Effects of higher spin mesons in elastic electron-nucleon scattering

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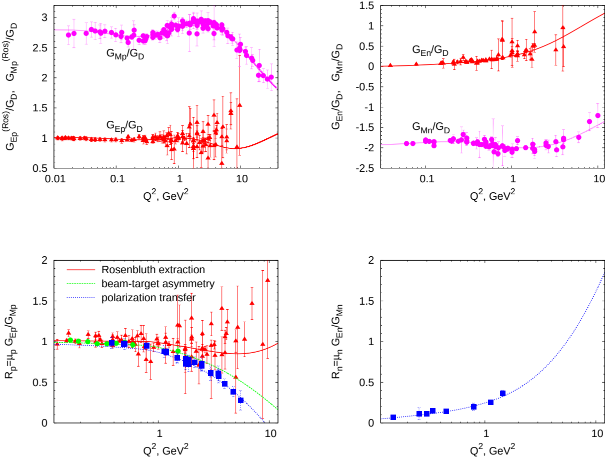
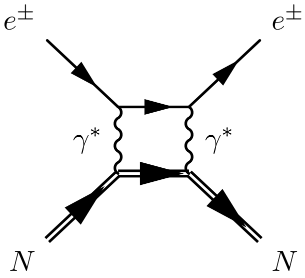
Experimental data



Plots from G. Vereshkov et al. Eur. Phys. J. A34, 223 (2007)

Two photon effects



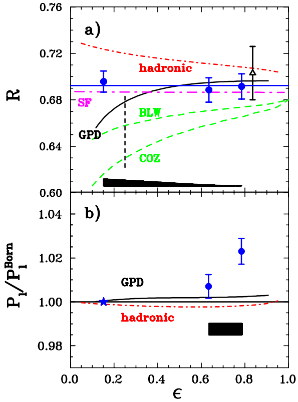


FIGURE: Meziane et al. Phys. Rev. Lett. 106, 132501 (2011)

Proton charge radius puzzle

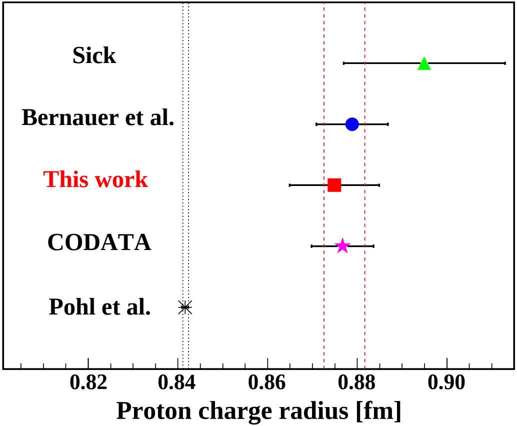
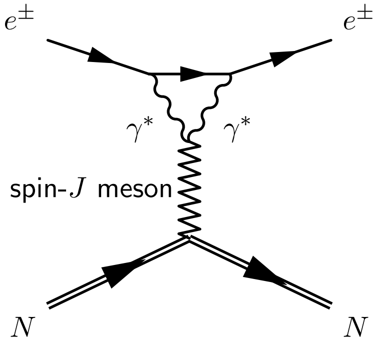


Figure: K. Zhan et al. Phys. Lett. B 705 (2011) 59

Higher-spin meson exchange



Gauge symmetry of spin-2 field

Fierz-Pauli Lagrangian of the free symmetric tensor field $\varphi_{\mu\nu}$:

$$\mathscr{L} = -\varphi_{\mu\nu} G^{\mu\nu} - \frac{m^2}{2}\left[\varphi_{\mu\nu}\varphi^{\mu\nu} - \left(\varphi^{\lambda}_{\lambda}\right)^2\right],$$

$$G_{\mu\nu} = \varphi_{\mu\lambda\nu}{}^{\lambda} - \frac{1}{2} g_{\mu\nu} \varphi_{\lambda\sigma}{}^{\lambda\sigma},$$

$$\varphi_{\mu\nu\lambda\sigma} = \frac{1}{2}\left(\partial_\mu\partial_\lambda\varphi_{\nu\sigma} - \partial_\nu\partial_\lambda\varphi_{\mu\sigma} - \partial_\mu\partial_\sigma\varphi_{\nu\lambda} + \partial_\nu\partial_\sigma\varphi_{\mu\lambda}\right).$$

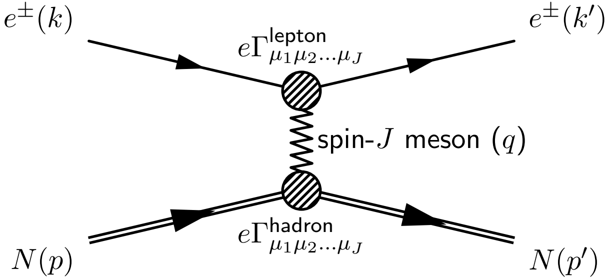
Internal gauge symmetry of the kinetic term:

$$\delta\mathscr{L} = 0 \text{ for } m^2 = 0,\ \delta\varphi_{\mu\nu} = \frac{1}{2}\left(\partial_\mu\theta_\nu + \partial_\nu\theta_\mu\right), \quad \forall\theta_\mu.$$

Constraints:

$$\varphi^{\mu}_{\mu} = 0 = \partial^\nu \varphi_{\nu\mu}.$$

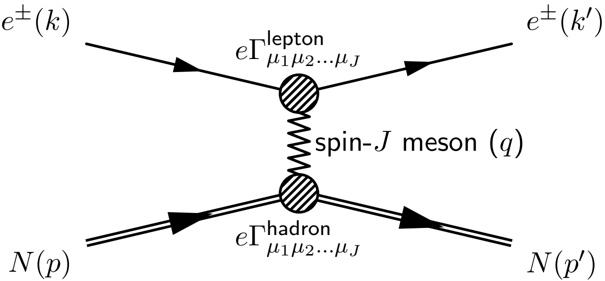
Higher-spin meson exchange in $e^{\pm}N \to e^{\pm}N$



To eliminate nonphysical DsOF of higher spin meson, it has to be assumed that

$$q^{\mu_1}\Gamma^{\text{lepton}}_{\mu_1\mu_2\ldots\mu_J} = 0 = q^{\mu_1}\Gamma^{\text{hadron}}_{\mu_1\mu_2\ldots\mu_J}.$$

Higher-spin meson exchange in $e^{\pm}N \to e^{\pm}N$



$$\Gamma^{\text{lepton}}_{\mu_1\mu_2\ldots\mu_J} = \frac{h_{(J)}}{JM^{J-1}}\left(\gamma_{\mu_1}K_{\mu_2}\cdots K_{\mu_J} + \text{permutations}\right),$$

$$\Gamma^{\text{hadron}}_{\mu_1\mu_2\ldots\mu_J} = \frac{g_{(J)M}}{JM^{J-1}}\left(\gamma_{\mu_1}P_{\mu_2}\cdots P_{\mu_J} + \text{permutations}\right) + \frac{g_{(J)2}}{M^J}P_{\mu_1}\cdots P_{\mu_J},$$

$$K_\mu = \frac{1}{2}(k_\mu + k'_\mu), \qquad P_\mu = \frac{1}{2}(p_\mu + p'_\mu), \qquad h_{(1)} = 1.$$

Cross section of $e^{\pm}N \to e^{\pm}N$

Differential cross section in the laboratory frame:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \sigma_{(0)a}\sigma_a^{\pm}(\tau,\epsilon)\left[1 + h(\boldsymbol{\zeta}\hat{\mathbf{z}})P_l^a(\tau,\epsilon) + h(\boldsymbol{\zeta}\hat{\mathbf{x}})P_t^a(\tau,\epsilon)\right],$$

$$\tau = \frac{Q^2}{4M_N^2}, \qquad \epsilon = \left[1 + 2(1+\tau)\tan^2\frac{\theta}{2}\right]^{-1}$$

Reduced cross section:

$$\sigma_a^{\pm} = \tau|\mathscr{G}_{Ma}^{\pm}|^2 + \epsilon|\mathscr{G}_{Ea}^{\pm}|^2 + \tau|\mathscr{G}_{Ta}^{\pm}|^2, \qquad a = p,\, n.$$

Polarization transfer coefficients:

$$P_l^a = \tau\sqrt{1-\epsilon^2}\,\frac{1}{\sigma_p^-}\Re\left[\left(\mathscr{G}_{Ma}^- + \sqrt{\frac{1-\epsilon}{1+\epsilon}}\mathscr{G}_{Ta}^-\right)\left(\mathscr{G}_{Ma}^- - \sqrt{\frac{1+\epsilon}{1-\epsilon}}\mathscr{G}_{Ta}^-\right)^*\right],$$

$$P_t^a = -\sqrt{2\tau\epsilon(1-\epsilon)}\,\frac{1}{\sigma_a^-}\Re\left[\mathscr{G}_{Ea}^-\left(\mathscr{G}_{Ma}^- - \sqrt{\frac{1+\epsilon}{1-\epsilon}}\mathscr{G}_{Ta}^-\right)^*\right].$$

Cross section of $e^{\pm}N \to e^{\pm}N$

Generalized form factors for arbitrarily large spin J of the mesons:

$$\mathscr{G}^{\pm}_{Ma}(\tau,\epsilon) = \boldsymbol{F^a_M(Q^2)} + \sum_{J\geqslant 2}\left(\mp\frac{\alpha}{\pi}\tilde{\nu}\right)^{J-1} R^{(J)}_M(\epsilon) G^{(J)}_{Ma}(Q^2),$$

$$\mathscr{G}^{\pm}_{Ea}(\tau,\epsilon) = \boldsymbol{F^a_E(Q^2)} + \sum_{J\geqslant 2}\left(\mp\frac{\alpha}{\pi}\tilde{\nu}\right)^{J-1} R^{(J)}_E(\epsilon) G^{(J)}_{Ea}(Q^2),$$

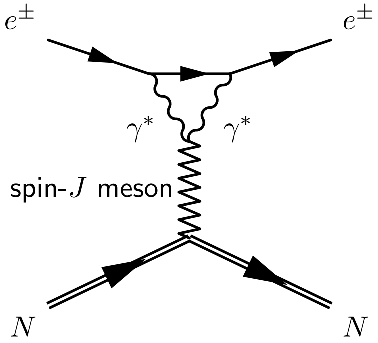
$$\mathscr{G}^{\pm}_{Ta}(\tau,\epsilon) = \epsilon\sqrt{\frac{1-\epsilon}{1+\epsilon}}\sum_{J\geqslant 2}\left(\mp\frac{\alpha}{\pi}\tilde{\nu}\right)^{J-1} R^{(J)}_T(\epsilon) G^{(J)}_{Ma}(Q^2),$$

where

$$\tilde{\nu} = \sqrt{\tau(1+\tau)}\sqrt{\frac{1+\epsilon}{1-\epsilon}}$$

and $R^{(J)}_i(\epsilon)$, $i = E,\ M,\ T$ are positive regular rational functions of $\epsilon \in [0,\ 1]$.

Higher-spin meson exchange



Point invariance of the spin-2 field

Point symmetry of equivalent class $\mathscr{L}(\eta)$ of the free spin-2 field Lagrangians:

$$\varphi_{\mu\nu} \to \varphi_{\mu\nu} + \frac{\eta - 1}{4} g_{\mu\nu}\phi^{\lambda}_{\lambda} : \mathscr{L}_{\text{Fierz-Pauli}} \to \mathscr{L}(\eta)$$

Point invariance of the interaction Lagrangian leads to cancellation of UV divergences in loops.

SPIN-2–SPIN-1–SPIN-1 VERTEX

Interaction Lagrangian:

$$
\begin{aligned}
\mathscr{L} = & \frac{g_1}{M^3} C_{\mu\nu\lambda\sigma} V_1^{\mu\nu} V_2^{\lambda\sigma} \\
& + \frac{g_2}{M^5} C_{\mu\nu\lambda\sigma} \partial^\lambda V_1^{\mu\rho} \partial^\sigma V_2{}^{\nu}{}_{\rho} \\
& + \frac{g_3}{M^7} C_{\mu\nu\lambda\sigma} \partial^\mu \partial^\lambda \left(\partial^\nu V_1^{\rho\omega} \partial^\sigma V_{2\rho\omega} \right) \\
& + \frac{g_4}{M^7} C_{\mu\nu\lambda\sigma} \partial^\nu \partial_\omega \left(\partial^\mu V_1^{\rho\omega} \partial_\rho V_2^{\lambda\sigma} + \partial_\rho V_1^{\lambda\sigma} \partial^\nu V_2^{\rho\omega} \right) \\
& + \frac{g_5}{M^9} C_{\mu\nu\lambda\sigma} \partial^\nu \partial^\sigma \partial^\alpha \partial^\beta \left(\partial_\alpha V_1^{\lambda\rho} \partial_\beta V_2{}^{\mu}{}_{\rho} \right) .
\end{aligned}
$$

Linearised Weyl tensor:

$$
\begin{aligned}
C_{\mu\nu\lambda\sigma} = \varphi_{\mu\nu\lambda\sigma} & - \frac{1}{2} \varphi_{\mu\rho\lambda}{}^{\rho} g_{\nu\sigma} + \frac{1}{2} \varphi_{\nu\rho\lambda}{}^{\rho} g_{\mu\sigma} + \frac{1}{2} \varphi_{\mu\rho\sigma}{}^{\rho} g_{\nu\lambda} - \frac{1}{2} \varphi_{\nu\rho\sigma}{}^{\rho} g_{\mu\lambda} \\
& + \frac{1}{6} \varphi_{\rho\omega}{}^{\rho\omega} \left(g_{\mu\lambda} g_{\nu\sigma} - g_{\mu\sigma} g_{\nu\lambda} \right) ,
\end{aligned}
$$

$$
\varphi_{\mu\nu\lambda\sigma} = \frac{1}{2} \left(\partial_\mu \partial_\lambda \varphi_{\nu\sigma} - \partial_\mu \partial_\sigma \varphi_{\nu\lambda} - \partial_\nu \partial_\lambda \varphi_{\mu\sigma} - \partial_\nu \partial_\sigma \varphi_{\mu\lambda} \right)
$$

Fit

≈ 600 data points on 7 polarized and unpolarized observables:

$$\sigma_p^-(\tau_p,\epsilon), \qquad R^p_{\mathsf{PT}}(\tau_p,\epsilon) = -\mu_p\sqrt{\frac{\tau_p(1+\epsilon)}{2\epsilon}}\,\frac{P^p_t(\tau_p,\epsilon)}{P^p_l(\tau_p,\epsilon)},$$

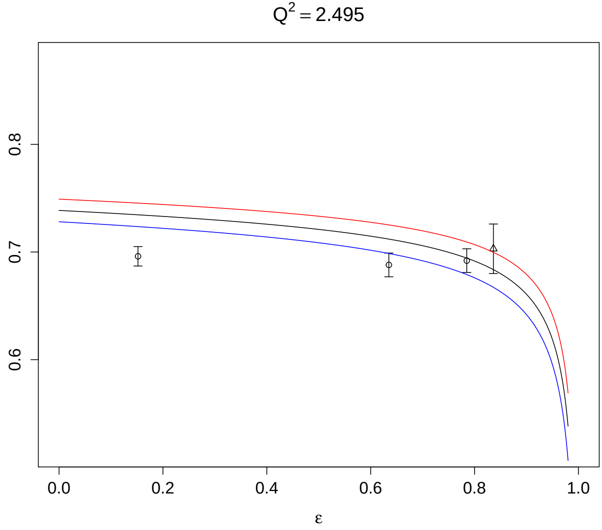
$$\frac{P^p_l(\tau_p,\epsilon)}{P^{p(\mathsf{Born})}_l(\tau_p,\epsilon)}, \qquad R^p_{e^+/e^-}(\tau_p,\epsilon) = \frac{\sigma_p^+(\tau_p,\epsilon)}{\sigma_p^-(\tau_p,\epsilon)},$$

$$R_{n/p}(\tau_a,\epsilon) = \frac{\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}(e^-n\to e^-n)}{\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}(e^-p\to e^-p)},$$

$$R^n_{\mathsf{PT}}(\tau_n,\epsilon) = -\sqrt{\frac{\tau_n(1+\epsilon)}{2\epsilon}}\,\frac{P^n_t(\tau_n,\epsilon)}{P^n_l(\tau_n,\epsilon)}, \qquad P^n_t(\tau_n,\epsilon).$$

Quality of the fit: $\chi^2/\mathsf{DOF} \approx 2.3$.

Proton FF ratio (PT) at 2.495 GeV^2



Results, conclusions, and plans

- Effective gauge invariant vertices for the interactions of higher-spin mesons with leptons and nucleons has been written. In the case of spin-2 mesons, the general Lagrangian for the interactions with two vector fields has been constructed. The symmetry of the Lagrangian ensures mathematical consistence of the theory and cancellation of UV divergences.

- The model of dominance of vector and tensor mesons constrained by high-Q^2 pQCD predictions is in satisfactory agreement with available experimental data on the elastic eN-scattering.

- The model will be extended to include both box and triangle two-photon effects.