Electromagnetic Form-Factors of the $\Lambda(1405)$ in $(2+1)$-flavour Lattice QCD

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Outline

The $\Lambda(1405)$

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- It has a mass of 1405.1 MeV.
  - This is lower than the lowest odd-parity nucleon state, even though it has has a valence strange quark.
- What is special about this state? Why does it lie so low?

The $\Lambda(1405)$

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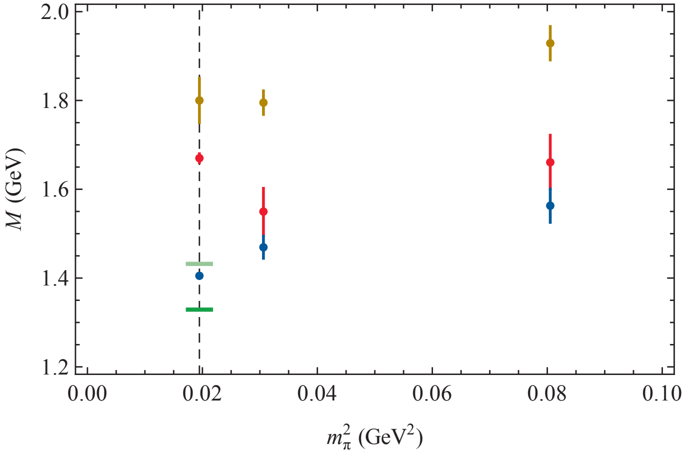

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  - We used a correlation matrix analysis together with source and sink smearing.
- Using the same technique, we can investigate the electromagnetic structure of these states.
  - Negative-parity – need to be careful with formalism.

Simulation Details

- We use the PACS-CS $(2+1)$-flavour lattices, available through the ILDG.

S. Aoki, et al (PACS-CS Collaboration), Phys. Rev. D **79**, 034503 (2009)

  - Lattice size of $32^3 \times 64$ with $\beta = 1.90$.
  - Physical lattice spacing of $a = 0.0907(33)\,\mathrm{fm}$.
  - 5 pion masses, ranging from 640 MeV down to 156 MeV.
  - Fixed strange quark $\kappa_s = 0.13640$.

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    - This gives a kaon that's slightly too heavy, so we partially quench the strange quark sector by using $\kappa_{\text{s}} = 0.13665$ for the valence quarks.
- We focus on the heaviest quark mass, with $\kappa_{\text{u,d}} = 0.13700$.
  - There are 400 independent configurations available.
  - We have analysed 128 configurations so far – first look.

Correlation Matrix Analysis

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- We calculate the $N \times N$ matrix of cross-correlation functions from these operators,

$$
\begin{aligned}
G_{ij}(t, \mathbf{p}) &= \sum_{\mathbf{x}} \mathrm{e}^{-\mathrm{i}\mathbf{p}\cdot\mathbf{x}} \operatorname{tr}\left(\Gamma \langle \Omega | \chi_i(x, t) \overline{\chi}_j(0) | \Omega \rangle\right) \\
&= \sum_{\alpha=1}^{N} Z_i^{\alpha}(\mathbf{p}) Z_j^{\alpha\dagger}(\mathbf{p}) \mathrm{e}^{-E_\alpha(\mathbf{p})t} \operatorname{tr}\left(\Gamma \sum_s u^\alpha(p, s) \overline{u}^\alpha(p, s)\right),
\end{aligned}
$$

where Z_i^{α} and $Z_i^{\alpha\dagger}$ are the couplings of the operator χ_i to the state α at the source and sink, respectively.

Correlation Matrix Analysis

- Construct a set of N "perfect" operators $\phi_\alpha(x)$ that completely isolate the N lowest states, so that

$$\langle\Omega|\phi^\alpha|\beta, p, s\rangle = \delta^{\alpha\beta}\mathcal{Z}^\alpha(\mathbf{p})u(p, s).$$

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- Using the linearity of the operator space, we write

$$\phi_\alpha = \sum_i v_i^\alpha(\mathbf{p}) \chi_i, \quad \text{and}$$
$$\overline{\phi}_\alpha = \sum_i u_i^\alpha(\mathbf{p}) \overline{\chi}_i.$$

Correlation Matrix Analysis

- The coefficient-vectors $\mathbf{u}^\alpha$ and $\mathbf{v}^\alpha$ form the left and right generalised eigenvectors of the matrices $G(t_0 + \Delta t)$ and $G(t_0)$:

$$G(t_0 + \Delta t)\mathbf{u}^\alpha = e^{-m_\alpha \Delta t} G(t_0)\mathbf{u}^\alpha$$
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- Using this, we can define eigenstate-projected correlation functions

$$G^\alpha(t) := \mathbf{v}^{\alpha\top} G(t)\mathbf{u}^\alpha,$$

which contain correlation functions for a single energy eigenstate.

Choice of Operators

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- There are quite a few operators that couple to the Λ baryon.
  - We can exploit the possible flavour symmetry structures:

$$\chi_i^8 = \epsilon^{abc}(2(u_a^\top A_i d_b)B_i s_c + (u_a^\top A_i s_b)B_i d_c - (d_a^\top A_i s_b)B_i u_c)/\sqrt{6},$$
$$\chi_i^1 = -2\epsilon^{abc}(-(u_a^\top A_i d_b)B_i s_c + (u_a^\top A_i s_b)B_i d_c - (d_a^\top A_i s_b)B_i u_c),$$
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  - We can also use different Dirac structures:

$$A_1 = C\gamma_5, \quad A_2 = C, \quad A_4 = C\gamma_5\gamma_4$$
$$B_1 = \mathbb{I}, \quad B_2 = \gamma_5, \quad B_4 = \mathbb{I}$$

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  - Not enough signal to isolate 28 states, but we can use smaller subsets and compare to ensure we have completely isolated the states.
  - These results use χ_1^1, χ_1^8, and χ_2^8, with 16 and 100 sweeps, giving a 6×6 matrix.

Extracting Form Factors

- To extract form factors we calculate the both the two-point and three-point correlation matrices,

$$\mathcal{G}_{ij}(\Gamma; t_2; \mathbf{p}') = \sum_{\mathbf{x}_2} \mathrm{e}^{-\mathrm{i}\mathbf{p}' \cdot \mathbf{x}_2} \operatorname{tr}(\Gamma \langle \Omega | \chi_i(x_2) \overline{\chi}_j(0) | \Omega \rangle)$$

and

$$\begin{aligned} &\mathcal{G}^{\mu}_{ij}(\Gamma; t_2, t_1; \mathbf{p}', \mathbf{p}) \\ &\quad = \sum_{\mathbf{x}_1, \mathbf{x}_2} \mathrm{e}^{-\mathrm{i}\mathbf{p}' \cdot \mathbf{x}_2} \mathrm{e}^{i(\mathbf{p}' - \mathbf{p}) \cdot \mathbf{x}_1} \operatorname{tr}(\Gamma \langle \Omega | \chi_i(x_2) j^{\mu}(x_1) \overline{\chi}_j(0) | \Omega \rangle), \end{aligned}$$

where the χ_i and χ_j are interpolating fields that couple to the state of interest, and $x_i := (\mathbf{x}_i, t_i)$.

Extracting Form Factors

- We use the correlation matrix analysis to project out both two- and three-point correlation functions for individual states:

$$\mathcal{G}_\alpha(\Gamma; t_2; \mathbf{p}') := v_i^\alpha(\mathbf{p}')\mathcal{G}_{ij}(\Gamma; t_2; \mathbf{p}')u_j^\alpha(\mathbf{p}'),$$
$$\mathcal{G}_\alpha^\mu(\Gamma; t_2, t_1; \mathbf{p}', \mathbf{p}) := v_i^\alpha(\mathbf{p}')\mathcal{G}_{ij}^\mu(\Gamma; t_2, t_1; \mathbf{p}', \mathbf{p})u_j^\alpha(\mathbf{p}).$$

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- The eigenvectors $\mathbf{u}^\alpha$ and $\mathbf{v}^\alpha$ are momentum dependent.
- We use the two-point eigenvectors to project the three-point correlation functions.

Extracting Form Factors

- For sufficiently large $t_2 - t_1$ and t_1, $\mathcal{G}^{\mu}_{\alpha}$ takes the form

$$\sum_{s,\,s'} \mathrm{e}^{-E_{\mathbf{p}'}(t_2-t_1)}\mathrm{e}^{-E_{\mathbf{p}}t_1}\,\mathrm{tr}(\Gamma\,\langle\Omega|\chi_i|p',s'\rangle\,\langle p',s'|j^{\mu}|p,s\rangle\,\langle p,s|\overline{\chi}_j|\Omega\rangle),$$

where the current matrix element is

$$\langle p',s'|j^{\mu}|p,s\rangle = \left(\frac{M^2}{E_{\mathbf{p}}E_{\mathbf{p}'}}\right)^{1/2}\overline{u}\left(F_1(q^2)\gamma^{\mu} + \mathrm{i}F_2(q^2)\sigma^{\mu\nu}\frac{q_{\nu}}{2M}\right)u,$$

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  with $q := p' - p$ being the momentum transferred.
- The F_1 and F_2 form factors are related to the Sachs forms through

$$\mathcal{G}_{\mathrm{E}}(q^2) = F_1(q^2) - \frac{q^2}{(2M)^2} F_2(q^2)$$
$$\mathcal{G}_{\mathrm{M}}(q^2) = F_1(q^2) + F_2(q^2)$$

Extracting Form Factors

- To eliminate the time dependence of the three-point correlation function, we construct the ratio

$$R^{\mu}_{\alpha}(\Gamma_2, \Gamma_1; t_2, t_1; \mathbf{p}', \mathbf{p}) := \left(\frac{\mathcal{G}^{\mu}_{\alpha}(\Gamma_1; t_2, t_1; \mathbf{p}', \mathbf{p}) \mathcal{G}^{\mu}_{\alpha}(\Gamma_1; t_2, t_1; \mathbf{p}, \mathbf{p}')}{\mathcal{G}_{\alpha}(\Gamma_2; t_2; \mathbf{p}') \mathcal{G}_{\alpha}(\Gamma_2; t_2; \mathbf{p})} \right)^{1/2}$$

- We then define the reduced ratio

$$\overline{R}^{\mu}_{\alpha} := \left(\frac{2E_{\mathbf{p}}}{E_{\mathbf{p}} + M} \right)^{1/2} \left(\frac{2E_{\mathbf{p}'}}{E_{\mathbf{p}'} + M} \right)^{1/2} R^{\mu}_{\alpha}$$

Extracting Form Factors

- A suitable choice of Γ_1 and Γ_2 allows us to extract the Sachs form factors:

$$\mathcal{G}_{\mathrm{E}}^{\alpha\pm}(q^2) = \overline{R}_{\alpha}^{4}(\Gamma_4^{\pm}, \Gamma_4^{\pm}; \mathbf{q}, \mathbf{0})$$
$$|\epsilon_{ijk} q^i| \mathcal{G}_{\mathrm{M}}^{\alpha\pm}(q^2) = (E_{\mathbf{q}} + M)\overline{R}_{\alpha}^{k}(\Gamma_4^{\pm}, \Gamma_j^{\pm}; \mathbf{q}, \mathbf{0}),$$

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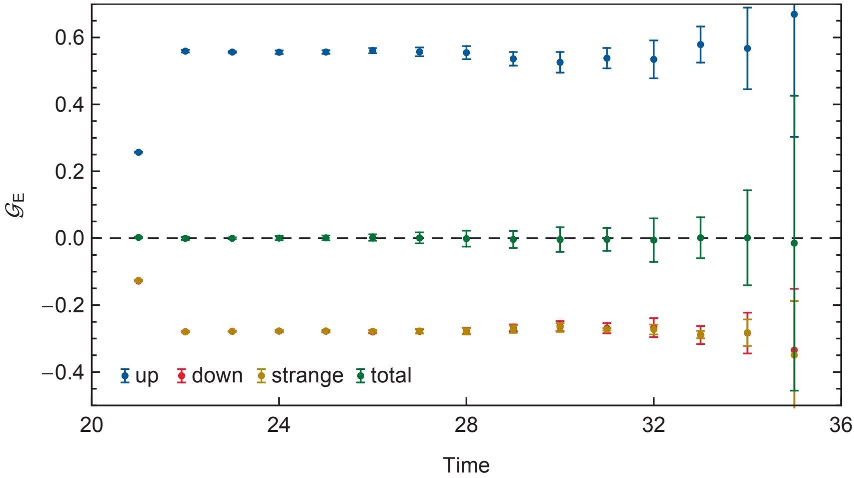
and for negative parity,

$$\Gamma_j^{-} = \gamma_5 \Gamma_j^{+} \gamma_5 = \frac{1}{2}\begin{bmatrix} 0 & 0 \\ 0 & \sigma_j \end{bmatrix}, \quad \Gamma_4^{-} = \gamma_5 \Gamma_4^{+} \gamma_5 = \frac{1}{2}\begin{bmatrix} 0 & 0 \\ 0 & \mathbb{I} \end{bmatrix}.$$

State 1 – Λ(1405)



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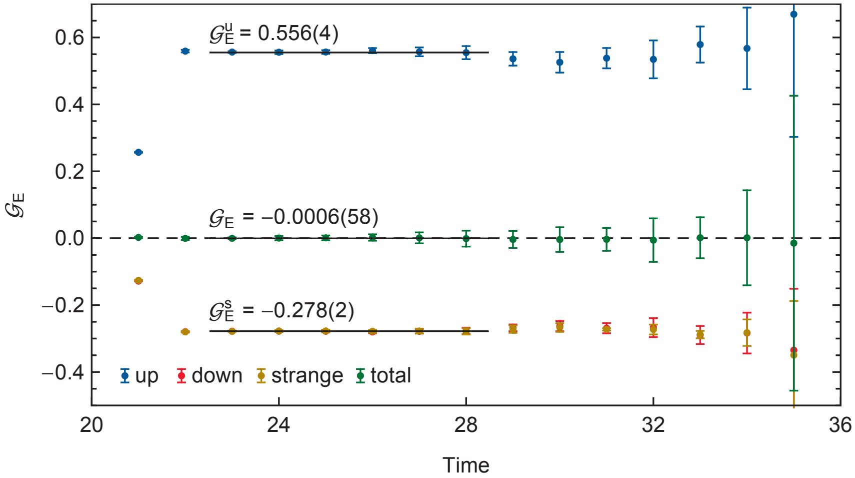
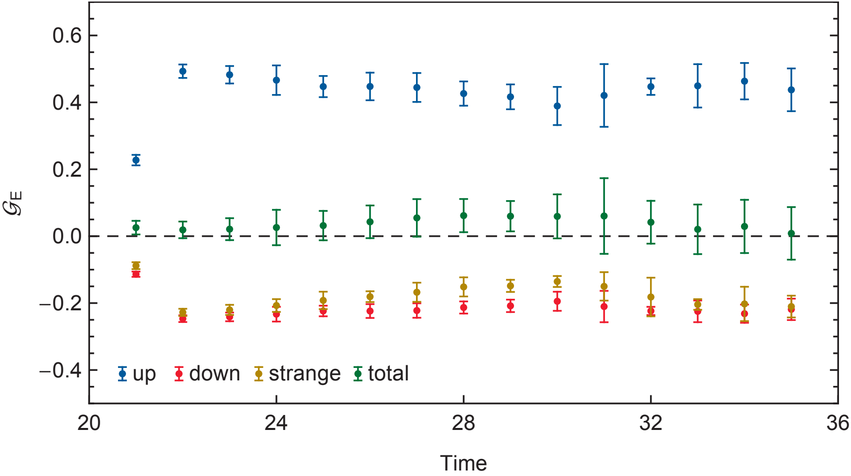


State 2



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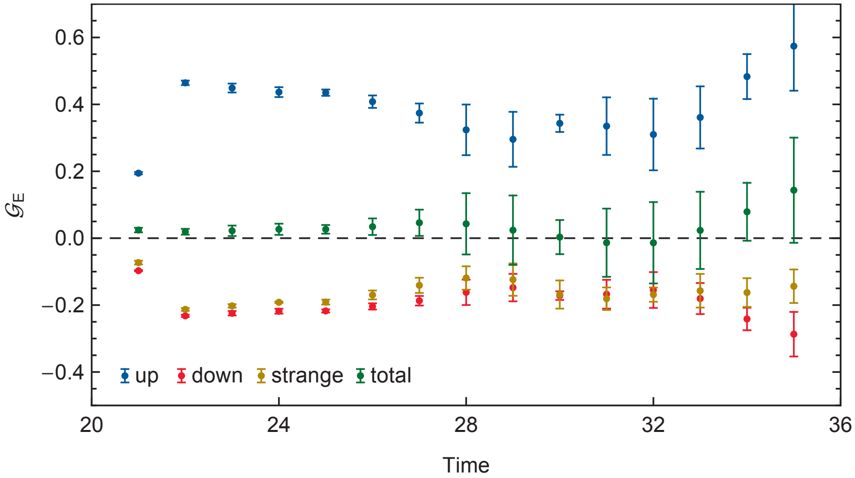
State 3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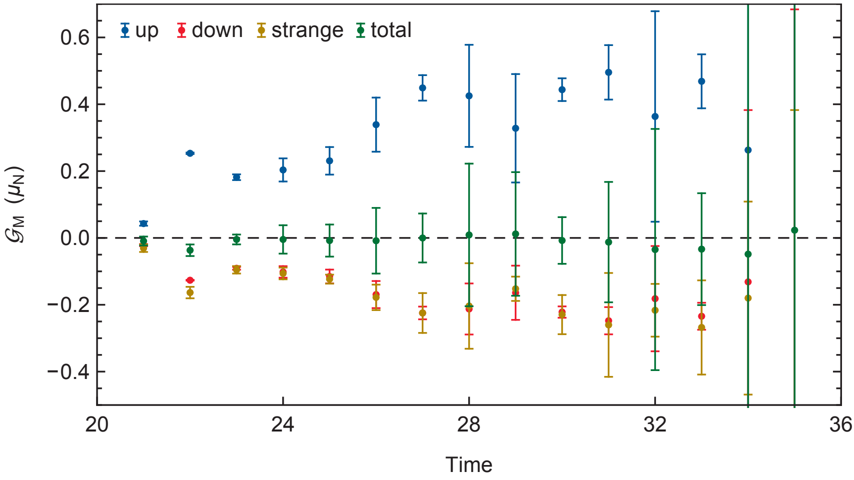

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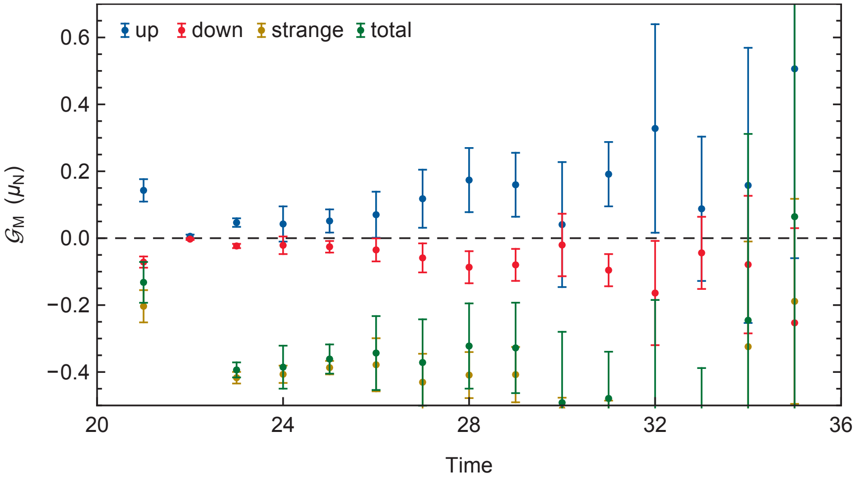
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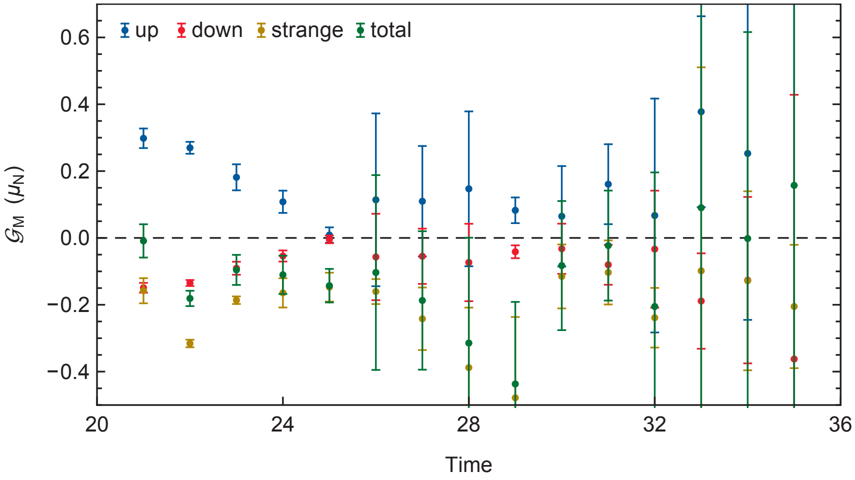
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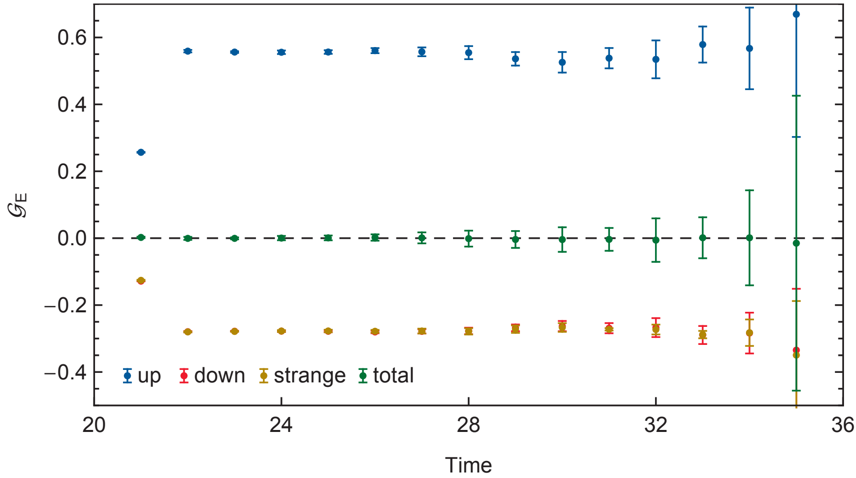
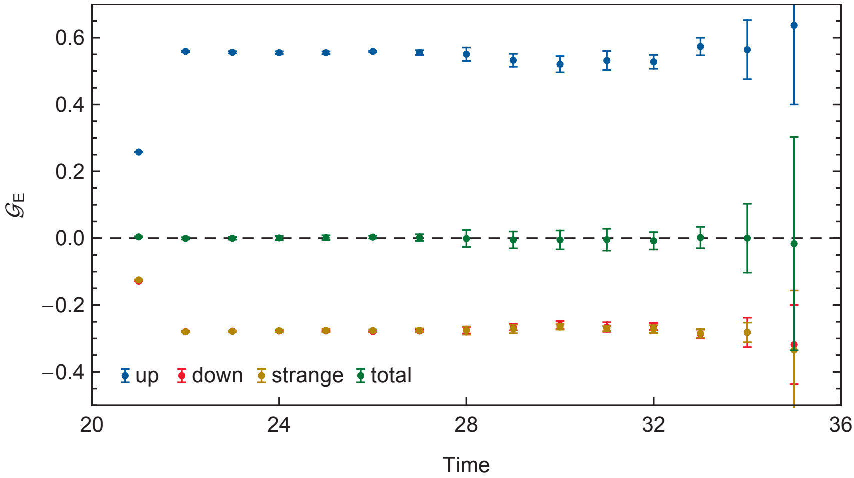
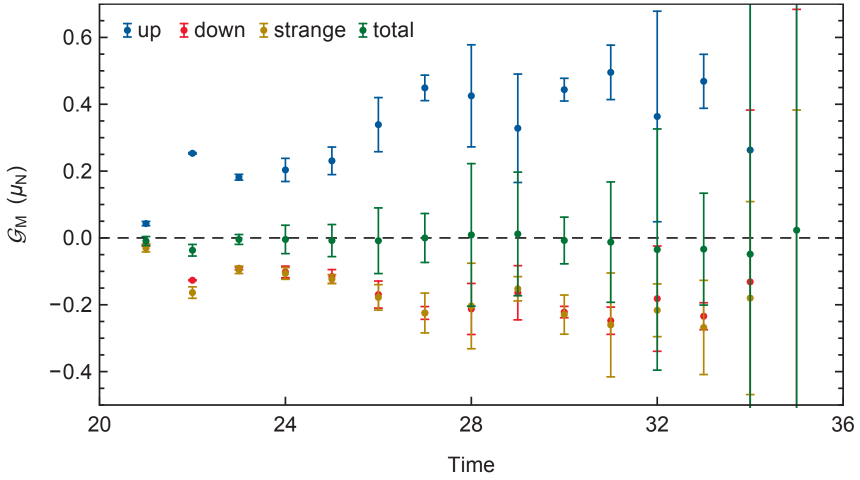
$\mathcal{G}_E$ – State 1 – $\Lambda(1405)$



$\mathcal{G}_{\mathrm{E}}$ – State 1 – $\Lambda(1405)$



$\mathcal{G}_\mathrm{M}$ – State 1 – $\Lambda(1405)$



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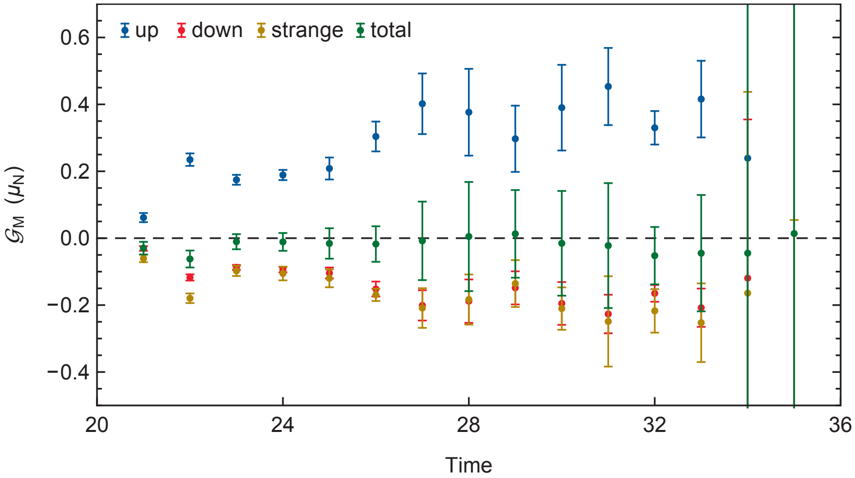

Remarks

- Conclusions
  - Demonstrated the concept of extracting negative-parity baryon EM form factors using correlation matrix techniques.
  - First look at the EM form factors for negative-parity Λ states, particularly the $\Lambda(1405)$.
- Further Work
  - Complete the calculation for the remainder of this ensemble.
  - Repeat the analysis for the other light quark $\kappa_{\mathrm{u,d}}$.
  - Include multi-particle operators to isolate and exclude any multi-particle states.