Electromagnetic form factors of baryons in the nuclear medium and at large q^2

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Hadron properties in a nuclear medium from the quark and gluon degrees of freedom (via ZOOM)
July 14, 2021

Plan of the talk

- **Introduction** – Covariant Spectator Quark Model
- **Octet baryon form factors in the spacelike region** $Q^2 = -q^2 \geq 0$
  Extension of model to nuclear medium
- **Hyperon form factors in the timelike region** $Q^2 = -q^2 < 0$

$$q^2 = (\text{photon four-momentum})^2$$

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

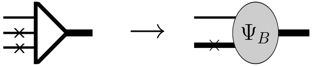
GR, JPBC Melo, K Tsushima, PRD 100, 014030 (2019)

GR, MT Peña, K Tsushima, PRD 101, 014014 (2020)

GR, PRD 103, 074018 (2021)

Covariant Spectator Quark Model – Introduction

- Baryon: 3 constituent quark system – $SU_F(3) \times SU_S(2)$ structure
- Covariant Spectator Theory: wave function Ψ_B defined in terms of a 3-quark vertex Γ with 2 on-mass-shell quarks – integrate into quark-pair degrees of freedom



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

Mean value theorem: $s=(k_1+k_2)^2 \to m_D^2$; effective diquark mass m_D

Gross and Agbakpe PRC 73, 015203 (2006); Gross, GR and Peña PRC 77, 015202 (2008)

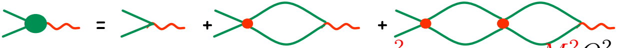
- $\Rightarrow$ **reduction to a quark-diquark structure:** $\Psi_B(P_B,k)$
  Baryon wave function $\Psi_B(P_B,k)$ free of singularities

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

- Radial wave function $\psi_B(P_B,k)$ **determined phenomenologically**
  Not a solution of a dynamical wave equation – mass $M_B \equiv M_B^{\rm exp}$
  Shape determined by momentum scale parameters using experimental data or lattice data of some ground state systems

Covariant Spectator Quark Model – Quark current

- $j_q^\mu = j_1 \gamma^\mu + j_2 \frac{i\sigma^{\mu\nu} q_\nu}{2M_N}$, Quark form factors: $j_i = \frac{1}{2} f_{i+} \lambda_0 + \frac{1}{6} f_{i-} \lambda_3 + \frac{1}{2} f_{i0} \lambda_s$
  [parametrize gluon and $q\bar{q}$ dressing of quarks] λ_l: Gell-Mann matrices
  Vector meson dominance parameterization: PRC77 015202 (2008)



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

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

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

$$f_{20} = \kappa_0 \left\{ d_0 \frac{m_\phi^2}{m_\phi^2+Q^2} + (1-d_0)\frac{M_h^2}{M_h^2+Q^2} \right\}$$

Light mesons ($m_v = m_\rho$), m_ϕ and **effective** heavy meson: $M_h = 2M_N$
Fix coefficients (c_0, $c_\pm$, d_0, $d_+ = d_-$) and a. m. m. $\kappa_\pm$, κ_0, – universal parameters

Use: Nucleon EM form factors; Lattice QCD data

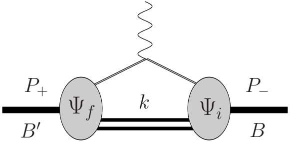
Covariant Spectator Quark Model – Transition current

$\gamma^* B \to B'$ transition and $\gamma^* B \to B$ reactions

- Transition current – relativistic impulse approximation

  F Gross, GR, MT Peña, PRC 77, 015202 (2008)

$$J^\mu = 3 \sum_\lambda \int_k \bar{\Psi}_f(P_+, k) j_q^\mu \Psi_i(P_-, k)$$



diquark on-shell

- **Generalization to lattice QCD:**
  - $f_{i\ell}(Q^2; m_v, M_N) \to f_{i\ell}(Q^2; m_v^{\rm latt}, M_N^{\rm latt})$, $\ell = 0, \pm$ – VMD
  - $\psi_B(M_B) \to \psi_B(M_B^{\rm latt})$

GR, MT Peña, JPG 36, 115011 (2009); PRD 80, 013008 (2009); GR, K Tsushima, F Gross, PRD 80, 033004 (2009);

GR, K Tsushima, AW Thomas, JPG 40, 015102 (2013); In medium: $M_h \to M_h^*$ (in medium masses)

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

Radial wave functions: dependence on $(P-k)^2$

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); $\beta_4 > \beta_3 > \beta_2 > \beta_1$

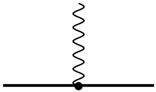
long range: β_1 (all systems) — universal parameters

short range: β_2 (lll systems); β_3 (sll systems); β_4 (ssl systems)

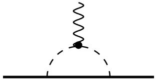
CSQM: total electromagnetic current – including pion cloud

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

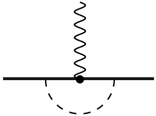
$J^\mu_{0B} \leftrightarrow$ QM



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



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



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

$\tilde{B}_i, \tilde{C}_i$ 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); – **fit** $\tilde{B}_i$, $\tilde{C}_i$, $\tilde{D}_i$ Z_B : normalization

Dressed form factors – Nucleon – example

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

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

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

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

$$F_{2n} = Z_N \left\{ \tilde{\kappa}_{0n} - 2\beta_N \tilde{B}_2 + \beta_N (2\tilde{e}_{0p} + \tilde{e}_{0n}) \tilde{C}_2 + \beta_N (2\tilde{\kappa}_{0p} + \tilde{\kappa}_{0n}) \tilde{D}_2 \right\}$$

F Gross, GR and K Tsushima PLB 690, 183 (2010): $Z_N = 1/(1 + 3\beta_N B_1)$

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

Bare form factors – octet baryon (optional)

Quark current: $j_i^A = \langle M_A | j_i | M_A \rangle, \quad j_i^S = \langle M_S | j_i | M_S \rangle$

$$\begin{aligned}
\tilde{e}_{0B} &= B(Q^2) \times \\
&\left(\frac{3}{2} j_1^A + \frac{1}{2} \frac{3-\tau}{1+\tau} j_1^S - 2 \frac{\tau}{1+\tau} \frac{M_B}{M_N} j_2^S \right), \\
\tilde{\kappa}_{0B} &= B(Q^2) \times \\
&\left[\left(\frac{3}{2} j_2^A - \frac{1}{2} \frac{1-3\tau}{1+\tau} j_2^S \right) \frac{M_B}{M_N} - 2 \frac{1}{1+\tau} j_1^S \right],
\end{aligned}$$

$$\tau = \frac{Q^2}{4M_B^2}, \qquad B(Q^2) = \int_k \psi_B(P_+, k) \psi_B(P_-, k)$$

Octet baryons

Methodology:

- Estimate **bare component** of octet electromagnetic form factors
  – use lattice QCD data $G^B_{E,M}$ HW Lin, K Orginos, PRD 79, 074507 (2009)
  – fix radial wave functions
- Estimate **pion cloud** contribution ($\boldsymbol{Z_B}$ – normalization):

$$G_{E,M} = \boldsymbol{Z_B}[G^B_{E,M} + G^\pi_{E.M}]$$

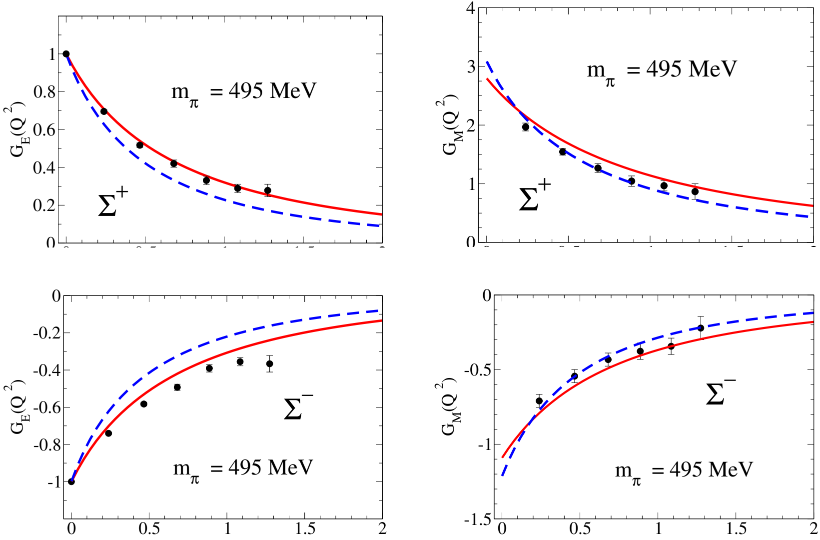
using $G^B_{E.M}$ (extrapolated from lattice)

physical data: proton, neutron, and octet baryon magnetic moments

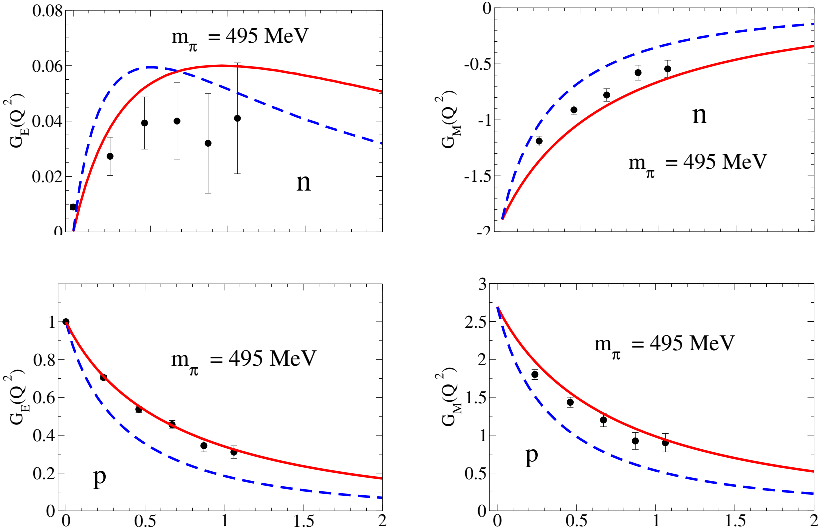
$*\Lambda, \Sigma^{0,\pm}$ compared with lattice $m_\pi = 306$ MeV [Boinepalli at al, PRD 74, 093005 (2006)]

GR and K Tsushima, PRD 84, 054014 (2011);
GR, K Tsushima, AW Thomas, JPG 40, 015102 (2013)

Octet baryons – Example 1 —- **lattice** - - physical



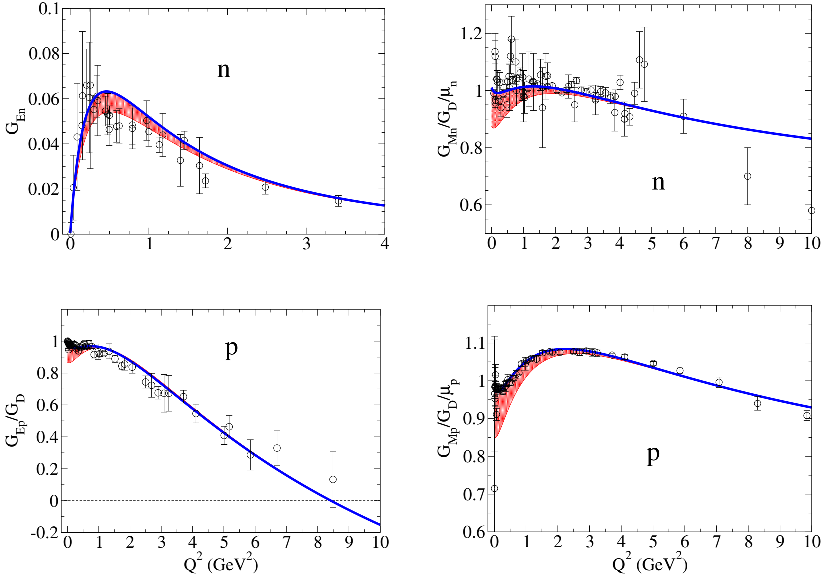
Octet baryons – Example 2 —- **lattice** - - physical



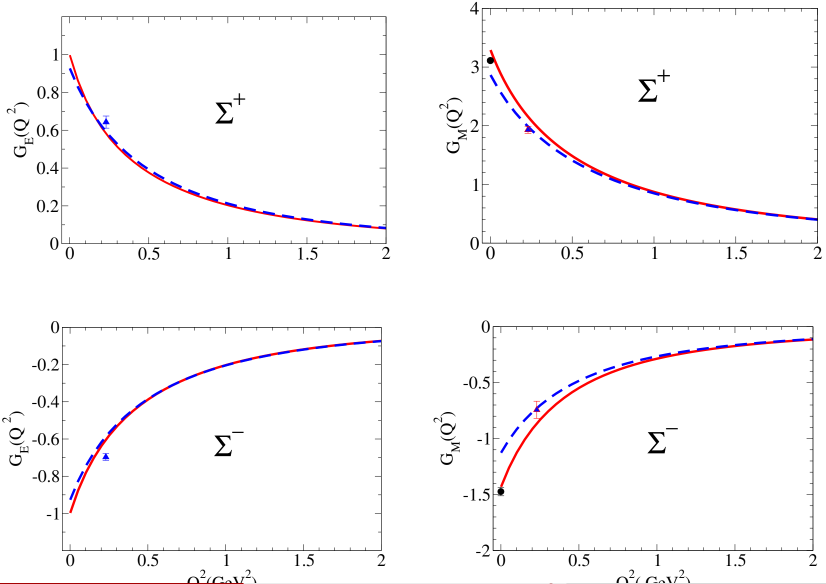
Octet baryon form factors in the spacelike region

GR and K Tsushima, PRD 84, 054014 (2011)
GR, K Tsushima and AW Thomas, JPG 40, 015102 (2013)

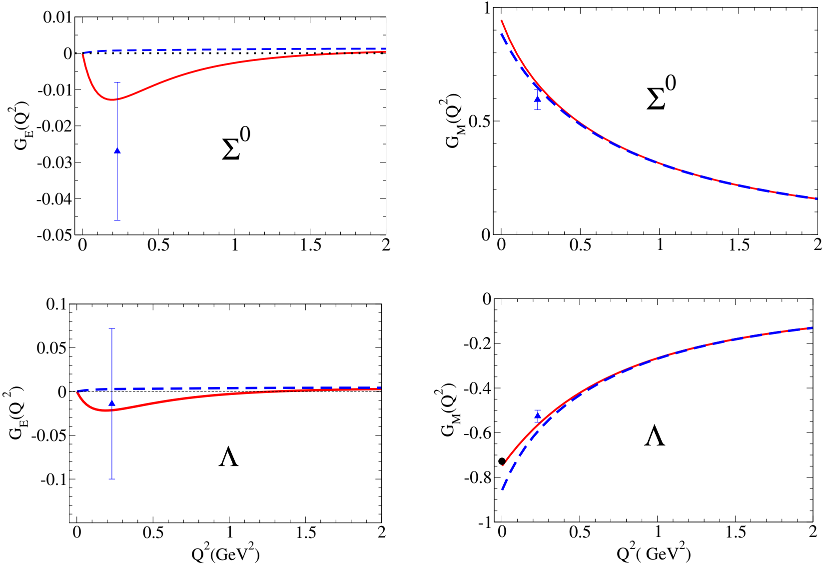
Nucleon elastic form factors $G_D = (1 + Q^2/0.71)^{-2}$



Σ^+, Σ^- elastic form factors (total —; bare - - - -)



Σ^0, Λ elastic form factors – test results ($m_\pi \simeq 306$ MeV)



Octet baryon form factors in the nuclear medium

EM structure in medium; $G_{MB} \to \frac{M_N}{M_B} G_{MB}$

[normalization by the nucleon magnetic moment

$\mu_B = G_{MB}(0) \frac{e}{2M_B} \equiv \frac{M_N}{M_B} G_{MB}(0) \frac{e}{2M_N}$]

GR, JPBC de Melo, K Tsushima, PRD D100, 014030 (2019);

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

Octet baryon EM FF – Motivation – In vacuum

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

Jefferson Lab 1999–...

Polarization transfer method

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

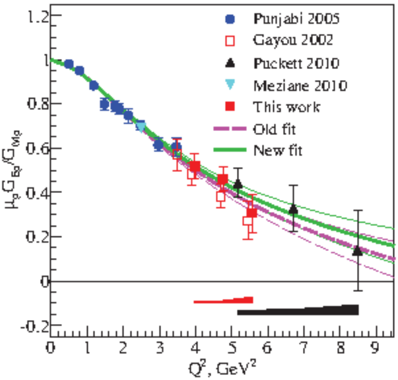
P_t = parallel

P_l = longitudinal

Jones PRL 84 (2000); Gayou PRL 88 (2002);

Punjabi PRC 71 (2005); Puckett PRL 104 (2010)

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



Octet baryon EM FF – Motivation – In medium

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

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^*

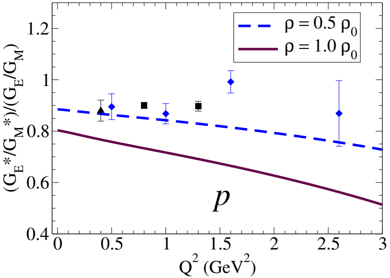
Define **Double Ratio**

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

Measures modifications in-medium

Octet baryon EM FF – Motivation – In medium (ρ)

proton **In Medium**



$\rho_0 = 0.15$ fm^{-3}
normal nuclear density

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**

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

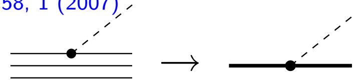
Measures modifications in-medium

Symmetric nuclear matter - Equation of state

Quark-Meson-Coupling model

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

$$M_B^* = M_B - g_\sigma \sigma + \dots$$



Calculate medium modifications of **masses** and **coupling constants** for $\rho = 0.5\rho_0$ and $\rho = \rho_0$ ($\rho_0 = 0.15$ fm^{-3}) – masses **reduced** in medium

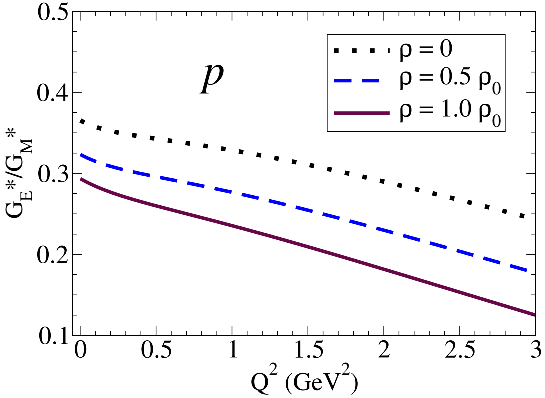
Goldberger-Treimann relation: $\frac{g^*_{\pi BB}}{g_{\pi BB}} \simeq \left(\frac{f_\pi}{f^*_\pi}\right)\left(\frac{g_A^{N*}}{g_A^N}\right)\left(\frac{M_B^*}{M_B}\right)$

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

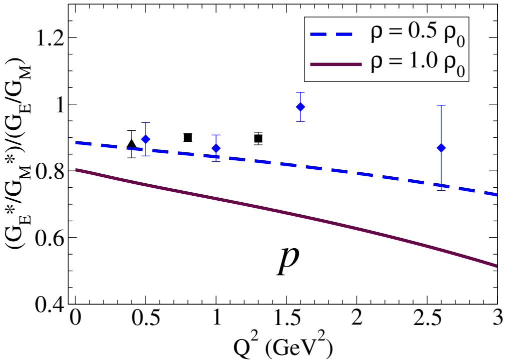
	$\rho = 0$	$\rho = 0.5\rho_0$	$\rho = \rho_0$
$g^*_{\pi NN}/g_{\pi NN}$	1	0.921	0.899
$g^*_{\pi\Lambda\Sigma}/g_{\pi\Lambda\Sigma}$	1	0.973	0.996
$g^*_{\pi\Sigma\Sigma}/g_{\pi\Sigma\Sigma}$	1	0.977	1.004
$g^*_{\pi\Xi\Xi}/g_{\pi\Xi\Xi}$	1	1.012	1.067

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



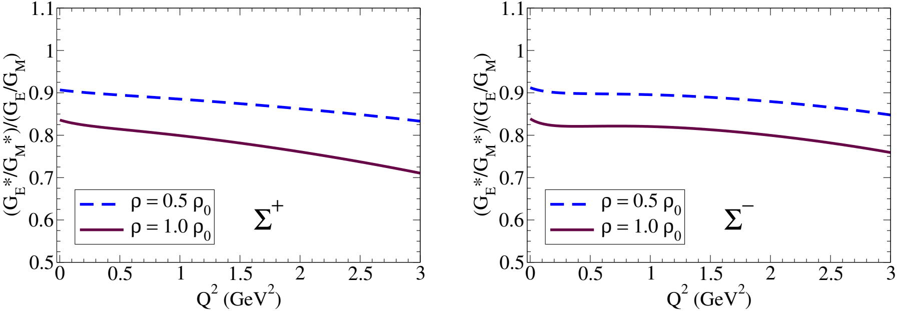
- $\frac{G_E^*}{G_M^*} \simeq \frac{1}{G_M^*(0)} \left[1 - \left(r_{EB}^{*\,2} - r_{MB}^{*\,2} \right) \frac{Q^2}{6} \right]$ – almost linear falloff; $\frac{G_E^*}{G_M^*}(0) \to \frac{1}{G_M^*(0)}$
- $r_{EB}^{*\,2} - r_{MB}^{*\,2}$ **enhanced** in medium; G_E^*/G_M^* **suppressed** in medium

Medium: proton G_E^*/G_M^* **double ratio** (DR)



- G_E/G_M suppressed in medium (DR < 1); Larger suppression for larger densities
- Data ^{4}He: Dieterich, PLB 500 (2001); Strauch, EPJA 19 S1 (2004); Paolone, PRL 105 (2010)

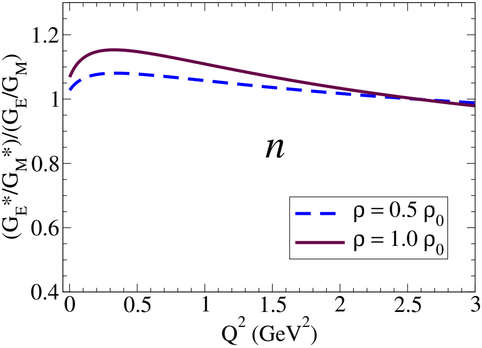
Medium: $\Sigma^\pm$ – G_E^*/G_M^* double ratio



- Similar to **proton**; smaller reduction (slower falloff)
- strange quarks ⇒ smaller medium effects

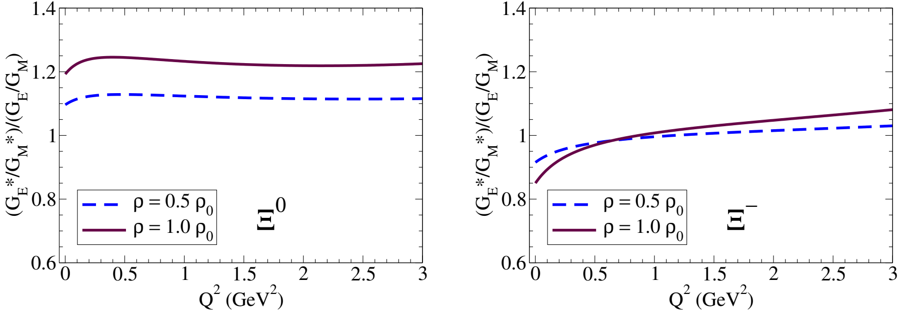
GR, JPBC de Melo, K Tsushima, PRD D100, 014030 (2019)

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



- Prediction: $Q^2 < 2$ GeV^2: G^*_{En}, G^*_{Mn} enhanced; Enhancement of G^*_{En}/G^*_{Mn}
- Proposals to measure DR: R. Gilman et al, "Neutron properties in the nuclear medium studied by polarization measurements" (Letter of intent JLab PAC 35)
- **Enhancement** consistent with other calculations:
  Cloet, Miller, Piasetzky, Ron, PRL 103, 082301 (2009);
  Aráujo, Melo, Tsushima, NPA 970, 325 (2018)

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



- Rough estimate of Ξ double ratios (limitations in the description of lattice data)
- Weak dependence on Q^2

GR, JPBC de Melo, K Tsushima, PRD D100, 014030 (2019)

Hyperon form factors at large q^2

GR, MT Peña and K Tsushima, PRD 101, 014014 (2020)
GR, PRD 103, 074018 (2021)

Elastic form factors – Timelike vs Spacelike $Q^2 = -q^2$

Asymptotic relations between spacelike ($G_l^{\rm SL}$) and the timelike regions ($G_l^{\rm TL}$) $l = E, M$

$$G_l^{\rm TL}(q^2) \overset{q^2 \to \infty}{=} G_l^{\rm SL}(-q^2)$$

Phragmén-Lindelöf theorem, Pacetti, Ferroli, Tomasi-Gustafsson, Phys. Rep. 550-551, 1 (2015), App. D

There is a gap between $]-\infty, 0]$ and $[4M^2, +\infty[$

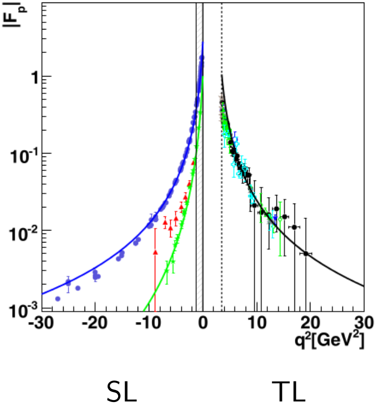
Finite corrections (central value):

$$G_l^{\rm TL}(q^2) \simeq G_l^{\rm SL}(2M^2 - q^2)$$

Upper limit: $G_l^{\rm SL}(-q^2)$
Lower limit: $G_l^{\rm SL}(4M^2 - q^2)$

Kuraev, Dbeyssi, Tomasi-Gustafsson, PLB 712, 240 (2012)

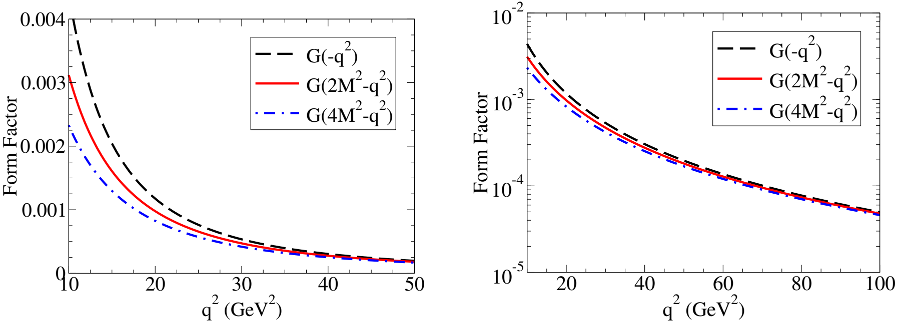
Proton form factors G_M, $|G_M|$



Elastic form factors – Timelike vs Spacelike   Example

Finite corrections to $G_\ell(q^2) \simeq G_\ell^{\rm SL}(-q^2)$

$q^2 \to q^2 - 2M_B^2; \quad q^2 \to q^2 - 4M_B^2$



$$G(Q^2) = \left(\frac{\Lambda_D^2}{\Lambda_D^2 + Q^2}\right)^2, \qquad \Lambda_D^2 = 0.71 \text{ GeV}^2$$

Elastic form factors – Timelike form factors

$e^+e^- \to \gamma^* \to B\bar{B}$

$G_E(q^2)$ and $G_M(q^2)$ not measured directly (... except for Λ)

Integrated Cross section: $\tau = \frac{q^2}{4M^2}$, $\beta = \sqrt{1 - \frac{1}{\tau}}$, $C \simeq 1$

$$\boldsymbol{\sigma}_{\mathbf{Born}} = \frac{4\pi\alpha^2\beta C}{3q^2}\left(1 + \frac{1}{2\tau}\right)|G(q^2)|^2$$

$$|G(q^2)|^2 = \frac{2\tau|G_M(q^2)|^2 + |G_E(q^2)|^2}{2\tau + 1}$$

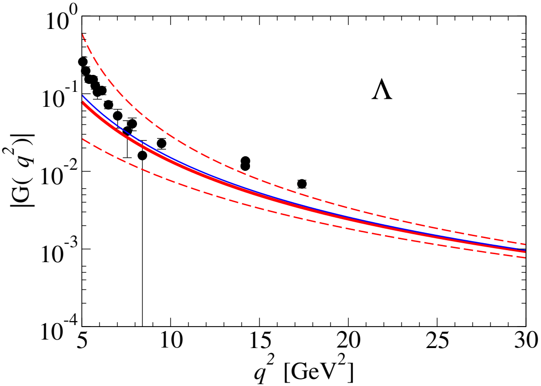
Measure $\boldsymbol{\sigma}_{\mathbf{Born}}$ and *effective* form factor $|G(q^2)|^2$

Calculations:

Ignore imaginary components and relative phases (very large q^2)

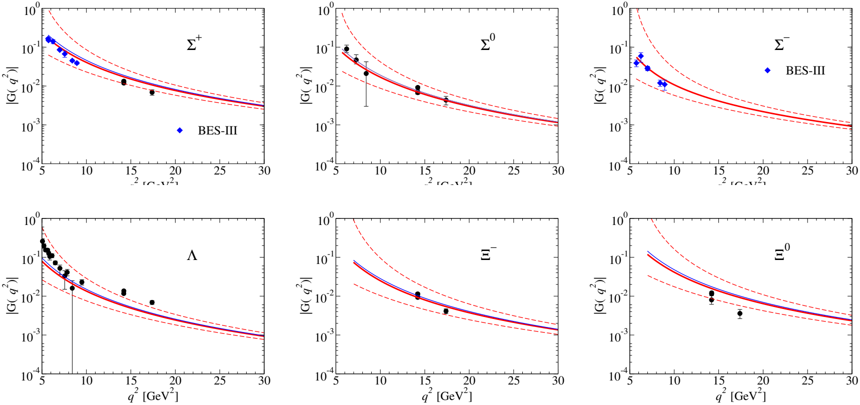
Elastic form factors – Λ

—— $G(q^2 - 2M^2)$; - - - - Upper limit: $G(q^2)$; Lower limit: $G(q^2 - 4M^2)$



Data from CLEO, BaBar, BES-III – underestimation of the data

Hyperon elastic form factors **at large** q^2 ($e^+e^-, p\bar{p} \to B\bar{B}$)



GR, MT Peña and K Tsushima PRD 101, 014014 (2020) — Data from CLEO, BaBar, BES-III (new data Σ^-)

Elastic form factors – Summary of results

- The estimates of $|G|$ have the magnitude of the data
- Approximated agreement with data within the **theoretical bands for large q^2**
- Average $\frac{G^{\rm exp}}{G^{\rm mod}} \simeq 1$

B	$\left\langle \frac{G^{\rm exp}}{G^{\rm mod}} \right\rangle$
Λ	2.19
Σ^+	0.65
Σ^0	1.08
Ξ^0	0.60
Ξ^-	1.08
Average	1.12

Table : Comparison between the ratios between the experimental value ($G^{\rm exp}$) and the model estimate of G ($G^{\rm mod}$) for the different baryons, for $q^2 \simeq 14.2$ and 17.4 GeV^2.

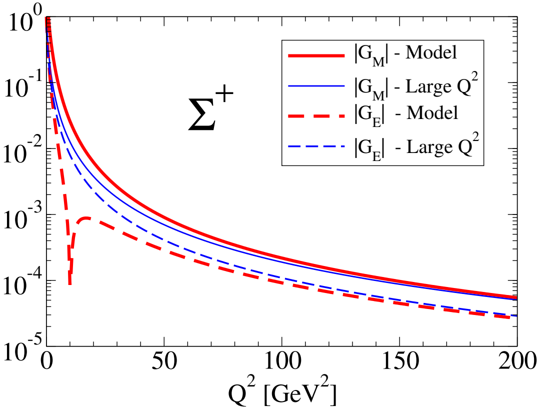
Elastic form factors – Summary of results

- The estimates of $|G|$ have the magnitude of the data
- Approximated agreement with data within the **theoretical bands for large** q^2
- Average $\frac{G^{\rm exp}}{G^{\rm mod}} \simeq 1$
- What about larger values ?
  - Predictions
    Table up to $q^2 = 60$ GeV^2
  - How far are we from pQCD estimates ?
    (pointlike quarks)

B	$\left\langle \frac{G^{\rm exp}}{G^{\rm mod}} \right\rangle$
Λ	2.19
Σ^+	0.65
Σ^0	1.08
Ξ^0	0.60
Ξ^-	1.08
Average	1.12

Table : Comparison between the ratios between the experimental value ($G^{\rm exp}$) and the model estimate of G ($G^{\rm mod}$) for the different baryons, for $q^2 \simeq 14.2$ and 17.4 GeV^2.

Comparison with pointlike quarks



Model: exact (*extended quarks*) —— - - - -

Large Q^2: pointlike quarks [$f_{1l}(Q^2) \to \lambda_q$ & $Q^2 f_{2l}(Q^2) \to$ const.] —— - - - -

Convergence for $Q^2 \approx 150$ GeV^2 (perturbative regime – pQCD)

Extension to spin 3/2 baryons: Ω^- elastic FF

- The formalim can be extended to $\frac{3}{2}^+$ baryons (redefining G_E and G_M).
- First estimate

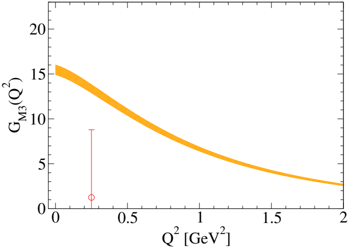
  GR, MT Peña, PRD 83, 054011 (2011)

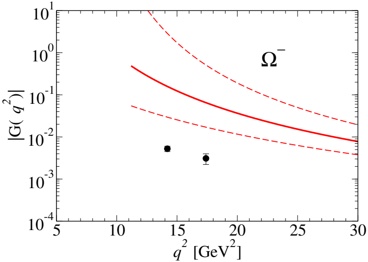
  $(G_{E0}, G_{M1}, G_{E2}, G_{M3})$
- Overestimation of G
  - Very large $G_{M3}(0)$ ...
  - ... or slower falloff ?
- **Opportunity to study Ω^-**

  Global fit to TL and SL data

  Estimate $G_{E2}(0)$ and $G_{M3}(0)$

  GR, PRD 103, 074018 (2021)





Ω^- elastic form factors **at large** q^2

GR, PRD 103, 074018 (2021)

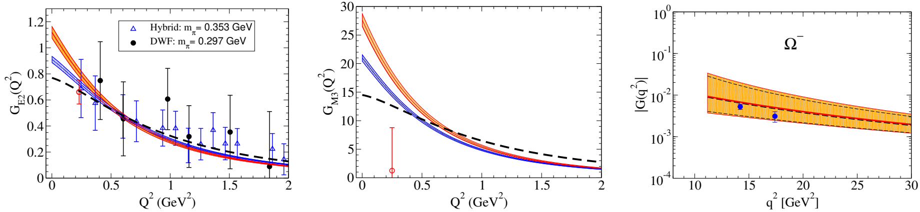
(S, $D1$ and $D3$ states)

SL/TL global fit

$G_+ \propto \frac{1}{Q^3}, G_{01}, G_{03} \propto \frac{1}{Q^4}, G_- \propto \frac{1}{Q^5}$

Large Q^2 constraint (LQ2):

$G_{M1}(Q^2) = \frac{4}{5}\frac{Q^2}{4M_\Omega^2} G_{M3}(Q^2)$



C Alexandrou et al, PRD 82, 034504 (2010) [lattice]; S Dobbs, et al, PRD 96, 092004 (2017) [TL data]

Overall description of G_{E0}, G_{M1} and G_{E2}; large result for G_{M3}; TL within limits; LQ2

Conclusions

- Use **covariant spectator quark model** with **meson cloud** dressing to estimate octet EM form factors in medium and at large q^2 (timelike)
- **In-medium form factors**
  - Estimate G_E/G_M ratios in medium
  - proton Σ^+, Σ^-: suppression
  - neutron: enhanced
    Measurements of neutron double ratio projected
    neutron recoil polarization in the ^{4}He$(\vec{e}, e'\vec{n})^3$He reaction (JLab)
  - Method can be extended to higher densities ...
    (heavy-ion collisions, neutron stars, compact stars, ...)
- **Hyperon form factors at large q^2**
  - Use high q^2 TL/SL relations to estimate *effective form factors* $|G|$
  - Very good estimate for octet baryon elastic form factors within the uncertainties $q^2 \to q^2 \pm 2M_B^2$
    Data from CLEO (Large q^2)
  - Calculations suggest that $q^2 \approx 40$ GeV^2 is not in the pQCD region (difference to quark pointlike limit)

Thank you very much 🙂

Selected bibliography (part 1)

- **Octet baryon electromagnetic form factor double ratios $(G_E^*/G_M^*)/(G_E/G_M)$ in a nuclear medium,**
  G. Ramalho, J. P. B. C. de Melo and K. Tsushima,
  Phys. Rev. D 100, 014030 (2019) [arXiv:1902.08844 [hep-ph]].
- **Hyperon electromagnetic timelike elastic form factors at large q^2,**
  G. Ramalho, M. T. Peña and K. Tsushima,
  Phys. Rev. D 101, 014014 (2020) [arXiv:1908.04864 [hep-ph]].
- **Electromagnetic form factors of the Ω^- baryon in the spacelike and timelike regions,**
  G. Ramalho, **Phys. Rev. D 103, 074018 (2021)** [arXiv:2012.11710 [hep-ph]].
- **Octet Baryon Electromagnetic form Factors in Nuclear Medium**,
  G. Ramalho, K. Tsushima and A. W. Thomas, **J. Phys. G 40, 015102 (2013)** [arXiv:1206.2207 [hep-ph]].
- **Nucleon and hadron structure changes in the nuclear medium and impact on observables**,
  K. Saito, K. Tsushima and A. W. Thomas,
  Prog. Part. Nucl. Phys. 58, 1 (2007) [hep-ph/0506314].

Selected bibliography (part 2)

- **Octet baryon electromagnetic form factors in a relativistic quark model**, G. Ramalho and K. Tsushima, **Phys. Rev. D 84, 054014 (2011)** [arXiv:1107.1791 [hep-ph]].
- **Extracting the Ω^- electric quadrupole moment from lattice QCD data,** G. Ramalho and M. T. Peña, **Phys. Rev. D 83, 054011 (2011)** [arXiv:1012.2168 [hep-ph]].
- **A Relativistic quark model for the Ω^- electromagnetic form factors,** G. Ramalho, K. Tsushima and F. Gross, **Phys. Rev. D 80, 033004 (2009)** [arXiv:0907.1060 [hep-ph]].
- N^* **Form Factors based on a Covariant Quark Model,** G. Ramalho, **Few Body Syst. 59, 92 (2018)** [arXiv:1801.01476 [hep-ph]].
- **A pure S-wave covariant model for the nucleon**, F. Gross, G. Ramalho and M. T. Peña, **Phys. Rev. C 77, 015202 (2008)** [arXiv:nucl-th/0606029].

More ...

Backup slides

Results: Form Factors – nucleon units

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

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

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

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

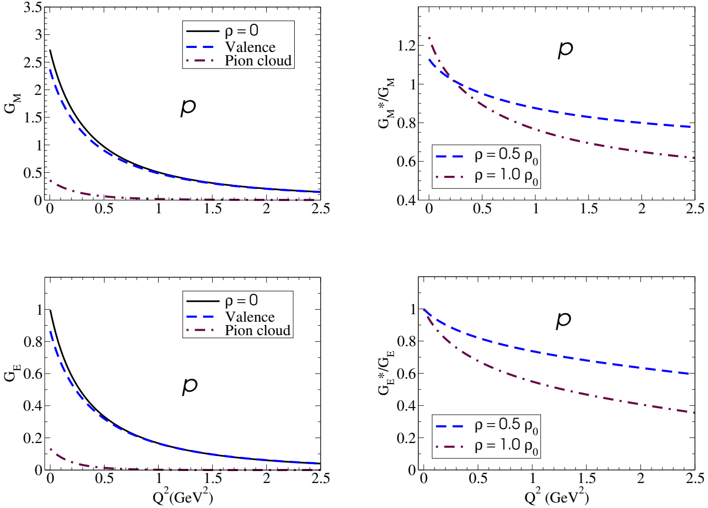
$$G_{MB}(Q^2) = \left[F_{1B}(Q^2) + F_{2B}(Q^2)\right]\frac{M_N}{M_B}$$

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

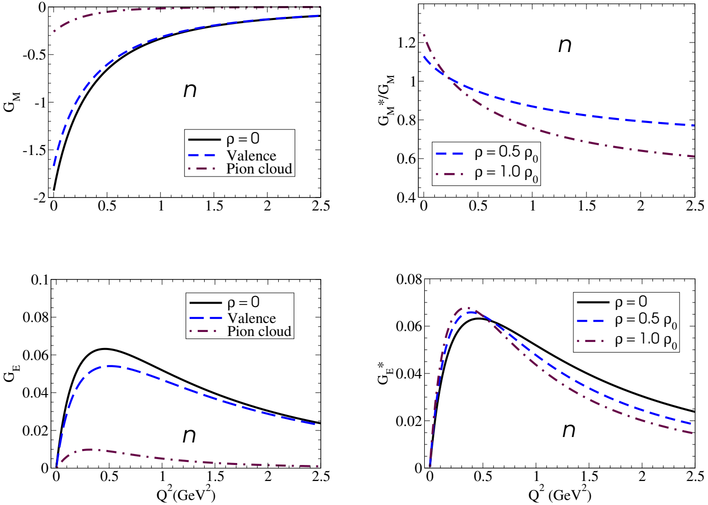
$$G^*_{EB}(Q^2) = F^*_{1B}(Q^2) - \frac{Q^2}{4{M^*_B}^2}F^*_{2B}(Q^2)$$

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

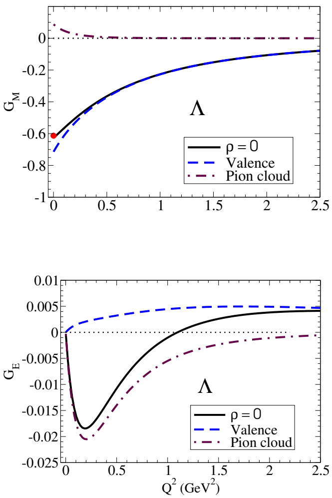
Results: Proton form factors in medium



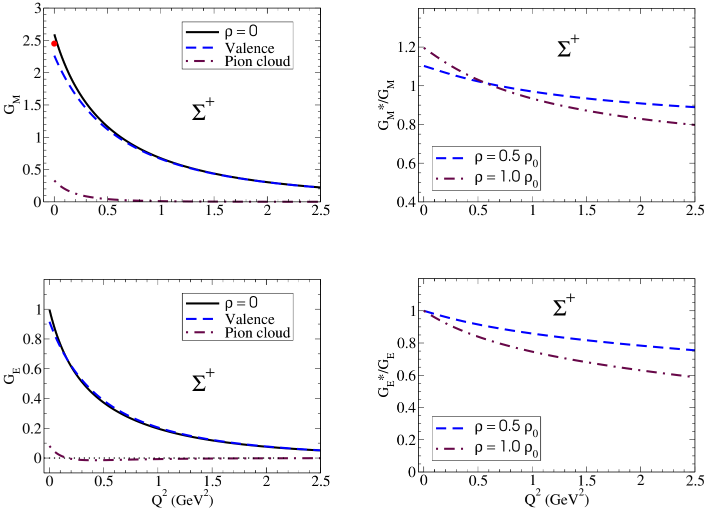
Results: Neutron form factors in medium



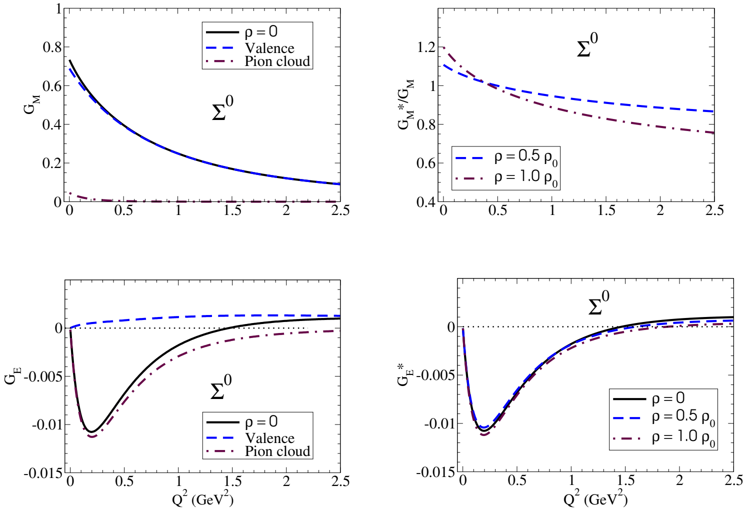
Results: Λ form factors in medium $-\cdot-$ $G_E \simeq G_E^\pi$



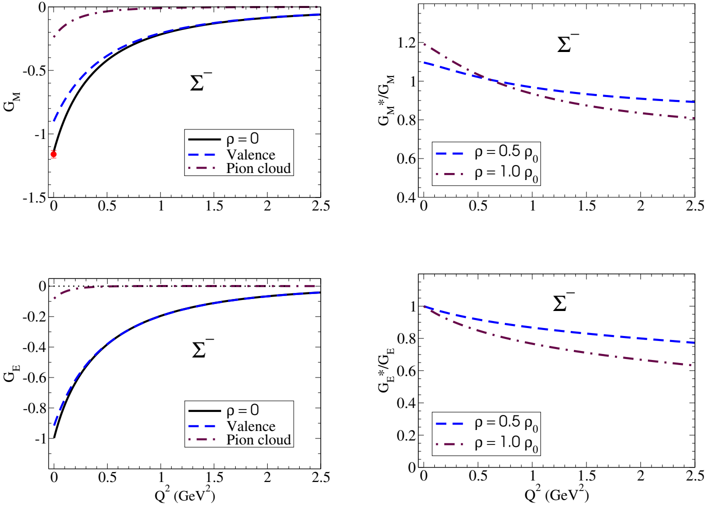
Results: Σ^+ form factors in medium



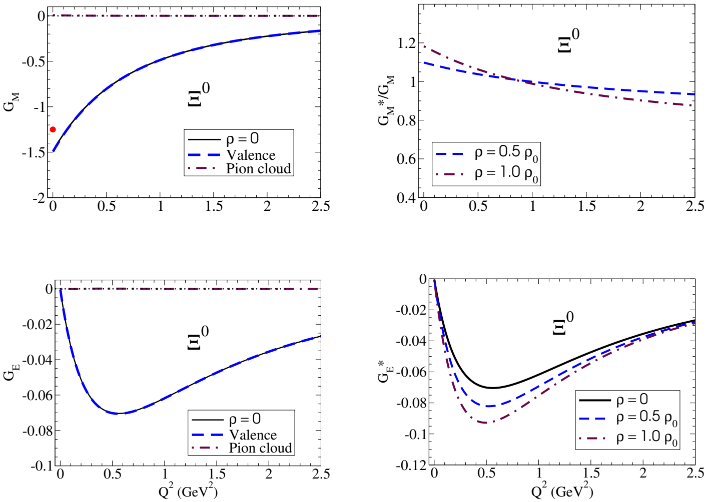
Results: Σ^0 form factors in medium $- \cdot -$ $G_E \simeq G_E^\pi$



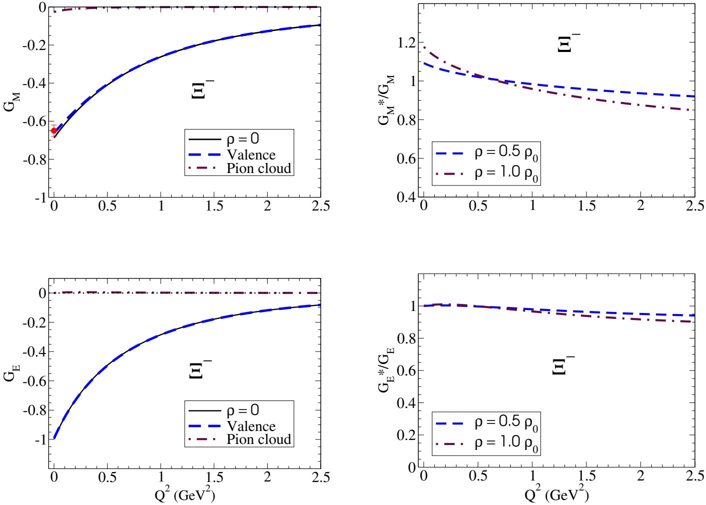
Results: Σ^- form factors in medium



Results: Ξ^0 form factors in medium



Results: Ξ^- form factors in medium

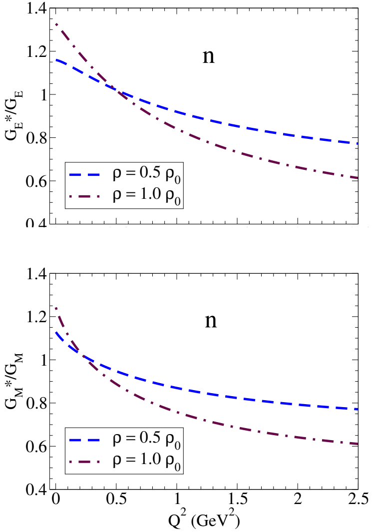


Results in vacuum/in medium – summary

- **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
  (n, Ξ^0 dominated by valence part)

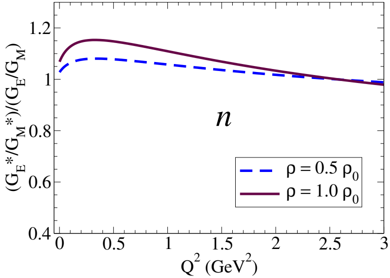
Next: results for the **Double Ratios**

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



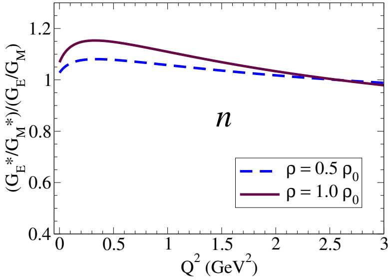
- $Q^2 \approx 0$:
  G^*_{En} enhanced
  G^*_{Mn} enhanced
  Enhancement increases with ρ
- Low-Q^2: $G^*_{En} \simeq -\frac{1}{6} r^{*\,2}_{En} Q^2$
  $-r^{*\,2}_{En}$ enhanced in medium
  $\frac{G^*_{En}}{G_{En}} \approx \frac{r^{*\,2}_{En}}{r^2_{En}} > 1$
- Low-Q^2: $G^*_{Mn} \propto 1/M^*_N$
  $\frac{G^*_{Mn}}{G_{Mn}} \approx \frac{M_N}{M^*_N} > 1$
- **Global effect** (low Q^2):
  $\frac{G^*_E/G^*_M}{G_E/G_M} \approx \frac{r^{*\,2}_{En}}{r^2_{En}} \frac{M^*_N}{M_N} > 1$
- G^*_E effects dominate over G^*_M effect

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



- $Q^2 \approx 0$:
  G^*_{En} enhanced
  G^*_{Mn} enhanced
  Enhancement increases with ρ
- Low-Q^2: $G^*_{En} \simeq -\frac{1}{6} r^{*\,2}_{En} Q^2$
  $-r^{*\,2}_{En}$ enhanced in medium
  $\frac{G^*_{En}}{G_{En}} \approx \frac{r^{*\,2}_{En}}{r^2_{En}} > 1$
- Low-Q^2: $G^*_{Mn} \propto 1/M^*_N$
  $\frac{G^*_{Mn}}{G_{Mn}} \approx \frac{M_N}{M^*_N} > 1$
- **Global effect** (low Q^2):
  $\frac{G^*_E/G^*_M}{G_E/G_M} \approx \frac{r^{*\,2}_{En}}{r^2_{En}} \frac{M^*_N}{M_N} > 1$
- G^*_E effects dominate
  over G^*_M effect

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: $\frac{G_E^*/G_M^*}{G_E/G_M} < 1$