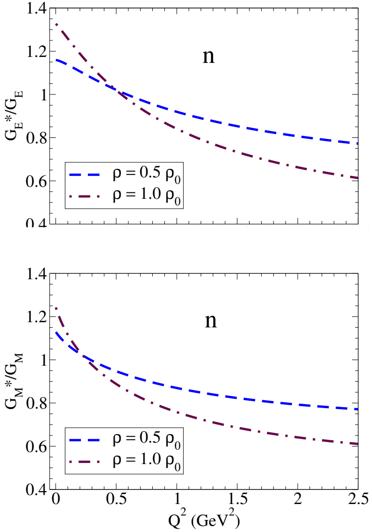

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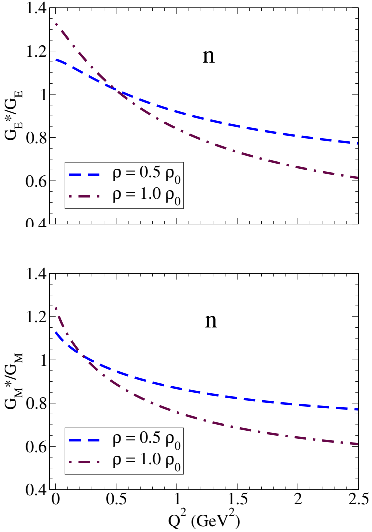
  $-r^{*\,2}_{En}$ enhanced in medium
  $\frac{G^*_{En}}{G_{En}} \approx \frac{r^{*\,2}_{En}}{r^2_{En}} > 1$
- Low-Q^2: $G^*_{Mn} \propto 1/M^*_N$
  $\frac{G^*_{Mn}}{G_{Mn}} \approx \frac{M_N}{M^*_N} > 1$

Medium: neutron G_E^*/G_M^* double ratio (1)



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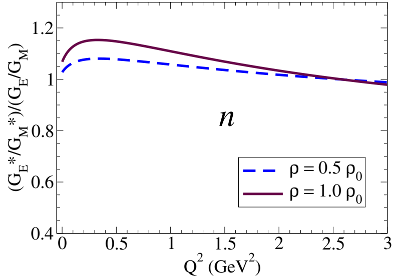
- Low-Q^2: $G_{Mn}^* \propto 1/M_N^*$
  $\frac{G_{Mn}^*}{G_{Mn}} \approx \frac{M_N}{M_N^*} > 1$
- **Global effect** (low Q^2):
  $\frac{G_E^*/G_M^*}{G_E/G_M} \approx \frac{r_{En}^{*\,2}}{r_{En}^2} \frac{M_N^*}{M_N} > 1$
- G_E^* effects dominate over G_M^* effect

Medium: neutron G^*_E/G^*_M **double ratio** (2)



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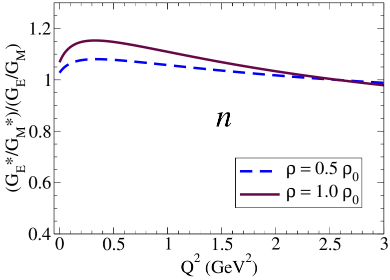
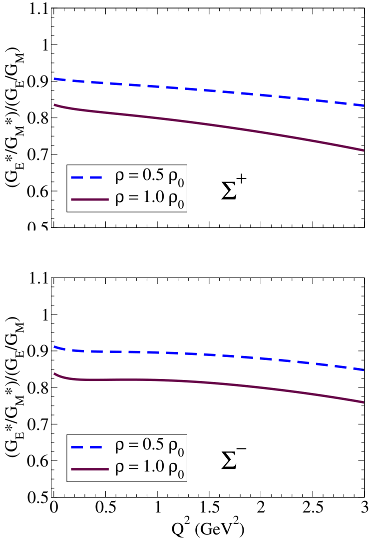
Medium: neutron G_E^*/G_M^* **double ratio** (2')



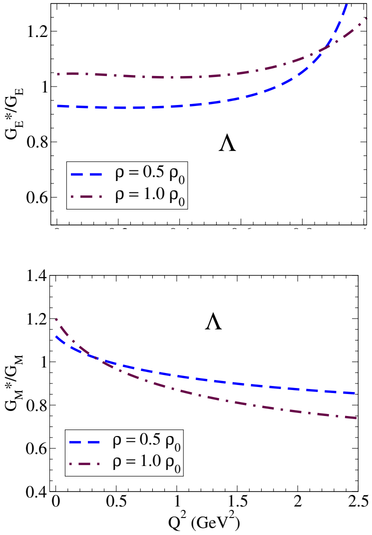
- $\frac{G_E^*}{G_M^*}$ enhanced in medium
- Q^2-dependence important
- No linear effect
- **Large Q^2:**
  Enhancement decreases with Q^2
  Large Q^2: $\frac{G_E^*/G_M^*}{G_E/G_M} < 1$

Medium: $\Sigma^\pm$ – G_E^*/G_M^* double ratio



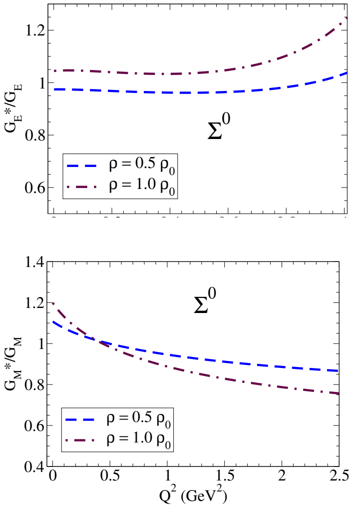
- Similar to **proton**
- Slower falloff with Q^2
- $(r^{*2}_{EB} - r^{*2}_{MB})$ reduced comparative to **proton** [effect of strange quark]
- Strange quarks
  $\Rightarrow$ smaller medium effect

Medium: Λ – G_E^*, G_M^*



- G_E dominated by pion cloud
- Almost no medium effects: $Q^2 \approx 0$: $\frac{G_E^*}{G_E} \approx 1$ (5% error)
- Low-Q^2:
  G_M enhanced in medium
  Valence quark effects
  $\rightarrow G_M$ dominate DR

Medium: Σ^0 – G_E^*, G_M^* (similar to Λ)



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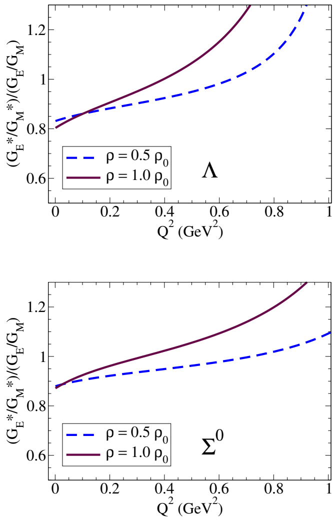
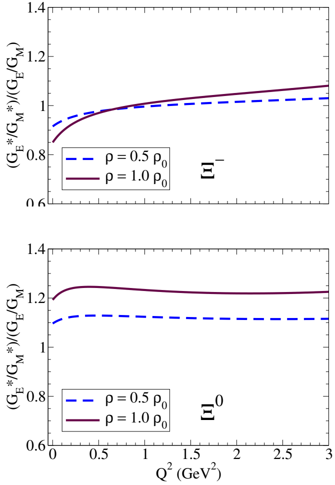
Medium: Λ, Σ^0 – G_E^*/G_M^* double ratio



- Low Q^2 suppression: similar to **proton**
- **Increasing** Q^2: **increasing** medium effects
- $Q^2 > 1$ GeV^2: $\frac{G_E^*/G_M^*}{G_E/G_M} > 1$
- Divergence for $Q^2 > 1$ GeV^2 $(G_E \to 0)$

Medium: Ξ^0, Ξ^- – G_E^*/G_M^* **double ratio**



- Rough estimate of Ξ double ratio (limitation of the fit to Ξ lattice data)
- Weak deppendence on Q^2

Conclusions

- Calculations of Octet Baryon form factors in nuclear medium
  Cov. Spectator Quark Model $\bigoplus$ Quark-Meson-Coupling Model

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Thank you very much 

More ...

Backup slides

Extension of the model for lattice QCD regime

GR and MT Peña JPG 36, 115011 (2009)

- Quark current (VMD):
  $j_I^\mu(M_N; m_\rho, M_h = 2M_N) \to j_I^\mu(M_N^{latt}; m_\rho^{latt}, 2M_N^{latt})$
- Wave functions:
  $\Psi_B(\{M_B\}) \to \Psi_B(\{M_B^{latt}\})$

$\Rightarrow$ Implicit m_π dependence in G_X [Form factors]

G_X include only valence quark (bare) contributions $\to G_X^B$

Meson cloud effects suppressed for large m_π:

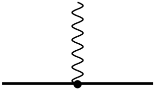
Compare G_X^B with lattice data

Pion cloud: total electromagnetic current

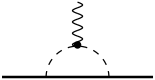
$$J^\mu = J^\mu_{0B} + J^\mu_{\pi B} + J^\mu_{\gamma B}$$

$J^\mu_{0B} \leftrightarrow$ QM

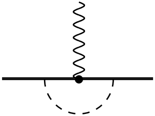
$$J^\mu_{0B} = Z_B \left[\tilde{e}_B \gamma^\mu + \tilde{\kappa}_B \frac{i\sigma^{\mu\nu} q_\nu}{2M_B} \right]$$



$$J^\mu_{\pi B} = Z_B \left[\tilde{B}_1 \gamma^\mu + \tilde{B}_2 \frac{i\sigma^{\mu\nu} q_\nu}{2M_B} \right] G_{\pi B}$$



$$J^\mu_{\gamma B} = Z_B \left[\tilde{C}_1 \gamma^\mu + \tilde{C}_2 \frac{i\sigma^{\mu\nu} q_\nu}{2M_B} \right] G_{eB} + Z_B \left[\tilde{D}_1 \gamma^\mu + \tilde{D}_2 \frac{i\sigma^{\mu\nu} q_\nu}{2M_B} \right] G_{\kappa B}$$



$\tilde{B}_i, \tilde{C}_i$ and $\tilde{D}_i$ octet functions $SU(3)$; $G_{\pi B}, G_{eB}$ and $G_{\kappa B}$ flavor deppendent;
GR and K Tsushima, PRD 84, 054014 (2011)

Pion cloud parametrization

Functions $\tilde{B}_i, \tilde{C}_i, \tilde{D}_i$

$$\tilde{B}_1 = B_1 \left(\frac{\Lambda_1^2}{\Lambda_1^2 + Q^2} \right)^5 \times \left[1 + \frac{1}{Z_N B_1} \left(\frac{1}{24} \frac{\alpha_1}{\alpha_0} \log m_\pi + b_1' \right) Q^2 \right]$$

$$\tilde{C}_1 = B_1 \left(\frac{\Lambda_1^2}{\Lambda_1^2 + Q^2} \right)^2, \qquad \tilde{D}_1 = D_1' \frac{Q^2 \Lambda_1^4}{(\Lambda_1^2 + Q^2)^3}$$

$$\tilde{B}_2 = B_2 \left(\frac{\Lambda_2^2}{\Lambda_2^2 + Q^2} \right)^6 \times \left[1 + \frac{1}{Z_N B_2} \left(-\frac{1}{24} \frac{\alpha_2}{\alpha_0} \frac{M}{m_\pi} + b_2' \right) Q^2 \right]$$

$$\tilde{C}_2 = C_2 \left(\frac{\Lambda_2^2}{\Lambda_2^2 + Q^2} \right)^3, \qquad \tilde{D}_2 = D_2 \left(\frac{\Lambda_2^2}{\Lambda_2^2 + Q^2} \right)^3$$

Coefficients B_1, D_1', B_2, C_2, D_2 and cutoffs Λ_1, Λ_2 adjustable parameters

Pion cloud: form factors

Nucleon dresssed form factors [GR and K Tsushima, PRD 84, 054014 (2011)]

$$
\begin{aligned}
F_{1p} &= Z_N \left\{ \tilde{e}_{0p} + 2\beta_N \tilde{B}_1 + \beta_N (\tilde{e}_{0p} + 2\tilde{e}_{0n}) \tilde{C}_1 + \beta_N (\tilde{\kappa}_{0p} + 2\tilde{\kappa}_{0n}) \tilde{D}_1 \right\} \\
F_{2p} &= Z_N \left\{ \tilde{\kappa}_{0p} + 2\beta_N \tilde{B}_2 + \beta_N (\tilde{e}_{0p} + 2\tilde{e}_{0n}) \tilde{C}_2 + \beta_N (\tilde{\kappa}_{0p} + 2\tilde{\kappa}_{0n}) \tilde{D}_2 \right\}
\end{aligned}
$$

$$
\begin{aligned}
F_{1n} &= Z_N \left\{ \tilde{e}_{0n} - 2\beta_N \tilde{B}_1 + \beta_N (2\tilde{e}_{0p} + \tilde{e}_{0n}) \tilde{C}_1 + \beta_N (2\tilde{\kappa}_{0p} + \tilde{\kappa}_{0n}) \tilde{D}_1 \right\} \\
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\end{aligned}
$$

F Gross, GR and K Tsushima PLB 690, 183 (2010):

$F_{1p}(0) = 1$ and $F_{1n}(0) = 0 \Longrightarrow \tilde{D}_1(0) = 0$ and $\tilde{B}_1(0) = \tilde{C}_1(0) \equiv B_1$

Pion cloud: Normalization factor

Z_B normalization factor; determined by the charge or self-energy

Nucleon case, using $B_1 = \tilde{B}_1(0) = \tilde{C}_1(0)$

$$G_{En}(0) = Z_N \left[0 + 2\beta_N B_1 - 2\beta_N B_1\right] = 0$$
$$G_{Ep}(0) = Z_N \left[1 + \beta_N B_1 + 2\beta_N B_1\right] = 1$$

Then $G_{Ep}(0) = 1 = Z_N[1 + 3\beta_N B_1]$:

$$Z_N = \frac{1}{1 + 3\beta_N B_1}$$

Similar for Z_Λ, Z_Σ and Z_Ξ

Pion cloud parametrization

- Simulate falloff of pion cloud with Q^2

$$\delta F_{1B} \sim \frac{1}{Q^4} \times \frac{1}{Q^4}, \qquad \delta F_{2B} \sim \frac{1}{Q^4} \times \frac{1}{Q^6},$$

factor $1/Q^4$ from $\bar{q}q$ contributions at high Q^2;
$F \sim \frac{1}{Q^{(N-1)}}$, for $N = 3 + 2$ constituents

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- Simulate the m_π deppendence form χPT of nucleon V radii

$$(r_1^V)^2 = -\frac{\alpha_1}{\alpha_0} \log m_\pi + ...$$

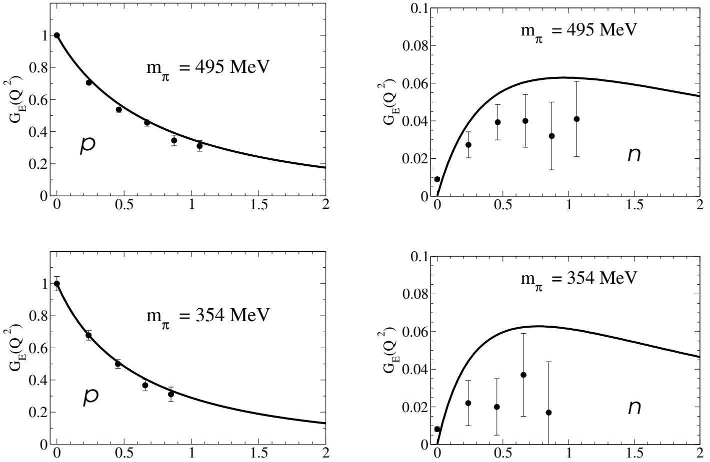
$$(r_2^V)^2 = +\frac{\alpha_2}{\alpha_0} \frac{M}{m_\pi} + ...$$

$\alpha_0 = 8\pi^2 F_\pi^2$, $\alpha_1 = 5g_A^2 + 1$ and $\alpha_2 = \pi g_A^2$

$G^*_{MB}(0)$ valence quark contribution

B	$G^*_{MB}(0)$
p	$\left[1+\left(\frac{8}{9}\kappa_u+\frac{1}{9}\kappa_d\right)\right]\frac{M_N}{M_N^*}$
n	$-\left[\frac{2}{3}+\left(\frac{2}{9}\kappa_u+\frac{4}{9}\kappa_d\right)\right]\frac{M_N}{M_N^*}$
Λ	$-\frac{1}{3}\frac{M_N}{M_\Lambda^*}-\frac{1}{3}\kappa_s\frac{M_N}{M_N^*}$
Σ^+	$\frac{M_N}{M_\Sigma^*}+\left(\frac{8}{9}\kappa_u+\frac{1}{9}\kappa_s\right)\frac{M_N}{M_N^*}$
Σ^0	$\frac{1}{3}\frac{M_N}{M_\Sigma^*}+\left(\frac{4}{9}\kappa_u-\frac{2}{9}\kappa_d+\frac{1}{9}\kappa_s\right)\frac{M_N}{M_N^*}$
Σ^-	$-\frac{1}{3}\frac{M_N}{M_\Sigma^*}-\left(\frac{4}{9}\kappa_d-\frac{1}{9}\kappa_s\right)\frac{M_N}{M_N^*}$
Ξ^0	$-\frac{2}{3}\frac{M_N}{M_\Xi^*}-\left(\frac{2}{9}\kappa_u+\frac{4}{9}\kappa_s\right)\frac{M_N}{M_N^*}$
Ξ^-	$-\frac{1}{3}\frac{M_N}{M_\Xi^*}+\left(\frac{1}{9}\kappa_d-\frac{4}{9}\kappa_s\right)\frac{M_N}{M_N^*}$

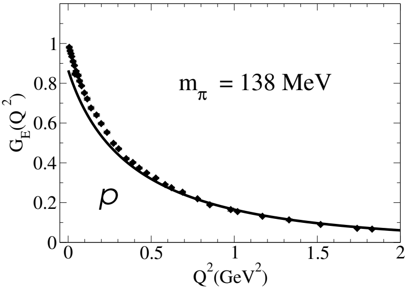
Results: Nucleon lattice data

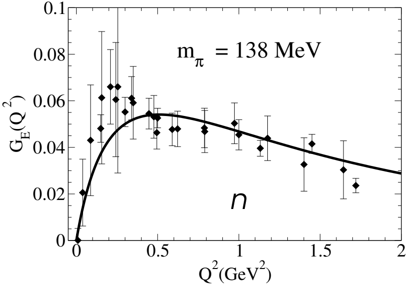


G_{En} with systematic errors $[G_{EB}(0) \neq 0]$

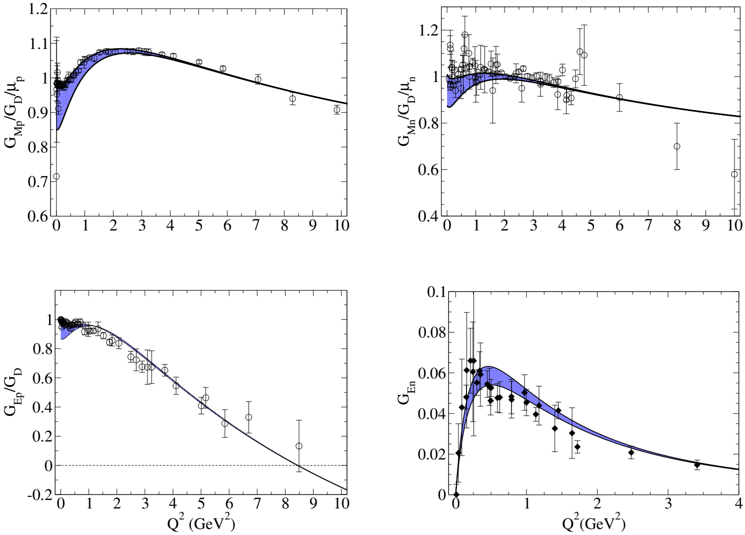
Quark current with isospin breaking $\Rightarrow$ describe lattice data

Results: Nucleon bare form factors (optional)





Results: Nucleon form factors in vacuum

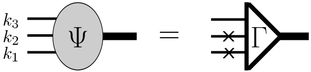


Octet square radii

B	$(r^2_{EB})_b$	$(r^2_{EB})_\pi$	r^2_{EB}	$(r^2_{MB})_b$	$(r^2_{MB})_\pi$	r^2_{MB}
p	0.614	0.168	0.782	0.601	0.117	0.718
n	-0.097	-0.016	**-0.113**	0.624	0.105	0.729
Λ	-0.005	0.073	0.068	0.449	-0.221	0.228
Σ^+	0.470	0.244	**0.713**	0.350	0.166	0.516
Σ^0	-0.001	0.040	0.039	0.291	0.097	0.388
Σ^-	0.480	0.162	**0.643**	0.388	0.253	0.642
Ξ^0	0.096	0.001	0.097	0.325	-0.005	0.319
Ξ^-	0.382	0.021	0.403	0.218	0.050	0.218

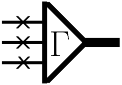
Spectator QM: Baryon wave functions

- Baryon: 3 constituent quark system
- Covariant Spectator Theory: wave function Ψ defined in terms of a 3-quark vertex Γ with 2 on-mass-shell quarks



$$\Psi_\alpha(P,k_3) = \left(\frac{1}{m_q - \not{k}_3 - i\varepsilon}\right)_{\alpha\beta} \Gamma^\beta(P,k_1,k_2)$$

- Confinement insures that vertex Γ vanishes when the 3 quarks are on-shell [Γ cancels the quark propagator singularity]



$$= \; 0$$

Stadler, Gross and Frank PRC 56, 2396 (1998); Savkli and Gross PRC 63, 035208 (2001)

- Ψ **free** of singularities
  Instead of modulate $\Gamma \Rightarrow$ modulate directly Ψ

Spectator QM: Baryon wave functions (II)

- Integrating over the on-mass-shell quark momenta:
  $k = k_1 + k_2$, $r = \frac{1}{2}(k_1 - k_2)$;
  reduce current integrals to the integration in $\mathbf{k}$ and $s = (k_1 + k_2)^2$
  F. Gross and P. Agbakpe, PRC 73, 015203 (2006);
  F. Gross, GR and M. T. Pena, arXiv:1201.6336 [hep-ph] :

$$\int \frac{d^3 k_1}{2E_{k_1}} \int \frac{d^3 k_2}{2E_{k_2}} = \frac{\pi}{4} \int d\Omega_{\hat{\mathbf{r}}} \int_{4m_q^2}^{+\infty} ds \sqrt{\frac{s - 4m_q^2}{s}} \int \frac{d^3 \mathbf{k}}{2E_k}$$

  with $E_k = \sqrt{s + \mathbf{k}^2}$ as the energy of the diquark.
- Mean value theorem: average in diquark mass $\sqrt{s} \to m_D$

$$\int \frac{d^3 k_1}{2E_{k_1}} \int \frac{d^3 k_2}{2E_{k_2}} \to \int \frac{d^3 \mathbf{k}}{2\sqrt{m_D^2 + \mathbf{k}^2}}$$

m_D=eff. mass; covariant integration in diquark **on-shell** momentum

Current conservation (1)

- Quark current in a Feynman diagram (one-body current)

$$j^\mu(q) = j_1 \gamma^\mu + j_2 \frac{i\sigma^{\mu\nu} q_\nu}{2M}$$

on-shell: current conserved $q_\mu [\bar{u}(p') j^\mu u(p)] = 0$.
When the Dirac particle is off-shell, it is necessary to modify this current in order to maintain current conservation.

- If a dynamics exists, we can do this in the manner of Gross and Riska, PRC 36, 1928 (1987); Adam *et. al*, PRC66, 044003 (2002)

$$\tilde{S}(p) = \frac{h(p)}{m - \not{p}}, \qquad j_R^\mu(p', p) = j_R^\mu\left(j^\mu, h(p'), h(p); p', p\right)$$

j_R^μ off-shell current, satisfies Ward-Takahashi identity

$$q_\mu j_R^\mu = \tilde{S}^{-1}(p') - \tilde{S}^{-1}(p')$$

Current conservation (2)

- When no dynamics exists a purely phenomenological treatment is needed

$$\begin{aligned} j^\mu &\to j^\mu - (q_\nu j^\nu)\frac{q^\mu}{q^2} \\ &= j_1\left(\gamma^\mu - \frac{\not{q} q^\mu}{q^2}\right) + j_2 \frac{i\sigma^{\mu\nu} q_\nu}{2M} \end{aligned}$$

  On-shell: $\not{q}$ term vanishes; current reduced to the 1st case
- Calculations of $\gamma^* N \to N^*$: equivalent to Landau prescripton
  Kelly, PRC 56, 2672 (1997); Batiz and Gross, PRC 58, 2963 (1998)

$$J^\mu \to J^\mu - (q \cdot J)\frac{q^\mu}{q^2}$$

  Restores current conservation but does not affect the observables
- DIS calculations: subtraction term $-\frac{\not{q} q^\mu}{q^2}$ arises naturally from interaction currents neglected in impulse approximation
  Batiz and Gross, PRC 58, 2963 (1998)

Spectator QM: Nucleon wave function

Nucleon wave function: [PRC 77,015202 (2008); EPJA 36, 329 (2008)]
Simplest structure –S-state in quark-diquark system

$$\Psi_N(P,k) = \frac{1}{\sqrt{2}}\left[\Phi_I^0\Phi_S^0 + \Phi_I^1\Phi_S^1\right]\psi_N(P,k)$$

Spin states:

$$\Phi_S^0(s) \equiv u(P,s) \qquad \Phi_S^1(s) \equiv -\varepsilon_\alpha^* U^\alpha(P,s)$$

$$U^\alpha(P,s) = \sum_{\lambda\ s'}\langle\frac{1}{2}s';1\lambda|\frac{1}{2}s\rangle\varepsilon_\lambda^\alpha u(P,s') \to \frac{1}{\sqrt{3}}\gamma_5\left(\gamma^\alpha - \frac{P^\alpha}{M}\right)u(P,s)$$

$\varepsilon_\lambda = \varepsilon_{\lambda P}$ function of nucleon momentum
Fixed-Axis polarization states; PRC 77, 035203 (2008)
$\Longrightarrow$ Ψ_N pure S-state

Scalar wave function: Nucleon

Scalar wave functions deppendent of $(P-k)^2$= (quark momentum)^2

$$\chi_B = \frac{(M_B - m_D)^2 - (P-k)^2}{M_B m_D} \xrightarrow{NR} \frac{\mathbf{k}^2}{m_D^2}$$

M_B = baryon mass; m_D = diquark mass

Nucleon scalar wave function:

$$\psi_N(P,k) = \frac{N_0}{m_D}\frac{1}{(\beta_1+\chi_N)(\beta_2+\chi_N)} = \frac{N_0}{m_D}\frac{1}{\beta_2-\beta_1}\left[\frac{1}{\beta_1+\chi_N} - \frac{1}{\beta_2+\chi_N}\right]$$

$$\xrightarrow{NR} \frac{N_0}{m_D}\frac{1}{\beta_2-\beta_1}\left[\frac{1}{\beta_1+\frac{\mathbf{k}^2}{m_D^2}} - \frac{1}{\beta_2+\frac{\mathbf{k}^2}{m_D^2}}\right]$$

Position space:

$$\psi_N(P,k) \xrightarrow{FT} \frac{e^{-m_D\sqrt{\beta_1}r}}{r} - \frac{e^{-m_D\sqrt{\beta_2}r}}{r}$$

β_1, β_2 momentum range parameters; $\beta_2 > \beta_1$:

β_1 long spatial range; β_2 short spatial range

Baryon wave function -example: Nucleon spin (I)

Example $|p\uparrow\rangle$: $\uparrow = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$; $\chi_S = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$

Spin-0: $$\Phi_S^0 = \overbrace{\frac{1}{\sqrt{2}}(\uparrow\downarrow - \downarrow\uparrow)}^{\varepsilon^s}\uparrow \quad = \quad \varepsilon^s \chi_S$$

Relativistic generalization $\rightarrow$ $\varepsilon^s\, u(P,\uparrow)$

Spin-1: $$\Phi_S^1 = \frac{1}{\sqrt{6}}\left[2\uparrow\uparrow\downarrow - (\downarrow\uparrow + \downarrow\uparrow)\uparrow\right] \quad = \quad -\frac{1}{\sqrt{3}}(\sigma\cdot\varepsilon_P^*)\,\chi_S$$

Relativistic generalization $\rightarrow$ $-(\varepsilon_P^*)_\alpha U^\alpha(P,\uparrow)$

ε_P^*in **rest frame**: $\varepsilon_P^\alpha(0) = (0,0,0,1)$ $\quad \varepsilon_P^\alpha(\pm) = \mp\frac{1}{\sqrt{2}}(0,1,\pm i,0)$

$\Longrightarrow$ Fixed-axis polarization base

$\Phi_S^{0,1}$ **in terms of baryon properties**

Spectator quark model

Baryon wave functions: $B =$ **diquark** $\oplus$ **quark**

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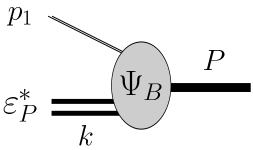
$$\Psi_B = \sum \text{(color)} \otimes \text{(flavor)} \otimes \text{(spin)} \otimes \text{(orbital)} \otimes \underbrace{\psi_B(P,k)}_{\text{radial}}$$



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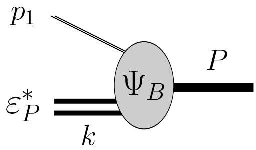

- **Phenomenology on ψ_B parametrization**

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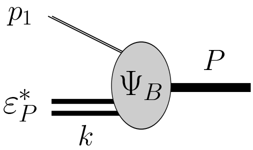

- **Phenomenology on ψ_B parametrization**
- Ψ_B in **rest frame** using quark states

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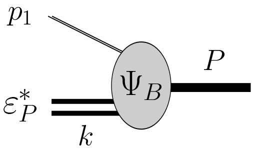


- **Phenomenology on ψ_B parametrization**
- Ψ_B in **rest frame** using quark states
- **Covariant** generalization of Ψ_B in terms **baryon** properties

CSQM: Electromagnetic currents ($\gamma B \to B'$)

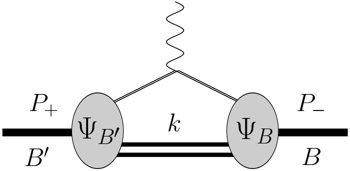
Quark current j_q^μ $\bigoplus$ Baryon wave function $\Psi_B \Rightarrow J^\mu$

Transition current J^μ in spectator formalism

Franz Gross et al PR 186 (1969); PRC 45, 2094 (1992)

Gross, Peña and GR, PRC77 015202 (2008); arXiv:1201.6336 [hep-ph]

Relativistic impulse approximation:

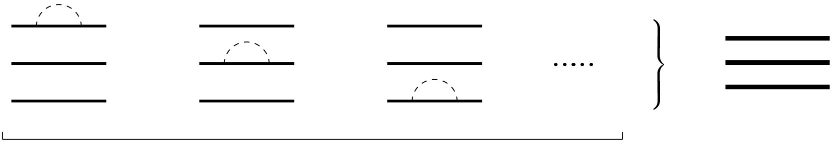


$$J^\mu = 3 \sum_\lambda \int_k \bar{\Psi}_{B'}(P_+, k) j_q^\mu \Psi_B(P_-, k)$$

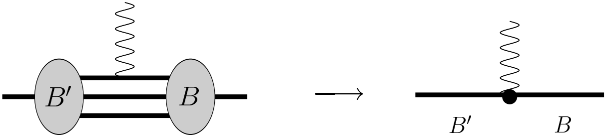
diquark on-shell

$$q = P_+ - P_-, \qquad P = \tfrac{1}{2}(P_+ + P_-), \qquad Q^2 = -q^2$$

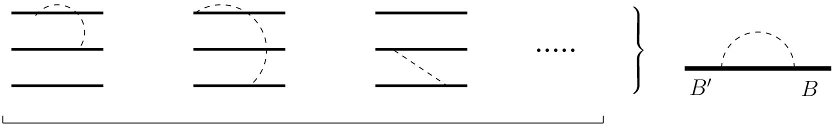
Quark structure and electromagnetic interaction (I)



γ coupling:



Quark structure and electromagnetic interaction (II)



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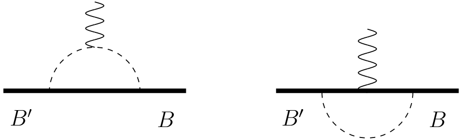

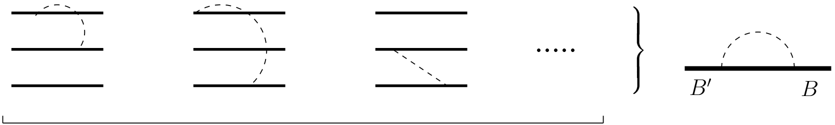

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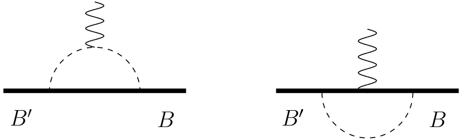
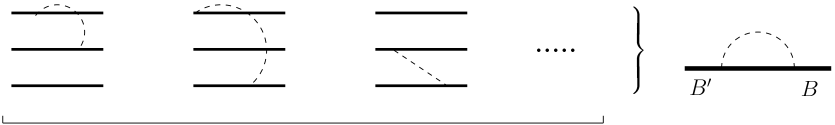


- Not important at high Q^2 [pQCD: supression $1/Q^4$], Very important at low Q^2

Quark structure and electromagnetic interaction (II)



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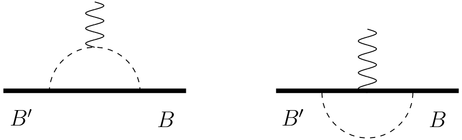

- Not important at high Q^2 [pQCD: supression $1/Q^4$], Very important at low Q^2
- Assume NO interference with quark dressing processes

$$F = F^B + F^{mc}$$

(bare ⊕ meson cloud)

Goldberger-Treimann relation

$$\frac{g^*_{\pi BB}}{g_{\pi BB}} = \left(\frac{f_\pi}{f^*_\pi}\right)\left(\frac{g_A^{B*}}{g_A^B}\right)\left(\frac{M_B^*}{M_B}\right)$$
$$\simeq \left(\frac{f_\pi}{f^*_\pi}\right)\left(\frac{g_A^{N*}}{g_A^N}\right)\left(\frac{M_B^*}{M_B}\right)$$

M. L. Goldberger and S. B. Treiman, Phys. Rev. 110, 1178 (1958)

f^*_π: M. Kirchbach and A. Wirzba, NPA 616, 648 (1997)

$\frac{g_A^{N*}}{g_A^N}$: D. H. Lu, A. W. Thomas and K. Tsushima, arXiv:nucl-th/0112001

K. Tsushima, H. c. Kim and K. Saito, PRC 70, 038501 (2004)