

Parity Expanded Correlation Matrix Techniques at Non-Zero Momentum

Finn M. Stokes

Waseem Kamleh and Derek B. Leinweber

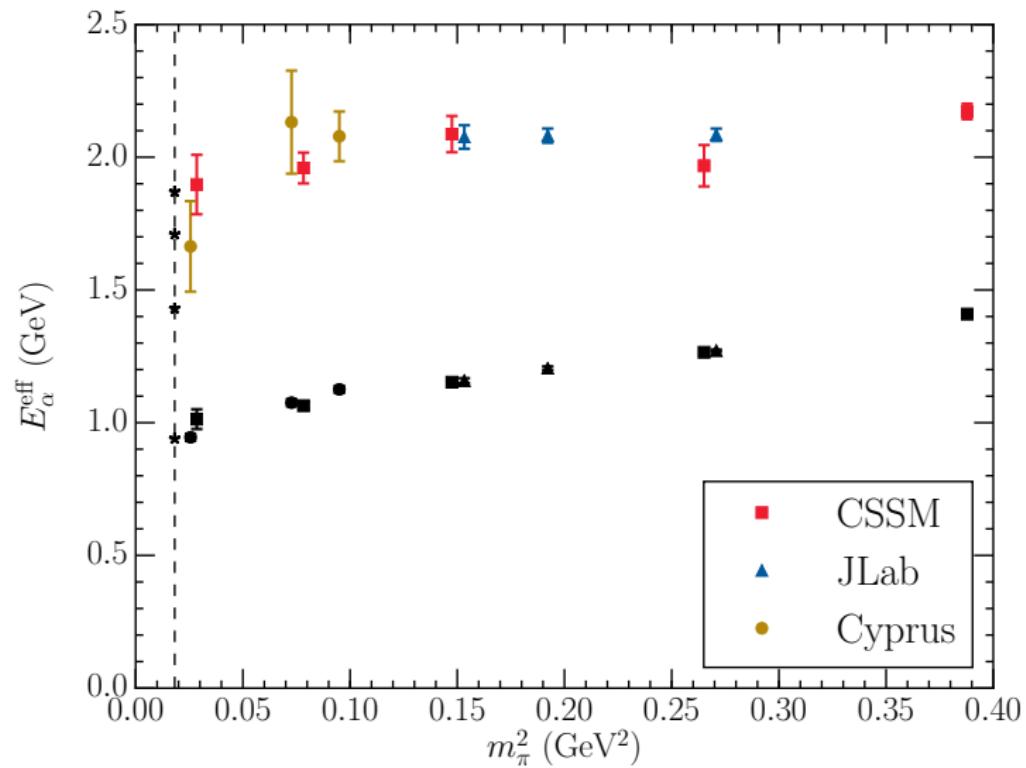
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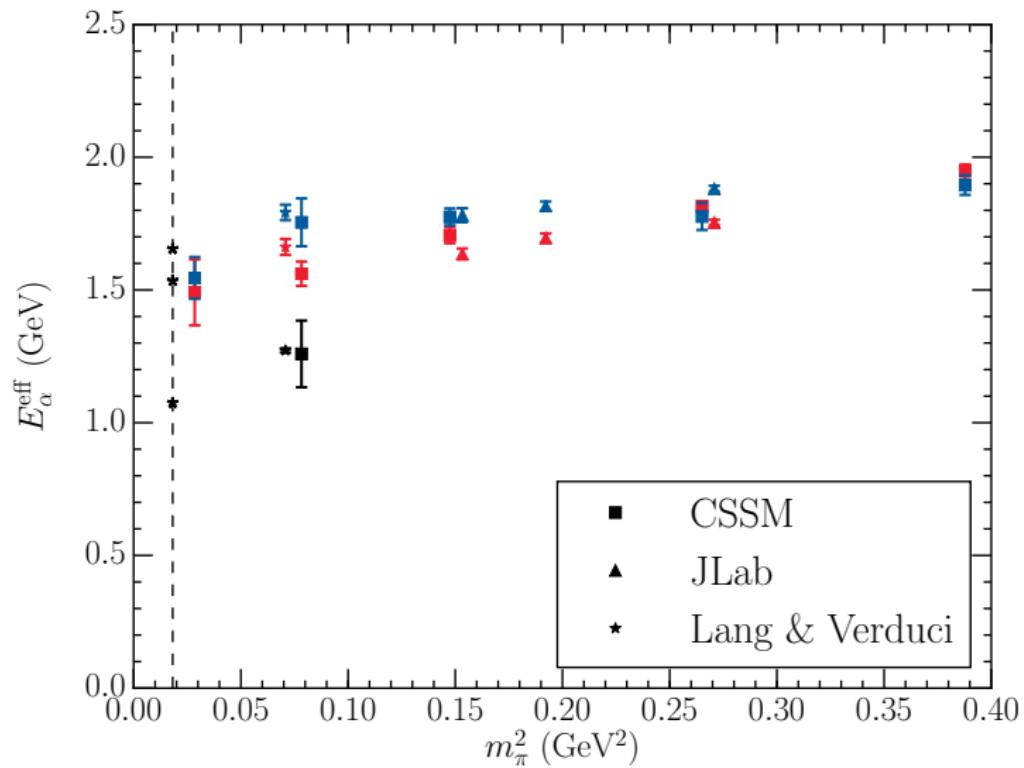
Baryon spectroscopy

Positive parity nucleon spectrum



Baryon spectroscopy

Negative parity nucleon spectrum



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- Call states that transform positively under parity in their rest frame “positive parity states” (B^+)
- Call states that transform negatively under parity in their rest frame “negative parity states” (B^-)

Conventional analysis

- Conventional baryon operators $\{\chi^i\}$ couple to states of both parities

$$\langle \Omega | \chi^i | B^+ \rangle = \lambda_i^{B^+} \sqrt{\frac{m_{B^+}}{E_{B^+}}} u_{B^+}(p, s)$$

$$\langle \Omega | \chi^i | B^- \rangle = \lambda_i^{B^-} \sqrt{\frac{m_{B^-}}{E_{B^-}}} \gamma_5 u_{B^-}(p, s)$$

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Zero momentum

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

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- Can analyse states of each parity independently

Lattice results

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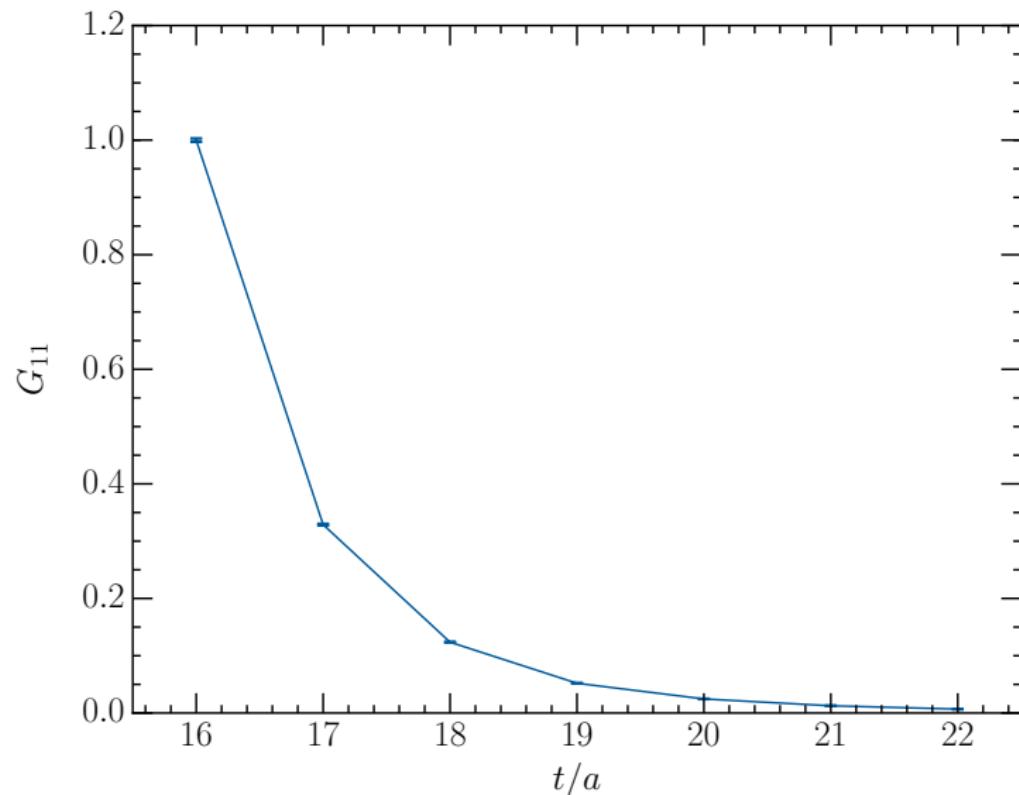
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- Apply 16, 35, 100 and 200 sweeps of stout-link smearing in creating the propagators

Correlation function

$$G_{11}(\Gamma_+; \mathbf{0}; t)$$



Non-zero momentum

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- $O(|\mathbf{p}|)$ opposite parity contaminations at non-zero momentum
- Can remove single opposite parity state with

$$\Gamma_{\pm}(\mathbf{p}) = \frac{1}{2} \left(\frac{m_{B^{\mp}}}{E_{B^{\mp}}(\mathbf{p})} \gamma_4 \pm \mathbb{I} \right)$$

New operators

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- Both couple to states with consistent Dirac structure $\Gamma_{\mathbf{p}}u_B(p, s)$

New operators

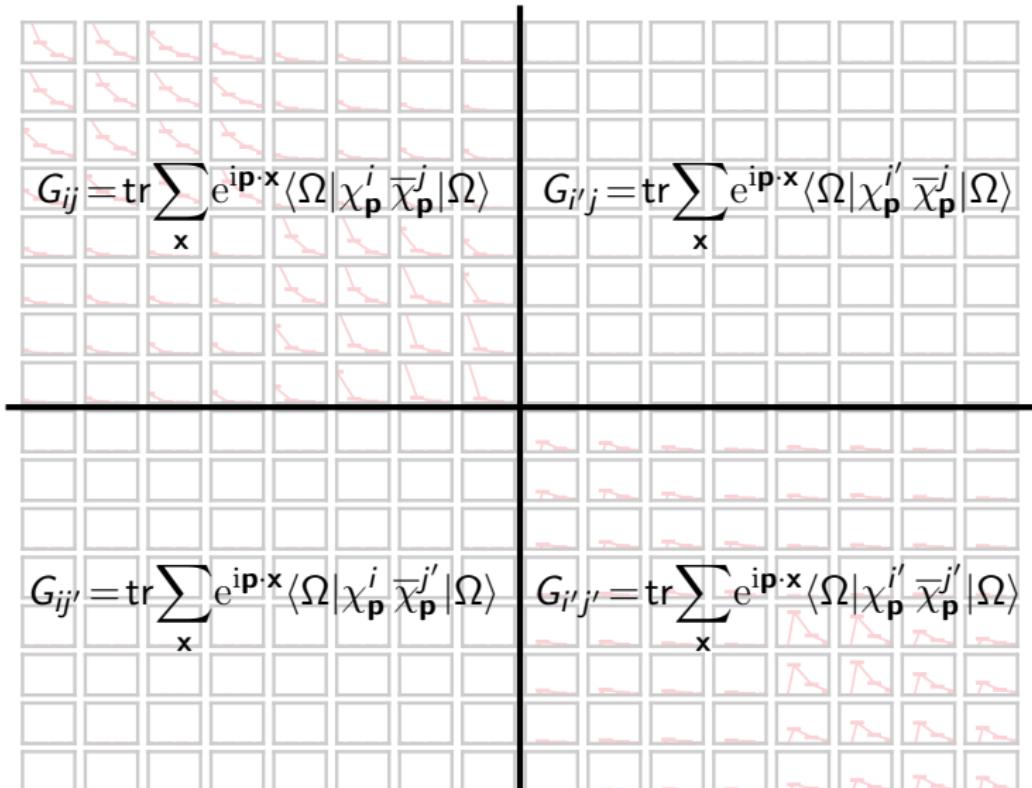
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- Both couple to states with consistent Dirac structure $\Gamma_{\mathbf{p}}u_B(p, s)$
- Use $\{\chi_{\mathbf{p}}^i, \chi_{\mathbf{p}}^{i'}\}$ as expanded basis for correlation matrix analysis

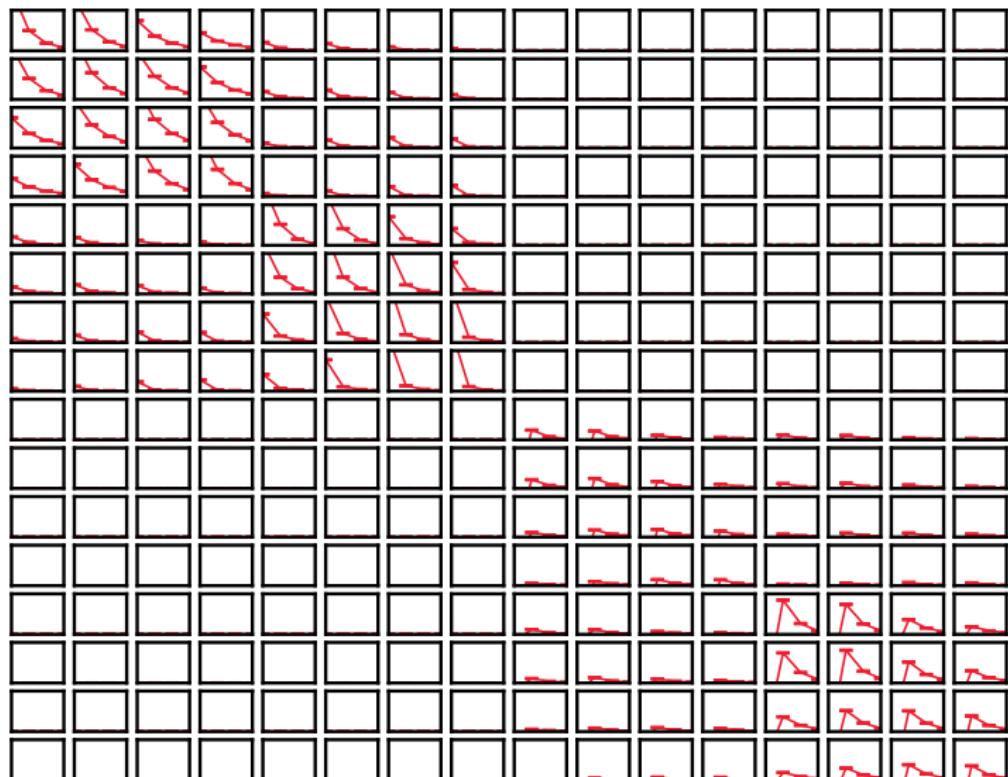
Correlation matrix

$$\mathbf{p}^2 = 0 \text{ GeV}^2$$



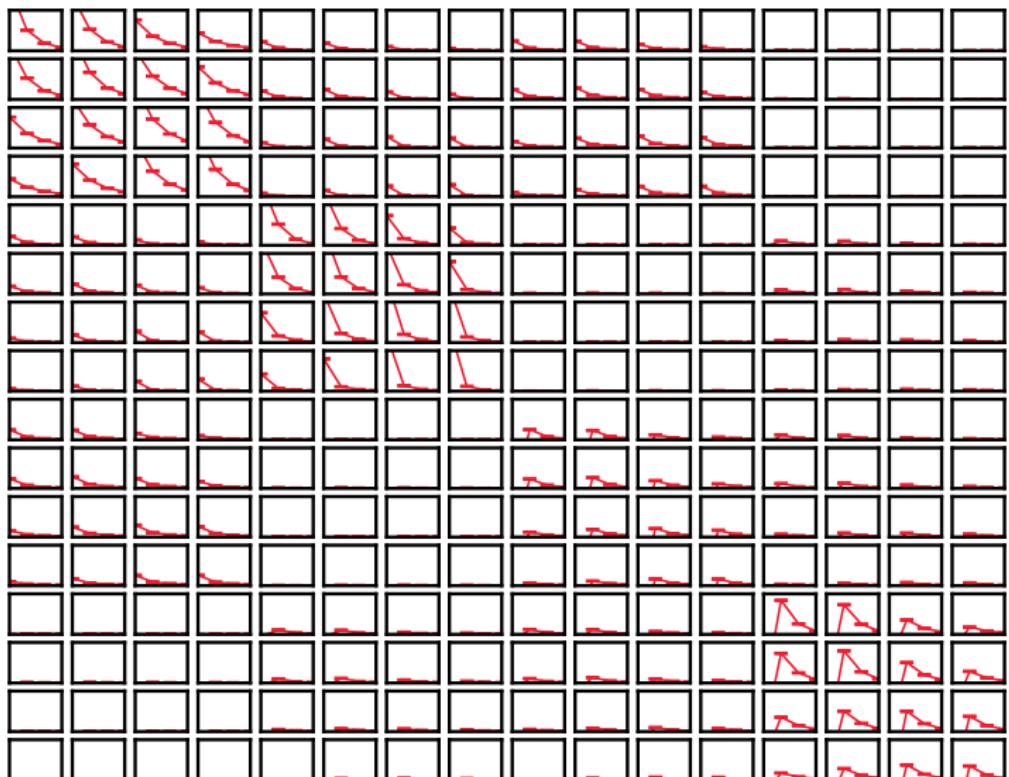
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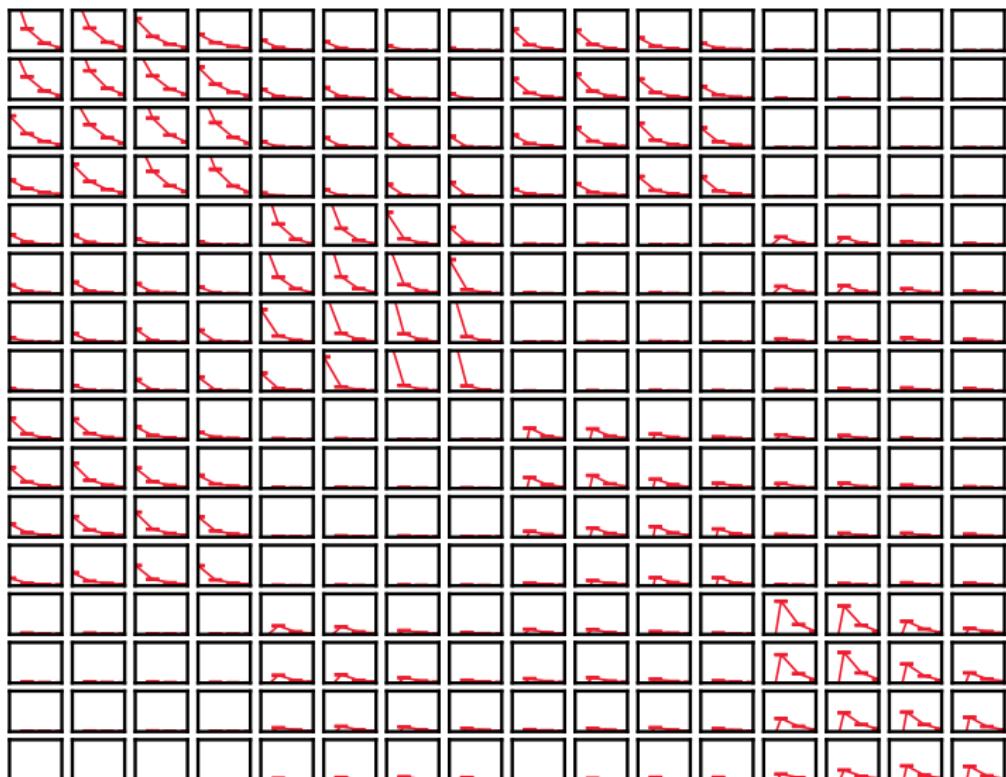
Correlation matrix

$$p^2 = 0.166 \text{ GeV}^2$$



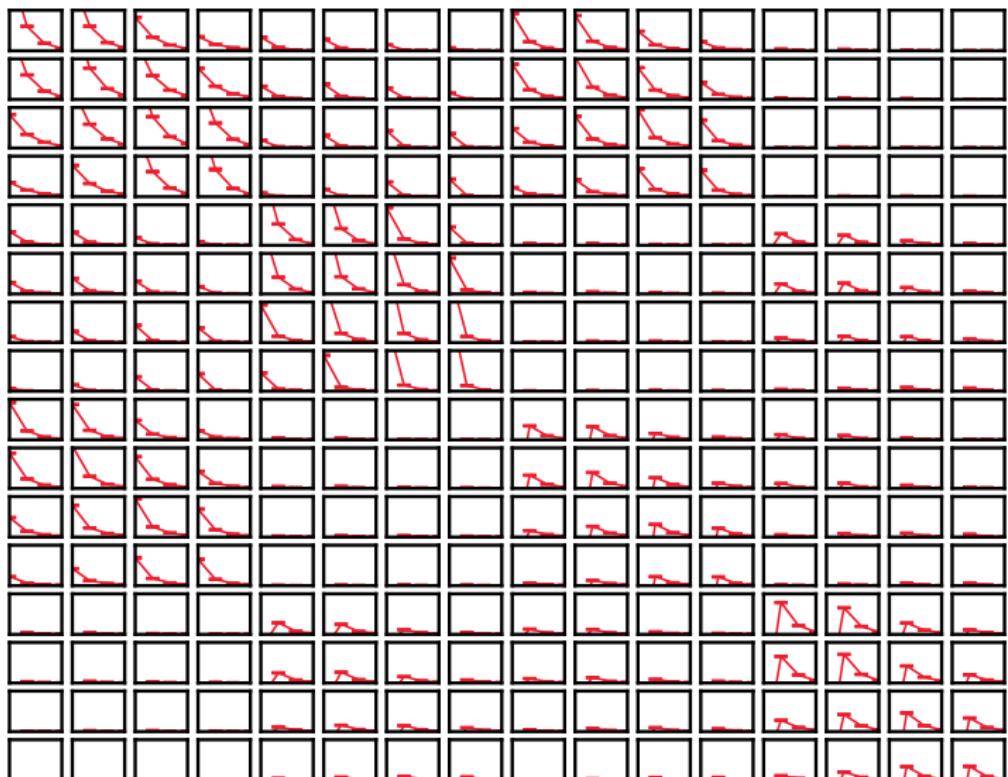
Correlation matrix

$$p^2 = 0.332 \text{ GeV}^2$$



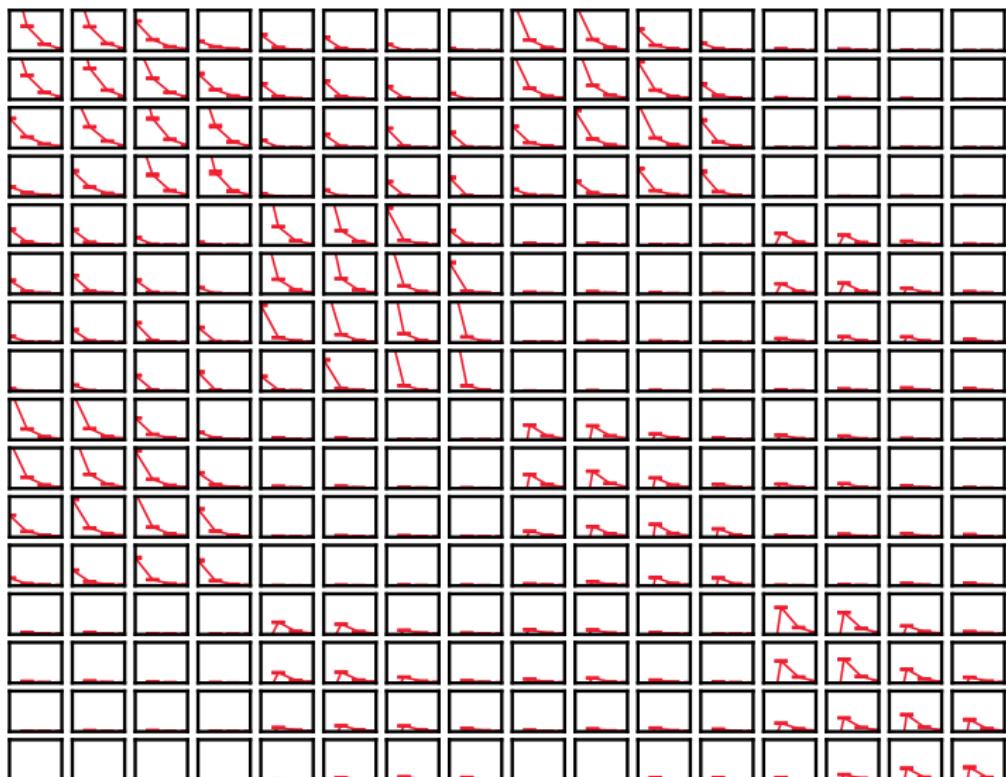
Correlation matrix

$$p^2 = 0.498 \text{ GeV}^2$$



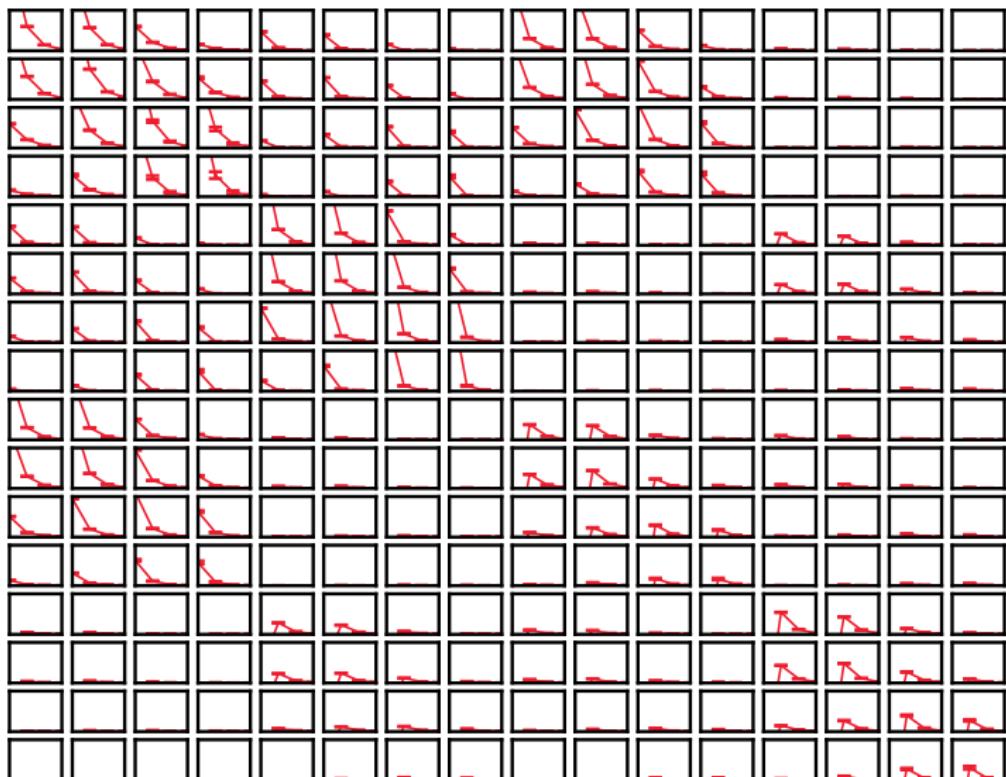
Correlation matrix

$$p^2 = 0.664 \text{ GeV}^2$$



Correlation matrix

$$p^2 = 0.830 \text{ GeV}^2$$



Eigenvectors

- Seek operators $\{\phi_{\mathbf{p}}^{\alpha}\}$ that perfectly isolate energy eigenstates

$$\langle \Omega | \phi_{\mathbf{p}}^{\alpha} | B^{\beta} \rangle = \delta^{\alpha\beta} \sqrt{\frac{m_{\alpha}}{E_{\alpha}}} Z^{\alpha} \Gamma_{\mathbf{p}} u_{\alpha}(p, s),$$

$$\langle B^{\beta} | \bar{\phi}_{\mathbf{p}}^{\alpha} | \Omega \rangle = \delta^{\alpha\beta} \sqrt{\frac{m_{\alpha}}{E_{\alpha}}} \bar{Z}^{\alpha} \bar{u}_{\alpha}(p, s) \Gamma_{\mathbf{p}}.$$

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- Can be written as linear combination of operators

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

$$\bar{\phi}_{\mathbf{p}}^{\alpha} = \sum_i u_i^{\alpha}(\mathbf{p}) \bar{\chi}_{\mathbf{p}}^i + \sum_{i'} u_{i'}^{\alpha}(\mathbf{p}) \bar{\chi}_{\mathbf{p}}^{i'}$$

Eigenvectors

- Then,

$$G(\mathbf{p}; t) \mathbf{u}^\alpha(\mathbf{p}) = \lambda^\alpha \bar{Z}^\alpha e^{-E_\alpha(\mathbf{p}) t}$$
$$\mathbf{v}^\alpha(\mathbf{p}) G(\mathbf{p}; t) = Z^\alpha \bar{\lambda}^\alpha e^{-E_\alpha(\mathbf{p}) t}$$

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- So $\mathbf{v}^\alpha(\mathbf{p})$ and $\mathbf{u}^\alpha(\mathbf{p})$ form the left and right generalised eigenvectors of $G(\mathbf{p}; t + \Delta t)$ and $G(\mathbf{p}; t)$

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- Can construct correlator for a single energy eigenstate

$$G^\alpha(\mathbf{p}; t) := \mathbf{v}^\alpha(\mathbf{p}) G(\mathbf{p}; t) \mathbf{u}^\alpha(\mathbf{p})$$

Effective energy

- Define effective energy

$$E_{\alpha}^{\text{eff}}(\mathbf{p}, t) := \frac{1}{\delta t} \ln \frac{G(\mathbf{p}; t)}{G(\mathbf{p}; t + \delta t)}$$

Effective energy

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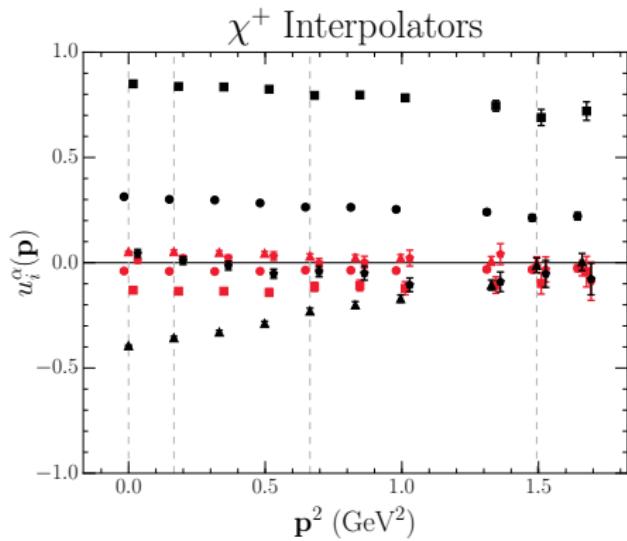
$$E_{\alpha}^{\text{eff}}(\mathbf{p}, t) := \frac{1}{\delta t} \ln \frac{G(\mathbf{p}; t)}{G(\mathbf{p}; t + \delta t)}$$

- Expect effective energy to approximately obey dispersion relation

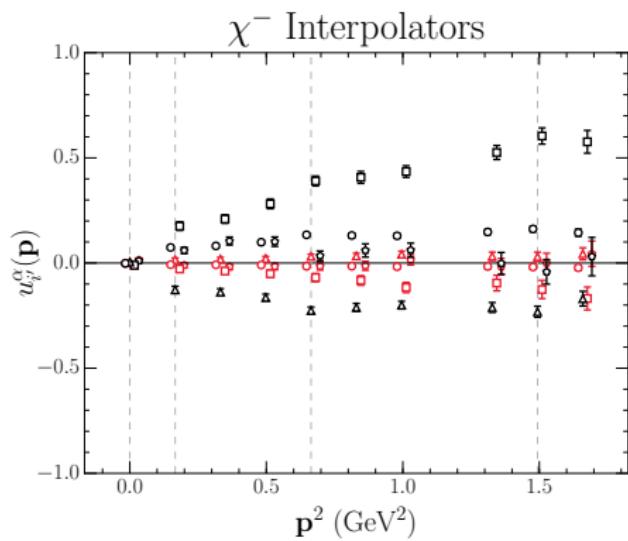
$$E_{\alpha}^{\text{eff}}(\mathbf{p}, t) \approx \sqrt{m_{\alpha}^2 + \mathbf{p}^2}$$

Eigenvector Components

Ground state



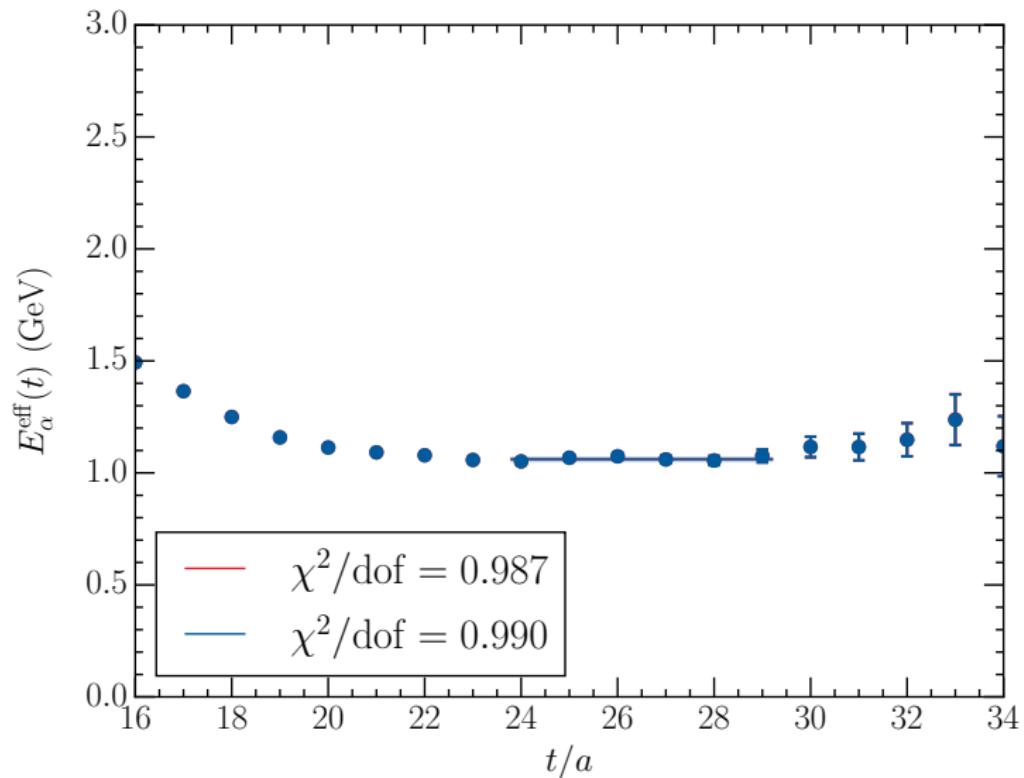
- | | |
|---|--|
| • $\chi_1^+ = \Gamma_{\mathbf{p}} \chi_1$ | ○ $\chi_1^- = \Gamma_{\mathbf{p}} \gamma_5 \chi_1$ |
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- | | |
|-------------|--------------|
| • 16 sweeps | ■ 100 sweeps |
| ▲ 35 sweeps | ● 200 sweeps |

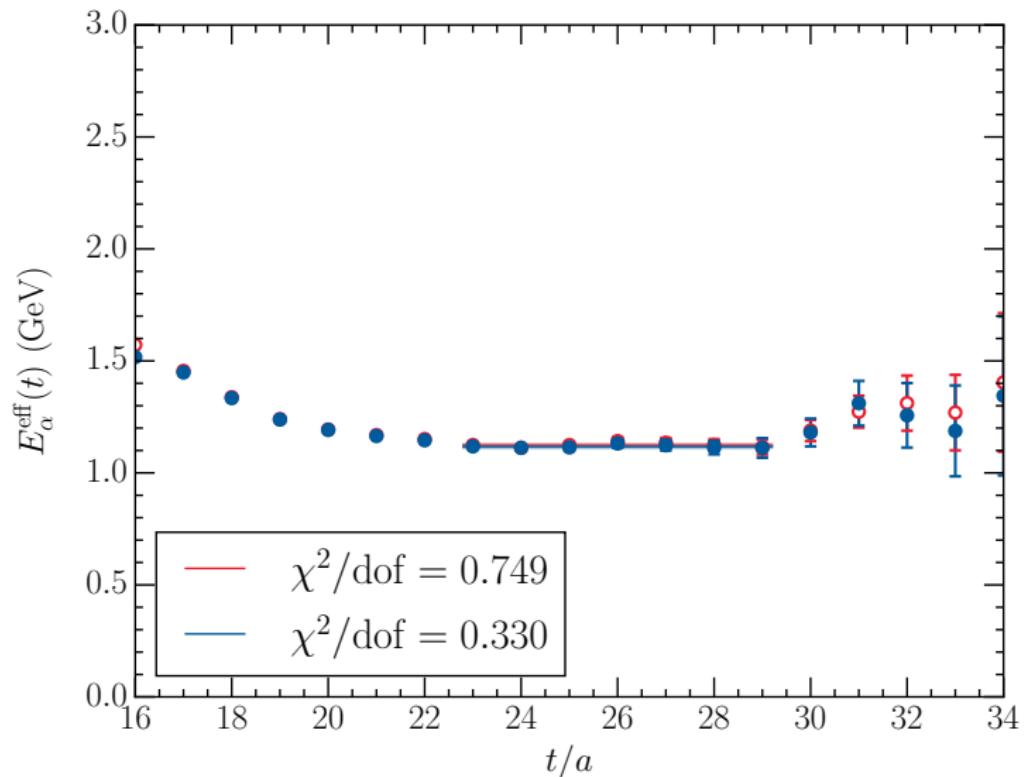
Effective Energy

Ground state - $\mathbf{p}^2 = 0 \text{ GeV}^2$



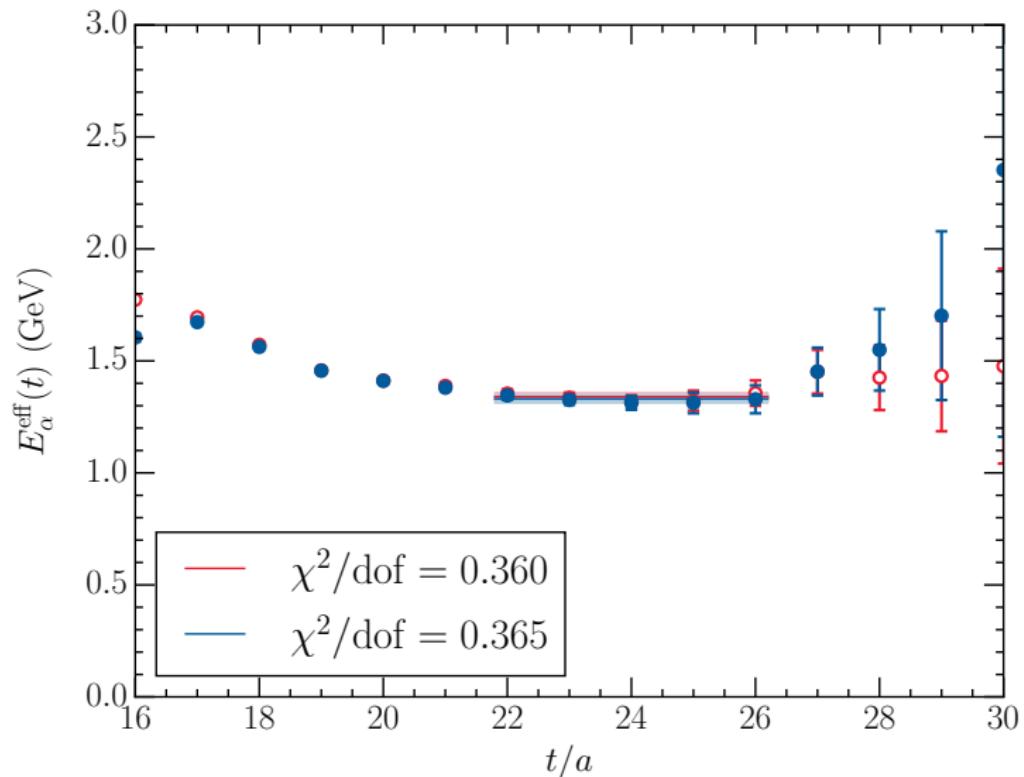
Effective Energy

Ground state - $\mathbf{p}^2 = 0.166 \text{ GeV}^2$



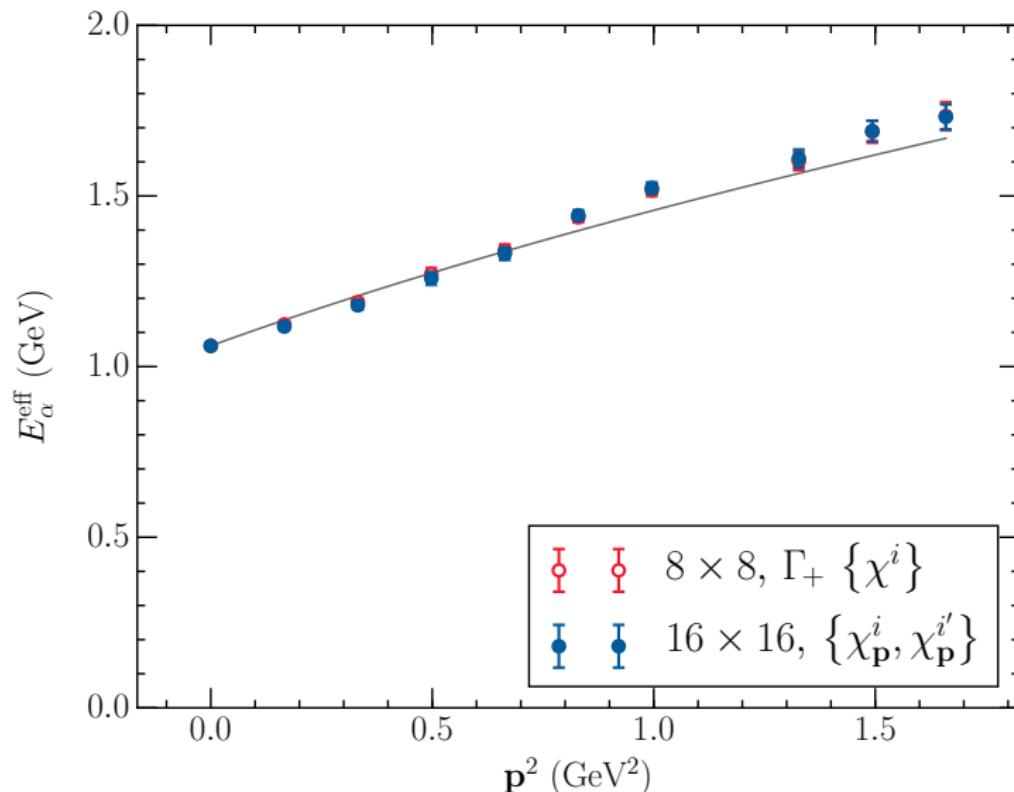
Effective Energy

Ground state - $\mathbf{p}^2 = 0.664 \text{ GeV}^2$



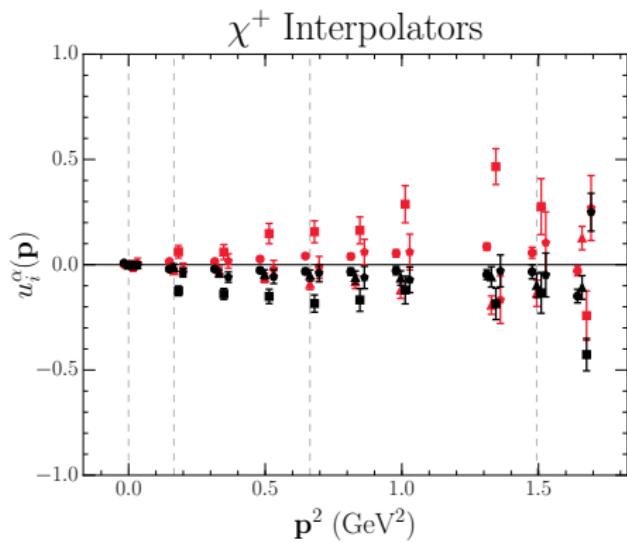
Effective Energy

Ground state

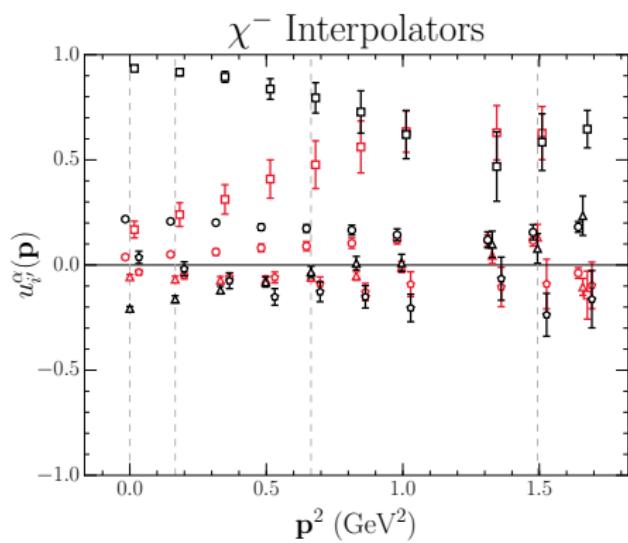


Eigenvector Components

First negative parity excitation



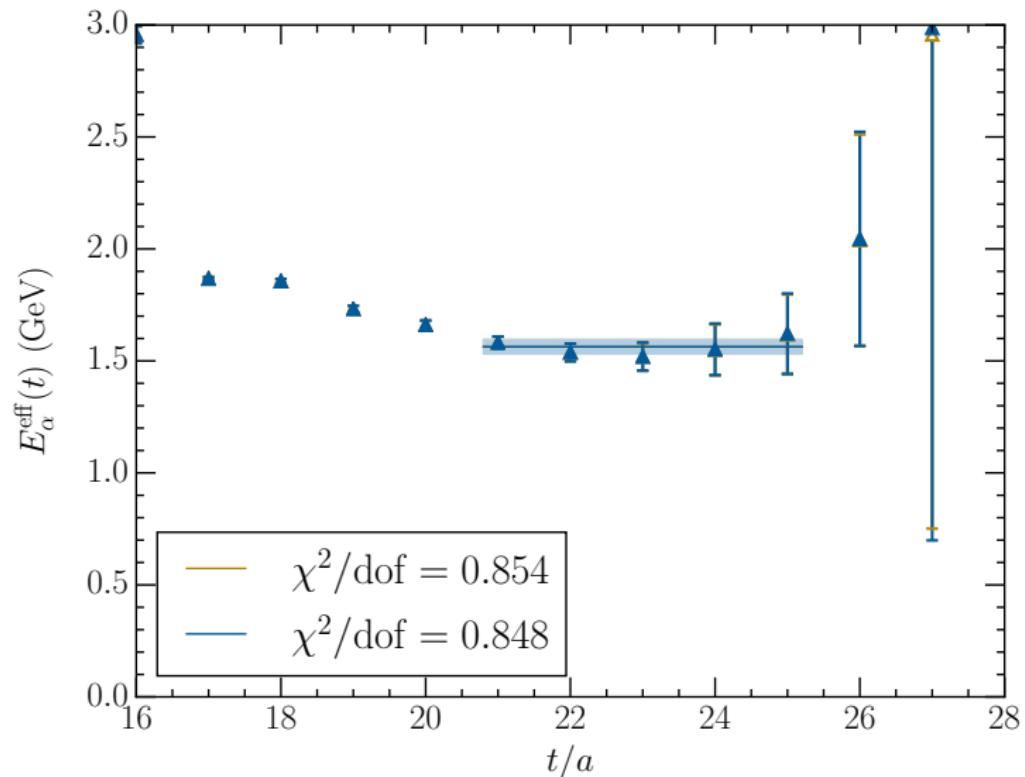
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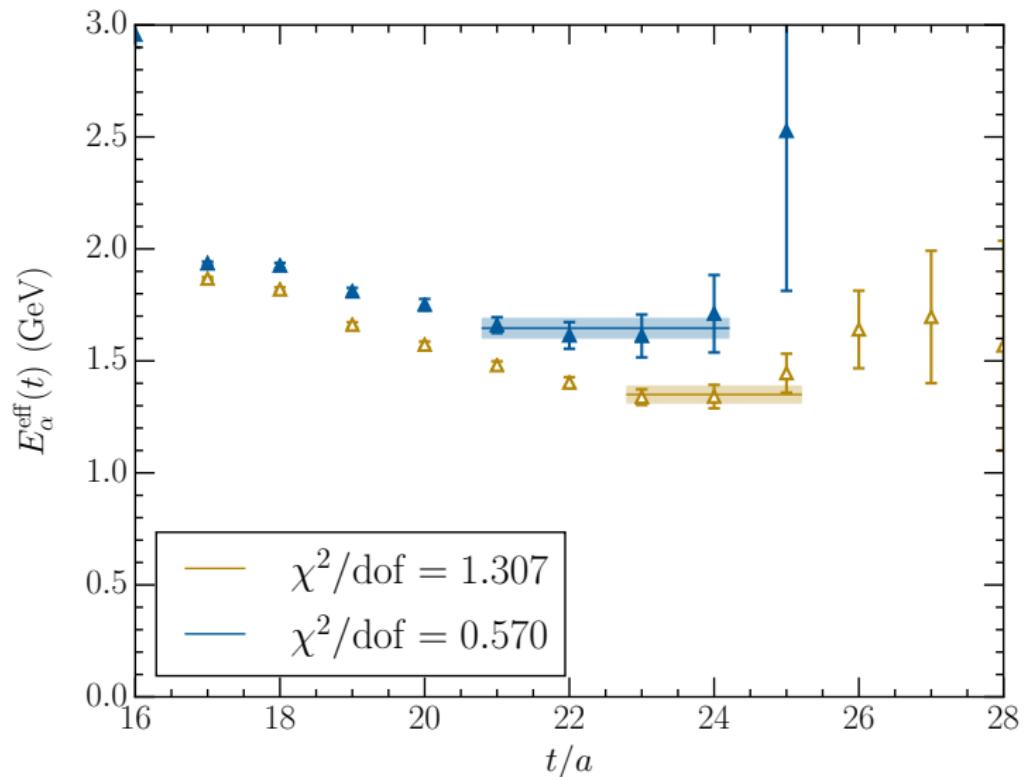
Effective Energy

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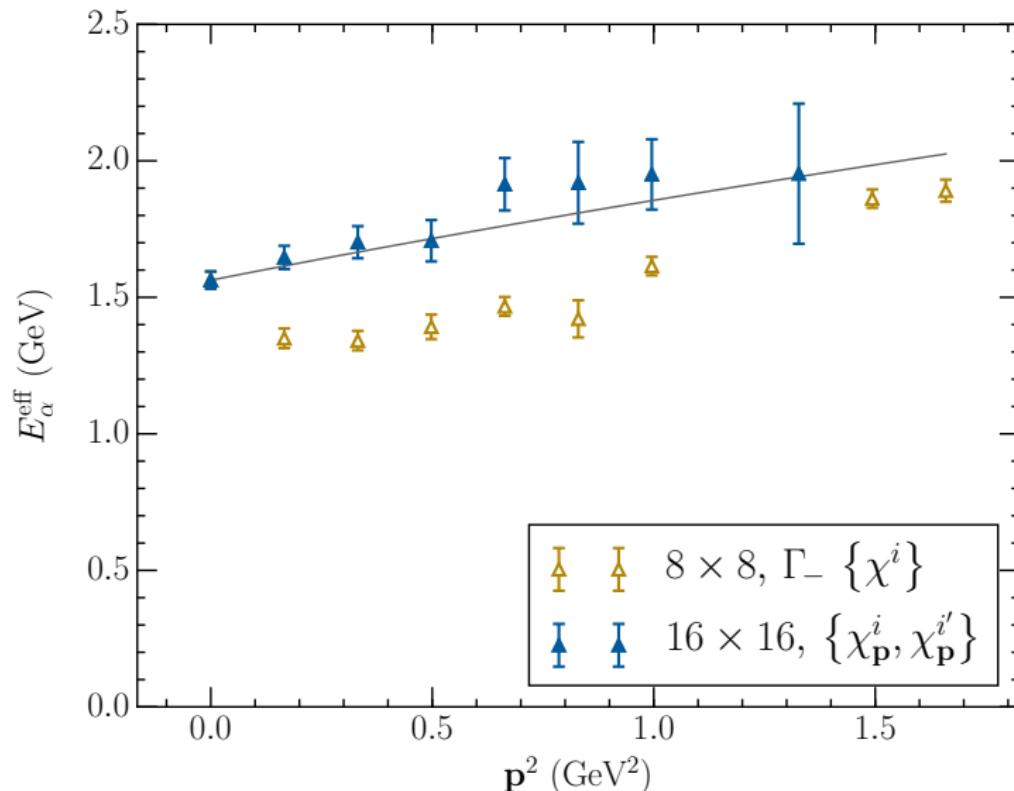
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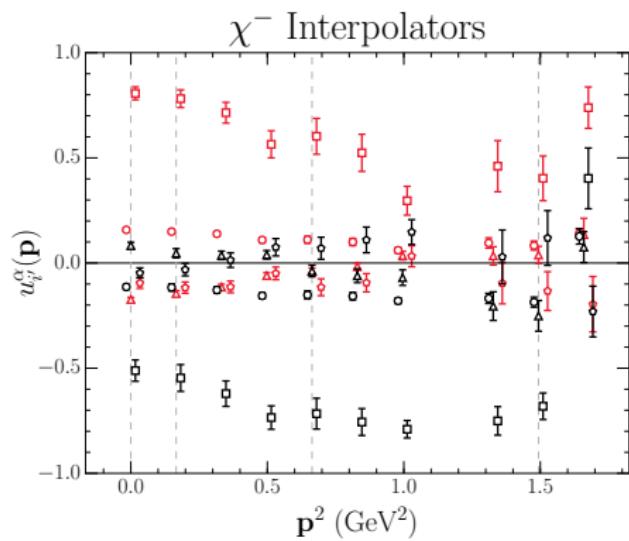
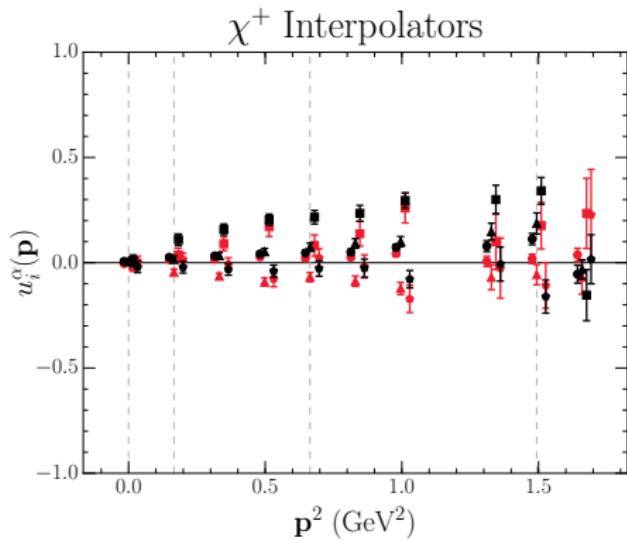
Effective energy

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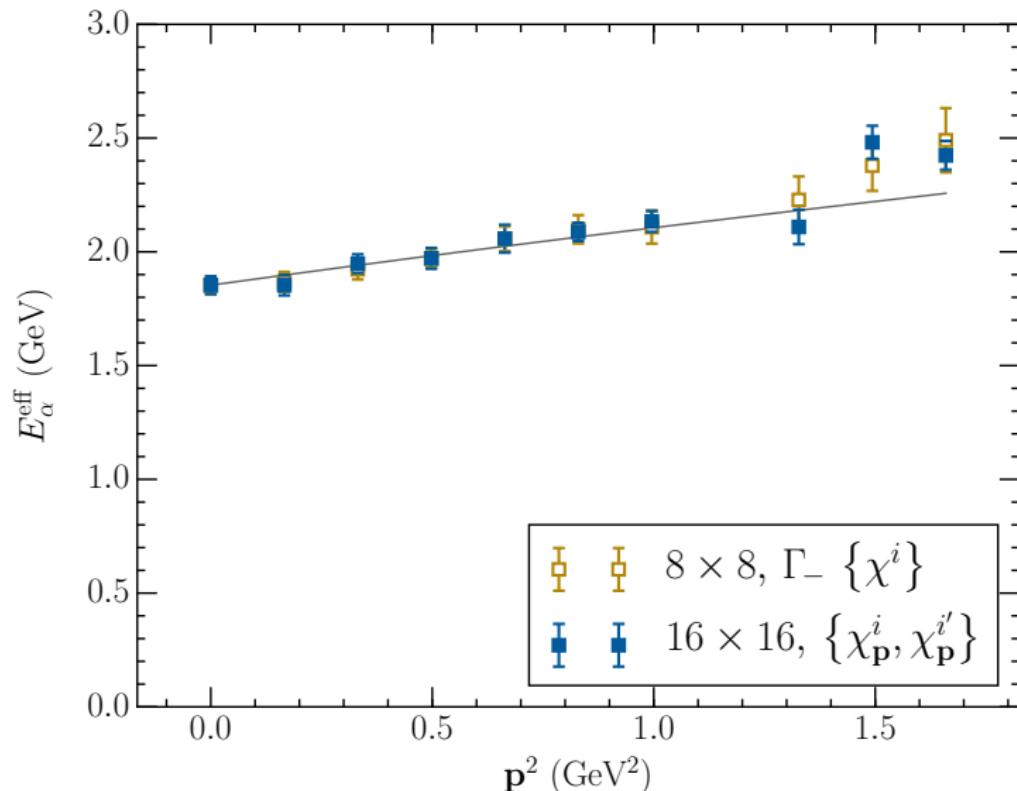
Eigenvector Components

Second negative parity excitation



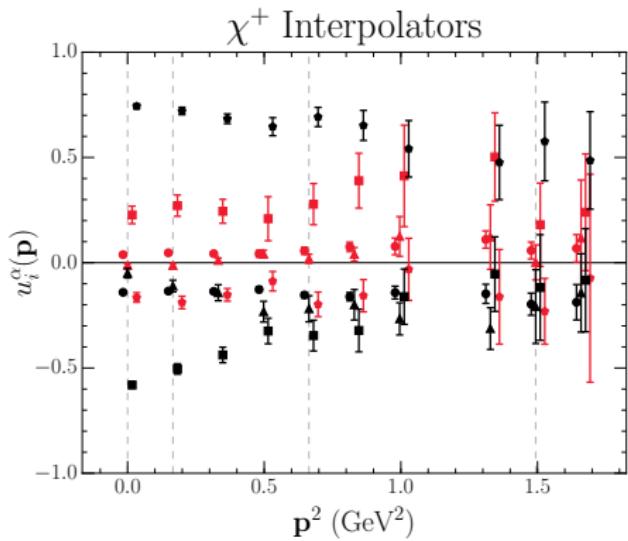
Effective energy

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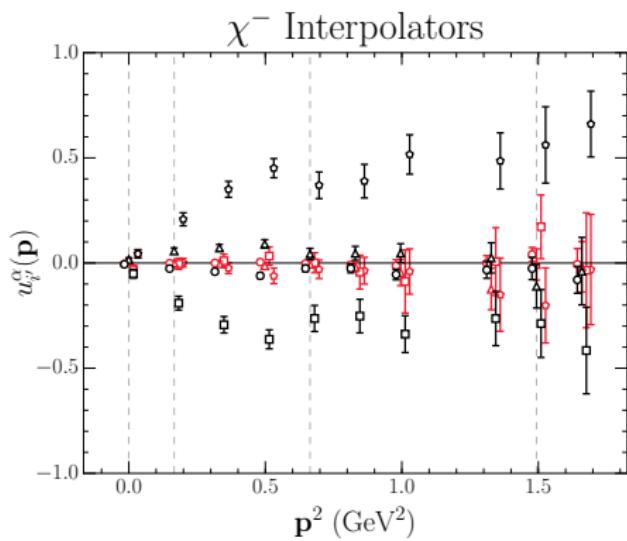


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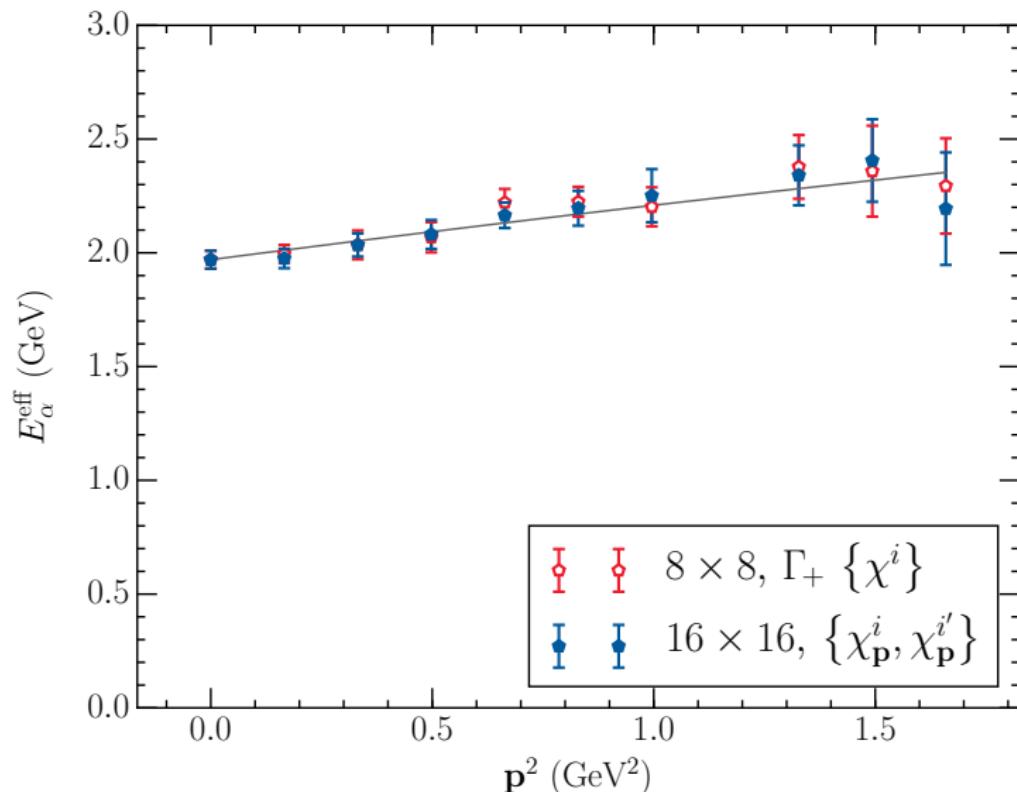
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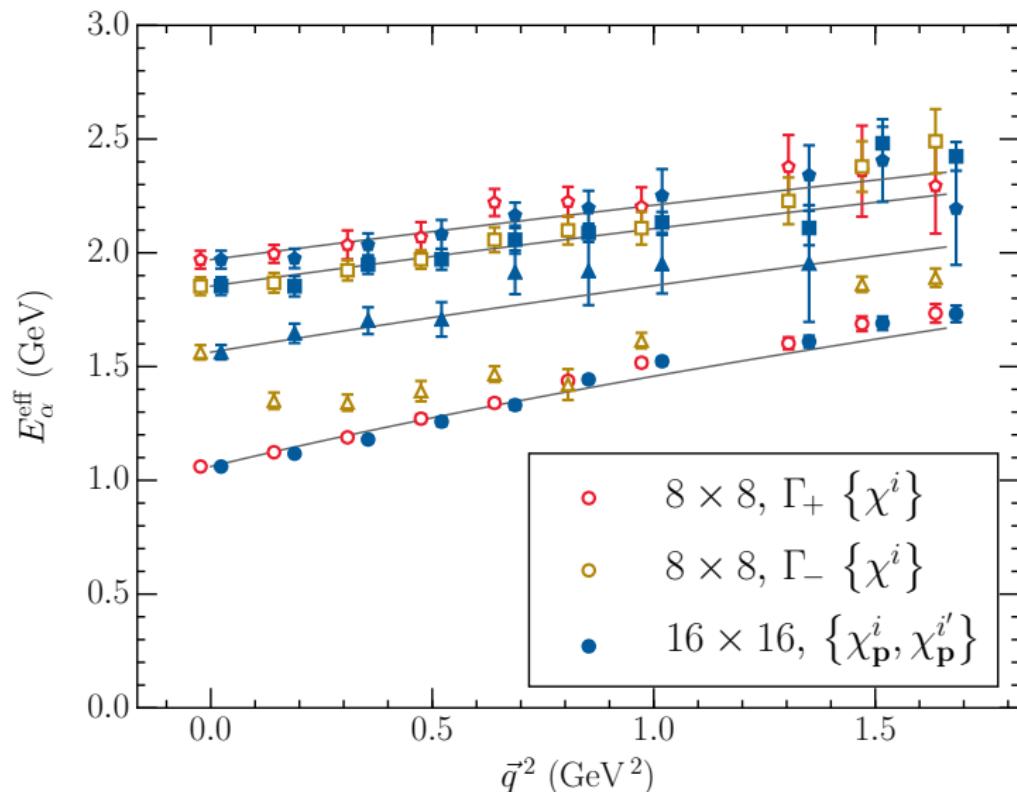
Effective energy

First positive parity excitation



Effective energy

Nucleon spectrum



Conclusion

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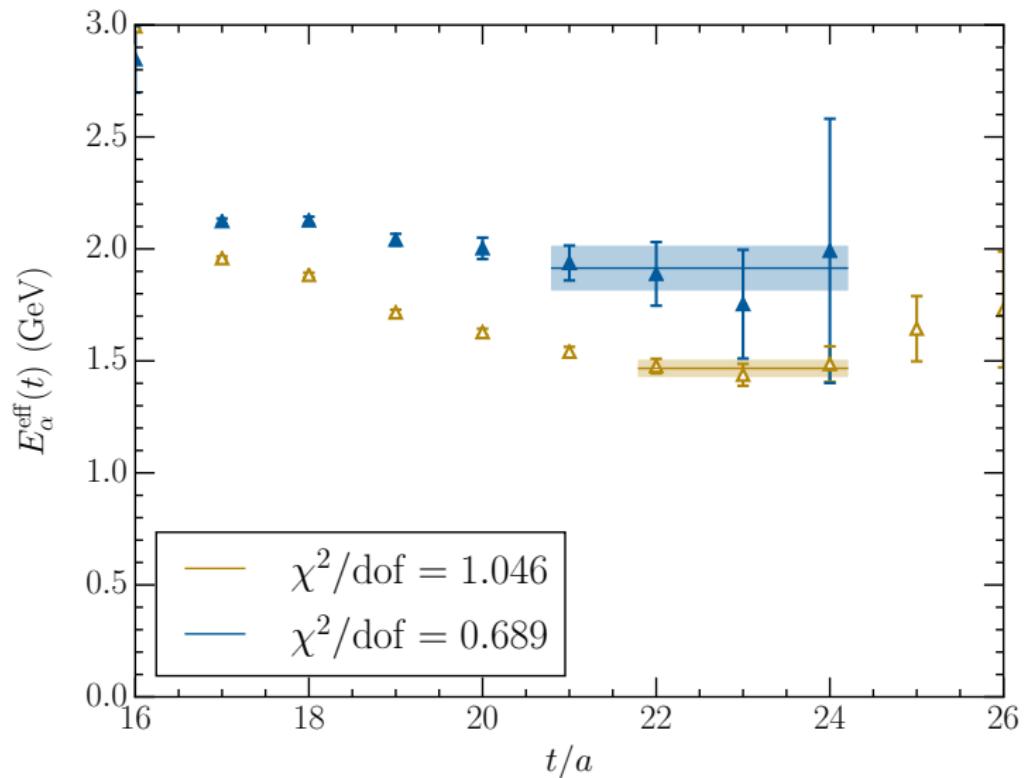
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- Our method is equivalent to conventional parity projection methods at zero momentum
- At non-zero momentum, we effectively remove opposite parity contaminations
- Cleanly isolate single energy eigenstates
- Clear effect on two point function for lowest lying negative parity excitation
- Could have even more significant effects in three point functions, where mixing could prevent current from accessing energy eigenstates

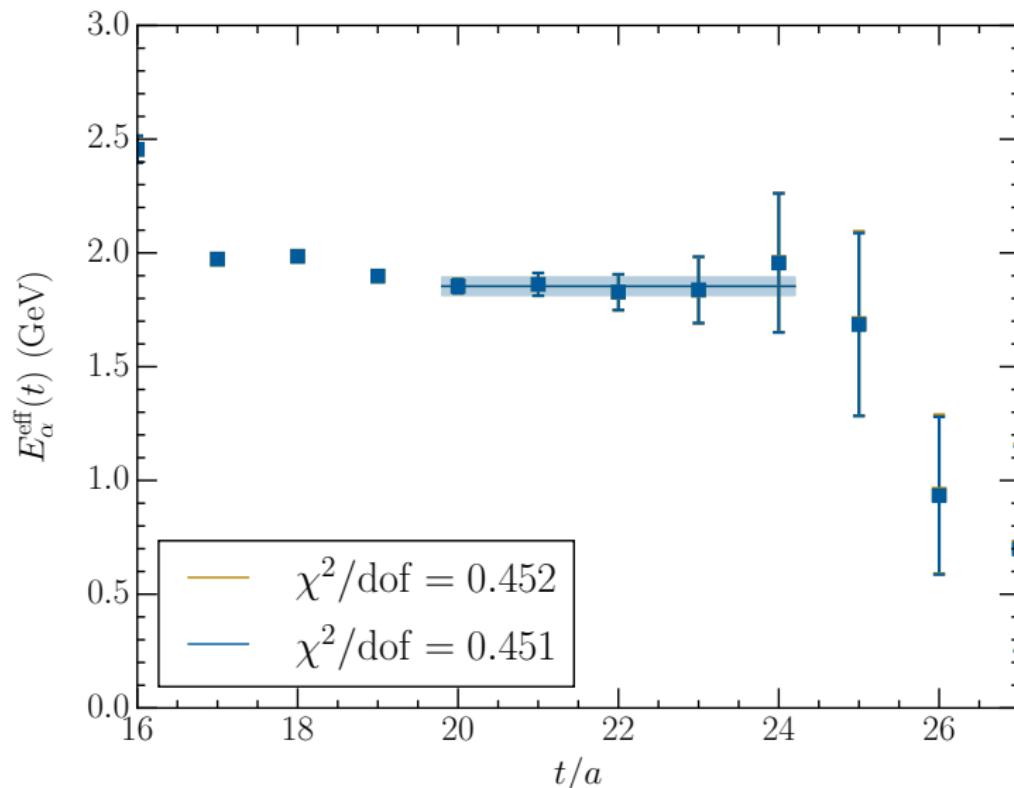
Effective Energy

First negative parity excitation - $\mathbf{p}^2 = 0.664 \text{ GeV}^2$



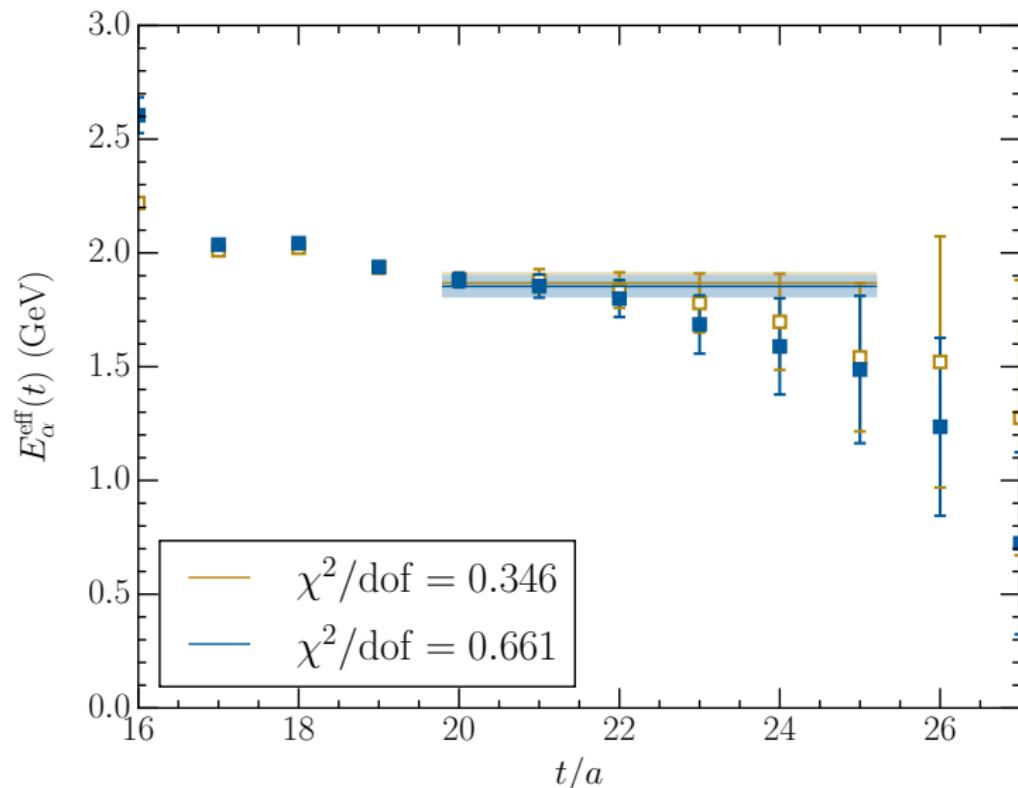
Effective Energy

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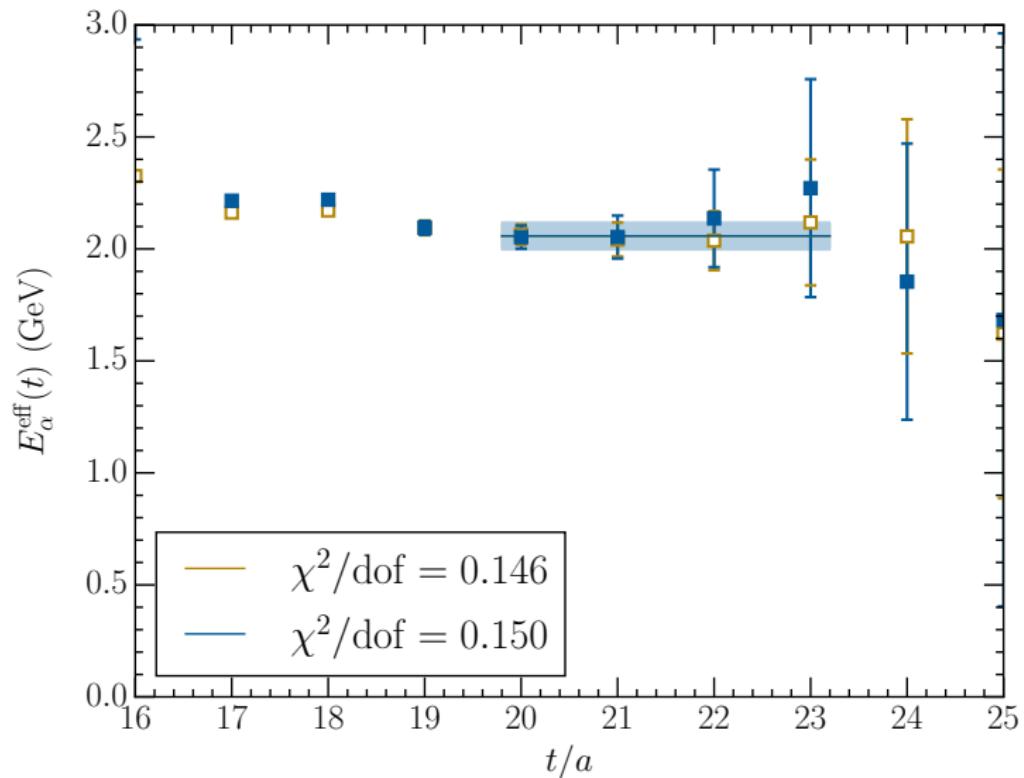
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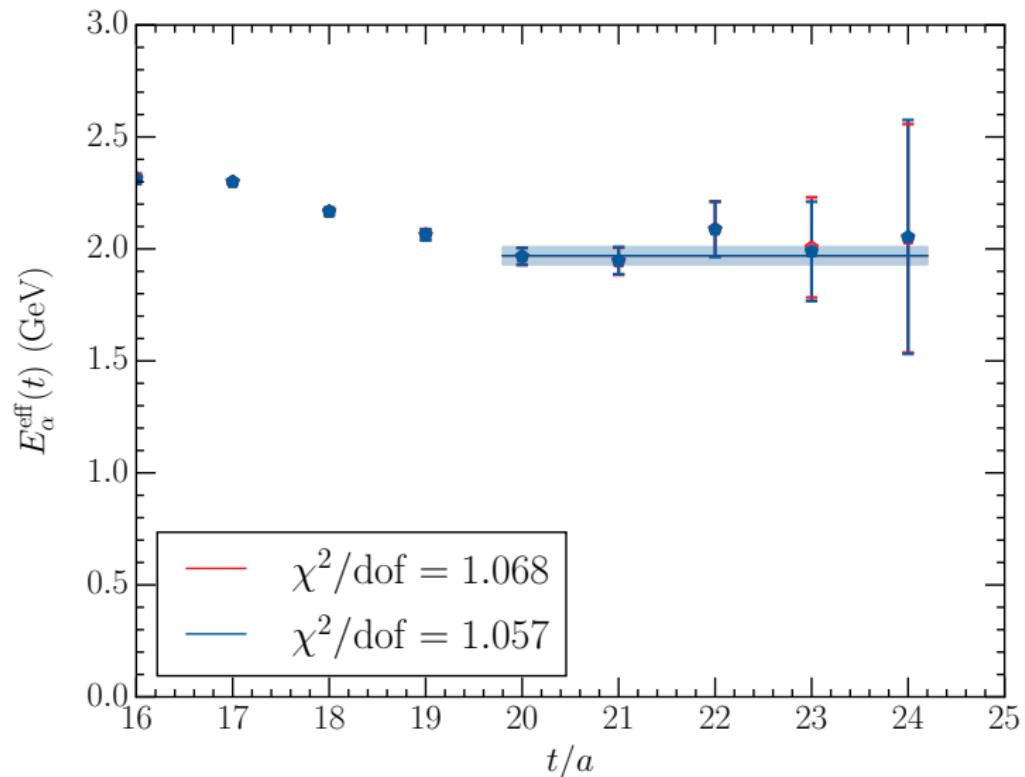
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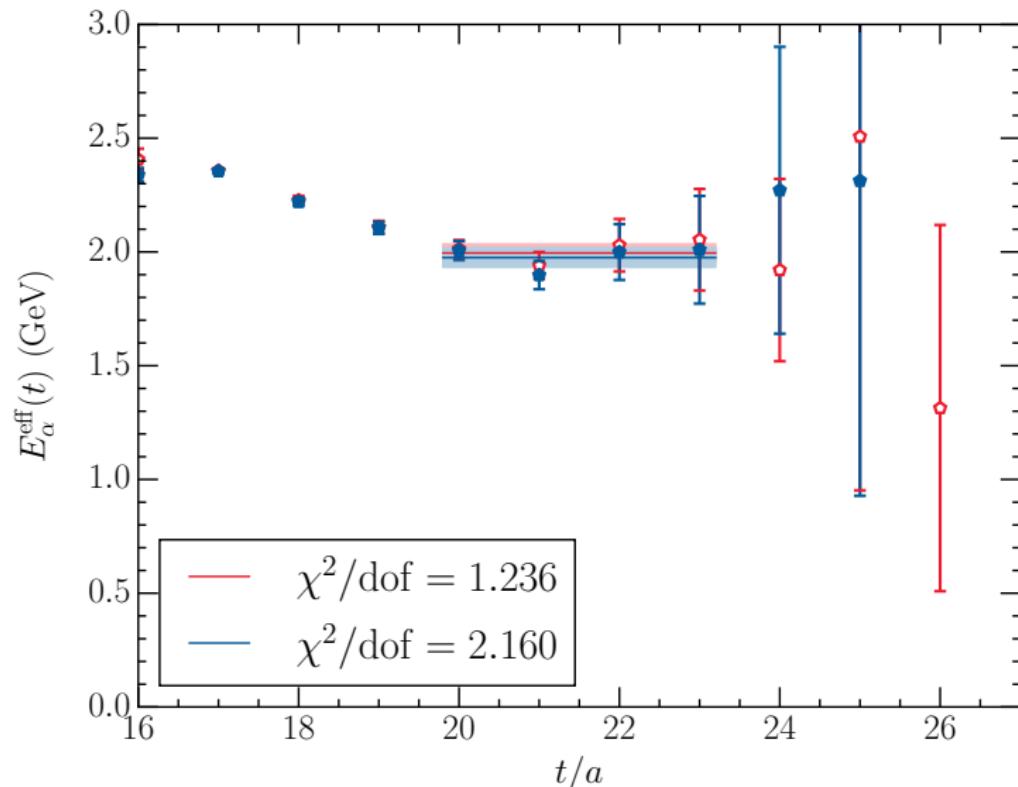
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