Electromagnetic form factors of baryons in nuclear medium

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Hadrons in medium - hyperons and mesons in nuclear matter
(via ZOOM)
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Plan of the talk

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

X^* represent the variable X in nuclear medium

GR, JPBC de Melo and K Tsushima, PRD 100, 014030 (2019)
GR, K Tsushima, AW Thomas, JPG 40, 015102 (2013);
GR and K Tsushima, PRD 84, 054014 (2011)

Motivation – single ratio **in vacuum**

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

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

Jefferson Lab 1999–...

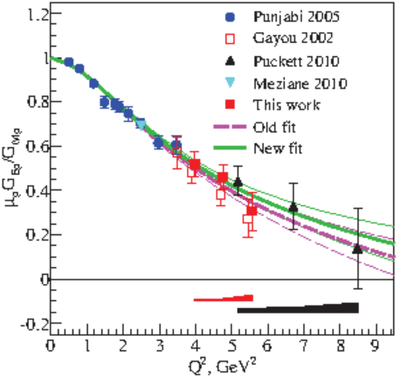
Polarization transfer method

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

P_t = parallel

P_l = longitudinal

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



Motivation – single ratio **in medium** (ρ)

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

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

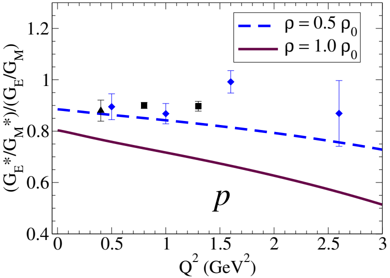
Medium: G_E^*/G_M^*

Define **Double Ratio**

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

Measures modifications in-medium

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

Motivation & goals

What about other baryons ?

- Octet baryon:
  neutron, $\Sigma^{\pm}$, Λ, Σ^0 (neutral), Ξ^-, Ξ^0 (two strange quarks)
- Verify if the ratio G_E^*/G_M^* is enhanced, suppressed or ...

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

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
- **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)

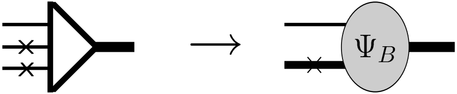
In nuclear medium: GR, K Tsushima, AW Thomas JPG **40**, 015102 (2013)

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

- **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	$\lvert M_S\rangle$	$\lvert M_A\rangle$
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

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

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

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

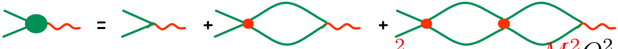
$$\psi_\Sigma(P,k) = \frac{N_\Sigma}{m_D(\beta_1 + \chi_\Sigma)(\beta_3 + \chi_\Sigma)}$$

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

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: 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)

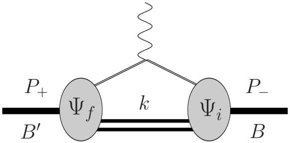
CSQM: Transition current

$\gamma^* B \to B'$ 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

- **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);

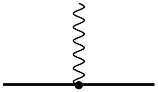
GR, K Tsushima, AW Thomas, JPG 40, 015102 (2013); In medium: $M_h \to M_h^*$ (in medium masses)

Pion cloud: total electromagnetic current †

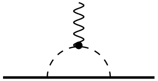
$$J^\mu = J^\mu_{0B} + J^\mu_{\pi B} + J^\mu_{\gamma B}$$

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

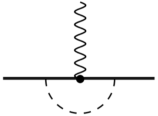
$$J^\mu_{0B} = Z_B \left[\tilde{e}_B \gamma^\mu + \tilde{\kappa}_B \frac{i\sigma^{\mu\nu} q_\nu}{2M_B} \right]$$



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



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



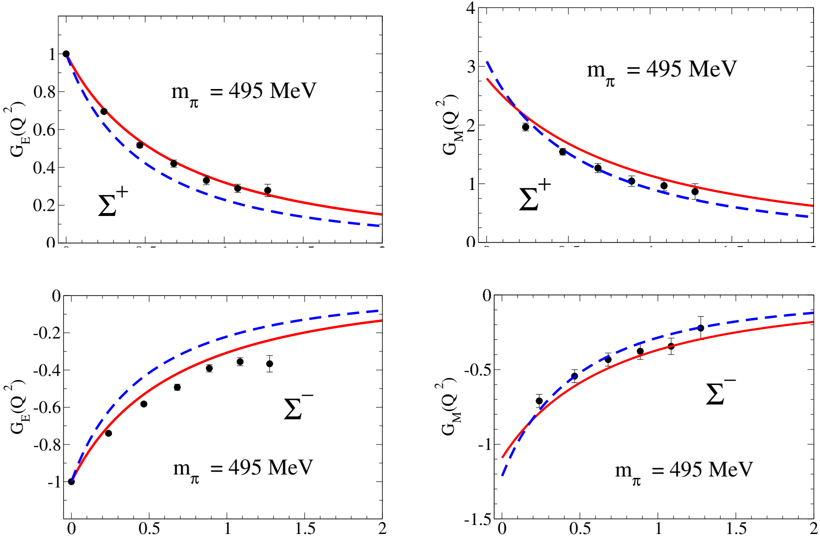
$G_{\pi B}, G_{eB}$ and $G_{\kappa B}$ flavor part – known; $SU(3)$ functions $\tilde{B}_i, \tilde{C}_i, \tilde{D}_i$ – fited
GR and K Tsushima, PRD 84, 054014 (2011)

Calibration of model in vacuum

Information included in the fit

- **Lattice QCD data** – bare part $\tilde{e}_B, \tilde{\kappa}_B$ (radial wf)
  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 $r^2_{E\Sigma^-}$
- **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

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



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^*]

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

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

Results in medium:

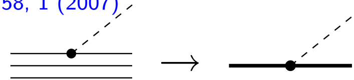
Normalization of G_M^* by Nucleon magnetic moment **in vacuum**: $G^*_{MB} \to \frac{M_N}{M_B^*} G^*_{MB}$

$$[\mu_B = G^*_{MB}(0) \frac{e}{2M_B^*} \equiv \frac{M_N}{M_B^*} G^*_{MB}(0) \frac{e}{2M_N} \;]$$

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

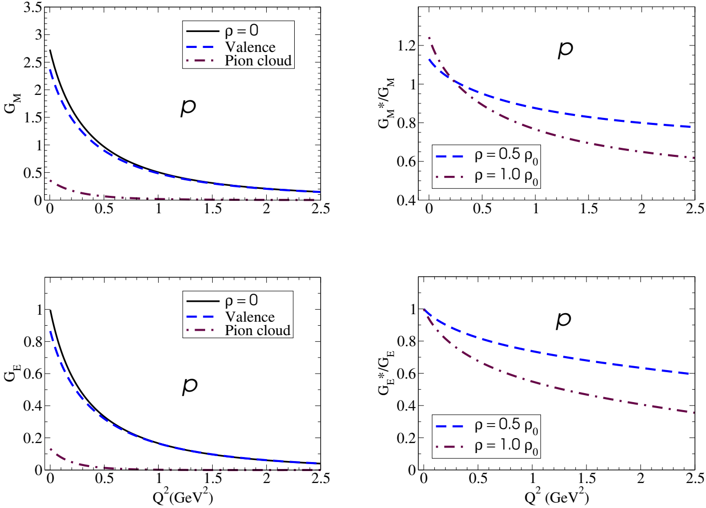
Goldberger-Treimann relation: $\frac{g^*_{\pi BB}}{g_{\pi BB}} \simeq \left(\frac{f_\pi}{f^*_\pi}\right)\left(\frac{g_A^{N*}}{g_A^N}\right)\left(\frac{M_B^*}{M_B}\right)$

Goldberger and Treiman, PRC 110, 1178 (1958)

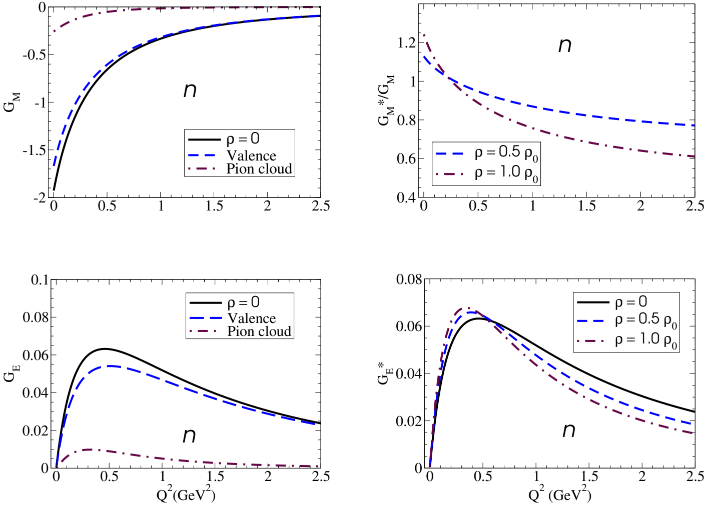
	$\rho = 0$	$\rho = 0.5\rho_0$	$\rho = \rho_0$
M_N	939.0	831.3	754.5
M_Λ	1116.0	1043.9	992.7
M_Σ	1192.0	1121.4	1070.4
M_Ξ	1318.0	1282.2	1256.7
m_ρ	779.0	706.1	653.7
m_ϕ	1019.5	1019.1	1018.9
m_π	138.0	138.0	138.0

	$\rho = 0$	$\rho = 0.5\rho_0$	$\rho = \rho_0$
$g^*_{\pi NN}/g_{\pi NN}$	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

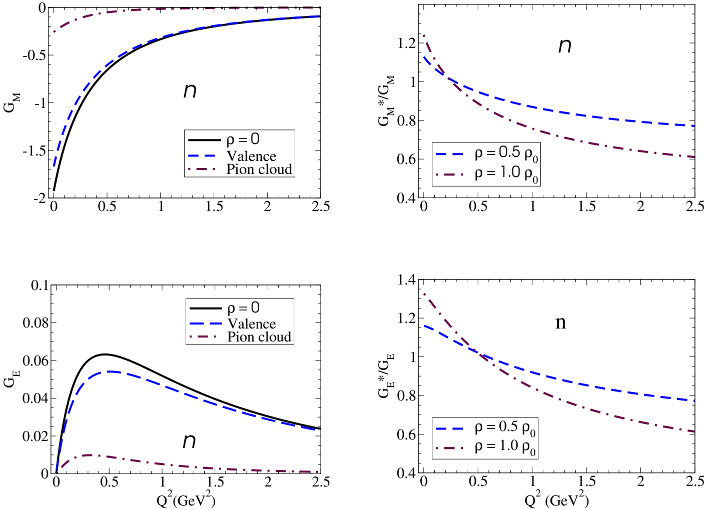
Results: Proton form factors in medium †



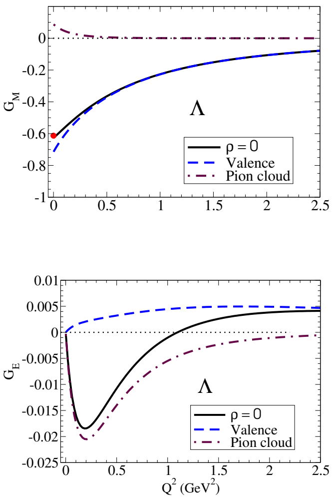
Results: Neutron form factors in medium †



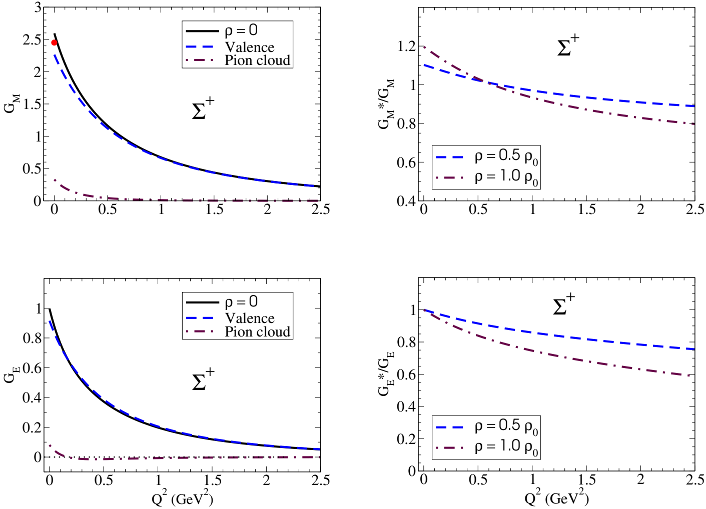
Results: Neutron form factors in medium ††



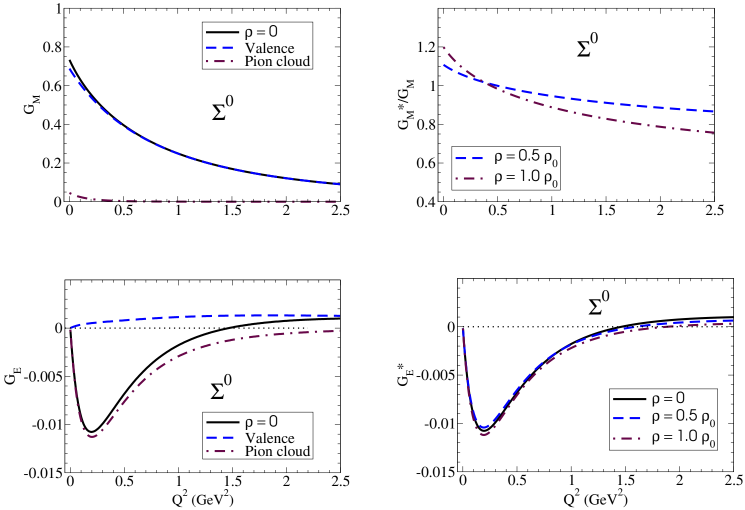
Results: Λ form factors in medium $- \cdot -$ $G_E \simeq G_E^\pi$ †



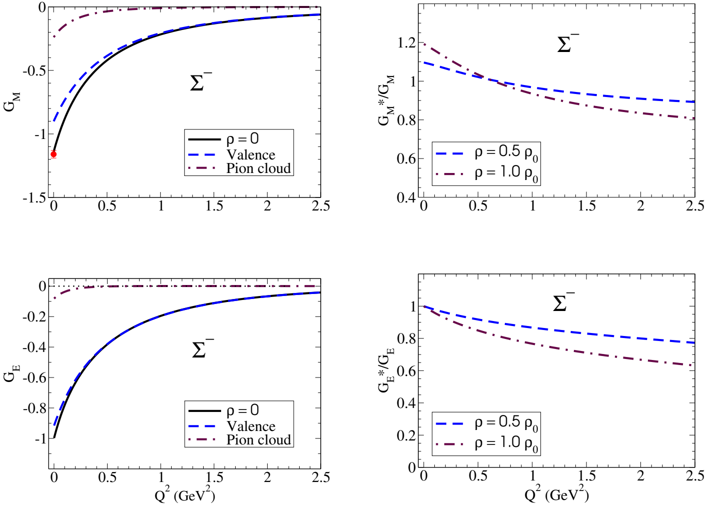
Results: Σ^+ form factors in medium †



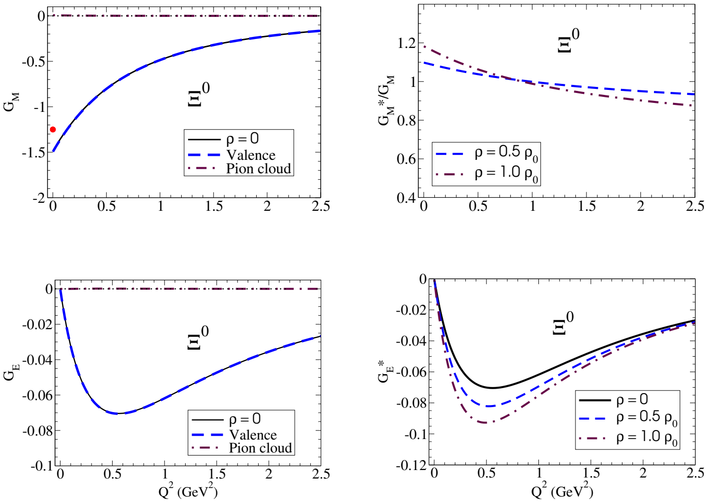
Results: Σ^0 form factors in medium $- \cdot -$ $G_E \simeq G_E^\pi$ †



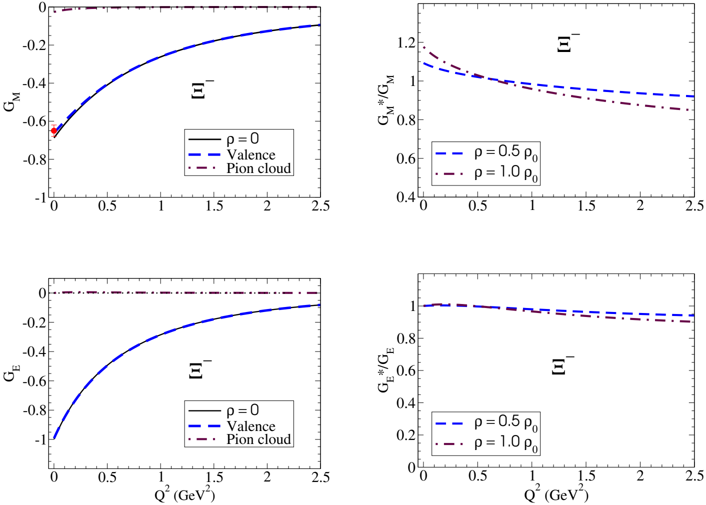
Results: Σ^- form factors in medium †



Results: Ξ^0 form factors in medium †



Results: Ξ^- form factors in medium †

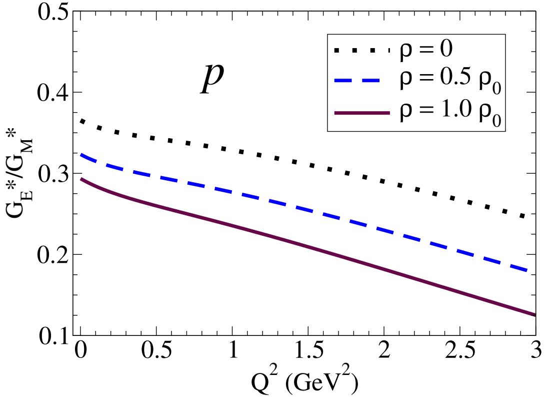


Results in medium – summary

- 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)

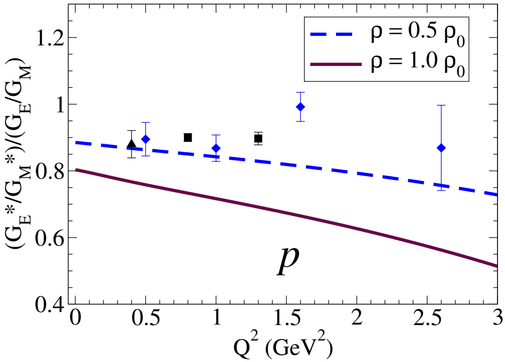
Next: results for the **Double Ratios**

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



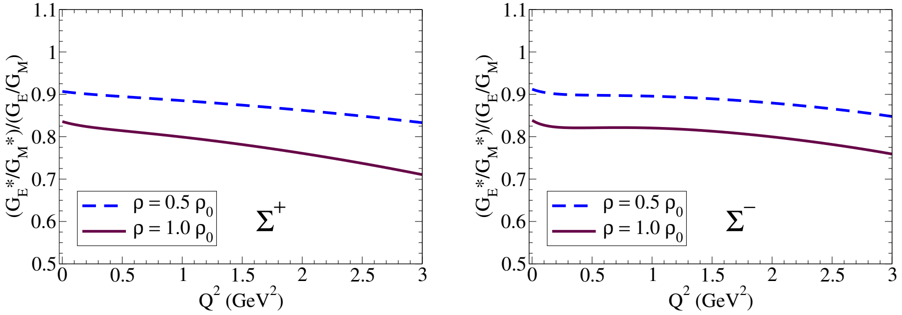
- $\frac{G_E^*}{G_M^*} \simeq \frac{1}{G_M^*(0)} \left[1 - ({r^*_{EB}}^2 - {r^*_{MB}}^2) \frac{Q^2}{6} \right]$ – almost linear falloff; $\frac{G_E^*}{G_M^*}(0) \to \frac{1}{G_M^*(0)}$
- ${r^*_{EB}}^2 - {r^*_{MB}}^2$ **enhanced** in medium; G_E^*/G_M^* **suppressed** in medium

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)

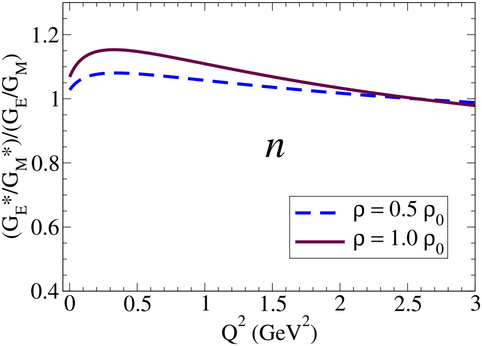
Medium: $\Sigma^{\pm}$ – G_E^*/G_M^* double ratio



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

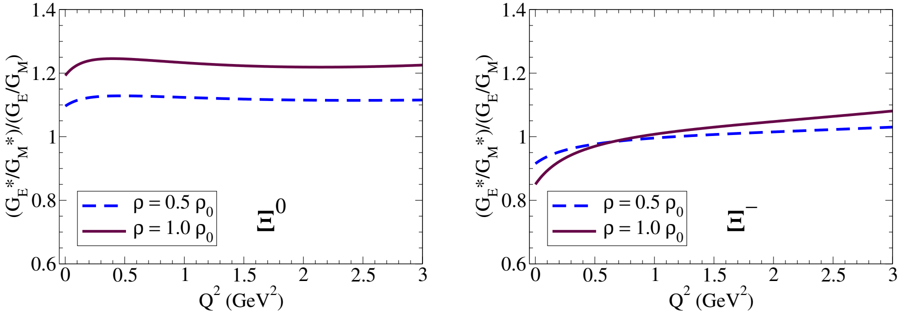
GR, JPBC de Melo, K Tsushima, PRD D100, 014030 (2019)

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);
  Araújo, 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)

Conclusions

- Proposal of tool to study the e.m. structure of **baryon** in medium (heavy-ion collisions, neutron stars, compact stars, ...)
  Method can be extended to higher densities ...
  Quark Model $\oplus$ Pion Cloud

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- Proposal of tool to study the e.m. structure of **baryon** in medium (heavy-ion collisions, neutron stars, compact stars, ...)
  Method can be extended to higher densities ...
  Quark Model $\oplus$ Pion Cloud
- Prediction to the **Octet baryon double ratios** $(G_E^*/G_M^*)/(G_E/G_M)$
  - proton, Σ^+, Σ^-: reduced
  - neutron: enhanced
  - Ξ^0, Ξ^-: weak Q^2 deppendence
  - **Not shown**: Λ, Σ^0: reduced at low Q^2; enhanced at large Q^2

Conclusions

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  Method can be extended to higher densities ...
  Quark Model $\oplus$ Pion Cloud
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- Measurements of neutron double ratio expected in a **near future:** neutron recoil polarization in the $^4\text{He}(\vec{e}, e'\vec{n})^3\text{He}$ reaction (JLab)
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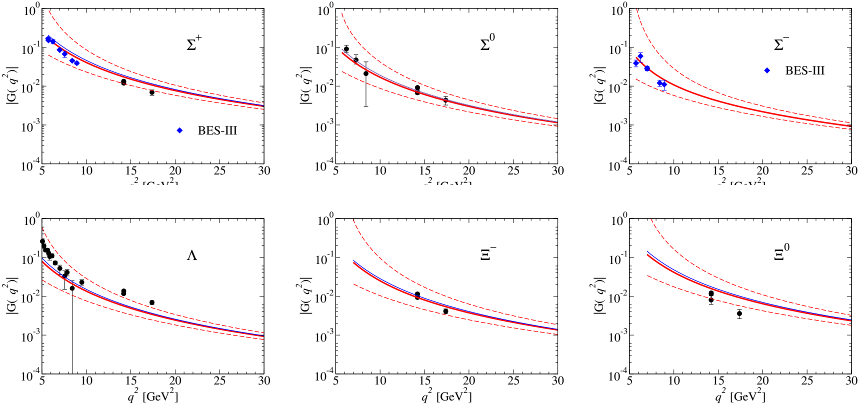
Hyperon elastic form factors **at large** q^2



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

Data from CLEO, BaBar, BES-III

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Thank you very much

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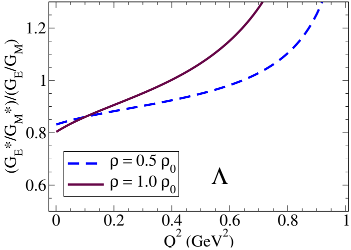
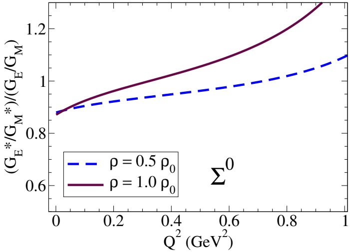
Backup slides

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 $(G_E \to 0)$