Octet baryon electroweak form factors in dense nuclear matter

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Motivation

Electromagnetic and Axial structure of hadrons **modified** in a nuclear medium

- Proton EM ratio G_E/G_M
- Nucleon axial-vector coupling constants g_A^*

S Strauch *et al.* **PLB 500, 47 (2001); P Gysbers** *et al.* **Nat. Phys. 15, 428 (2019)**

$\Longrightarrow$ Develop theoretical methods to study electroweak structure of baryons in dense nuclear matter: heavy-ion collisions; nucleon-nucleon collisions, cores of compact stars

Methodology: **Valence quark** $\oplus$ **pion/meson cloud** dressing (d.o.f.)

- **Covariant Spectator Quark Model**
  $\Longrightarrow$ **Model for the vacuum:** calibrated by physical and lattice QCD data
- **Extension to the nuclear medium**: **Quark-Meson-Coupling model**
  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: bare & MC

GR, K Tsushima, AW Thomas JPG 40, 015102 (2013); GR, JPBC Melo, K Tsushima PRD 100, 014030 (2019);
GR, K Tsushima, MK Cheoun PRD 111, 013002 (2025); Symmetry 17, 681 (2025)

EM and Axial form factors in medium and vacuum: †

- **Octet baryon electromagnetic form factors in a relativistic quark model,**

  G. Ramalho and K. Tsushima, **Phys. Rev. D 84, 054014 (2011)**
- **Octet electromagnetic form factors in nuclear medium,**

  G. Ramalho, K. Tsushima and A. W. Thomas, **J. Phys. G 40, 015102 (2013)**
- **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)**
- **Axial form factors of the octet baryons in a covariant quark model,**

  G. Ramalho and K. Tsushima, **Phys. Rev. D 94, 014001 (2016)**
- **Weak interaction axial form factors of the octet baryons in nuclear medium,**

  G. Ramalho, K. Tsushima and M. K. Cheoun, **Phys. Rev. D 111, 013002 (2025)**
- **Electroweak Form Factors of Baryons in Dense Nuclear Matter,**

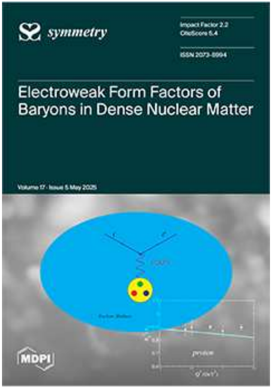
  G. Ramalho, K. Tsushima and M. K. Cheoun, **Symmetry 17, 681 (2025)** – **Review**

Plan of the talk

Baryon octet

- Calculate EM and Axial FF
  Density ρ: $G_\ell(Q^2, \rho) \quad \ell = E, M, A$
  Compare with free space $(\rho = 0)$
- **Part 1:** Dense nuclear matter
  Constant density
  $\rho = 0.5\rho_0,\ \rho_0,\ ...,\ 3.0\rho_0$
- **Part 2:** Nucleus
  Nucleons bound to nuclei
  Study *finite size effect* $\rho = \rho(r)$
  – in progress

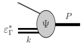
$\rho_0 = 0.15$ fm^{-3} = normal nuclear matter dens.



Review — **Electroweak Form Factors of Baryons in Dense Nuclear Matter,**

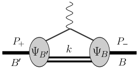
G. Ramalho, K. Tsushima and M. K. Cheoun, **Symmetry 17, 681 (2025)**

Formalism: Covariant Spectator Quark Model

- Baryons: systems of three quark 

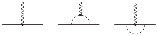
  $\Rightarrow$ System quark-diquark; diquark on-mass shell
  Stadler, Gross and Frank PRC 56, 2396 (1998); Gross, GR and Peña PRC 77, 015202 (2008); PRD 85, 093005 (2012)

- Wave functions defined by $SU(6)$; **Radial part:** phenomenology $\psi(P,k)$
  Gross, GR and Peña PRC 77, 015202 (2008); GR, K Tsushima, F Gross, PRD 80, 033004 (2009); GR and K Tsushima, PRD 84, 054014 (2011); GR, K Tsushima and AW Thomas, JPG 40, 015102 (2013) – lattice QCD, Nucleon/physical data $\psi(P,k)$ breaks $SU_F(3)$

- Electromagnetic interaction; relativistic impulse approximation 

  $J^\mu = 3\sum_\Gamma \int_k \overline{\Psi}_{B'}(P_+,k) j_q^\mu \Psi_B(P_-,k)$, j_q^μ parametrized in a VMD form
  GR and MT Peña, PRD 80, 013008 (2009); GR, K Tsushima, F Gross, PRD 80, 033004 (2009)

- Model can be extended to lattice QCD regime, timelike region, ...
  GR and MT Peña, PRD 80, 013008 (2009); J. Phys. G **36**, 115011 (2009); PRD 93, 033004 (2016)

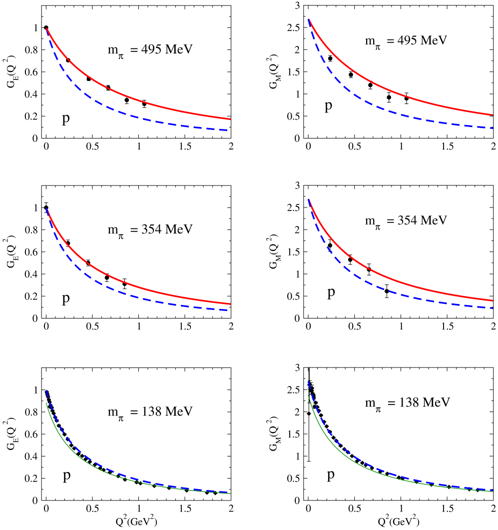
- Octet baryon: include phenomenological $SU(6)$ meson cloud 

- Model extended to nuclear medium $\oplus$ Quark Meson Coupling model
  GR, K Tsushima and AW Thomas, JPG 40, 015102 (2013); GR, K Tsushima and MK Cheoun, Symmetry 17, 681 (2025)
  Effective masses and coupling constants: M_N^*, m_ρ^*, $g_{\pi BB'}^*$ ... ($*$: in-medium)

CSQM: lattice QCD regime – proton/octet baryon

- Adjust parameters of ψ_B for octet baryon G_α^B ——— (bare parameters determined without MC contamination)
- Extrapolate result for the physical case G_α^B - - - -
- Adjust MC contributions $G_\alpha = Z_B \left[G_\alpha^B + G_\alpha^{\rm MC} \right]$ Nucleon EMFF $\oplus$ magnetic moments

  ψ_B breaks $SU(3)$



Dense nuclear matter

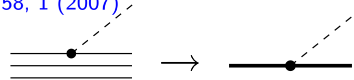
GR, K Tsushima, AW Thomas JPG 40, 015102 (2013)
GR, JPBC Melo, K Tsushima PRD 100, 014030 (2019)

GR, K Tsushima, MK Cheoun PRD 111, 013002 (2025)

Quark-Meson-Coupling model

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

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



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

Extension of calculations for higher densities

Treiman-Golberger relation

$$\frac{g^*_{\pi NN}}{g_{\pi NN}} \simeq \frac{M^*_N}{M_N}\frac{g^*_A}{g_A}\frac{f_\pi}{f^*_\pi}$$

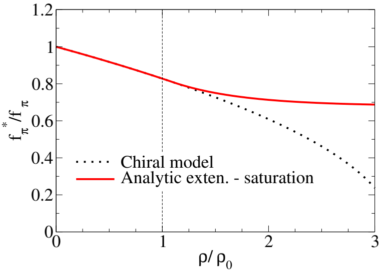
Sensitive to parametrization of $\frac{f^*_\pi}{f_\pi}$

Original calculation (valid for $\rho \leq \rho_0$)

χPT M Kirchbach and A Wirzba, NPA 616, 648 (1997)

New calculation: smooth extension

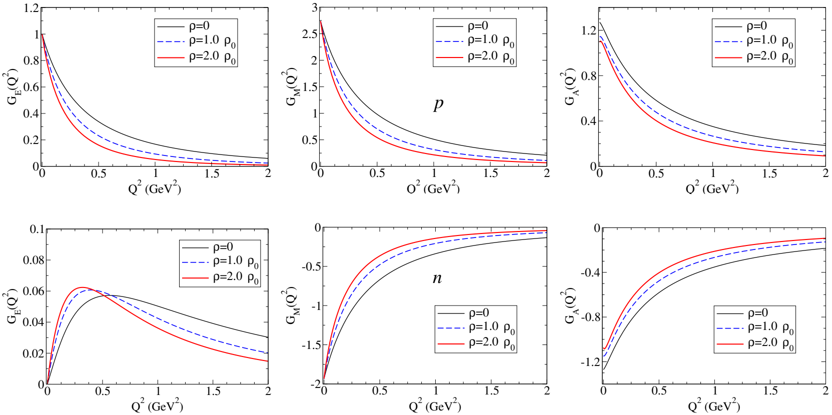
saturation in f^*_π, ...



In medium:

hadron masses M^*_N, M^*_B, m^*_ρ, ... coupling constants: $g^*_{\pi NN}$, $g^*_{\pi BB}$

Proton and Neutron Form Factors



PRD 111, 013002 (2025); **Include extension to $\rho > \rho_0$**

G_ℓ **reduced in medium (except for G^*_{En}); Effect increases with** ρ

Applications: Study of weak interactions with NC (neutral currents) and CC (charged currents)

M.K. Cheoun, K.S. Choi, S. Kim, K. Saito, T. Kajino, K. Tsushima and T. Maruyama, PRC 87, 065502 (2013)

we calculated differential cross sections of the neutrino (antineutrino) reactions on the nucleon via NC as follows [31,32]:

$$\left(\frac{d\sigma}{dQ^2}\right)^{NC}_{\nu(\bar{\nu})} = \frac{G_F^2}{2\pi}\left[\frac{1}{2}y^2(G_M)^2 + \left(1 - y - \frac{M}{2E_\nu}y\right)\frac{(G_E)^2 + \frac{E_\nu}{2M}y(G_M)^2}{1 + \frac{E_\nu}{2M}y} + \left(\frac{1}{2}y^2 + 1 - y + \frac{M}{2E_\nu}y\right)(G_A)^2 \mp 2y\left(1 - \frac{1}{2}y\right)G_M G_A\right],$$

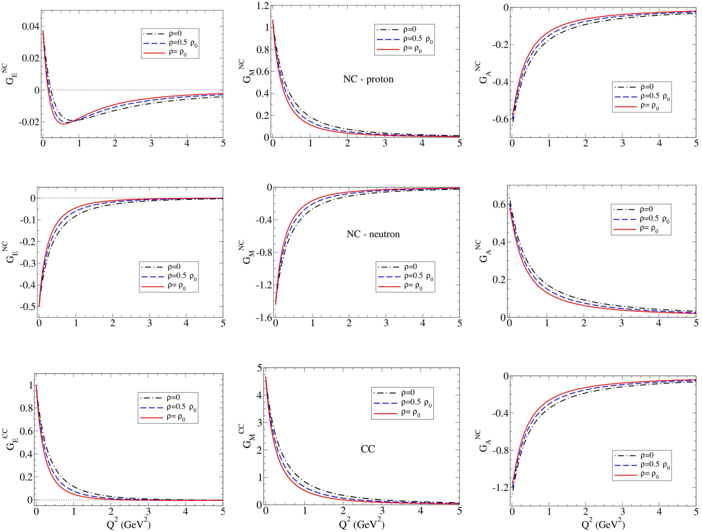
$$\left(\frac{d\sigma}{dQ^2}\right)^{CC}_{\nu(\bar{\nu})} = \left(\frac{d\sigma}{dQ^2}\right)^{NC}_{\nu(\bar{\nu})} (G_E \to G_E^{CC}, G_M \to G_M^{CC}, G_A \to G_A^{CC}), \tag{6}$$

with

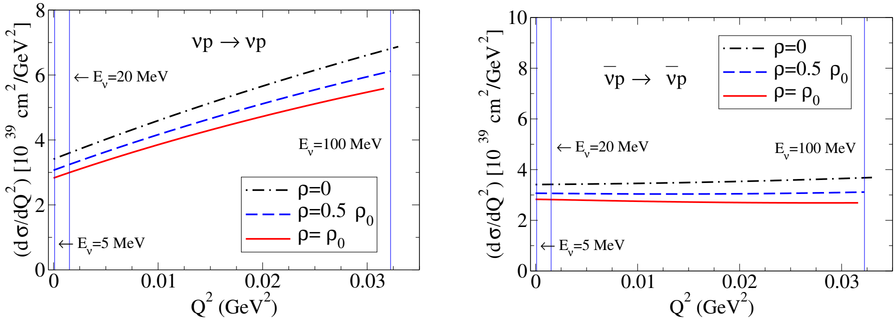
$$G_E^{CC} = G_E^p(Q^2) - G_E^n(Q^2), \quad G_M^{CC} = G_M^p(Q^2) - G_M^n(Q^2). \tag{7}$$

Include EMFF G_E, G_M and Axial FF G_A (mixture of p and n), $y = \frac{Q^2}{2ME_\nu}$

Form factors NC and CC transitions



Neutrino-nucleon cross sections in medium



E_ν determine range of Q^2: $0 \le Q^2 \le \frac{4E_\nu^2}{1+2\frac{E_\nu}{M}}$

Example with $E_\nu = 100$ MeV

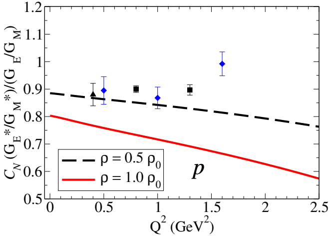
Cross sections **reduced** in nuclear medium (quenched)

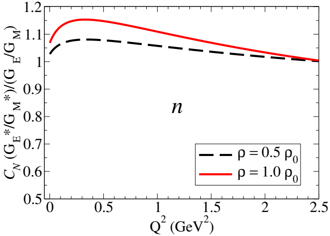
Cross section νp **dominate** over cross section $\bar{\nu} p$

Similar trend for $\nu n/\bar{\nu} n$ and $\nu n \to e^- p/\bar{\nu} p \to e^+ n$ cross sections

Octet baryon EM FF – double ratios $(G^*_E/G^*_M)/(G_E/G_E)$

We can measure G_E/G_M in vacuum and in medium (^{4}He)



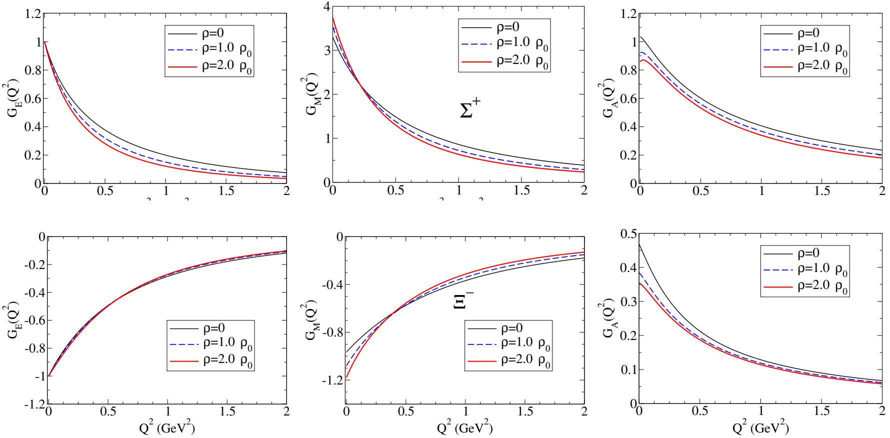


Proton: G_E/G_M is suppressed in medium, Data from JLab and MAMI

Dieterich, PLB 500 (2001); Strauch, EPJA 19 S1 (2004); Paolone, PRL 105 (2010)

Neutron: G_E/G_M enhanced in medium (prediction)

Hyperon Form Factors in medium



Σ^+, Ξ^- form factors: G_A, G_E, G_M reduced; G_M enhanced at low Q^2

Nucleons bound to nuclei

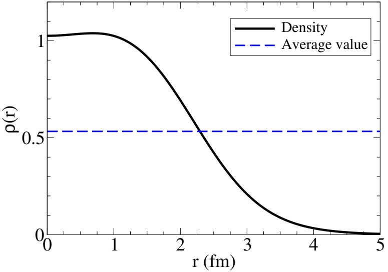
GR, K Tsushima and MK Cheoun, Symmetry 17, 681 (2025)

... in progress

Form factors in finite nucleus – average density †

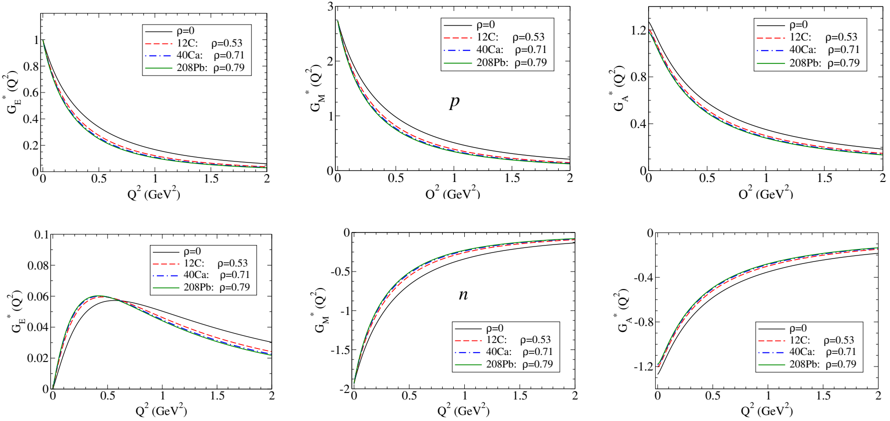
Average density $\langle\rho\rangle$ using $\rho(r)$

Estimate of G_E, G_M and G_A for bound nucleons



Nucleus	ρ/ρ_0
12C	0.533
16O	0.612
40Ca	0.711
90Zr	0.767
97Au	0.783
208Pb	0.786

Form factors in finite nucleus ($N = p, n$) average density



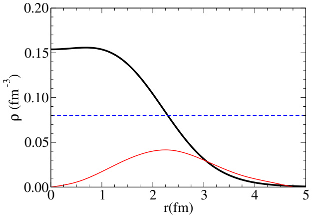
Proton/neutron form factors **suppressed** in nucleus (except for G_{En})

Taking into account nucleus finite size

Integration on the density:

$$\overline{G_\ell^*}(Q^2) = \frac{1}{A}\int_0^\infty G_\ell^*\left(Q^2, \rho(r)\right)[\rho(r) r^2] dr$$
$$\simeq \sum_i g(r_i)\, G_\ell^*\left(Q^2, \bar{\rho}_i\right) \Delta r_i$$

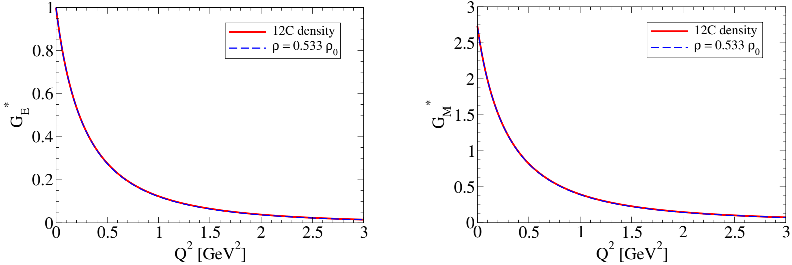
$$g(r) \equiv \frac{r^2 \rho(r)}{A}$$



Compare results with the average density calculations

Example ^{12}C

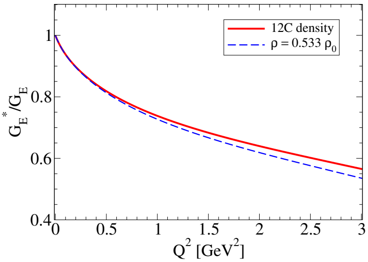
Results: ^{12}C electric and magnetic FF

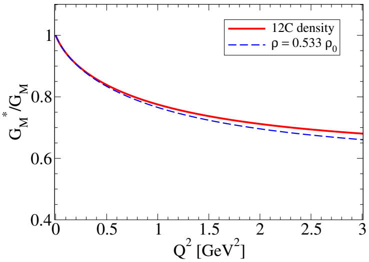


Calculation with $\rho(r)$ — and average density – – –

Difference of results **not percetible** in linear scale

Results: ^{12}C electric and magnetic FF (2)



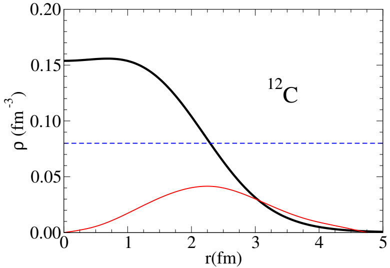


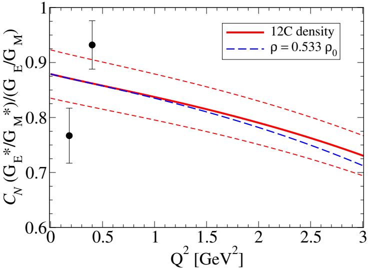
Normalize using form factors in the vacuum (1–5%)

ρ effect: softer suppression; Surface effects visible for large Q^2

Average density: very good approximation at low-Q^2.

Results: ^{12}C double ratio $(G_E^*/G_M^*)/(G_E/G_M)$





Ratio estimation: $\frac{G_E^*}{G_M^*} \propto \frac{P_z^*}{P_x^*}$ (include 5% deviation)

—— $\rho(r)$ — — — average density

Surface effects visible for large Q^2

Similar results for ^{16}O, ^{40}Ca ... work in progress

Outlook and Conclusions

- Calculations of EM and Axial form factors in-medium
  are important to study interactions in **dense nuclear matter**
- Electromagnetic and Axial form factors are modified
  in nuclear medium (quenched or enhanced) and in nucleus
  Effects increase with density
  Milder effects for hyperons with more strange quarks
- νN and $\bar{\nu} N$ cross sections are in general **reduced** in medium
- **In progress:**
  Extension of calculations to higher densities (up to $\rho = 3\rho_0$)
  Estimate impact of **finite size of nucleus** on EM and Axial FF
  Small effect at low-Q^2

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Thank you

More questions: gilberto.ramalho2013@gmail.com

Selected bibliography

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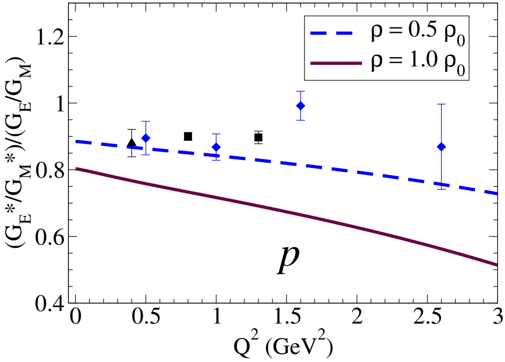
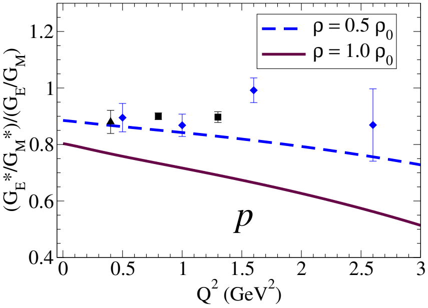
Extra slides

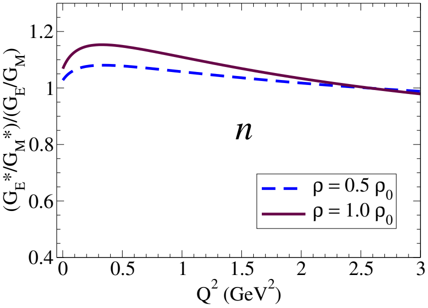
Medium: proton G_E^*/G_M^* **double ratio** (DR) [Extra]



- 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) $^4\text{He}(\vec{e}, e'\vec{p})^3\text{H}$ JLab, MAMI

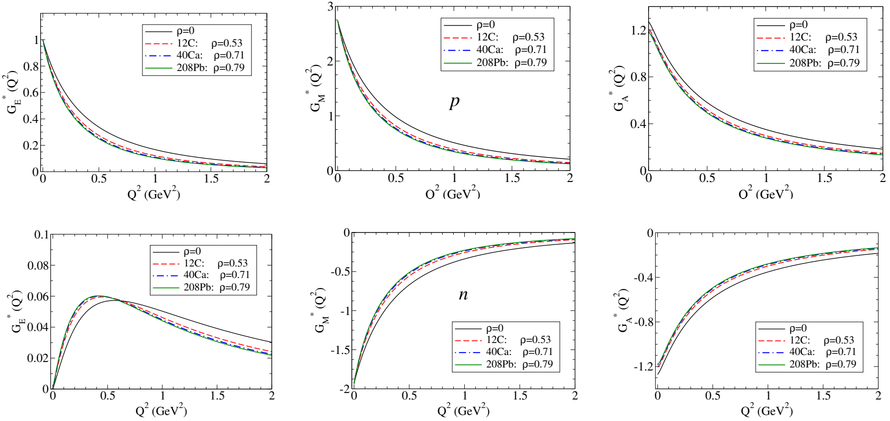
Results: Nucleon EMFF in medium G_E/G_M





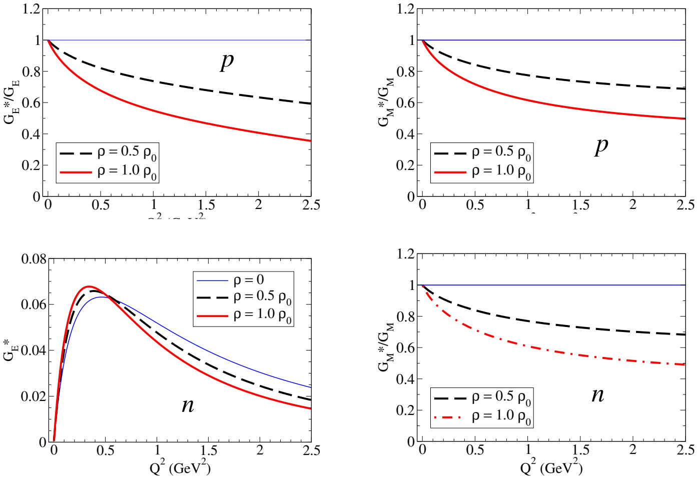
Proton: G_E/G_M suppressed in-medium; **Neutron:** G_E/G_M enhanced in-medium

Form factors in finite nucleus ($N = p, n$)



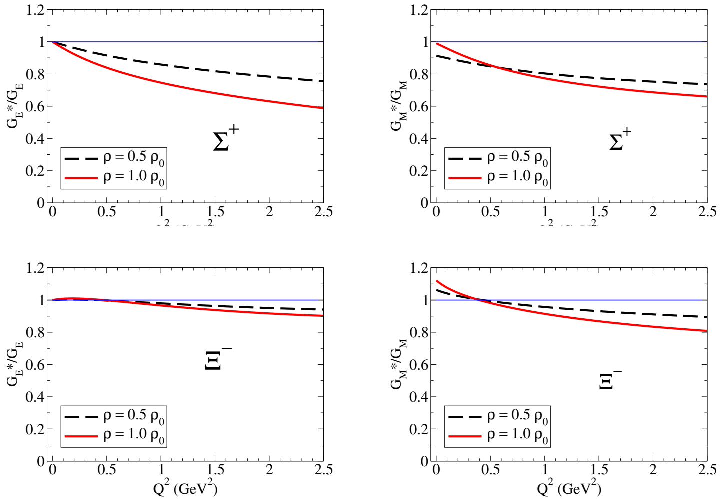
Proton/neutron form factors **suppresed** in nucleus (except for G_{En})

Octet baryon EM form factors



- **Proton:** G_E, G_M suppressed in medium (quenched effect)
- **Neutron:** G_E small effect; $\frac{G_E^*}{G_E} \propto \frac{r_{En}^{*2}}{r_{En}^2}$ enhancement; G_M suppress.

Hyperon EM form factors



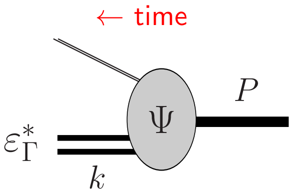
G_E: quenched (softer than p); G_M: low Q^2: enhanced; large Q^2: suppressed

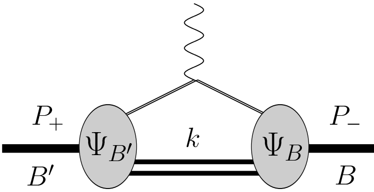
Ξ^-: **Milder effects** (softer medium effects for strange quarks)

Formalism

Covariant Spectator Quark Model (CSQM)

- **Covariant Spectator Theory: BARYONS**
  Active quark off-shell; 2 spectator on-shell quarks
  Stadler, Gross and Frank PRC 56, 2396 (1998); Gross and Agbakpe PRC 73, 015203 (2006)
- Integration into quark pair d.o.f.
  Reduction of system to quark-diquark system
  diquark on-shell Gross, GR and Peña PRC 77, 015202 (2008); PRD 85, 093005 (2012)
- Wave functions: relativistic generalization of $SU_S(2) \otimes SU_F(3) \otimes O(3)$ symmetries
- Radial w.f. ψ_B **determined phenomenologically** (Physical or Lattice QCD data)
- Electromagnetic interaction; relativistic impulse approximation **diquark on-shell**
  $J^\mu = 3 \sum_\Gamma \int_k \overline{\Psi}_{B'}(P_+, k) j_q^\mu \Psi_B(P_-, k)$
- Constituent quark current $j_q^\mu(q)$ $(q = u, d, s)$
  Simulate quark dressing (gluons and $q\bar{q}$ effects)





CSQM Quark Current $\oplus$ Transition current

- **Quark current:**

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

$$j_i(q) = f_{i+}\lambda_0 + f_{i-}\lambda_3 + f_{i0}\lambda_s$$

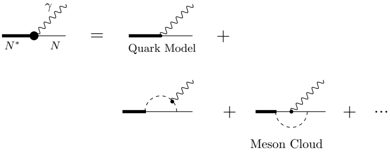
λ_l Gell-Mann matrices; $\lambda_s = \mathrm{diag}(0, 0, -2)$ [strange quark]

- Functions $f_{i\ell}$ ($\ell = 0, \pm$) determined by the nucleon and decuplet lattice QCD data
  F Gross, GR and MT Peña PRC 77, 015202 (2008);
  GR, K Tsushima, F Gross, PRD 80, 033004 (2009)
- $f_{i\ell}(q^2)$ parametrized using VMD
  Vector Meson Dominance
  Include terms in m_ω, m_ρ and m_ϕ
- Quark current can be generalized to
  - Lattice QCD regime (bare prop.)
  - Nuclear medium
  - Timelike region (decay width Γ_v)

    $m_v \to m_v - i\Gamma_v(q)$

GR and MT Peña, PRD 80, 013008 (2009);
GR, K Tsushima and AW Thomas, JPG 40, 015102 (2013)

Transition current $\leftarrow$ time



$$J^\mu = J^\mu_{\mathrm{Bare}} + J^\mu_{\mathrm{MC}}$$

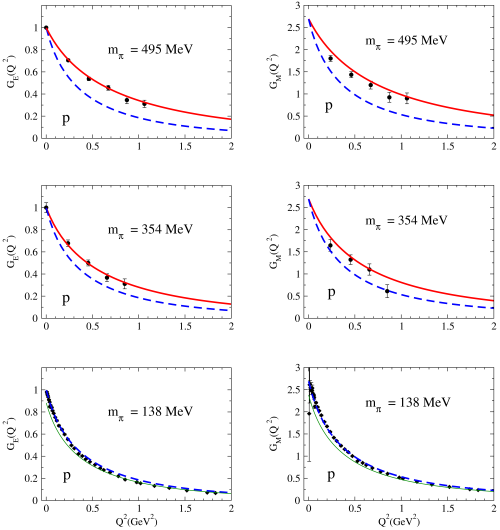
Total current =
[Bare (Valence Quark) current]
+ [Meson Cloud current]

- **Bare current:** quark model
  Use calibration of quark current and radial w.f.
- **Meson cloud current:**
  Educated phenomenological parametrizations

$$G_\alpha(q^2) = G_\alpha^{\mathrm{Bare}}(q^2) + G_\alpha^{\mathrm{MC}}(q^2)$$

CSQM: lattice QCD regime

- Adjust parameters of ψ_B for octet baryon G_α^B —— (bare parameters determined without MC contamination)
- Extrapolate result for the physical case G_α^B - - - -
- Adjust MC contributions $G_\alpha = Z_B \left[G_\alpha^B + G_\alpha^{\rm MC} \right]$ Nucleon EMFF $\oplus$ magnetic moments



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

S-state approximation (quark-diquark) $\quad P$: 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 wave functions: $\psi_B[(P-k)^2]$
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)

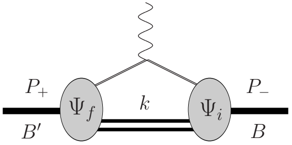
CSQM: Transition current

$\gamma^* B \to B'$ 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

- $j_q^\mu = j_1 \gamma^\mu + j_2 \frac{i\sigma^{\mu\nu} q_\nu}{2M_N}$, Quark form factors: $j_i = \frac{1}{2} f_{i+} \lambda_0 + \frac{1}{6} f_{i-} \lambda_3 + \frac{1}{2} f_{i0} \lambda_s$

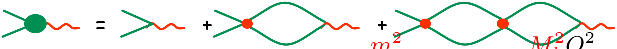
  [parametrize gluon and $q\bar{q}$ dressing of quarks] λ_l: Gell-Mann matrices

- VMD form: $f_{i\ell}$ combination of VM factor s $\frac{m_v^2}{m_v^2 + Q^2}$, $\frac{M_h^2}{M_h^2 + Q^2}$

  ($m_v = m_\rho$, m_ϕ, $M_h \sim 2M_N$ effective VM)

CSQM: Photon-Quark coupling

- $j_q^\mu = j_1 \gamma^\mu + j_2 \frac{i\sigma^{\mu\nu} q_\nu}{2M_N}$, 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: PRD 80, 033004 (2009)



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

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

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

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

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 (decuplet baryon)

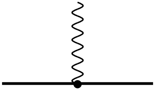
Meson Cloud

Octet baryon: total electromagnetic current

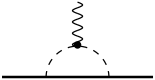
$$J^\mu = J^\mu_{0B} + J^\mu_{\pi B} + J^\mu_{\gamma B}$$

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

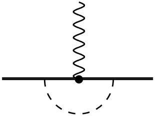
$$J^\mu_{0B} = Z_B \left[\tilde{e}_B \gamma^\mu + \tilde{\kappa}_B \frac{i\sigma^{\mu\nu} q_\nu}{2M_B} \right]$$



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



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



$G_{\pi B}, G_{eB}$ and $G_{\kappa B}$ flavor part – known; $SU(3)$ functions $\tilde{B}_i, \tilde{C}_i, \tilde{D}_i$ – fited

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

- Fit functions of Q^2: $\tilde{B}_i, \tilde{C}_i$, $\tilde{D}_i \longrightarrow \delta G_{EB}$, 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 the model in vacuum

$$G_X(Q^2) = Z_B \left[G_X^B(Q^2) + G_X^\pi(Q^2) \right] \qquad X = E, M$$

- Calibration of model in **vacuum** by **Lattice QCD data** (radial wave functions) – bare part
- **Physical data** (N form factors, magnetic moments, baryon radii) – pion cloud part: coefficients (B_1, B_2, C_2,, D_1', D_2) $\oplus$ cutoffs Λ_1, Λ_2

$$|B\rangle = \sqrt{Z_B} \left[|qqq\rangle + |\pi B_0\rangle \right] \qquad Z_B = \frac{1}{1 + a_B B_1}$$

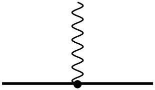
GR, Tsushima, Thomas, JPG 40, 015102 (2013); GR and K Tsushima, PRD 84, 054014 (2011)

Octet baryon: total electromagnetic current (pion)

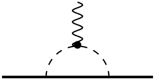
$$J^\mu = J^\mu_{0B} + J^\mu_{\pi B} + J^\mu_{\gamma B}$$

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

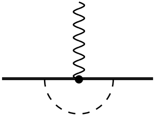
$$J^\mu_{0B} = Z_B \left[\tilde{e}_B \gamma^\mu + \tilde{\kappa}_B \frac{i\sigma^{\mu\nu} q_\nu}{2M_B} \right]$$



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



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



$G_{\pi B}, G_{eB}$ and $G_{\kappa B}$ flavor part – known; $SU(3)$ functions $\tilde{B}_i, \tilde{C}_i, \tilde{D}_i$ – fited

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

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 $\tilde{B}_1(0) = \tilde{C}_1(0) \equiv B_1$

Pion cloud: Normalization factor

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

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

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

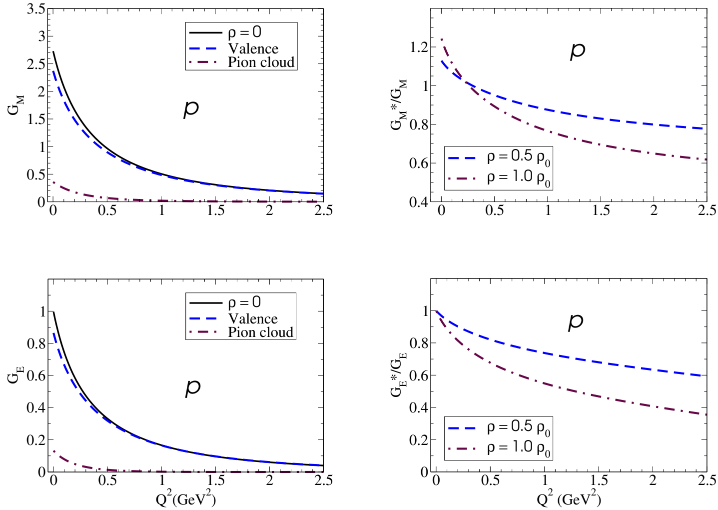
Then $G_{Ep}(0) = 1 = Z_N[1 + 3\beta_N B_1]$:

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

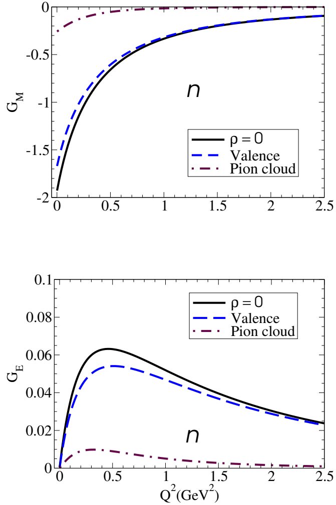
Similar for Z_Λ, Z_Σ and Z_Ξ

Results: Nuclear Medium

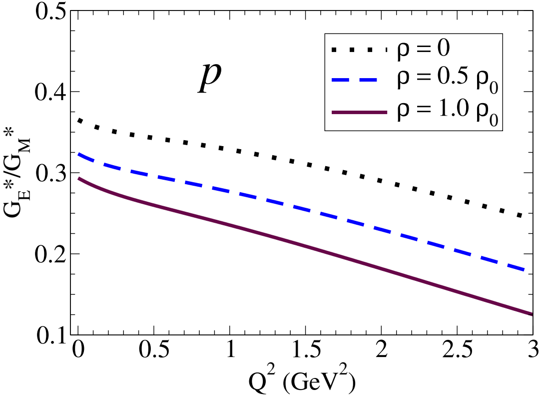
Results: Proton form factors in medium †



Results: Neutron form factors in medium †

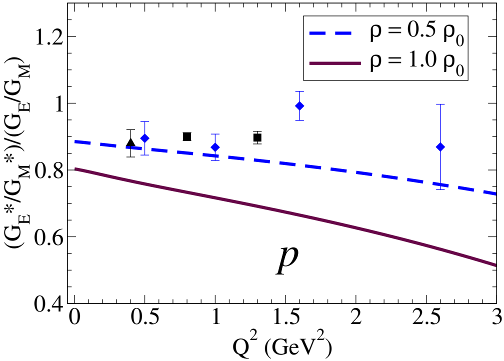


Medium: proton G_E^*/G_M^* **single ratio**



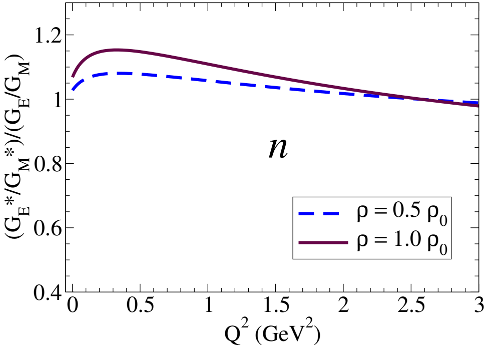
- $\frac{G_E^*(0)}{G_M^*(0)} \propto \frac{M_N^*}{M_N}$; $\quad \frac{G_E^*}{G_M^*} \simeq \frac{1}{G_M^*(0)}\left[1 - (r_{EB}^{*\,2} - r_{MB}^{*\,2})\frac{Q^2}{6}\right]$ – almost linear falloff
- G_E^*/G_M^* **suppressed** in medium; $r_{EB}^{*\,2} - r_{MB}^{*\,2}$ **enhanced** in medium (larger slop)

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



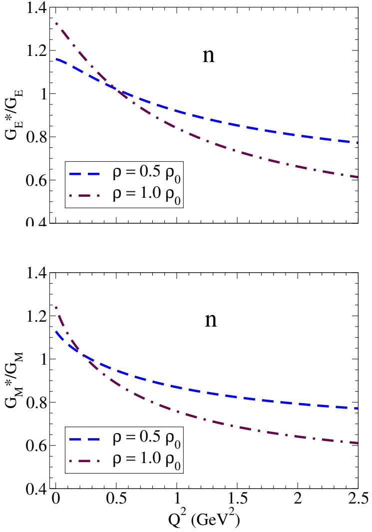
- G_E/G_M suppressed in medium (DR < 1); Larger suppression for larger densities
- Data ^{4}He: Dieterich, PLB 500 (2001); Strauch, EPJA 19 S1 (2004); Paolone, PRL 105 (2010) ^{4}He$(\vec{e}, e'\vec{p})^3$H JLab, MAMI

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) ^{4}He$(\vec{e}, e'\vec{n})^3$He
- **Enhancement** consistent with other calculations:
  Cloet, Miller, Piasetzky, Ron, PRL 103, 082301 (2009);
  Araújo, Melo, Tsushima, NPA 970, 325 (2018)

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



- $Q^2 \approx 0$:
  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