Electromagnetic Structure of the $\Lambda(1405)$

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Lattice 2013

Outline

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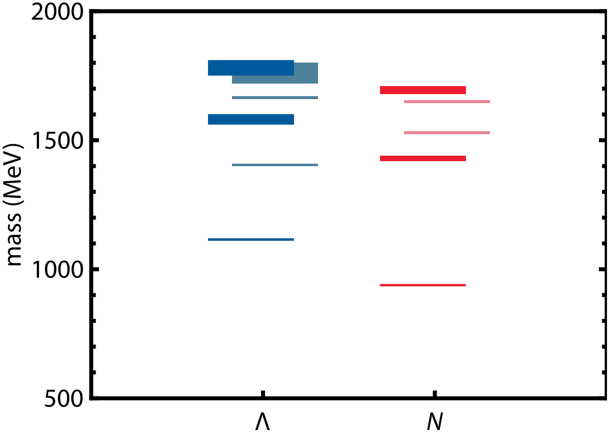

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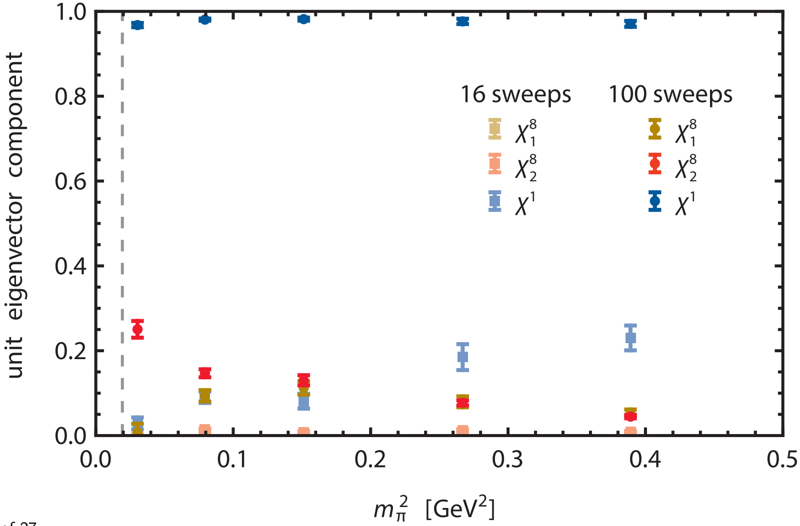
- It has a mass of $1405.1^{+1.3}_{-1.0}$ MeV.
  - This is lower than the lowest odd-parity nucleon state ($N(1535)$), even though it has a valence strange quark.
- We now understand this as a consequence of its flavour-singlet structure.

The Λ(1405)



1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.1
0.2
0.3
0.4
0.5
unit eigenvector component
m_π^2 [GeV^2]
16 sweeps
100 sweeps
χ_1^8
χ_2^8
χ^1

The $\Lambda(1405)$ and Lattice QCD

Our recent work has successfully isolated three low-lying states.

BM, W. Kamleh, D. B. Leinweber, M. S. Mahbub, Phys. Rev. Lett. **108**, 112001 (2012)

- An extrapolation of the trend of the lowest state reproduces the mass of the $\Lambda(1405)$.

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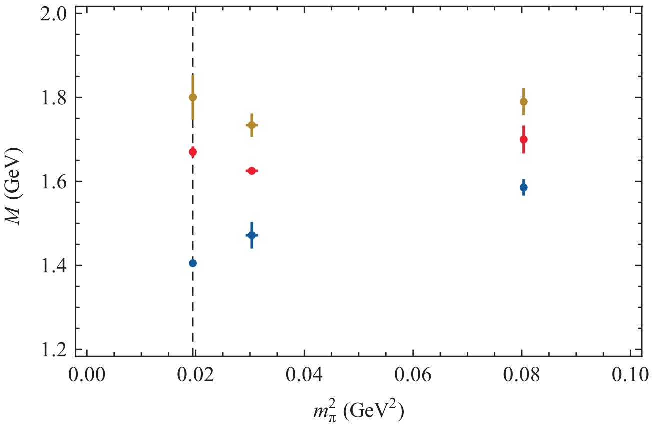

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- An extrapolation of the trend of the lowest state reproduces the mass of the $\Lambda(1405)$.
- Subsequent studies have confirmed these results.

G. P. Engel, C. B. Lang, A. Schäfer, Phys. Rev. D **87**, 034502 (2013)

The $\Lambda(1405)$ and Lattice QCD

The variational analysis is necessary to isolate and analyse the $\Lambda(1405)$.

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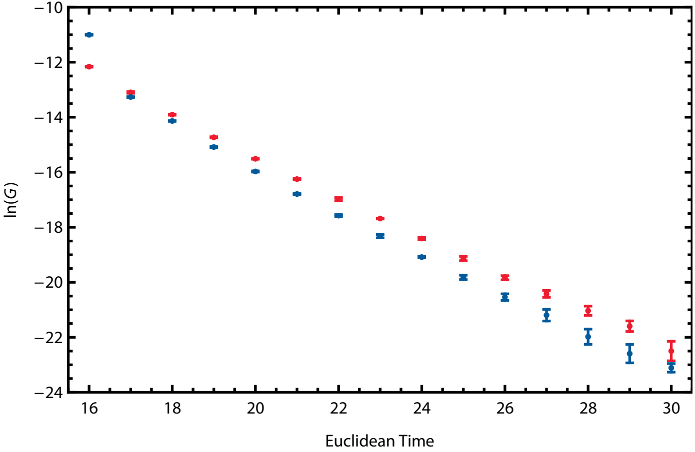

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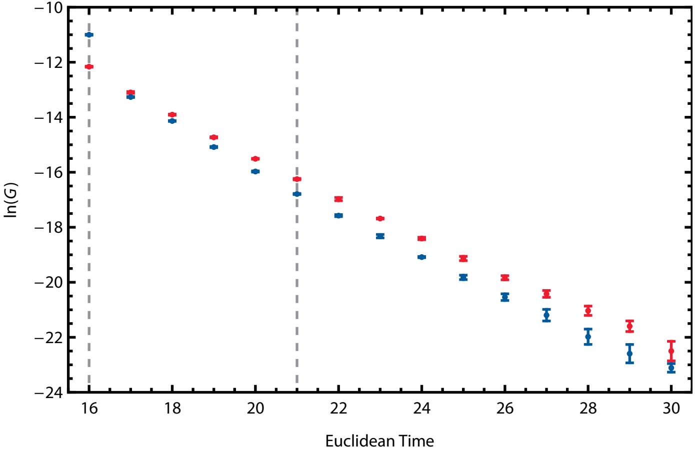
- Our current insertion ($t_{\mathsf{SST}} = 21$) is 5 time slices after the source ($t_{\mathsf{src}} = 16$).

The Λ(1405) and Lattice QCD



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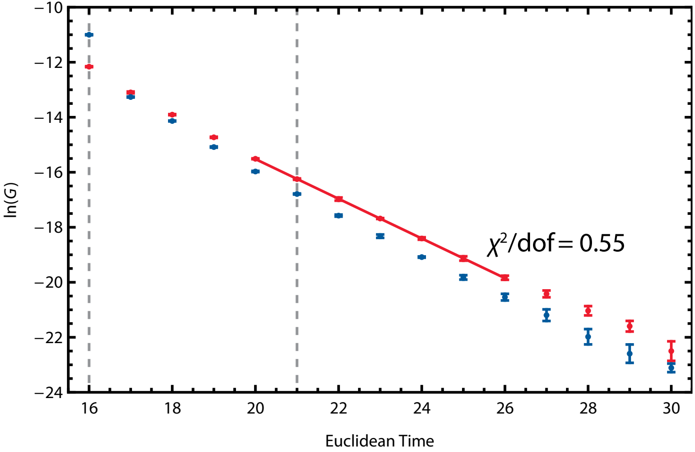

Simulation Details

We are using the PACS-CS $(2+1)$-flavour ensembles, 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 $\beta = 1.90$.
- 5 pion masses, ranging from 640 MeV down to 156 MeV.
- Single strange quark mass, with $\kappa_s = 0.13640$.
  - We partially quench by using $\kappa_s = 0.13665$ for the valence strange quarks to reproduce the physical kaon mass.
- We consider both the Sommer and PACS-CS schemes to set the scale.

Variational Analysis

By using multiple operators, we can isolate and analyse individual energy eigenstates:

- Construct the correlation matrix

$$G_{ij}(\mathbf{p}; t) = \sum_{\mathbf{x}} \mathrm{e}^{-\mathrm{i}\,\mathbf{p}\cdot\mathbf{x}} \, \langle \Omega | \chi_i(x) \, \overline{\chi}_j(0) | \Omega \rangle \, ,$$

  for some set $\{ \chi_i \}$ operators that couple to the states of interest.

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  for some set $\{\,\chi_i\,\}$ operators that couple to the states of interest.
- Note: all correlation functions have an implicit trace over the spinor indices with some Dirac matrix:

$$G \equiv \mathrm{tr}(\Gamma G)$$

Variational Analysis

- Solve for the left, $\mathbf{v}^\alpha(\mathbf{p})$, and right, $\mathbf{u}^\alpha(\mathbf{p})$, generalised eigenvectors of $G(\mathbf{p}; t + \delta t)$ and $G(\mathbf{p}; t)$:

$$G(\mathbf{p}; t + \delta t)\, \mathbf{u}^\alpha(\mathbf{p}) = \mathrm{e}^{-E_\alpha(\mathbf{p})\, \Delta t}\, G(\mathbf{p}; t)\, \mathbf{u}^\alpha(\mathbf{p})$$
$$\mathbf{v}^{\alpha\mathsf{T}}(\mathbf{p})\, G(\mathbf{p}; t + \delta t) = \mathrm{e}^{-E_\alpha(\mathbf{p})\, \Delta t}\, \mathbf{v}^{\alpha\mathsf{T}}(\mathbf{p})\, G(\mathbf{p}; t)$$

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- These eigenvectors identify "ideal" combinations of the original operators that perfectly isolate individual energy eigenstates at momentum $\mathbf{p}$:

$$\phi^{\alpha} = v_i^{\alpha}(\mathbf{p})\, \chi_i \qquad \overline{\phi}^{\alpha} = u_i^{\alpha}(\mathbf{p})\, \overline{\chi}_i$$

Eigenstate-Projected Correlation Functions

- Using these "perfect" operators, we can extract correlation functions for these energy eigenstates using

$$\begin{aligned} G_\alpha(\mathbf{p}; t) &= \sum_{\mathbf{x}} e^{-i\,\mathbf{p}\cdot\mathbf{x}} \langle \Omega | \phi^\alpha(x)\, \overline{\phi}^\alpha(0) | \Omega \rangle \\ &= \sum_{\mathbf{x}} e^{-i\,\mathbf{p}\cdot\mathbf{x}} \langle \Omega | v_i^\alpha(\mathbf{p})\, \chi_i(x)\, \overline{\chi}_j(0)\, u_j^\alpha(\mathbf{p}) | \Omega \rangle \\ &= \mathbf{v}^{\alpha\mathsf{T}}(\mathbf{p})\, G(\mathbf{p}; t)\, \mathbf{u}^\alpha(\mathbf{p}) \end{aligned}$$

Choice of Operators

- We have a lot of flexibility in the operators we choose.
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Choice of Operators

- We have a lot of flexibility in the operators we choose.
  - Only requirement is that they couple to the states of interest.
- However:
  - too few operators and the states won't be sufficiently isolated, and
  - insufficiently independent operators and the matrix will be too ill-conditioned to solve for the eigenvectors.

Operators Used in Λ(1405) Analysis

There are a number of operators that have the correct quantum numbers to couple to the Λ channel. We use

- the flavour-octet operators

$$\chi_1^8 = \frac{1}{\sqrt{6}}\varepsilon^{abc}(2(u^a C\gamma_5 d^b)s^c + (u^a C\gamma_5 s^b)d^c - (d^a C\gamma_5 s^b)u^c)$$

$$\chi_2^8 = \frac{1}{\sqrt{6}}\varepsilon^{abc}(2(u^a C d^b)\gamma_5 s^c + (u^a C s^b)\gamma_5 d^c - (d^a C s^b)\gamma_5 u^c)$$

- the flavour-singlet operator

$$\chi^1 = 2\varepsilon^{abc}((u^a C\gamma_5 d^b)s^c - (u^a C\gamma_5 s^b)d^c + (d^a C\gamma_5 s^b)u^c)$$

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We also use gauge-invariant Gaussian smearing to increase our operator basis.

- These results use 16 and 100 sweeps.
  - Gives a 6×6 matrix.

Operators Used in $\Lambda(1405)$ Analysis

We also use gauge-invariant Gaussian smearing to increase our operator basis.

- These results use 16 and 100 sweeps.
  - Gives a 6×6 matrix.
- Also considered 35 and 100 sweeps.
  - Results are consistent, however the statistical noise increases due to the increased smearing.

Extracting Form Factors from Lattice QCD

- To extract the form factors for a state α, we need to calculate the three-point correlation function

$$G^{\mu}_{\alpha}(\mathbf{p}', \mathbf{p}; t_2, t_1) = \sum_{\mathbf{x}_1, \mathbf{x}_2} e^{-i\,\mathbf{p}'\cdot\mathbf{x}_2} e^{i(\mathbf{p}'-\mathbf{p})\cdot\mathbf{x}_1} \langle\Omega|\phi^{\alpha}(x_2)\, j^{\mu}(x_1)\, \overline{\phi}^{\alpha}(0)|\Omega\rangle$$

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- This takes the form

$$e^{-E_{\alpha}(\mathbf{p}')(t_2-t_1)} e^{-E_{\alpha}(\mathbf{p})t_1} \sum_{s,\, s'} \langle\Omega|\phi^{\alpha}|p', s'\rangle \langle p', s'|j^{\mu}|p, s\rangle \langle p, s|\overline{\phi}^{\alpha}|\Omega\rangle$$

where $\langle p', s'|j^{\mu}|p, s\rangle$ encodes the form factors of the interaction.

Excited State Form Factors

- Using the nature of these "perfect" operators, the eigenstate-projected correlation function is

$$G^\mu_\alpha(\mathbf{p}', \mathbf{p}; t_2, t_1) = \sum_{\mathbf{x}_1, \mathbf{x}_2} e^{-i\,\mathbf{p}'\cdot\mathbf{x}_2} e^{i(\mathbf{p}'-\mathbf{p})\cdot\mathbf{x}_1} \times$$
$$\times \langle\Omega| v_i^\alpha(\mathbf{p}')\,\chi_i(x_2)\,j^\mu(x_1)\,\overline{\chi}_j(0)\,u_i^\alpha(\mathbf{p})|\Omega\rangle$$
$$= \mathbf{v}^{\alpha\mathsf{T}}(\mathbf{p}')\,G^\mu_{ij}(\mathbf{p}', \mathbf{p}; t_2, t_1)\,\mathbf{u}^\alpha(\mathbf{p})$$

where

$$G^\mu_{ij}(\mathbf{p}', \mathbf{p}; t_2, t_1) = \sum_{\mathbf{x}_1, \mathbf{x}_2} e^{-i\,\mathbf{p}'\cdot\mathbf{x}_2} e^{i(\mathbf{p}'-\mathbf{p})\cdot\mathbf{x}_1} \langle\Omega|\chi_i(x_2)\,j^\mu(x_1)\,\overline{\chi}_j(0)|\Omega\rangle$$

is the matrix constructed from the three-point correlation functions of the original operators $\{\,\chi_i\,\}$.

Extracting Form Factors from Lattice QCD

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

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

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- To further simply things, we define the reduced ratio

$$\overline{R}^\mu_\alpha = \left(\frac{2E_\alpha(\mathbf{p})}{E_\alpha(\mathbf{p}) + m_\alpha} \right)^{1/2} \left(\frac{2E_\alpha(\mathbf{p}')}{E_\alpha(\mathbf{p}') + m_\alpha} \right)^{1/2} R^\mu_\alpha$$

Current Matrix Element for Spin-1/2 Baryons

The current matrix element for spin-1/2 baryons can be written in the form

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

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- The Dirac and Pauli form factors are related to the Sachs form factors through

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

Sachs Form Factors for Spin-1/2 Baryons

- A suitable choice of momentum ($\mathbf{q} = (q, 0, 0)$) and the (implicit) Dirac matrices allows us to directly access the Sachs form factors:
  - for $\mathcal{G}_{\mathrm{E}}$: using $\Gamma_4^{\pm}$ for both two- and three-point,

$$\mathcal{G}_{\mathrm{E}}^{\alpha}(q^2) = \overline{R}_{\alpha}^{4}(\mathbf{q}, \mathbf{0}; t_2, t_1)$$

  - for $\mathcal{G}_{\mathrm{M}}$: using $\Gamma_4^{\pm}$ for two-point and $\Gamma_j^{\pm}$ for three-point,

$$|\varepsilon_{ijk}\, q^i|\, \mathcal{G}_{\mathrm{M}}^{\alpha}(q^2) = (E_{\alpha}(\mathbf{q}) + m_{\alpha})\, \overline{R}_{\alpha}^{k}(\mathbf{q}, \mathbf{0}; t_2, t_1)$$

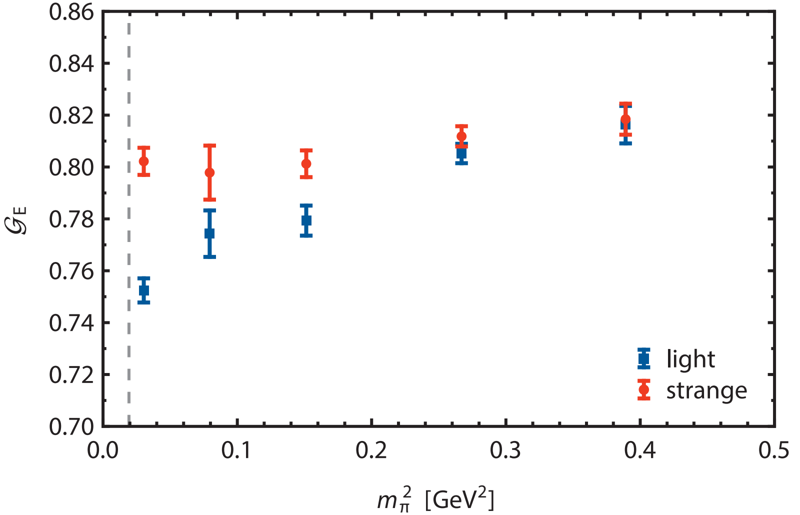
  - where for positive parity states,

$$\Gamma_j^{+} = \frac{1}{2}\begin{bmatrix} \sigma_j & 0 \\ 0 & 0 \end{bmatrix} \qquad \Gamma_4^{+} = \frac{1}{2}\begin{bmatrix} \mathbb{I} & 0 \\ 0 & 0 \end{bmatrix}$$

    and for negative parity states,

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

$\mathcal{G}_E$ for the $\Lambda(1405)$ at $Q^2 \sim 0.15\,\mathrm{GeV}^2$



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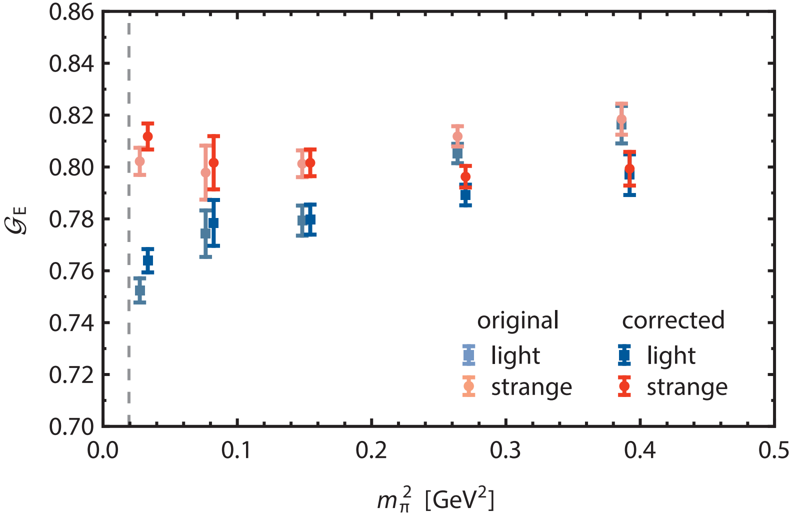
- solve for Λ using $\mathcal{G}_\mathsf{E}(0) = 1$ (unit charge quarks) for each m_π^2
- evaluate $\mathcal{G}_\mathsf{E}$ at a common Q^2 (we used $0.16\,\mathrm{GeV}^2$)

$\mathcal{G}_E$ for the $\Lambda(1405)$ at $Q^2 = 0.16\,\text{GeV}^2$



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- Noting that the centre of mass of the $\overline{K}N$ is nearer the heavier N, compared to the ground state,
  - the anti–light-quark contribution is distributed further out by the $\overline{K}$ and thus leaves an enhanced light-quark form factor.

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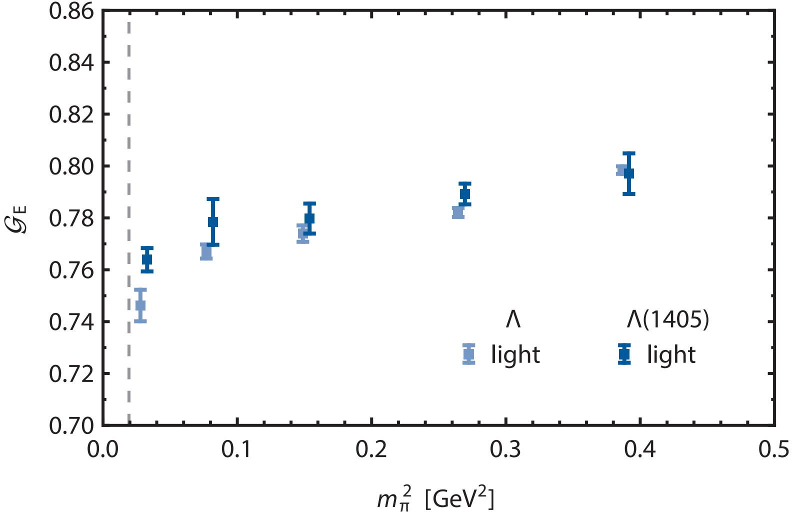

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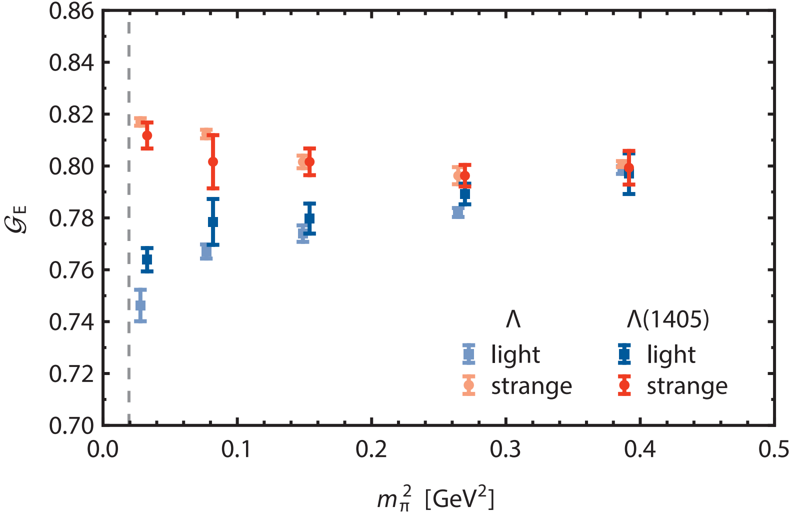
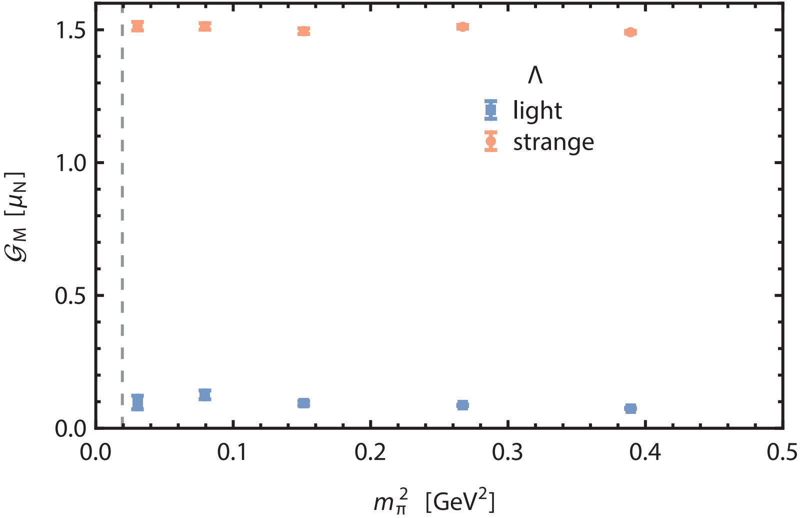
  - the anti–light-quark contribution is distributed further out by the $\overline{\mathrm{K}}$ and thus leaves an enhanced light-quark form factor.
  - the strange quark is distributed further out by the $\overline{\mathrm{K}}$ and thus has a smaller form factor.

Structure of the $\Lambda(1405)$



$\mathcal{G}_M$ for the Λ at $Q^2 \sim 0.15\,\text{GeV}^2$

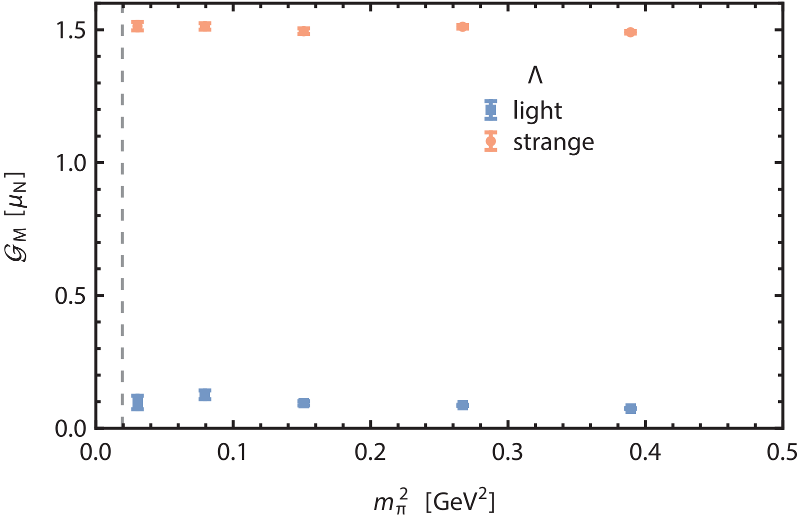


$\mathcal{G}_{\mathrm{M}}$ for the Λ at $Q^2 \sim 0.15\,\mathrm{GeV}^2$

The ground state Λ is flavour-octet:

- the light quarks form a scalar diquark, which has no spin
- the strange quark is the dominant contribution to the magnetic moment

$\mathcal{G}_M$ for the Λ at $Q^2 \sim 0.15\,\text{GeV}^2$



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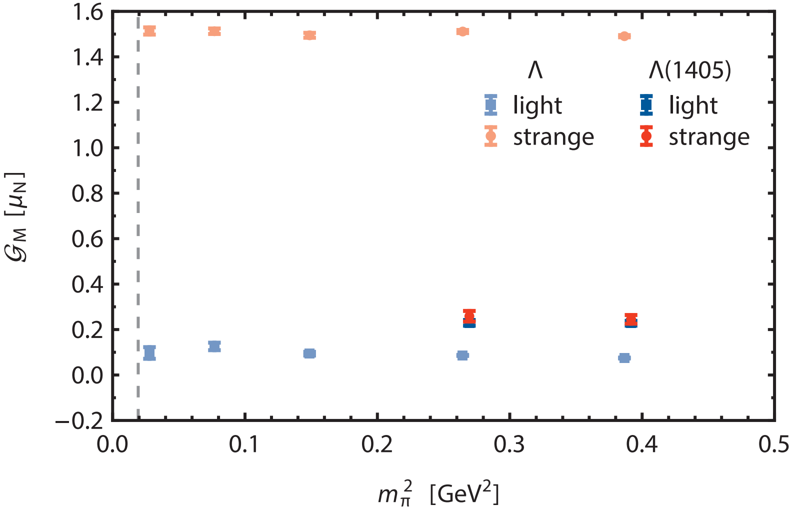

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- Expect $\mu = 0$ in the SU(3) limit, so that $\mathcal{G}_{\mathsf{M}}^{\mathsf{light}} = \mathcal{G}_{\mathsf{M}}^{\mathsf{strange}}$.
- The magnetic moment is proportional to $1/m$, so as the light quark mass decreases, the form factor should increase.

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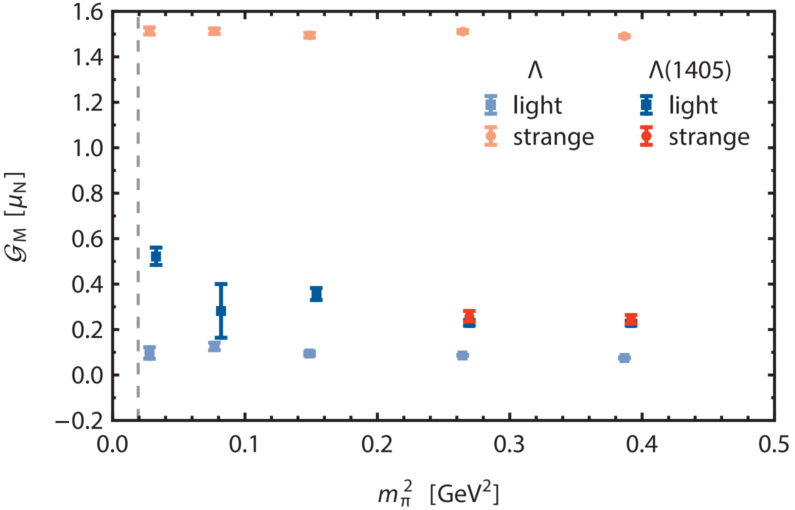

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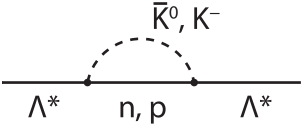
If we consider a $\overline{K}N$ dressing,



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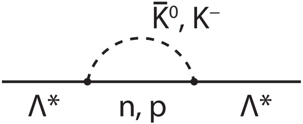

- The light quark sector will be governed by $\mathrm{p} + \mathrm{n}$.
  - This is a positive, non-analytic contribution to the dressing and will enhance the light form factor.

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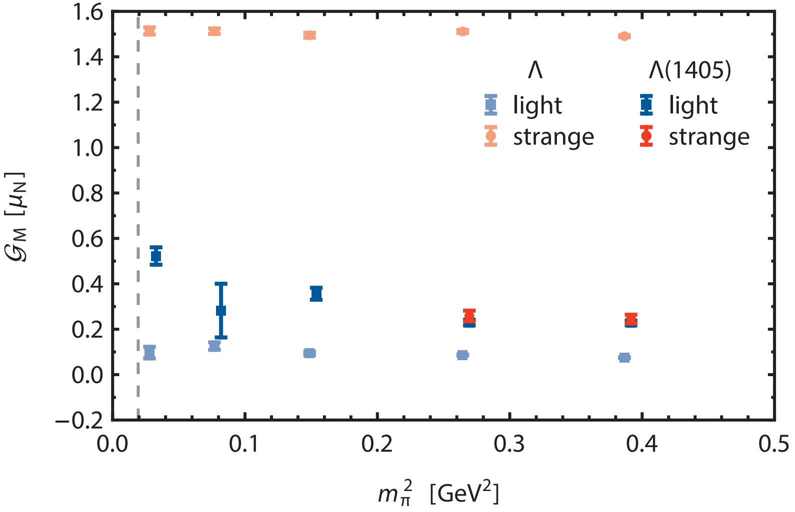

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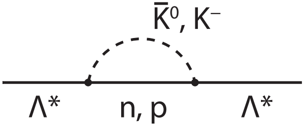

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  - This is a positive, non-analytic contribution to the dressing and will enhance the light form factor.
- There is no contribution to the strange quark magnetic moment
  - This will suppress the strange quark form factor of the $\Lambda(1405)$.

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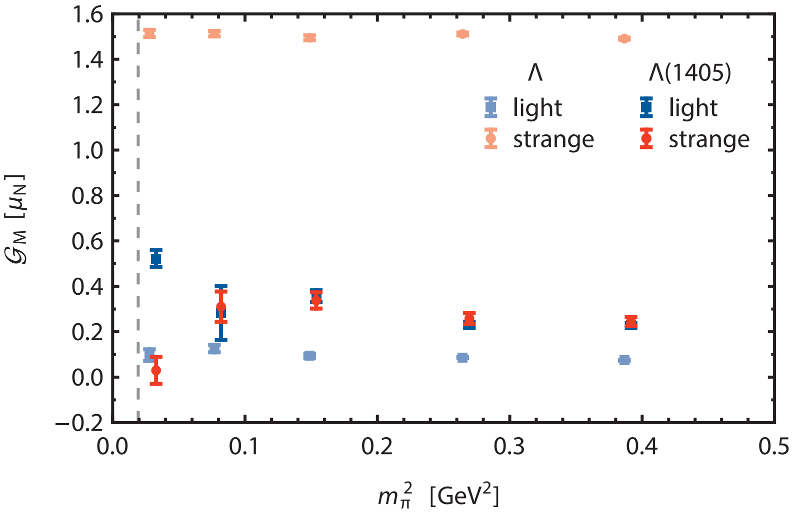

$\mathcal{G}_{\mathrm{M}}$ for the $\Lambda(1405)$ at $Q^2 \sim 0.15\,\mathrm{GeV}^2$

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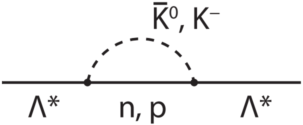
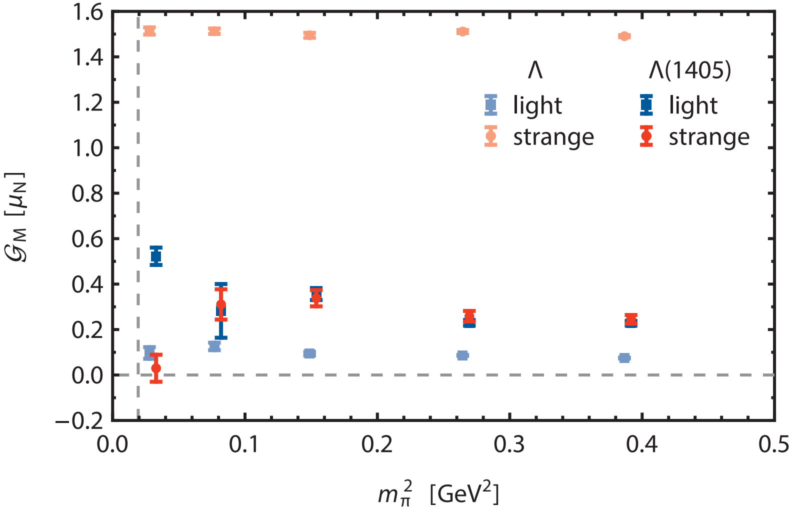


- The light quark sector will be governed by $\mathrm{p} + \mathrm{n}$.
  - This is a positive, non-analytic contribution to the dressing and will enhance the light form factor.
- There is no contribution to the strange quark magnetic moment
  - This will suppress the strange quark form factor of the $\Lambda(1405)$.
- $\mathcal{G}_{\mathrm{M}}^{\mathrm{strange}}$ is consistent with zero!

$\mathcal{G}_M$ for the $\Lambda(1405)$ at $Q^2 \sim 0.15\,\text{GeV}^2$



$\mathcal{G}_{\mathrm{M}}$ for the $\Lambda(1405)$ at $Q^2 \sim 0.15\,\mathrm{GeV}^2$

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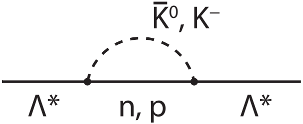

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- There is no contribution to the strange quark magnetic moment
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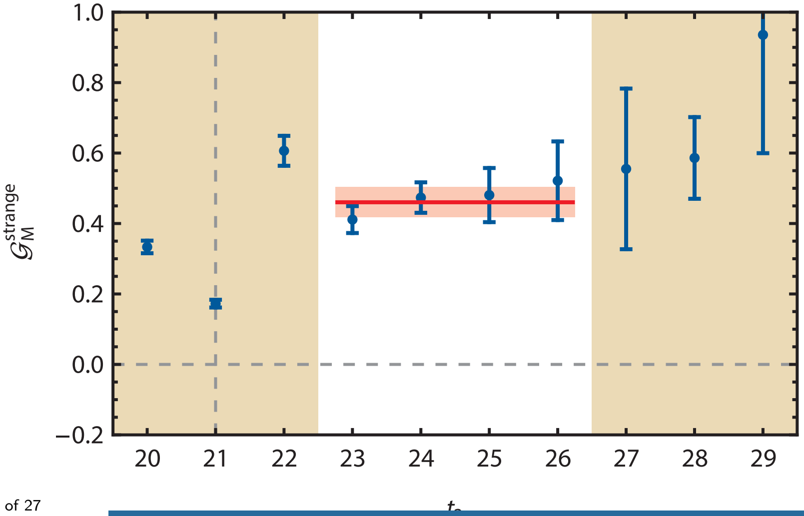
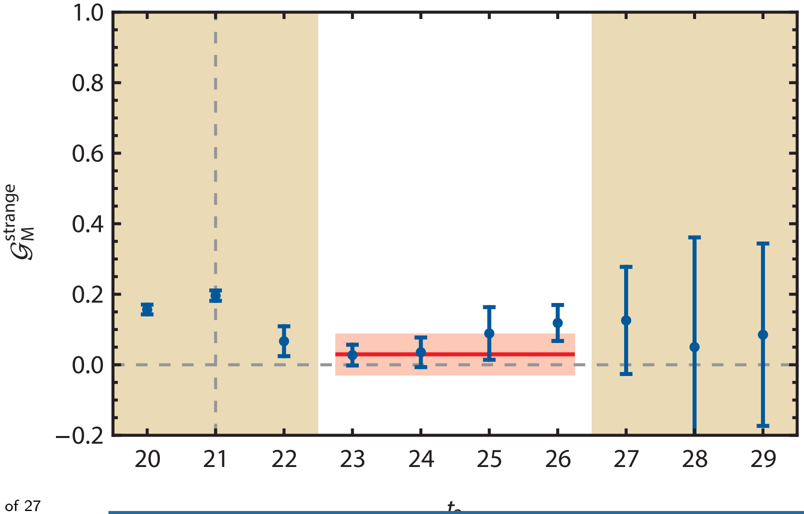
- $\mathcal{G}_{\mathrm{M}}^{\mathrm{strange}}$ is consistent with zero!
- The structure of the $\Lambda(1405)$ is dominated by a bound $\overline{\mathrm{K}}\mathrm{N}$.

Fitted $\mathcal{G}_M(t)$ at $m_\pi^2 = 0.151\,\mathrm{GeV}^2$, $Q^2 = 0.160\,\mathrm{GeV}^2$



Fitted $\mathcal{G}_{\mathrm{M}}(t)$ at $m_\pi^2 = 0.030\,\mathrm{GeV}^2$, $Q^2 = 0.169\,\mathrm{GeV}^2$



Conclusions

- After decade of speculation, the nature of $\Lambda(1405)$ is finally revealed from the first principles of QCD.
- Our results are consistent with the development of a non-trivial $\overline{\text{K}}\text{N}$ component as the quark masses become light.
- At the physical point the structure of the $\Lambda(1405)$ is dominated by a bound $\overline{\text{K}}\text{N}$.