Rho Meson Propreties in Medium with the Light-Front Approach

Light-Cone - 5-8/09/2016 - Lisboa - Portugal

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- **After Integrate in k^-: Bethe-Salpeter Amplitude (Wave Function)**
- **LF Lorentz Invariant Hamiltonian:** $P^2 = P^+ P^- - P_\perp^2$

Light-Front Coordinates

Four-Vector $\Longrightarrow$ $x^\mu = (x^0, x^1, x^2, x^3) = (x^+, x^-, x_\perp)$

$x^+ = t + z$ $\quad x^+ = x^0 + x^3$ $\Longrightarrow$ **Time**

$x^- = t - z$ $\quad x^- = x^0 - x^3$ $\Longrightarrow$ **Position**

Metric Tensor and Scalar product

$$x \cdot y = x^\mu y_\mu = x^+ y_+ + x^- y_- + x^1 y_1 + x^2 y_2 = \frac{x^+ y^- + x^- y^+}{2} - \vec{x}_\perp \vec{y}_\perp$$

$p^+ = p^0 + p^3$, $p^- = p^0 - p^3$, $p^\perp = (p^1, p^2)$

Dirac Matrix and Electromagnetic Current

$\gamma^+ = \gamma^0 + \gamma^3 \implies$ **Electr. Current** $J^+ = J^0 + J^3$
$\gamma^- = \gamma^0 - \gamma^3 \implies$ **Electr. Current** $J^- = J^0 - J^3$
$\gamma^\perp = (\gamma^1, \gamma^2) \implies$ **Electr. Current** $J^\perp = (J^1, J^2)$

$$p^\mu x_\mu = \frac{p^+x^- + p^-x^+}{2} - \vec{p}_\perp \vec{x}_\perp$$

$$x^+, x^-, \vec{x_\perp} \implies p^+, p^-, \vec{p}_\perp$$

$p^- \implies$ **Light-Front Energy**

$$p^2 = p^+ p^- - (\vec{p}_\perp)^2 \implies \quad p^- = \frac{(\vec{p}_\perp)^2 + m^2}{p^+}$$

On-shell

Bosons $\implies \quad S_F(p) = \frac{1}{p^2 - m^2 + \imath\epsilon}$

Fermions $\implies \quad S_F(p) = \frac{\not{p} + m}{p^2 - m^2 + \imath\epsilon} + \frac{\gamma^+}{2p^+}$

Review Papers:

- **Phys. Rept. 301, (1998) 299-486, Brodsky, Pauli and Pinsky**
- **A. Harindranath, Pramana, Journal of Indian Academy of Sciences Physics Vol.55, Nos 1 & 2, (2000) 241.**
- **An Introduction to Light-Front Dynamics for Pedestrians Avaroth Harindranath**

Light-Front book organizers: James Vary and Frank Wolz,(1997)

General Electromagnetic Current: Spin-1

$$J^{\mu}_{\alpha\beta} = [F_1(q^2) g_{\alpha\beta} - F_2(q^2)\frac{q_\alpha q_\beta}{2m_\rho^2}] p^\mu - F_3(q^2)(q_\alpha g^\mu_\beta - q_\beta g^\mu_\alpha) \; ,$$

- Polarization Vectors

$\epsilon^\mu_x = (-\sqrt{\eta}, \sqrt{1+\eta}, 0, 0)$, $\epsilon^\mu_y = (0,0,1,0)$, $\epsilon^\mu_z = (0,0,0,1)$,
$\epsilon'^\mu_x = (\sqrt{\eta}, \sqrt{1+\eta}, 0, 0)$, $\epsilon'^\mu_y = \epsilon_y$, $\epsilon'^\mu_z = \epsilon_z$,
where $\eta = q^2/4m_\rho^2$

- Breit Frame:

$p^\mu_i = (p^0, -q_x/2, 0, 0)$ (Initial) where $p^0 = m_\rho \sqrt{1+\eta}$.
$p^\mu_f = (p^0, q_x/2, 0, 0)$ (Final)

$$J^+_{ji} = \imath \int \frac{d^4k}{(2\pi)^4} \frac{Tr[\epsilon_j^{'\beta}\Gamma_\beta(k,k-p_f)(\not{k}-\not{p}_f+m)}{((k-p_i)^2-m^2+\imath\epsilon)(k^2-m^2+\imath\epsilon)}$$
$$\times \frac{\gamma^+(\not{k}-\not{p}_i+m)\epsilon_i^\alpha\Gamma_\alpha(k,k-p_i)(\not{k}+m)]\Lambda(k,p_f)\Lambda(k,p_i)}{((k-p_f)^2-m^2+\imath\epsilon}$$

- Regulator Function

$$\Lambda(k,p_{i(f)}) = N/((p-k)^2-m_R+\imath\epsilon)^2$$

- ρ-Meson Vertex

$$\Gamma^\mu(k,p) = \gamma^\mu - \frac{m_\rho}{2}\frac{2k^\mu - p^\mu}{p.k + m_\rho m - \imath\epsilon}$$

- Mass Squared $\left(x = \frac{k^+}{P^+} \implies 0 < x < 1\right)$

$$M^2(m_a, m_b) = \frac{k_\perp^2 + m_a^2}{x} + \frac{(\vec{p} - \vec{k})_\perp^2 + m_b^2}{1-x} - p_\perp^2$$

- Free Mass $M_0^2(m, m)$ and Function $M_R^2(m, m_R)$

The function M_R^2 is given by

$$M_R^2 = \frac{k_\perp^2 + m^2}{x} + \frac{(\vec{p} - \vec{k})_\perp^2 + m_R^2}{1-x} - p_\perp^2$$

$$M_0^2 = \frac{k_\perp^2 + m^2}{x} + \frac{(\vec{p} - \vec{k})_\perp^2 + m^2}{1-x} - p_\perp^2$$

- Wave Function

$$\Phi_i(x, \vec{k}_\perp) = \frac{N^2}{(1-x)^2(m_\rho^2 - M_0^2)(m_\rho^2 - M_R^2)^2}\vec{\epsilon}_i.[\vec{\gamma} - \frac{\vec{k}}{\frac{M_0}{2} + m}]$$

Refs.

- **Phy.Rev. C55 (1997) 2043 J.P.B. C. de Melo and T. Frederico**
- **Phy.Lett. B708 (2012) 87 J.P.B. C. de Melo and T. Frederico**
- **Few.Body.Syst. 52 (2012) 403, J.P.B. C. de Melo and T. Frederico**
- **Few Body Syst. 56, (2015) 509, C. S. Mello, A. N. da Silva, J. P. B. C. de Melo and T. Frederico**
- **Few Body Syst. 56, (2015) 503, J. P. B. C. de Melo, A. N. da Silva, C. S. Mello and T. Frederico**

- Instant-Form Spin Base

$$J^{+}_{ji} = \frac{1}{2}\begin{pmatrix} J^{+}_{xx} + J^{+}_{yy} & \sqrt{2}J^{+}_{zx} & J^{+}_{yy} - J^{+}_{xx} \\ -\sqrt{2}J^{+}_{zx} & 2J^{+}_{zz} & \sqrt{2}J^{+}_{zx} \\ J^{+}_{yy} - J^{+}_{xx} & -\sqrt{2}J^{+}_{zx} & J^{+}_{xx} + J^{+}_{yy} \end{pmatrix}$$

- Light-Front

$$I^{+}_{m'm} = \begin{pmatrix} I^{+}_{11} & I^{+}_{10} & I^{+}_{1-1} \\ -I^{+}_{10} & I^{+}_{00} & I^{+}_{10} \\ I^{+}_{1-1} & -I^{+}_{10} & I^{+}_{11} \end{pmatrix}$$

$$\Delta(q^2) = (1+2\eta)I^+_{11} + I^+_{1-1} - \sqrt{8\eta}I^+_{10} - I^+_{00} = (1+\eta)(J^+_{yy} - J^+_{zz}) = 0$$

- **Angular Condition: Violation !!**

$$q_x \Longrightarrow J^+_{yy} = J^+_{zz} \begin{cases} \textit{Parity} \\ + \\ \textit{Rotations} \end{cases}$$

$$\Delta(q^2) \neq 0$$

- **Ref:**
- **Sov. J. Nucl. Phys. 39 (1984) 198**

I.Grach and L.A. Kondratyku

- **Phy. Rev. Lett. 62 (1989) 387**

L.L. Frankfurt, I.Grach, L.A. Kondratyku and M. Strikman

Prescriptions

$$\begin{cases} FFS\ (Frederico, Frankfurt, Strikman) \\ GK\ (Grach, Kondratyku) \\ CCKP\ (Coester, Chung, Keister, Polyzou) \\ BH\ (Brodsky, Hiller) \end{cases}$$ **vs** **COVARIANT**

- **Breit Frame** $\Longrightarrow P^+ = P'^+,\ P^- = P'^-,\ \vec{P'}_\perp = -\vec{P}_\perp = \vec{q}/2$
- **B.F:** $q^+ = q^0 + q^3 = 0$
- $J^+_\rho \begin{cases} 4\ \textit{Current Matrix Elements} \\ 3\ \textit{Form Factors}\quad G_0\ ,\ G_1\ \textit{and}\ G_2 \end{cases}$

Inna Grach Prescription: I^{+}_{00}

$$G_0^{GK} = \frac{1}{3}[(3-2\eta)I^{+}_{11} + 2\sqrt{2\eta}I^{+}_{10} + I^{+}_{1-1}] = \frac{1}{3}[J^{+}_{xx} + \eta J^{+}_{zz}(2-\eta)J^{+}_{yy}]$$

$$G_1^{GK} = 2[I^{+}_{11} - \frac{1}{\sqrt{2\eta}}I^{+}_{10}] = J^{+}_{yy} - J^{+}_{zz} - \frac{J^{+}_{zx}}{\sqrt{\eta}}$$

$$G_2^{GK} = \frac{2\sqrt{2}}{3}[-\eta I^{+}_{11} + \sqrt{2\eta}I^{+}_{10} - I^{+}_{1-1}] = \frac{\sqrt{2}}{3}[J^{+}_{xx} + J^{+}_{yy}(-1-\eta) + \eta J^{+}_{zz}] \; .$$

CCKP

$$G_0^{CCKP} = \frac{1}{3(1+\eta)}[(\frac{3}{2}-\eta)(I_{11}^{+}+I_{00}^{+})+5\sqrt{2\eta}I_{10}^{+}+(2\eta-\frac{1}{2})I_{1-1}^{+}]$$
$$= \frac{1}{6}[2J_{xx}^{+}+J_{yy}^{+}+3J_{zz}^{+}]$$
$$G_1^{CCKP} = \frac{1}{(1+\eta)}[I_{11}^{+}+I_{00}^{+}-I_{1-1}^{+}-\frac{2(1-\eta)}{\sqrt{2\eta}}I_{10}^{+}] = -\frac{J_{zx}^{+}}{\sqrt{\eta}}$$
$$G_2^{CCKP} = \frac{\sqrt{2}}{3(1+\eta)}[-\eta I_{11}^{+}-\eta I_{00}^{+}+2\sqrt{2\eta}I_{10}^{+}-(\eta+2)I_{1-1}^{+}] = \frac{\sqrt{2}}{3}[J_{xx}^{+}-J_{yy}^{+}]$$

Brodsky-Hiller - (BH) - I_{11}^{+}

$$G_0^{BH} = \frac{1}{3(1+2\eta)}[(3-2\eta)I_{00}^{+} + 8\sqrt{2\eta}I_{10}^{+} + 2(2\eta-1)I_{1-1}^{+}]$$

$$= \frac{1}{3(1+2\eta)}[J_{xx}^{+}(1+2\eta) + J_{yy}^{+}(2\eta-1) + J_{zz}^{+}(3+2\eta)]$$

$$G_1^{BH} = \frac{2}{(1+2\eta)}[I_{00}^{+} - I_{1-1}^{+} + \frac{(2\eta-1)}{\sqrt{2\eta}}I_{10}^{+}]$$

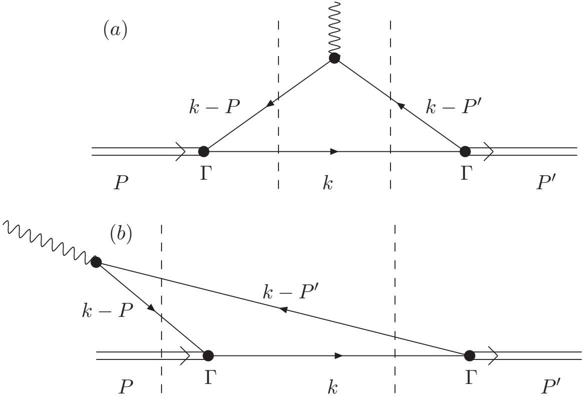
$$= \frac{1}{(1+2\eta)}[\frac{J_{zx}^{+}}{\sqrt{\eta}}(1+2\eta) - J_{yy}^{+} + J_{zz}^{+}]$$

$$G_2^{BH} = \frac{2\sqrt{2}}{3(1+2\eta)}[\sqrt{2\eta}I_{10}^{+} - \eta I_{00}^{+} - (\eta+1)I_{1-1}^{+}]$$

$$= \frac{\sqrt{2}}{3(1+2\eta)}[J_{xx}^{+}(1+2\eta) - J_{yy}^{+}(1+\eta) - \eta J_{zz}^{+}]$$

FFS

$$
\begin{aligned}
G_0^{FFS} &= \frac{1}{3(1+\eta)}[(\frac{3}{2}-\eta)(I_{11}^{+}+I_{00}^{+})+5\sqrt{2\eta}I_{10}^{+}+(2\eta-\frac{1}{2})I_{1-1}^{+}] \\
&= \frac{1}{6}[2J_{xx}^{+}+J_{yy}^{+}+3J_{zz}^{+}] \\
G_1^{FFS} &= G_1^{CCKP} \\
G_2^{FFS} &= G_2^{CCKP}
\end{aligned}
$$



(a) ⇒ Valence Component of the Electromagnetic Current
(b) ⇒ Non-Valence Component of the Electromagnetic Current
Ref.: de Melo and Frederico, PRC (1997) , de Melo, Naus, Frederico and Sauer, PRC(1999)

Elimination / Zero Modes: Vertex $\Gamma(\gamma^\mu, \gamma^\nu)$

$$Tr[gg]_{ji} = Tr[\not\epsilon_f^\alpha(\not k - \not p' + m)\gamma^+(\not k - \not p + m)\not\epsilon_i^\alpha(\not k + m)]$$

- **+Z (Pair Terms):** $\mathbf{Tr[gg]_{ji}^{+Z} = \frac{k^-}{2}\ R_{gg}}$
- **where:** $\mathbf{R_{gg} = Tr[\not\epsilon_f^\alpha(\not k - \not p' + m)\gamma^+(\not k - \not p + m)\not\epsilon_i^\alpha\gamma^+]}$
- **Simplification:** $[\gamma^\mu, \gamma^\nu]$ **Dirac Trace:**

$$\begin{aligned} Tr[gg]_{xx}^{+Z} &= -\eta\ Tr[gg]_{zz}^{+Z} \\ Tr[gg]_{zx}^{+Z} &= -\sqrt{\eta}\ Tr[gg]_{zz}^{+Z} \\ Tr[gg]_{zz}^{+Z} &= R_{gg} \end{aligned}$$

Also:

$$Tr[gg]_{yy}^{+Z} = 4k^-(p^+ - k^+)^2$$

- **Pair Terms**

$$J^{+Z}_{xx} = \lim_{\delta^+\to 0}\int d^3K \frac{Tr[J^{+Z}_{xx}]}{[1][2][4][5][6][7]} \neq 0$$

$$J^{+Z}_{zx} = \lim_{\delta^+\to 0}\int d^3K \frac{Tr[J^{+Z}_{zx}]}{[1][2][4][5][6][7]} \neq 0$$

$$J^{+Z}_{zz} = \lim_{\delta^+\to 0}\int d^3K \frac{Tr[J^{+Z}_{zz}]}{[1][2][4][5][6][7]} \neq 0$$

$$J^{+Z}_{yy} = \lim_{\delta^+\to 0}\int d^3K \frac{Tr[J^{+Z}_{yy}]}{[1][2][4][5][6][7]} = 0$$

- **Basis $I^{+}_{m'm}$:**

$$I^{+Z}_{11} = 0,\ I^{+Z}_{10} = 0$$
$$I^{+Z}_{1-1} = 0,\ I^{+Z}_{00} = (1+\eta)J^{+}_{zz} \neq 0$$

- **Pair Term Contribution:** **only: I^{+Z}_{00} !!**
- **Inna Grach: Elimination** I^{+}_{00}

$$
\begin{aligned}
G_0^{GK\ (+Z)} &= \frac{1}{3}\left(J_{xx}^{(+Z)}[gg] + \eta J_{zz}^{+Z}[gg]\right) = \\
&\quad \frac{1}{3}\left(-\eta J_{zz}^{+Z}[gg] + \eta J_{zz}^{+Z}[gg]\right) = 0 \\
G_1^{GK\ (+Z)} &= \left(-J_{zz}^{+Z}[gg] - \frac{J_{zx}^{+Z}[gg]}{\sqrt{\eta}}\right) = \\
&\quad -J_{zz}^{+Z}[gg] + \sqrt{\eta}\frac{J_{zz}^{+Z}[gg]}{\sqrt{\eta}} = 0 \\
G_2^{GK\ (+Z)} &= \frac{\sqrt{2}}{3}\left(J_{xx}^{+Z}[gg] + \eta J_{zz}^{+Z}[gg]\right) = \frac{\sqrt{2}}{3}\left(-\eta J_{zz}^{+} + \eta J_{zz}^{+Z}\right) = 0
\end{aligned}
$$

- **Vertex (Others):**
- **Cross term with γ^μ and derivatives:**

$$\gamma^\mu \cdot \frac{m_\rho}{2}\left[\frac{2k^\mu - p^\mu}{p^r.k_r + m_\rho m_q - \imath\epsilon}\right]$$

- **Direct term with derivative couplings:**

$$\frac{m_\rho}{2}\left[\frac{2k^\mu - p^\mu}{p^r.k_r + m_\rho m_q - \imath\epsilon}\right] \cdot \frac{m_\rho}{2}\left[\frac{2k^\nu - p^\nu}{p^r.k_r + m_\rho m_q - \imath\epsilon}\right]$$

Resume/Results:

$I_{11}^{+Z} = 0$, $I_{10}^{+Z} = 0$, $I_{1-1}^{+Z} = 0$ **and** $I_{00}^{+Z} = (1+\eta)J_{zz}^{+Z}$ **with** $\lim_{\delta^+ \to 0_+} J_{zz}^{+Z} \neq 0$

Inna Grach Prescription Final Result

No Zero Modes or Pair Terms Contribution with Inna Grach prescp.!!

REf.:

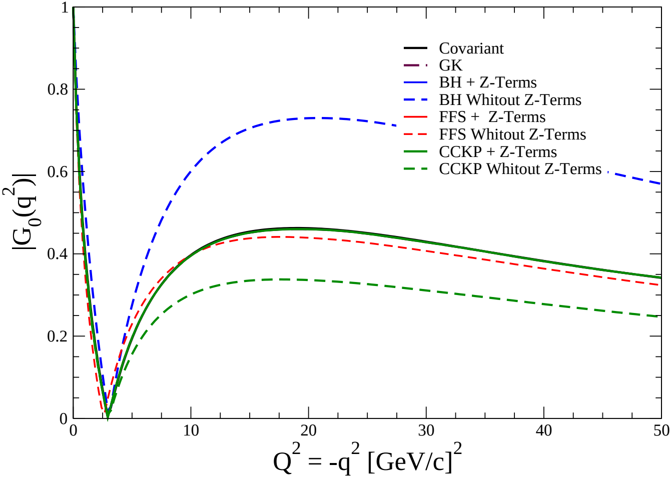
- **J.P.B.C. de Melo and T. Frederico,Phys. Lett. B708, (2012) 87**
- **J.P.B.C. de Melo and T. Frederico,Few Body Syst. 52 (2012) 403**

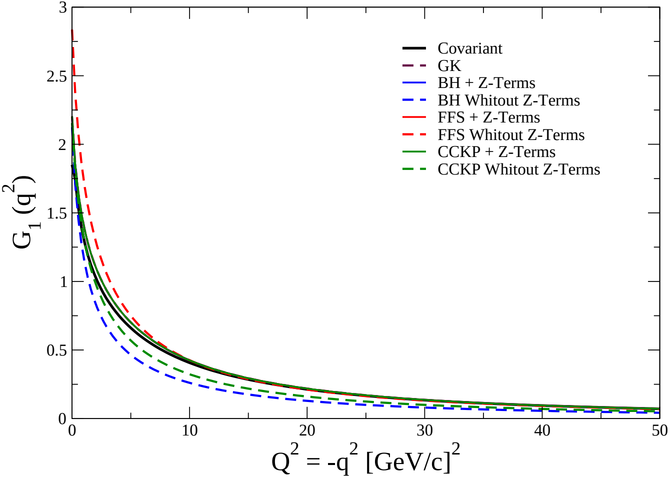
- **Similar Results are found by Ji, Bakker and Choi:**
- **Phy.Rev.D65 (2002) 116001**
- **Phy.Rev.D70 (2004) 053015**

Observables

m_q / m_R [GeV]	f_ρ [GeV]	$< r_\rho^2 >$ [fm^2]	μ_ρ	Q_d [e/m_ρ^2]
0.430 / 3.0	0.154	0.267	2.20	-0.898
[1]	0.134 / 0.151	0.296	2.10	-0.910
[2]	0.130	0.312	2.11	-0.850
[3]	0.207	0.540	2.01	-0.410
[4]	-	-	2.11±0.10	-
[5]	-	-	2.1±0.5	-
PDG	0.152 ± 0.008			

[1] **Phy.Rev.D65 (2002) 116001, B. Bakker, H. M. Choi and C. R. Ji ; / Phys.Rev. D89 (2014) 033011**
[2] Phy.Rev.C83 (2011) 065206, H. L. Roberts, A. Bashir, L.X.G. Guerrero, C. Roberts,
[3] Phy.Rev.C77 (2008) 025203, M. S. Bhagwat and P. Maris
[4] ArXiv:1608.3472v1[hep-lat], E.V. Luscheva, O.E. Solojeva and O. V. Teyaev
[5] Int. J. Mod. Phys. A 18 & 19 (2015) 155014, D.G. Gudino and G. T. Sánchez


Covariant
GK
BH + Z-Terms
BH Whitout Z-Terms
FFS + Z-Terms
FFS Whitout Z-Terms
CCKP + Z-Terms
CCKP Whitout Z-Terms
$|G_0(q^2)|$
$Q^2 = -q^2$ [GeV/c]^2
0
0.2
0.4
0.6
0.8
1
0
10
20
30
40
50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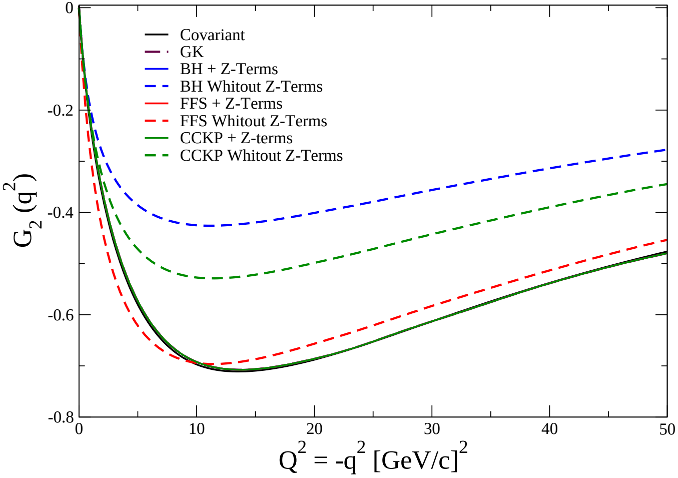
$G_1(q^2)$
$Q^2 = -q^2$ [GeV/c]^2
0
0.5
1
1.5
2
2.5
3
0
10
20
30
40
50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$G_2(q^2)$
$Q^2 = -q^2$ [GeV/c]^2
0
-0.2
-0.4
-0.6
-0.8
0
10
20
30
40
50

Quark Meson Coupling Model (QMC): Basic Ingredients

- **QMC Lagrangian:**

$$\mathcal{L} = \bar{\psi}[i\gamma \cdot \partial - m_N^*(\hat{\sigma}) - g_\omega \hat{\omega}^\mu \gamma_\mu]\psi + \mathcal{L}_{\mathbf{meson}}$$

- **ψ, $\hat{\sigma}$ and $\hat{\omega}$: Nucleon, Lorentz-scalar-isoscalar σ, and Lorentz-vector-isoscalar ω field operators,**
- **σ-Field Coupling Constant:**

$$m_N^*(\hat{\sigma}) = m_N - g_\sigma(\hat{\sigma})\hat{\sigma},$$

- **Free meson Lagrangian is:**

$$\mathcal{L}_{\mathrm{meson}} = \frac{1}{2}(\partial_\mu \hat{\sigma} \partial^\mu \hat{\sigma} - m_\sigma^2 \hat{\sigma}^2) - \frac{1}{2}\partial_\mu \hat{\omega}_\nu (\partial^\mu \hat{\omega}^\nu - \partial^\nu \hat{\omega}^\mu) + \frac{1}{2} m_\omega^2 \hat{\omega}^\mu \hat{\omega}_\mu \ ,$$

- Present work: **Nuclear matter in Rest Frame**
- Also: **Symmetric Nuclear Matter Case:** **(Mean-field Approximation)**

Nucleon Fermi momentum k_F // scalar density, Conected Sigma-mean Field

$$\rho\ (Baryon) = \frac{4}{(2\pi)^3}\int d\vec{k}\ \theta(k_F - |\vec{k}|) = \frac{2k_F^3}{3\pi^2},$$

$$\rho_s\ (Scalar) = \frac{4}{(2\pi)^3}\int d\vec{k}\ \theta(k_F - |\vec{k}|)\frac{m_N^*(\sigma)}{\sqrt{m_N^{*2}(\sigma) + \vec{k}^2}},$$

- $m_N^*(\sigma)$: **Effective nucleon mass at some density:** **with QMC model**

- **Dirac Equation: Light quark and antiquark**

$$\left[i\gamma\cdot\partial_x-(m_q-V^q_\sigma)\mp\gamma^0\left(V^q_\omega+\frac{1}{2}V^q_\rho\right)\right]\left(\begin{array}{c}\psi_u(x)\\ \psi_{\bar{u}}(x)\end{array}\right) = 0,$$
$$\left[i\gamma\cdot\partial_x-(m_q-V^q_\sigma)\mp\gamma^0\left(V^q_\omega-\frac{1}{2}V^q_\rho\right)\right]\left(\begin{array}{c}\psi_d(x)\\ \psi_{\bar{d}}(x)\end{array}\right) = 0,$$

- **Coulomb Interaction: Neglete**
- $SU(2)$ **Symmetry:** $\underline{m_q = m_u = m_d}$

- Bag radius in medium: R_ρ^* $\Rightarrow$ **Stability Condition for the mass of the Hadron**

Obs. Eigenenergies in units of $1/R_\rho^*$

$$\begin{pmatrix} \epsilon_u \\ \epsilon_{\bar{u}} \end{pmatrix} = \Omega_q^* \pm R_\rho^* \left(V_\omega^q + \frac{1}{2} V_\rho^q \right),$$
$$\begin{pmatrix} \epsilon_d \\ \epsilon_{\bar{d}} \end{pmatrix} = \Omega_q^* \pm R_\rho^* \left(V_\omega^q - \frac{1}{2} V_\rho^q \right),$$
$$\epsilon_Q = \epsilon_{\bar{Q}} = \Omega_Q .$$

- **Rho Meson Masse, m_ρ^*:**

$$m_h^* = \sum_{j=q,\bar{q}} \frac{n_j \Omega_j^* - z_\rho}{R_\rho^*} + \frac{4}{3}\pi R_\rho^{*3} B, \quad \left.\frac{\partial m_\rho^*}{\partial R_\rho}\right|_{R_\rho = R_\rho^*} = 0, \quad (1)$$

- $\Omega_q^* = \Omega_{\bar{q}}^* = [x_q^2 + (R_\rho^* m_q^*)^2]^{1/2}$, $m_q^* = m_q - g_\sigma^q \sigma$,
- x_q **Lowest bag eigenfrequencies**
- **QMC Review: K. Saito, K. Tsushima and A. W. Thomas Prog. Part. Nucl. Phys. 58 (2007) 1**

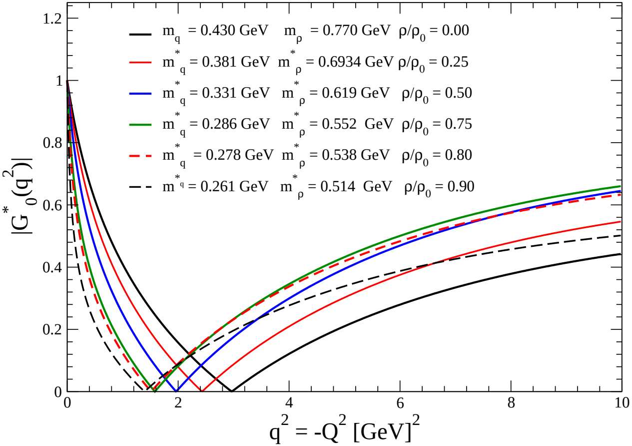
Table: The MIT bag model quantities and coupling constants, the parameter Z_N, bag constant B (in $B^{1/4}$), and the properties for symmetric nuclear matter at normal nuclear matter density $\rho_0 = 0.15$ fm^{-3}, for $m_q = 5,\ 220$ and 430 MeV. The effective nucleon mass, m_N^*, and the nuclear incompressibility, K, are quoted in MeV (the free nucleon bag radius used is $R_N = 0.8$ fm, the standard value in the QMC model.

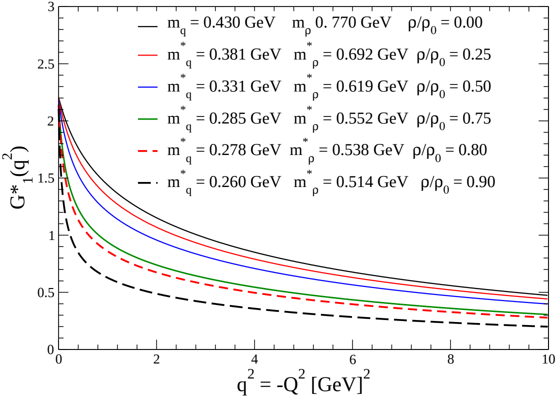
m_q(MeV)	$g_\sigma^2/4\pi$	$g_\omega^2/4\pi$	m_N^*	K	Z_N	$B^{1/4}$(MeV)
5	5.39	5.30	754.6	279.3	3.295	170
220	6.40	7.57	698.6	320.9	4.327	148
430	8.73	11.93	565.25	361.4	5.497	69.75

Results: Rho Meson in Medium

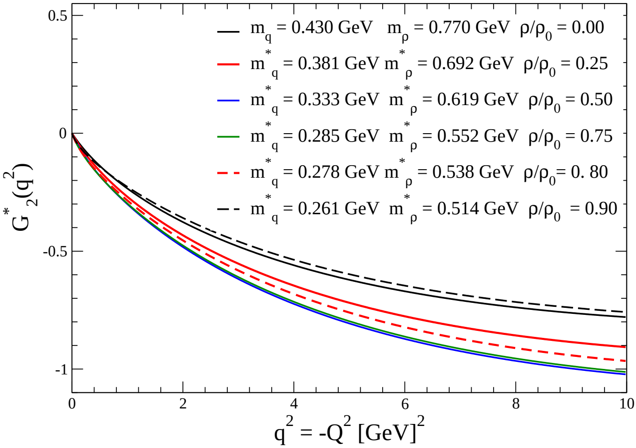
Table: **Observables in medium.**
Units: Masses in [GeV], radius [fm^2], magnetic momentum [$e/2m_\rho$], quadrupole momentum [fm^2].

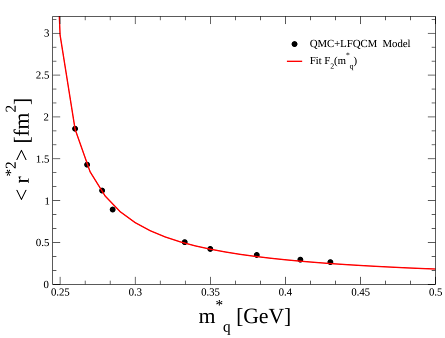
ρ/ρ_0	m_q^*	m_ρ^*	$< r_\rho^{*2} >$	f_ρ^* $[MeV]$	μ^*	Q_0^*
0.0	0.430	0.770	0.2667	153.657	2.20	-0.05895
0.10	0.410	0.738	0.2960	185.126	2.20	-0.06387
0.25	0.381	0.692	0.3520	166.147	2.19	-0.07214
0.40	0.350	0.648	0.4243	175.165	2.19	-0.081677
0.50	0.333	0.618	0.5053	177.694	2.18	-0.08840
0.75	0.285	0.552	0.8944	176.796	2.15	-0.09939
0.80	0.278	0.538	1.121	176.326	2.14	-0.10279
0.85	0.268	0.527	1.430	164.277	2.12	-011340
0.90	0.260	0.514	1.859	155.940	2.10	-0.11520
Exp.				152 ± 8		

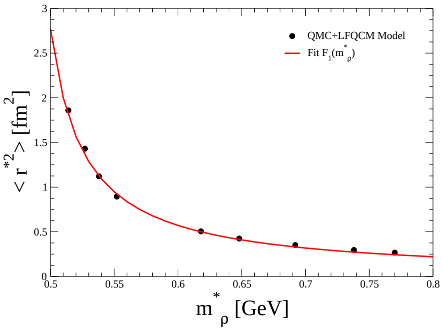

m_q = 0.430 GeV m_ρ = 0.770 GeV ρ/ρ_0 = 0.00
m*_q = 0.381 GeV m*_ρ = 0.6934 GeV ρ/ρ_0 = 0.25
m*_q = 0.331 GeV m*_ρ = 0.619 GeV ρ/ρ_0 = 0.50
m*_q = 0.286 GeV m*_ρ = 0.552 GeV ρ/ρ_0 = 0.75
m*_q = 0.278 GeV m*_ρ = 0.538 GeV ρ/ρ_0 = 0.80
m*_q = 0.261 GeV m*_ρ = 0.514 GeV ρ/ρ_0 = 0.90
|G*_0(q^2)|
q^2 = -Q^2 [GeV]^2
0
0.2
0.4
0.6
0.8
1
1.2
0
2
4
6
8
10



m_q = 0.430 GeV m_ρ 0. 770 GeV ρ/ρ_0 = 0.00
m*_q = 0.381 GeV m*_ρ = 0.692 GeV ρ/ρ_0 = 0.25
m*_q = 0.331 GeV m*_ρ = 0.619 GeV ρ/ρ_0 = 0.50
m*_q = 0.285 GeV m*_ρ = 0.552 GeV ρ/ρ_0 = 0.75
m*_q = 0.278 GeV m*_ρ = 0.538 GeV ρ/ρ_0 = 0.80
m*_q = 0.260 GeV m*_ρ = 0.514 GeV ρ/ρ_0 = 0.90
G*_1(q^2)
q^2 = -Q^2 [GeV]^2
0
0.5
1
1.5
2
2.5
3
0
2
4
6
8
10


m_q = 0.430 GeV m_ρ = 0.770 GeV ρ/ρ_0 = 0.00
m^*_q = 0.381 GeV m^*_ρ = 0.692 GeV ρ/ρ_0 = 0.25
m^*_q = 0.333 GeV m^*_ρ = 0.619 GeV ρ/ρ_0 = 0.50
m^*_q = 0.285 GeV m^*_ρ = 0.552 GeV ρ/ρ_0 = 0.75
m^*_q = 0.278 GeV m^*_ρ = 0.538 GeV ρ/ρ_0= 0. 80
m^*_q = 0.261 GeV m^*_ρ = 0.514 GeV ρ/ρ_0 = 0.90
$G^*_2(q^2)$
$q^2 = -Q^2$ [GeV]^2
0.5
0
-0.5
-1
0
2
4
6
8
10



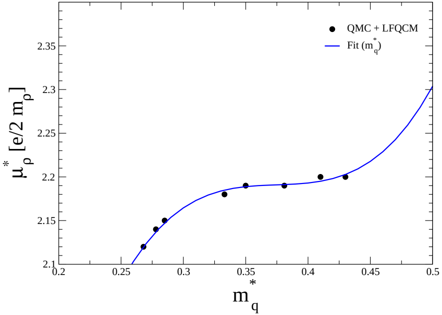


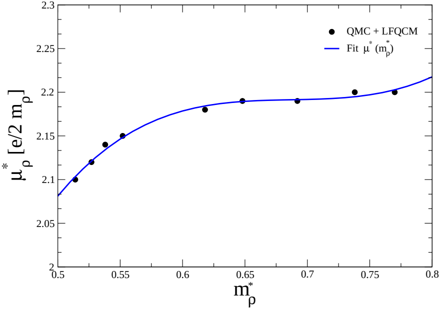
$$F_1(m^*_\rho) =< \ r^{*2}(m^*_\rho) \ > \ = \ \frac{a_0}{m^*_\rho - a_1} \ = \ \frac{0.0720}{m^*_\rho - 0.474}$$

where: $a_0 = [GeV][fm^2]$ **and** $a_1 = [GeV]$**.**

$$F_2(m^*_q) =< \ r^{*2}(m^*_q) \ > \ = \ \frac{b_0}{m^*_\rho - b_1} \ = \ \frac{0.049064}{m^*_q - 0.233531}$$

where: $b_0 = [GeV][fm^2]$ **and** $b_1 = [GeV]$**.**



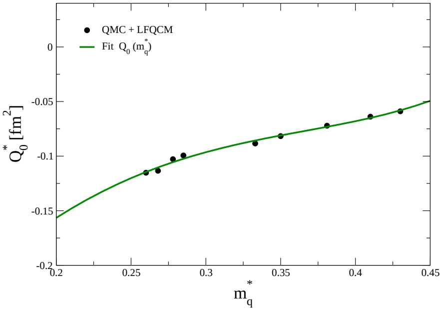


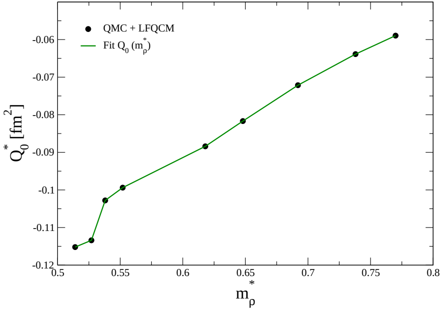
$$\mu^*_\rho(m^*_q) \; = \; a_0 \; m_q^{*3} + \; a_1 \; m_q^{*2} + \; a_2 \; m_q^{*2} + a_3$$

here, $a_0 = 54.2853$, $a_1 = -61.0225$, $a_2 = 22.9146$ **and** $a_3 = -0.683494$.

$$\mu^*_\rho(m^*_\rho) \; = \; b_0 \; m_q^{*3} + \; b_1 \; m_q^{*2} + \; b_2 \; m^*_q + b_3$$

here, $b_0 = 16.1392$, $b_1 = -33.2602$, $b_2 = 22.8736$, $b_3 = -3.05802$





$$Q^*_{0\rho}(m^*_q) \;=\; a_0\; m_q^{*5} + \; a_1\; m_q^{*4} + \; a_2\; m_q^{*3} + a_3 m_q^{*2} + a_4 m_\rho + a_5$$

here, $a_0 = 4.57347,\; a_1 = 2.90565,\; a_2 = -4.18667,\; a_3 = -5.39273,\; a_4 = 8.98056,\; a_5 = -1.46461$**.**

$$Q^*_{0\rho}(m^*_\rho) \;=\; b_0\; m_q^{*5} + \; b_1\; m_q^{*4} + \; b_2\; m_q^{*3} + b_3 m_q^{*2} + b_4 m_\rho + b_5$$

here, $a_0 = 0.0115492, a_1 = -0.256173, a_2 = -0.14145, a_3 = 0.510934, a_4 = -0.000000135009, a_5 = -0.211799$

Remarks

- Light-Front $\Longrightarrow \begin{cases} \textit{Bound States} \\ \textit{Covariance} \end{cases}$
- Rotational Invariance Broken $\Longrightarrow k^-$ Integrations is Problematic
- In order to **Restore Covariance**
- Need $\begin{cases} - \ \textbf{ValenceComponent} \\ - \ \textbf{Non} - \textbf{Valence Components or Z} - \textbf{Terms} \end{cases}$
- **Electromagnetic Current:**
- $\begin{cases} - \ \textbf{Present Work}: \ \mathbf{J}^+ \ \textbf{Component} \\ - \ \textbf{Future Works}: \ \mathbf{J}^- \ \textbf{and} \ \mathbf{J}_\perp \end{cases}$
- **Take New Informations about Bound States at Dense Nuclear Matter**
- $\begin{cases} - \ \textbf{Correlations} \ |\mathbf{q\bar{q}}> \\ - \ \textbf{Rho Meson Decay} \\ - \ \textbf{Deuteron} \end{cases}$

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- **FAPESP , CNPq and CAPES**

Thanks (Obrigado)!!