Structure and transitions of nucleon excitations via parity-expanded variational analysis

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Advances in Lattice Gauge Theory 2019

Baryon structure via variational analysis

Step 1: Construct correlation matrix

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Lattice results

PACS-CS $(2+1)$-flavour full-QCD ensembles

- $32^3 \times 64$ lattices
- Renormalisation-group improved Iwasaki gauge action
- Non-perturbatively O(a)-improved Wilson quarks
- $a = 0.0933(13)$–$0.1023(15)\,\mathrm{fm}$ by Sommer parameter
- $m_\pi = 156$–$702\,\mathrm{MeV}$

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Correlation Matrix

$$\mathcal{G}_{ij}(\boldsymbol{p};\,t) \equiv \sum_{\boldsymbol{x}} \mathrm{e}^{i\boldsymbol{p}\cdot\boldsymbol{x}}\,\langle\Omega|\chi^i(x)\,\overline{\chi}^j(0)|\Omega\rangle$$

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Step 2: Perform variational analysis

- Seek operators $\{\phi_{\boldsymbol{p}}^{\alpha}\}$ that couple strongly to a single energy eigenstate

$$\phi_{\boldsymbol{p}}^{\alpha} = \sum_{i} v_{i}^{\alpha}(\boldsymbol{p})\ \chi_{\boldsymbol{p}}^{i} + \sum_{i'} v_{i'}^{\alpha}(\boldsymbol{p})\ \chi_{\boldsymbol{p}}^{i'}$$

$$\overline{\phi}_{\boldsymbol{p}}^{\alpha} = \sum_{i} u_{i}^{\alpha}(\boldsymbol{p})\ \overline{\chi}_{\boldsymbol{p}}^{i} + \sum_{i'} u_{i'}^{\alpha}(\boldsymbol{p})\ \overline{\chi}_{\boldsymbol{p}}^{i'}$$

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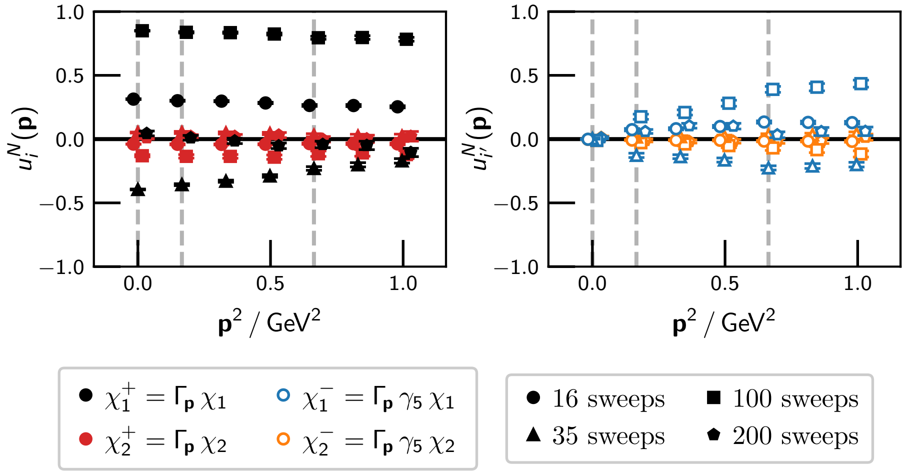
- Coefficients can be found by solving generalised eigenvalue problem

$$\boldsymbol{v}^{\alpha}(\boldsymbol{p})\ G(\boldsymbol{p};\, t_0) = \exp(-E^{\alpha}(\boldsymbol{p})\,\Delta t)\ \boldsymbol{v}^{\alpha}(\boldsymbol{p})\ G(\boldsymbol{p};\, t_0 + \Delta t)$$

$$G(\boldsymbol{p};\, t_0)\ \boldsymbol{u}^{\alpha}(\boldsymbol{p}) = \exp(-E^{\alpha}(\boldsymbol{p})\,\Delta t)\ G(\boldsymbol{p};\, t_0 + \Delta t)\ \boldsymbol{u}^{\alpha}(\boldsymbol{p})$$

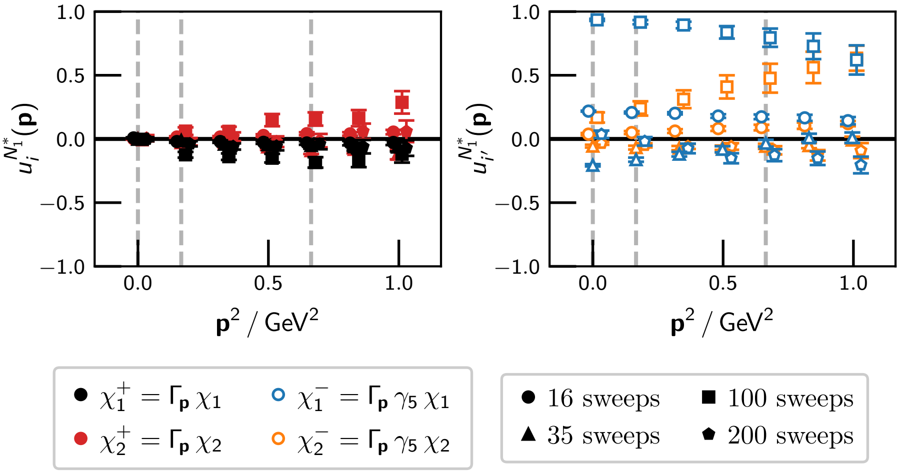
Eigenvector components

Ground state



Eigenvector components

First negative parity excitation



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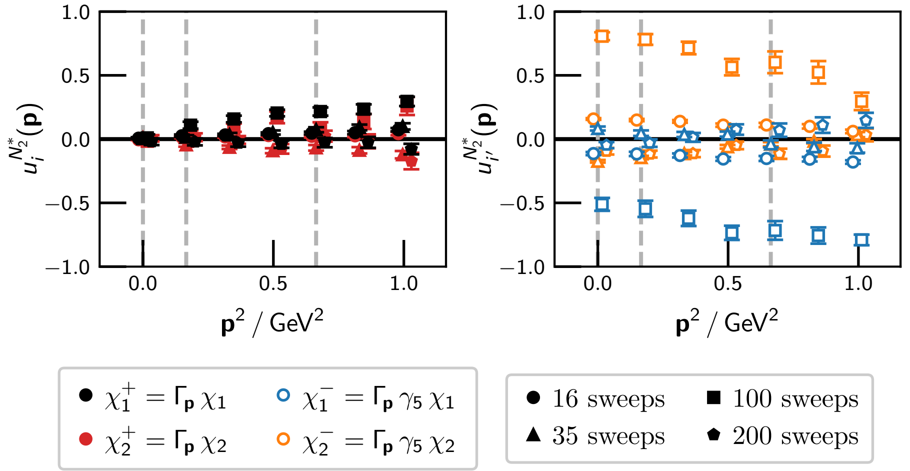

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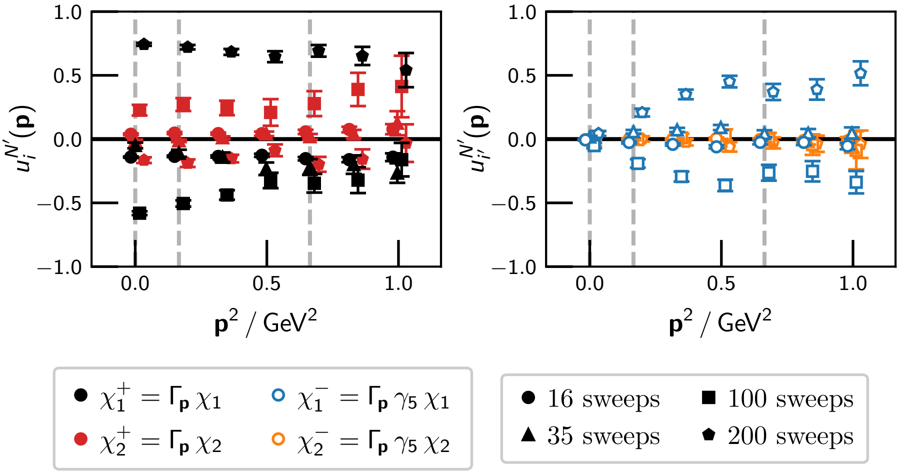
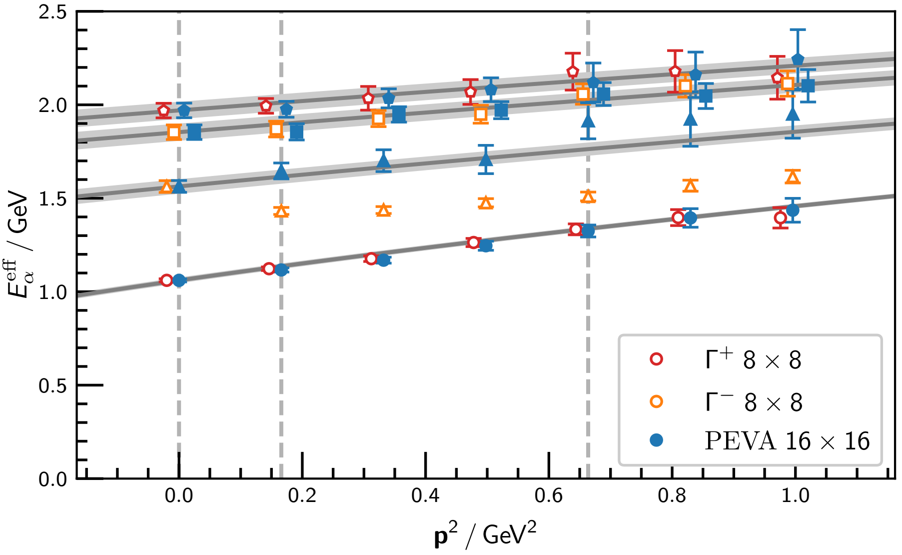


Effective energy

Nucleon spectrum



More information

“Parity-expanded variational analysis for nonzero momentum”
F. M. Stokes, W. Kamleh, D. B. Leinweber, M. S. Mahbub,
B. J. Menadue, B. J. Owen
Phys. Rev. D **92** (2015) 11, 114506
doi:10.1103/PhysRevD.92.114506
arXiv:1302.4152 (hep-lat).

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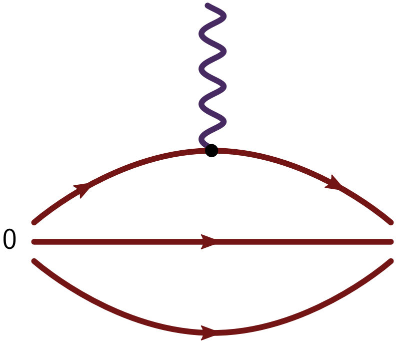

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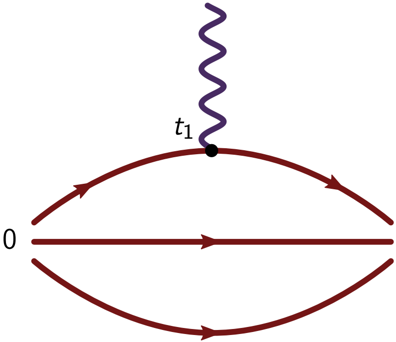

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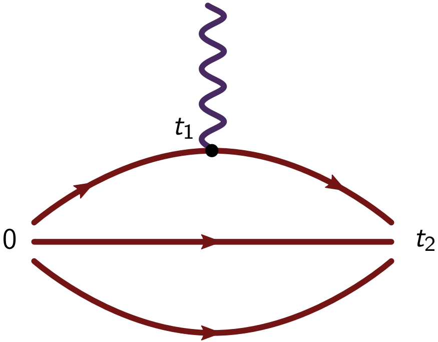

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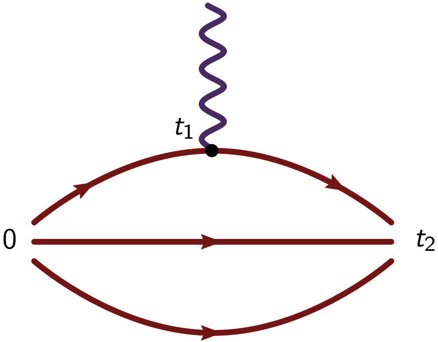

Matrix element

$$\langle B\,;p'\,;s'|\,j^\mu\,|\,B\,;p\,;s\rangle \propto$$

$$\overline{u}_B\left(\gamma^\mu F_1(Q^2) - \frac{\sigma^{\mu\nu}q_\nu}{2m_B}F_2(Q^2)\right)u_B$$

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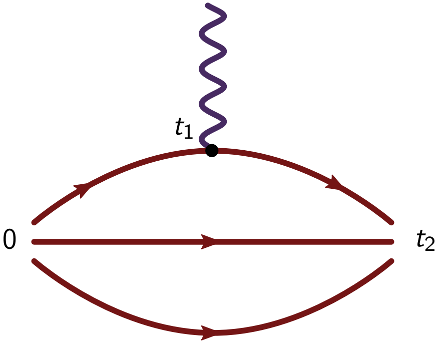

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Sachs form factors

$$G_E(Q^2) = F_1(Q^2) - \frac{Q^2}{2m_B}F_2(Q^2)$$
$$G_M(Q^2) = F_1(Q^2) + F_2(Q^2)$$

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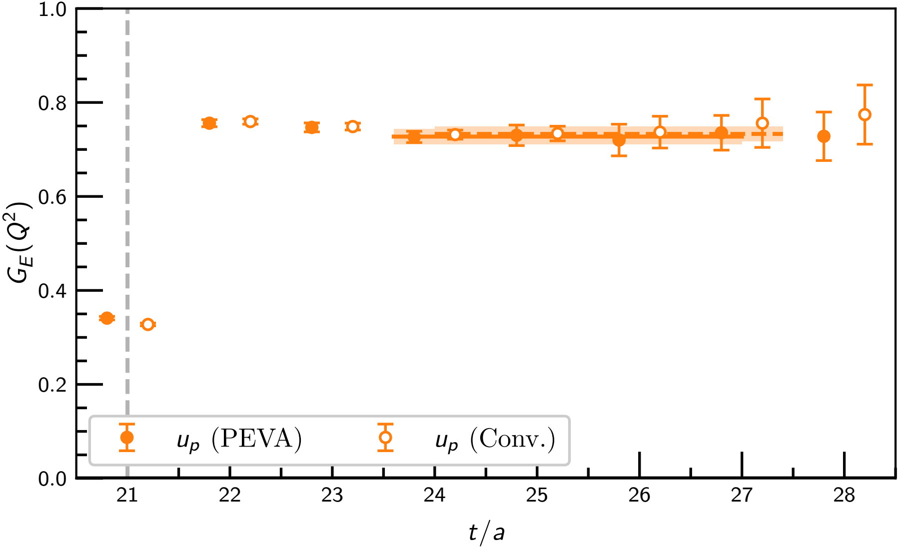
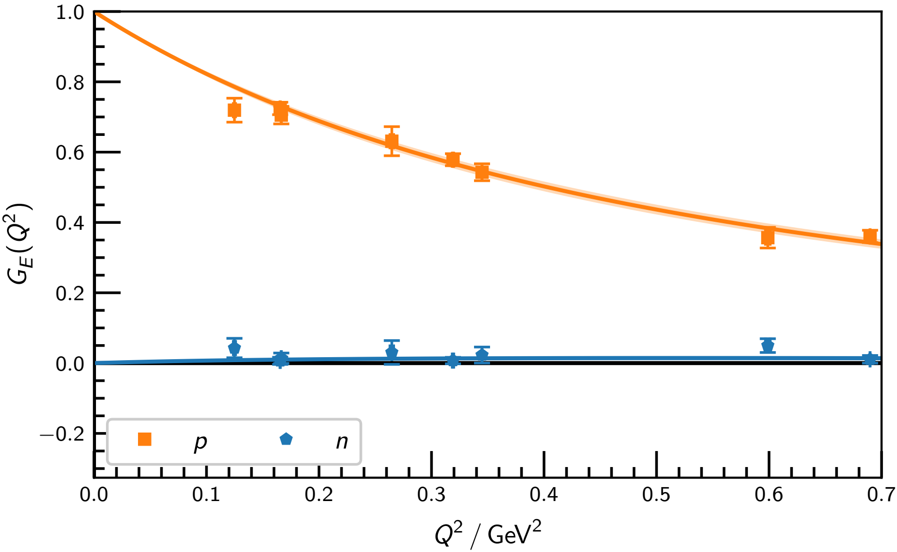
Ground state

Fits to $G_E(Q^2 = 0.166(4))$ ($m_\pi = 156\,\mathrm{MeV}$)



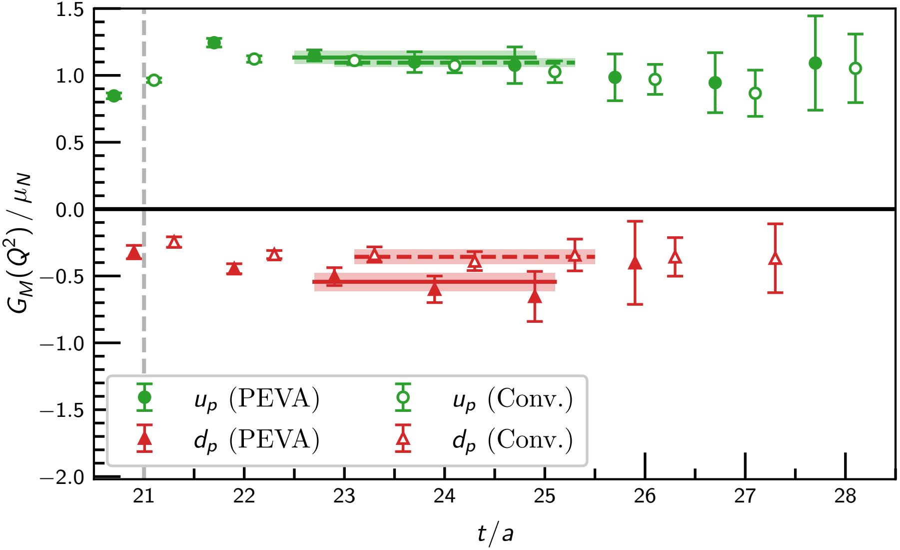
Ground state

Momentum-dependence of $G_E(Q^2)$ ($m_\pi = 156\,\mathrm{MeV}$)



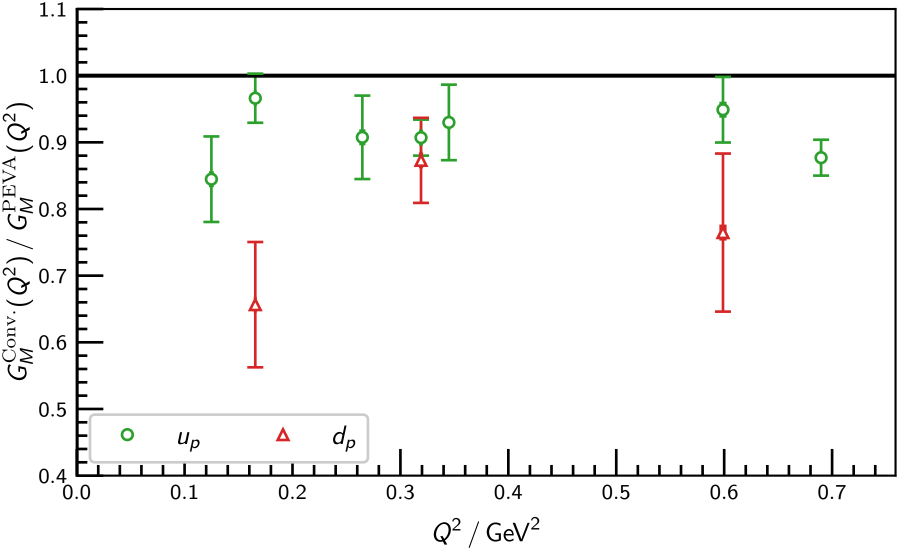
Ground state

Fits to $G_M(Q^2 = 0.166(4))$ ($m_\pi = 156\,\mathrm{MeV}$)



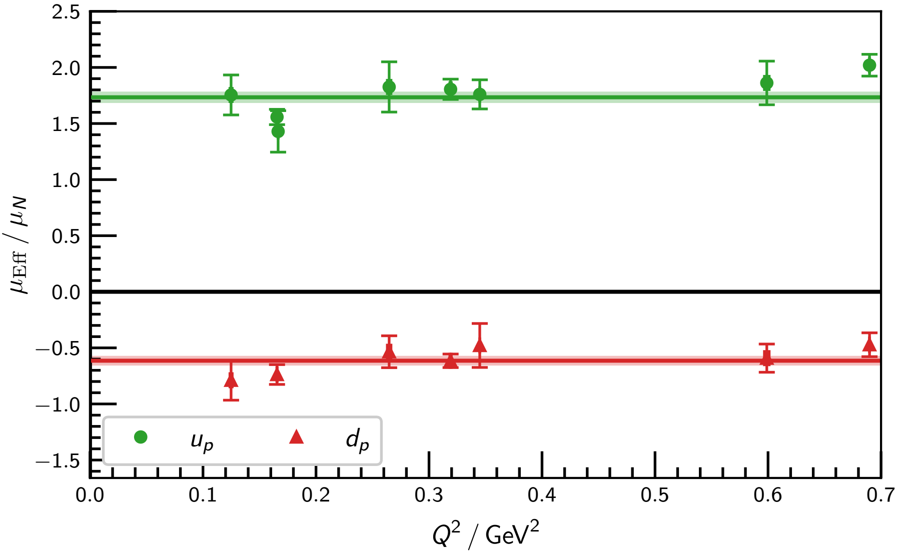
Ground state

Ratios of conventional $G_M(Q^2)$ plateaus to PEVA ($m_\pi = 156\,\mathrm{MeV}$)



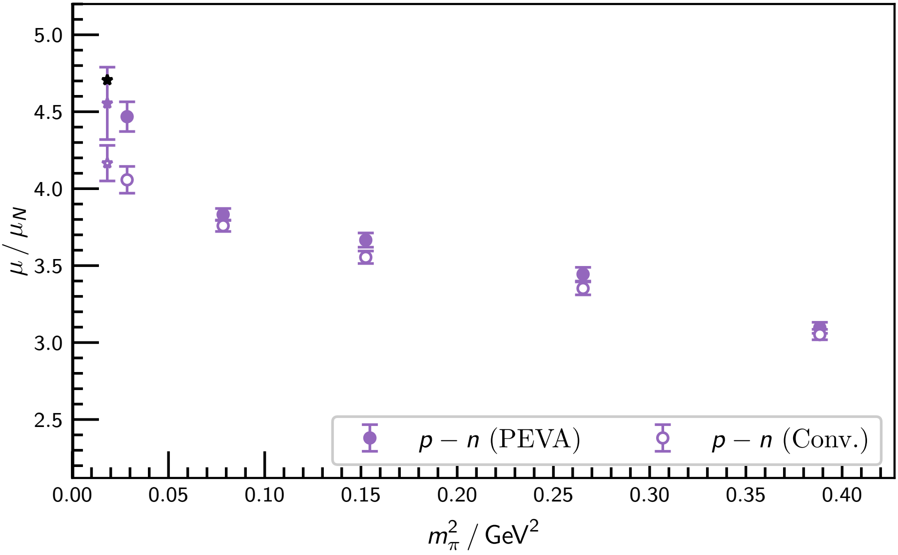
Ground state

Magnetic moment estimate ($m_\pi = 156\,\mathrm{MeV}$)



Ground state

Pion-mass dependence of magnetic moment

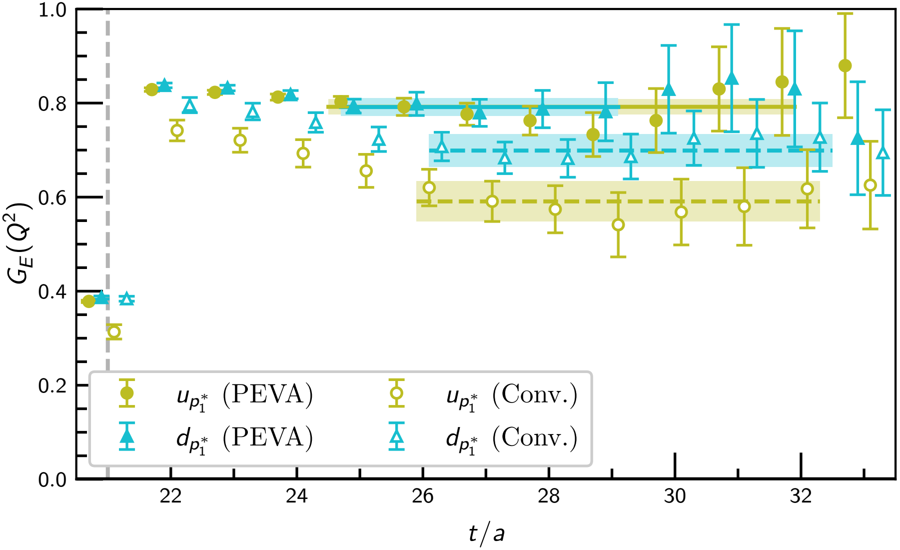


More information

“Opposite-Parity Contaminations in Lattice Nucleon Form Factors”
F. M. Stokes, W. Kamleh, D. B. Leinweber
Phys. Rev. D **99** (2019) 7, 074506
doi:10.1103/PhysRevD.99.074506
arXiv:1809.11002 (hep-lat).

First negative-parity excitation

Fits to $G_E(Q^2 = 0.142(4))$ ($m_\pi = 702\,\text{MeV}$)



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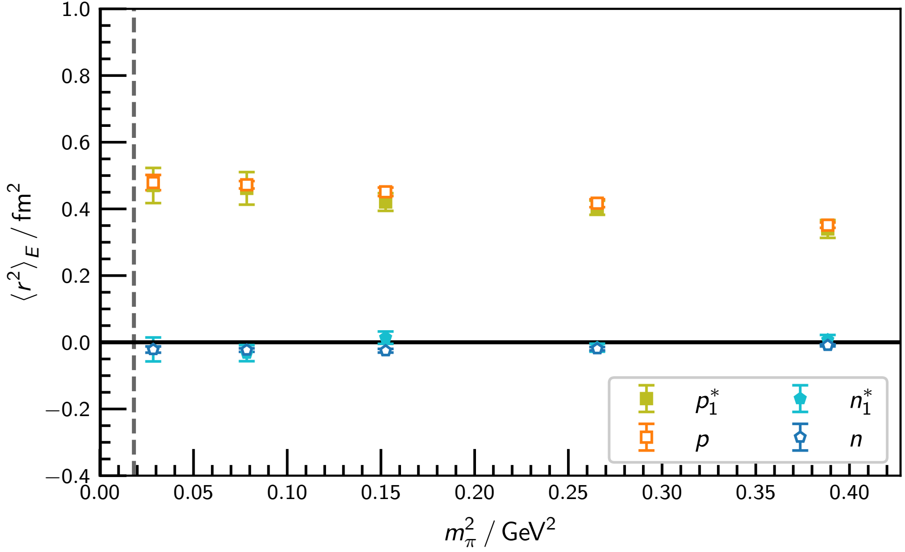
Pion-mass dependence of charge radius



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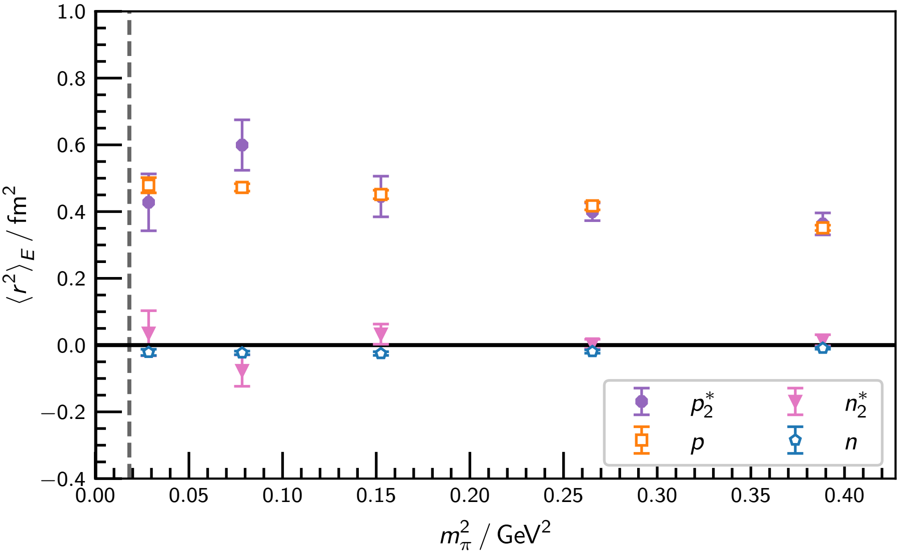

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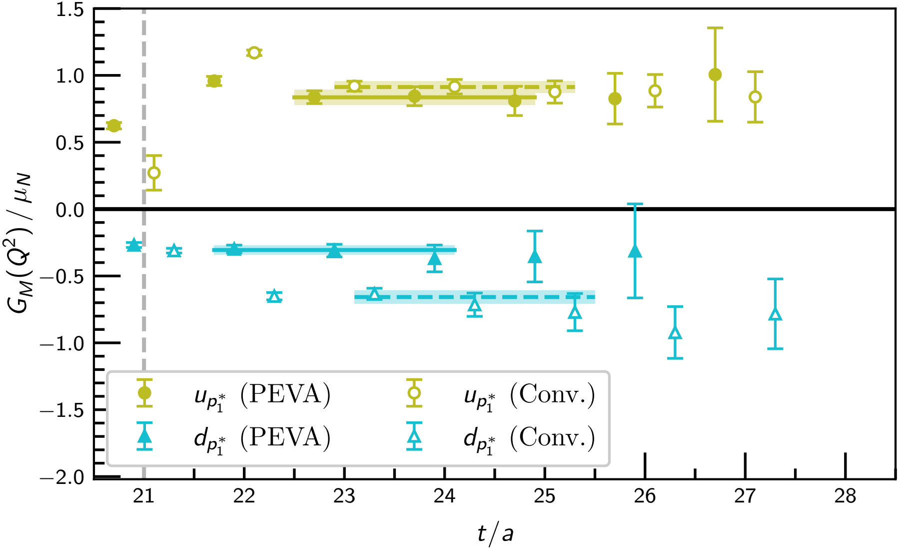

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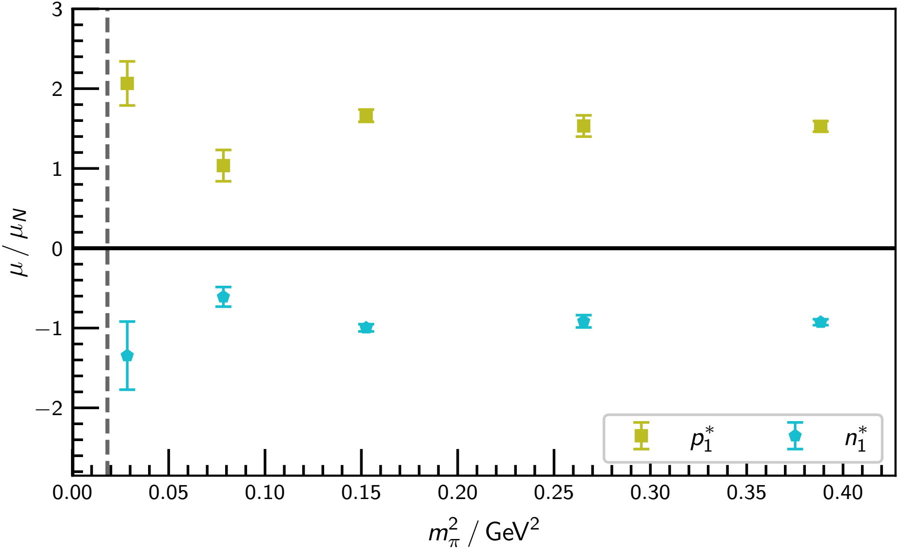

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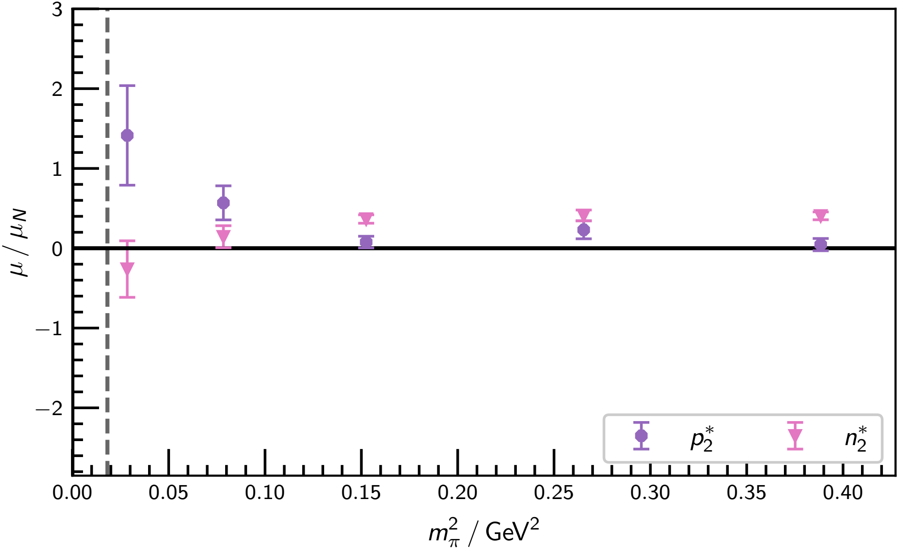

Comparison to constituent quark model

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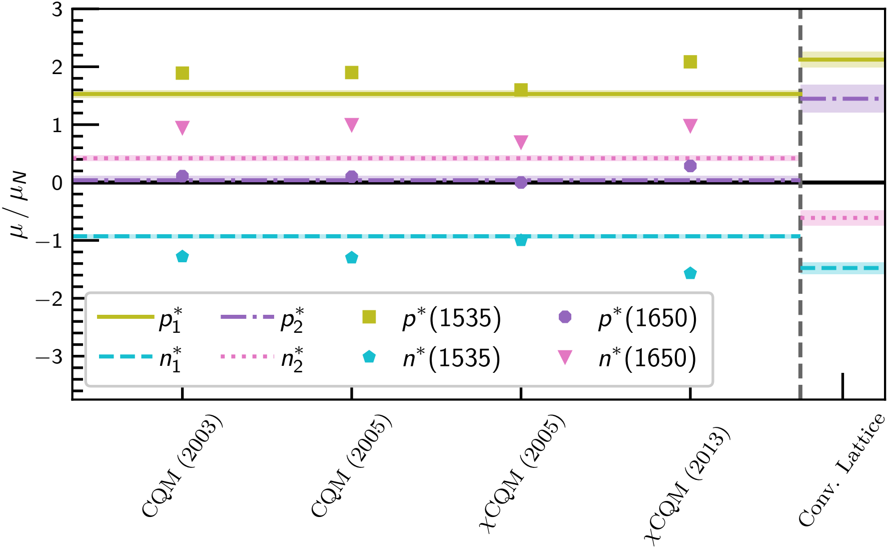

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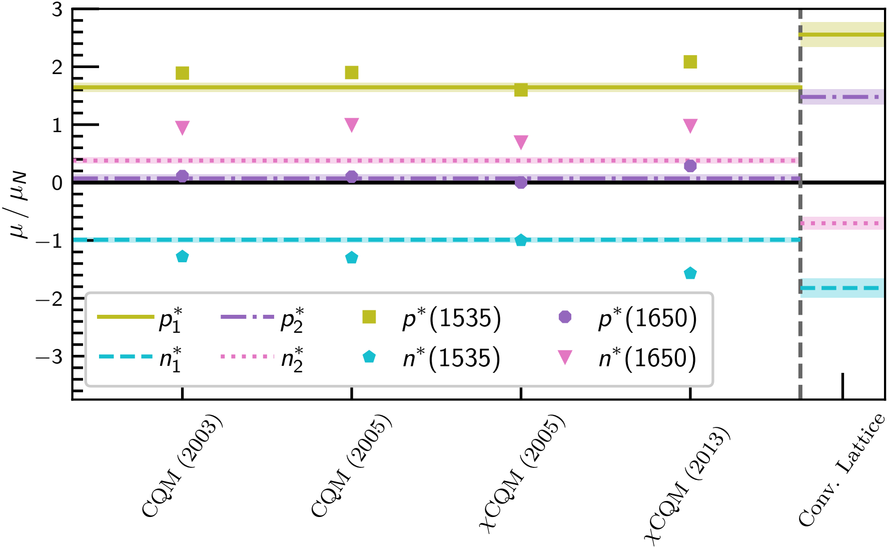

Comparison to constituent quark model

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- W.-T. Chiang, S. N. Yang, M. Vanderhaeghen and D. Drechsel, Nucl. Phys. A **723** (2003), doi:10.1016/S0375-9474(03)01160-6.
- J. Liu, J. He and Y. B. Dong, Phys. Rev. D **71** (2005), doi:10.1103/PhysRevD.71.094004.
- N. Sharma, A. Martinez Torres, K. P. Khemchandani and H. Dahiya, Eur. Phys. J. A **49** (2013), doi:10.1140/epja/i2013-13011-2.

Step 3: Compute three point correlation function

Matrix element

$$\langle \beta^- ; p' ; s' | \, j^\mu \, | \, \alpha^+ ; p ; s \rangle \propto$$
$$\overline{u}_\beta \left(\left(\delta^{\mu\nu} - \frac{q^\mu q^\nu}{q^2} \right) \gamma^\nu \gamma^5 F_1^*(Q^2) - \frac{\sigma^{\mu\nu} q_\nu}{m_\beta - m_\alpha} \gamma^5 F_2^*(Q^2) \right) u_\alpha$$

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Helicity amplitudes

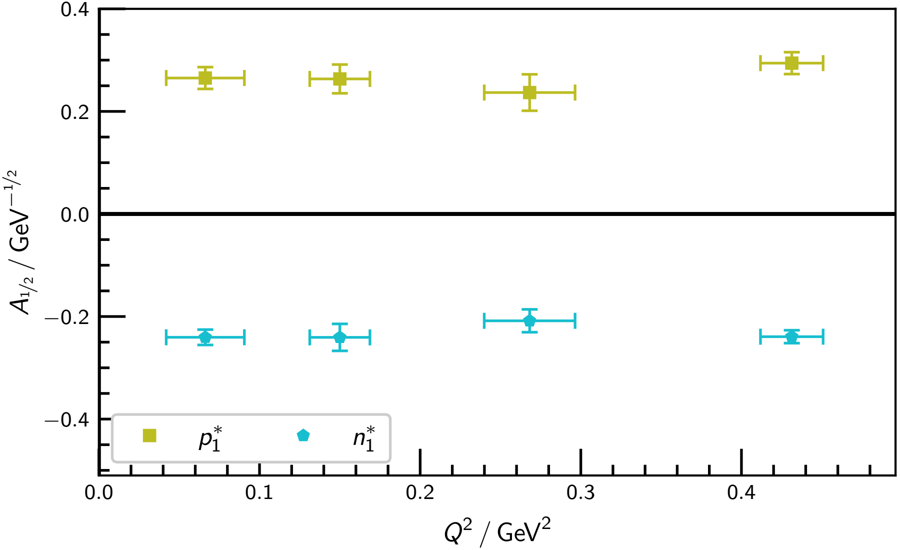
$$A_{1/2}(Q^2) = 2b_- \left(F_1^*(Q^2) + F_2^*(Q^2) \right)$$

$$S_{1/2}(Q^2) = -\sqrt{2} b_- \frac{(m_\beta - m_\alpha) \, |\vec{q}|}{Q^2} \left(F_1^*(Q^2) - \frac{Q^2}{m_\beta - m_\alpha} F_2^*(Q^2) \right)$$

$$b_- = \sqrt{\frac{Q^2 + (m_\beta + m_\alpha)^2}{8 m_\alpha (m_\beta^2 - m_\alpha^2)}}$$

Transition to first negative parity excitation

Transverse helicity amplitude at $m_\pi = 702\,\mathrm{MeV}$



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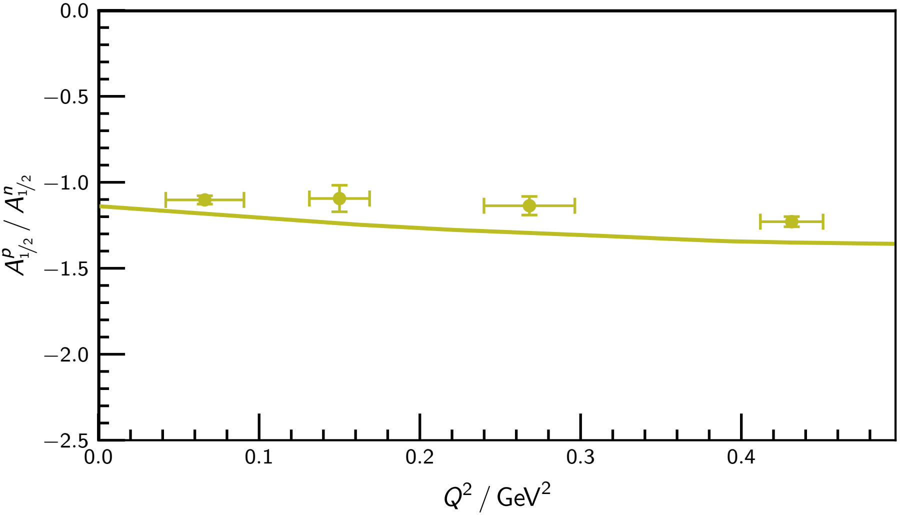
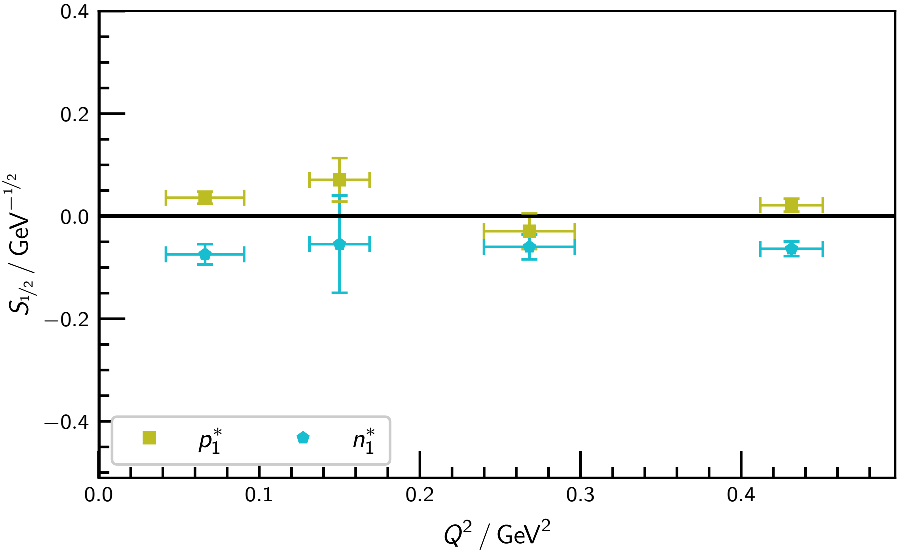
Transverse helicity amplitude ratio at $m_\pi = 702\,\mathrm{MeV}$



S. Capstick, B. D. Keister, Phys. Rev. D **51** (1995), doi:10.1103/PhysRevD.51.3598.

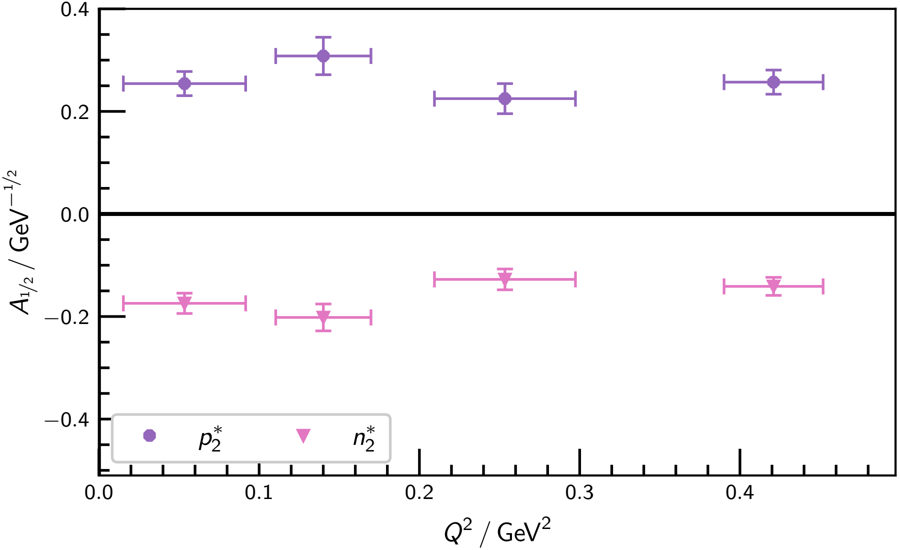
Transition to first negative parity excitation

Longitudinal helicity amplitude at $m_\pi = 702\,\mathrm{MeV}$



Transition to second negative parity excitation

Transverse helicity amplitude at $m_\pi = 702\,\mathrm{MeV}$



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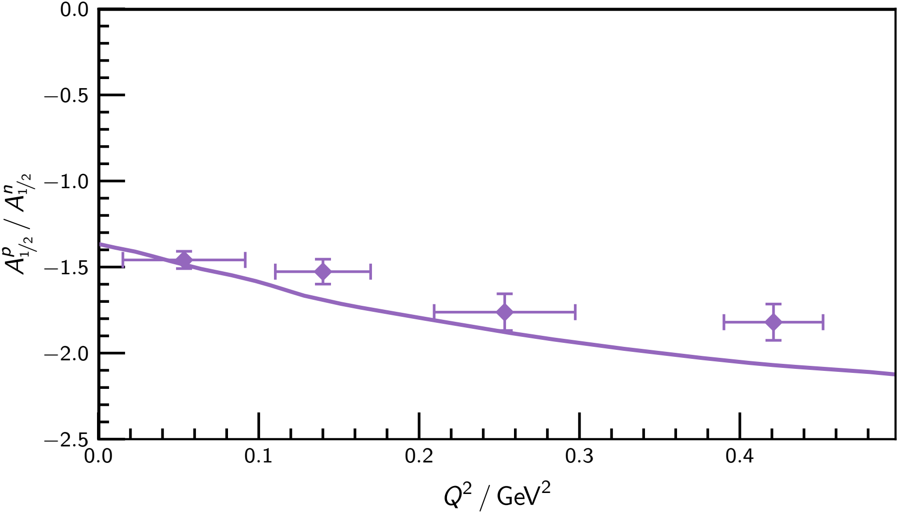

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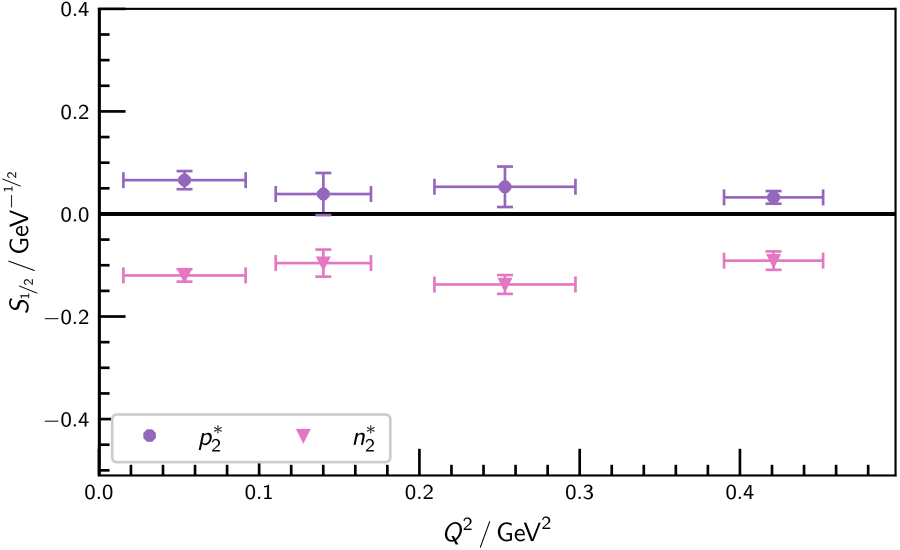
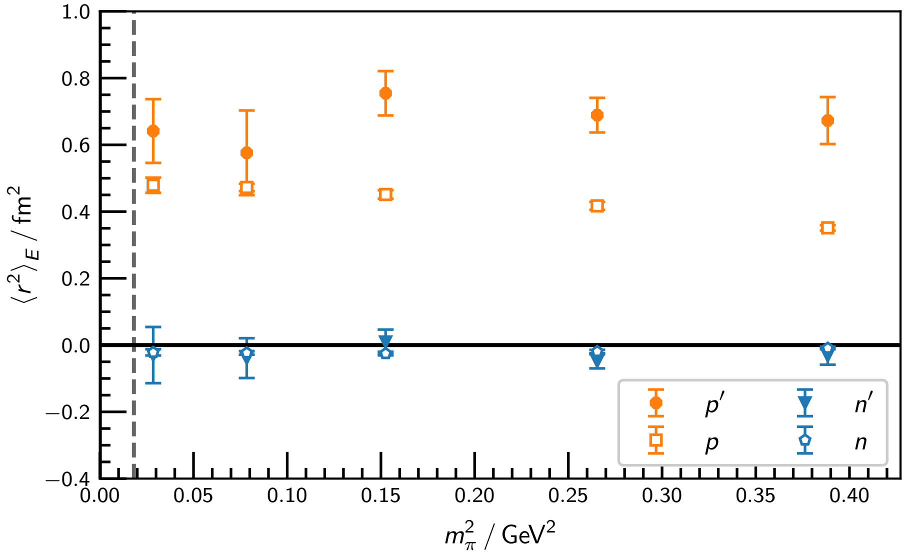


First positive-parity excitation

Pion-mass dependence of charge radius



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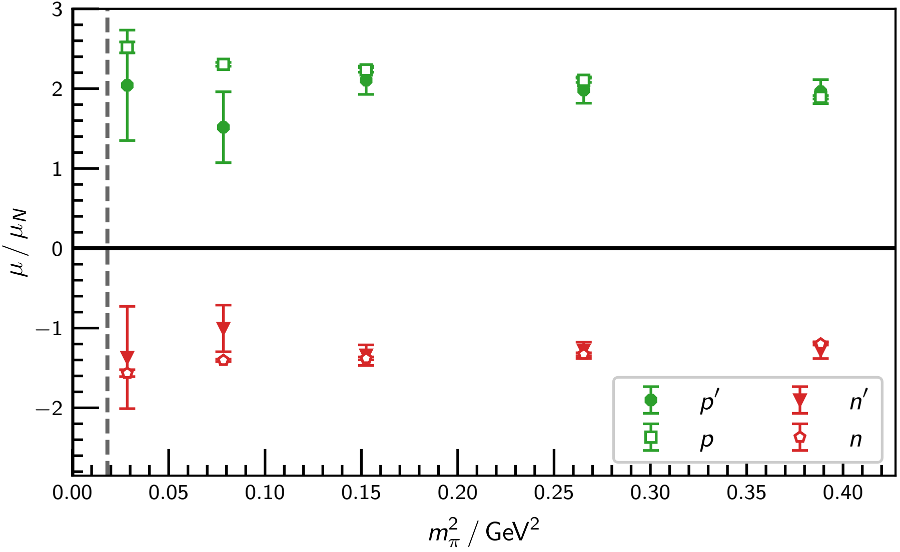
Pion-mass dependence of magnetic moment



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  - At heavier pion masses, have magnetic moments consistent with quark model expectations for the $N^*(1535)$ and $N^*(1650)$
  - At lighter pion masses, meson-baryon scattering states seem to play a more significant role

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- Two low-lying localised $\frac{1}{2}^-$ nucleon excitations on the lattice
  - At heavier pion masses, have magnetic moments consistent with quark model expectations for the $N^*(1535)$ and $N^*(1650)$
  - At lighter pion masses, meson-baryon scattering states seem to play a more significant role
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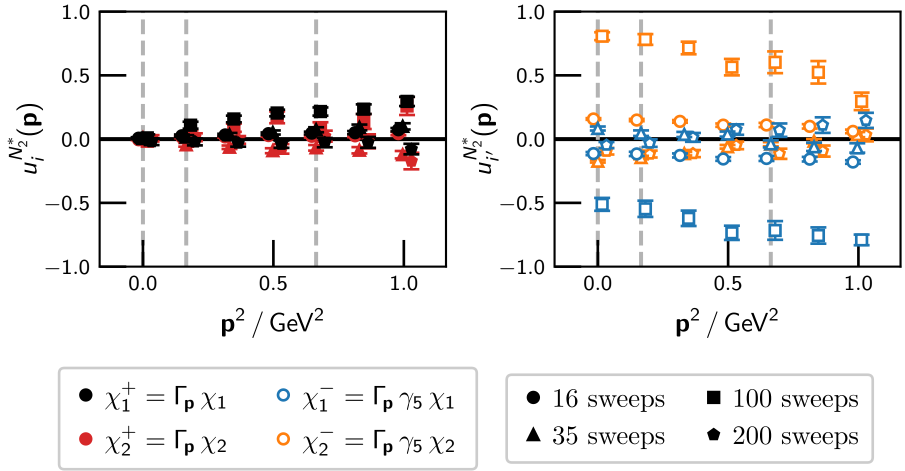
Eigenvector components

Second negative parity excitation



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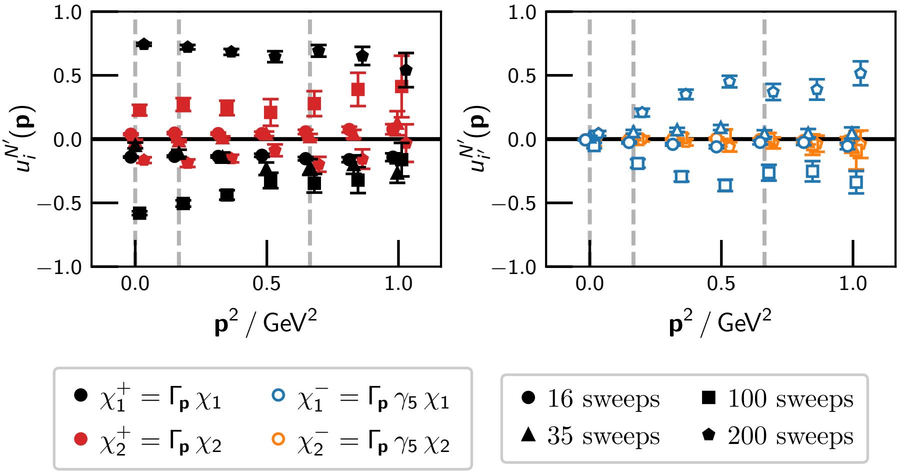
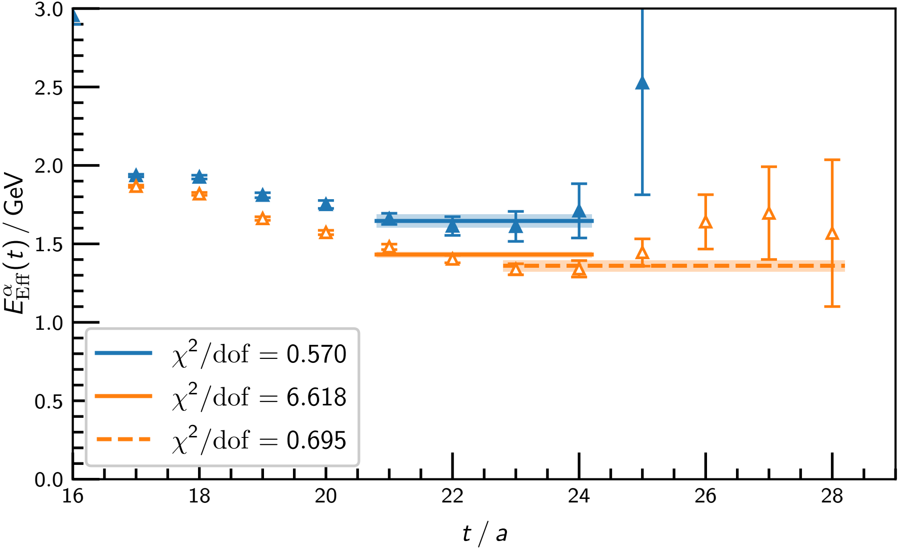


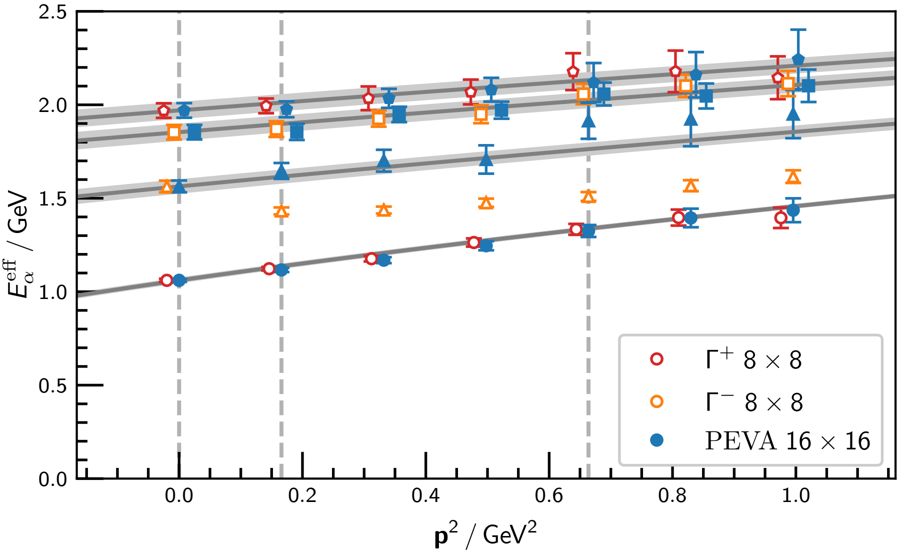
Effective energy

First negative parity excitation - $\boldsymbol{p}^2 \simeq 0.166\,\mathrm{GeV}^2$



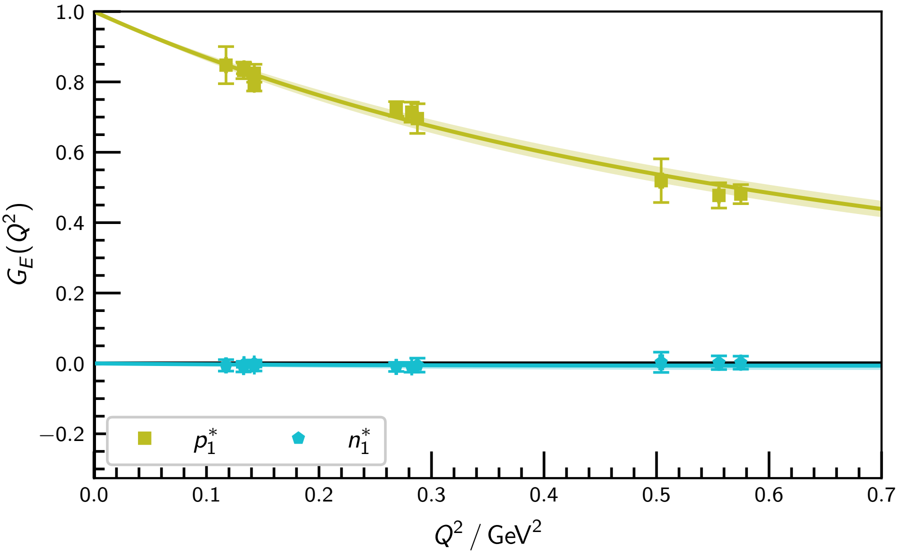
Effective energy

Nucleon spectrum



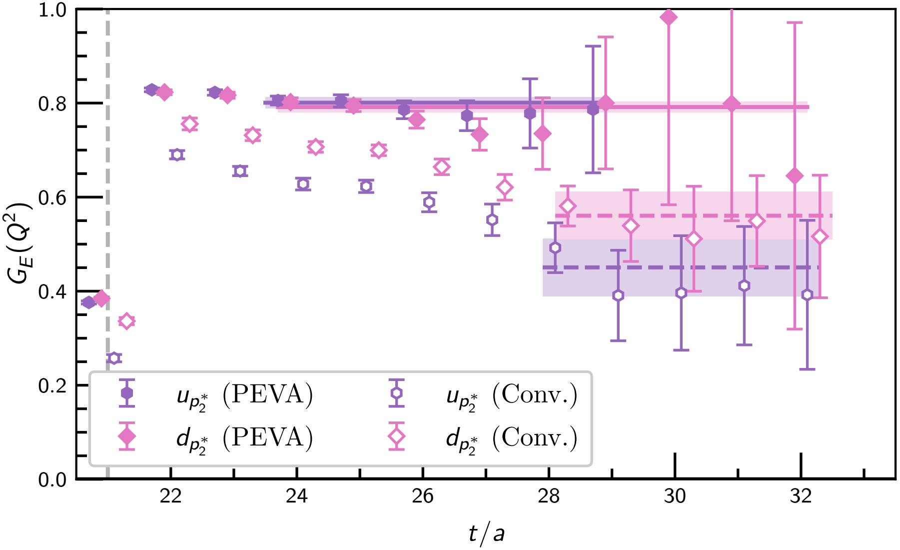
First negative-parity excitation

Momentum-dependence of $G_E(Q^2)$ ($m_\pi = 702\,\text{MeV}$)



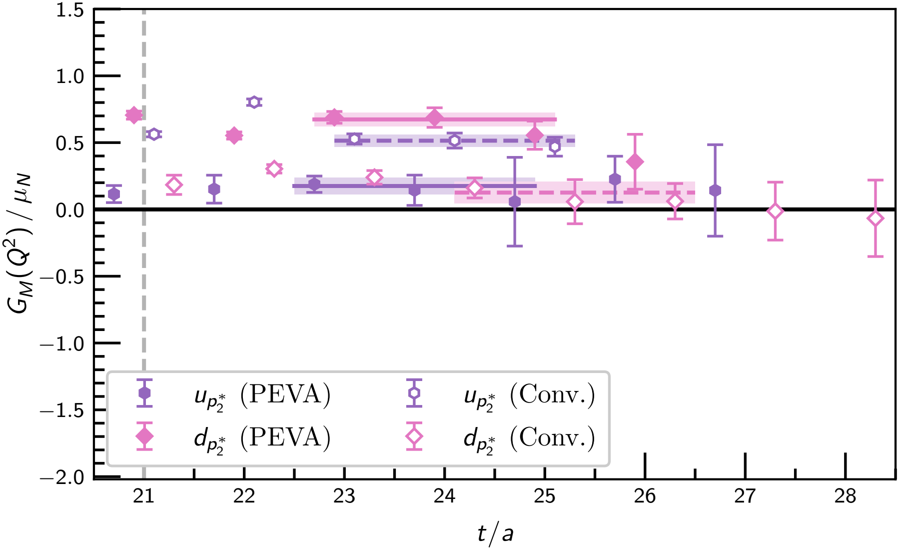
Second negative-parity excitation

Fits to $G_E(Q^2 = 0.142(4))$ ($m_\pi = 702\,\mathrm{MeV}$)



Second negative-parity excitation

Fits to $G_M(Q^2 = 0.142(4))$ $(m_\pi = 702\,\text{MeV})$



Parity projection

$$\mathcal{G}_{ij}(\boldsymbol{p};\ t) = \sum_{B^\pm} \mathrm{e}^{-E_{B^\pm}(\boldsymbol{p})\,t}\,\lambda_i^{B^\pm}\,\overline{\lambda}_j^{B^\pm}\,\frac{-i\,\gamma\cdot p \pm m_{B^\pm}}{2E_{B^\pm}(\boldsymbol{p})}$$

- Introduce $\Gamma_\pm = (\gamma_4 \pm \mathbb{I})/2$ and define $G_{ij}(\Gamma_\pm; \boldsymbol{p};\ t) \equiv \mathrm{Tr}\left(\Gamma_\pm\,\mathcal{G}_{ij}(\boldsymbol{p};\ t)\right)$

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- At zero momentum, $E_B(\mathbf{0}) = m_B$, so

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