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Construction and Analysis of Two Baryon Correlation functions

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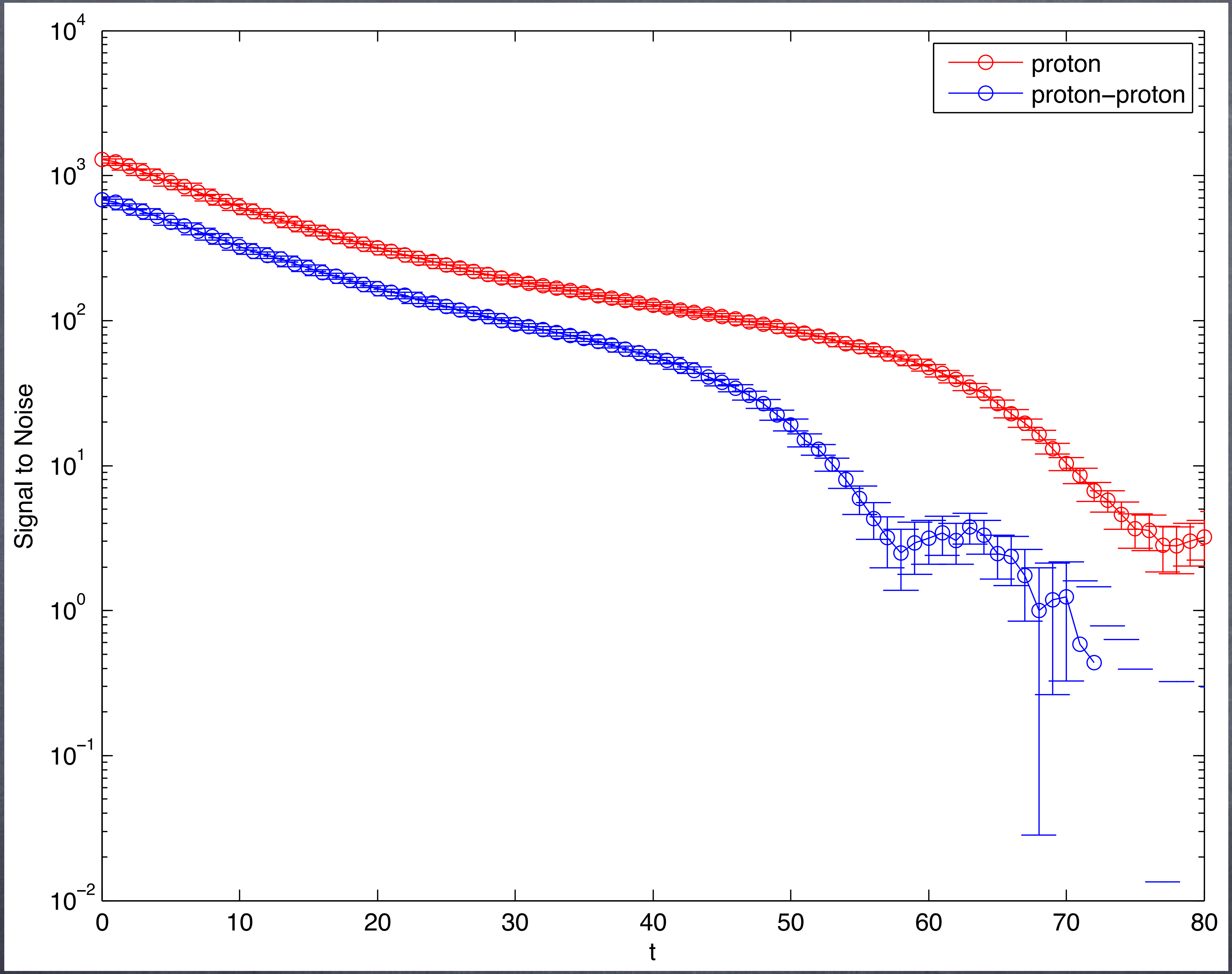
Summary

- The problem
  - Hadron-Hadron scattering phase shifts
- Methods for extracting masses from correlators
  - The variable projection method
  - A new use of the generalized eigenvalue problem
  - Application to Baryon-Baryon spectrum

Elastic Scattering Phases shifts

- Maiani-Testa no-go theorem
- Luscher: Finite volume two particle spectrum is related to elastic scattering phase shifts
- Computational problem: Calculate in Euclidean space and finite volume the two particle spectrum
- Extract energy levels from exponentially decaying correlation functions
- Baryons: Signal to noise ratio grows exponentially with Euclidean time

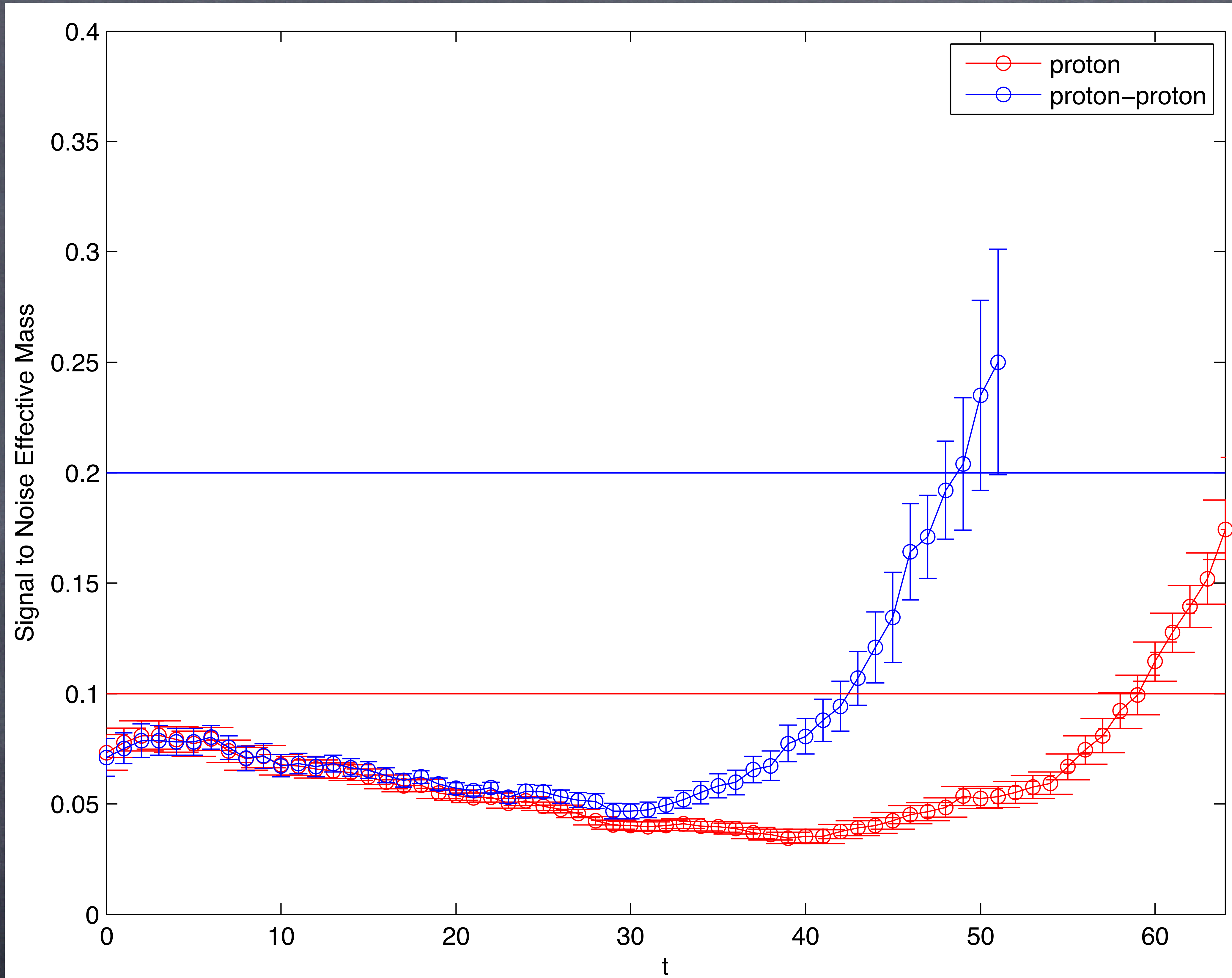


Signal to Noise

$24^3 \times 128$

M_π=390MeV

NPLQCD data



Signal to Noise Effective Mass

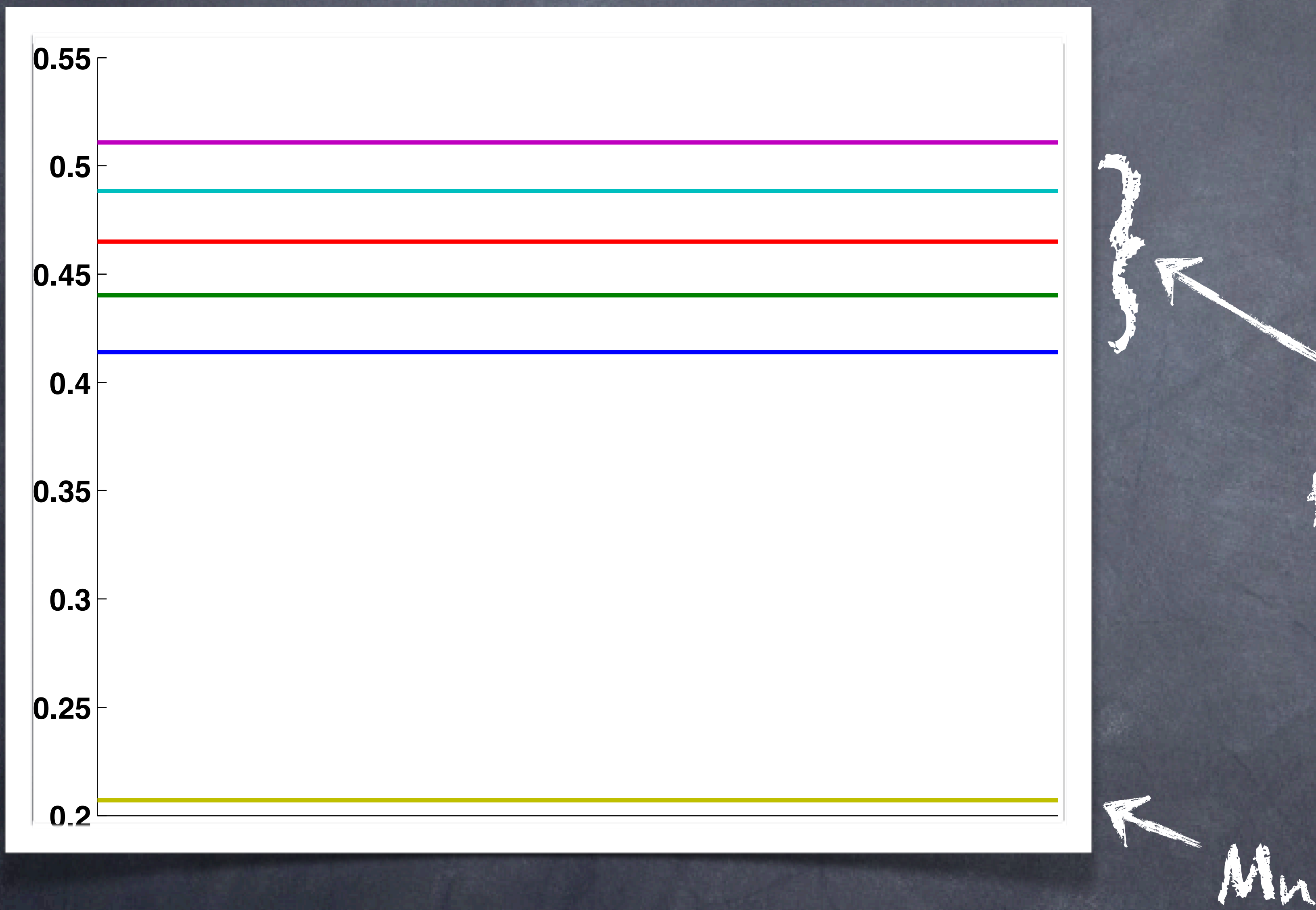
$24^3 \times 128$

M_π=390MeV

anisotropy factor 3.5

NPLQCD data

Expected Two Nucleon spectrum



24^3 box

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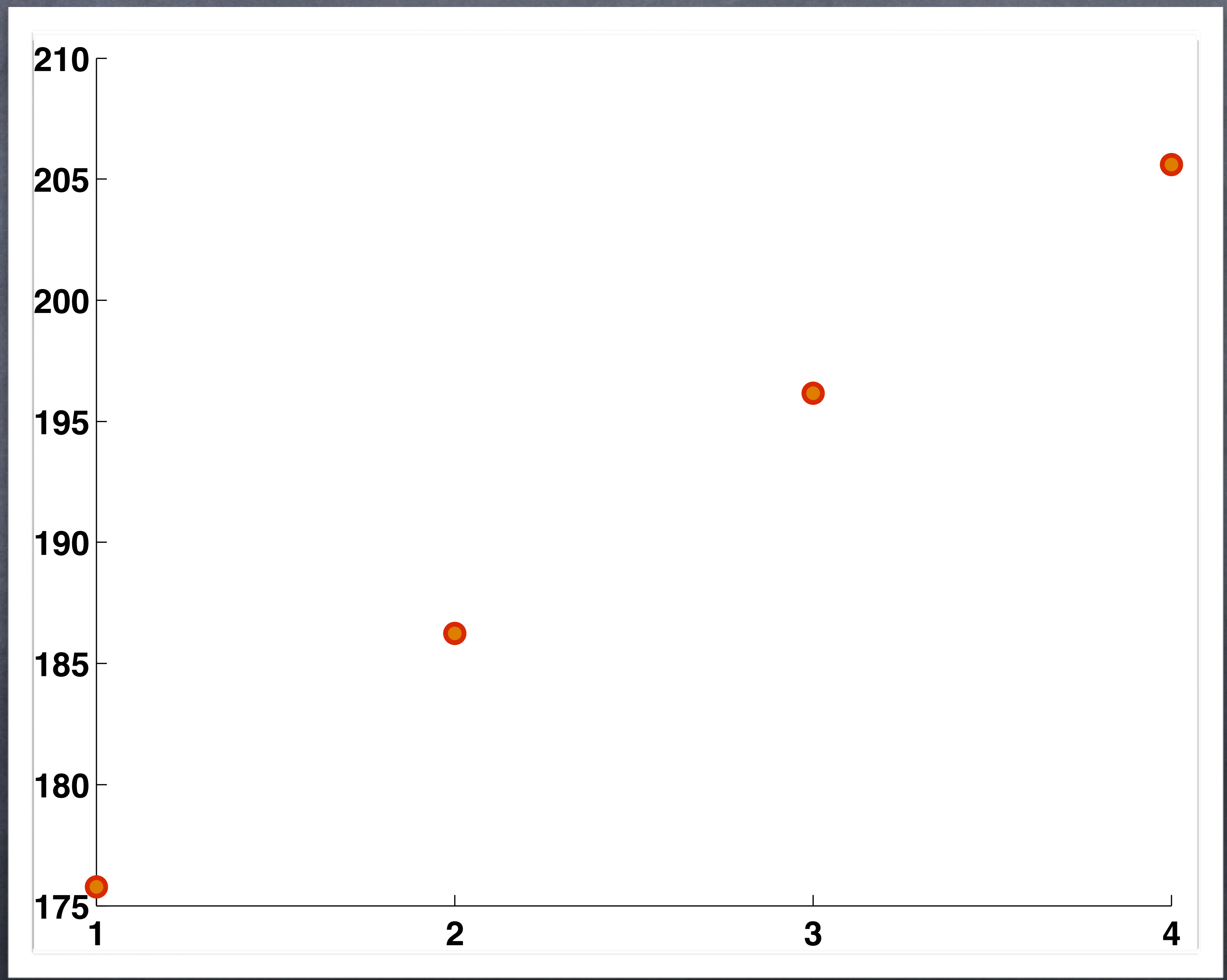
Needed Time Separation

$$e^{-\Delta E \delta t} \approx 10^{-2}$$

24^3 box



δt

Two particle state

anisotropy factor 3.5

Conclusion

We need to fit for several low lying states for reliable estimation of the ground state of the two particle system in a finite box

Fitting Exponentials

The Variable Projection method (VarPro)

Golub and Pereyra, SIAM J. Numer. Anal. Vol 10 No 2, 1973

$$t^2(Z,E) = \sum_{ij} \left[\bar{G}(t_i) - F(t_i,Z,E)\right] C^{-1}_{ij} \left[\bar{G}(t_j) - F(t_j,Z,E)\right]$$

$$F(t,Z,E) = \sum_{n=0}^{N} Z_n e^{-E_n t}$$

Separable Least Squares problem:

- Solve analytically for for the minimum for Z's at a given choice for E's
- Minimize numerically the resulting t^2 as a function of E's

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$$A_{in} = e^{-E_n t_i}$$

Solution for Z's:

$$Z(E) = [A^\dagger C^{-1} A]^{-1} A^\dagger C^{-1} Y$$

$$Y_i = \bar{G}(t_i)$$

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$$t^2(E) = \sum_{ij} d_i(E) C^{-1}_{ij} d_j(E)$$

$$d_i(E) = \bar{G}(t_i) - \sum_{n=1}^{N} A_{in} Z_n(E)$$

$$d(E) = Y - [A(E)^\dagger C^{-1} A(E)]^{-1} A(E)^\dagger C^{-1} Y$$

Fitting Exponentials

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- Regular χ^2 error analysis is done after minimization

Fitting Exponentials

The Variable Projection method (VarPro)

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- VarPro can be generalized for multiple correlation functions with full covariance
- Regular χ^2 error analysis is done after minimization
- Fitting exponentials is hard....

Alternative Methods

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Use multiple correlators and construct linear combinations that couple predominately to one state

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Use multiple correlators and construct linear combinations that couple predominately to one state

- "Variational": Symmetric positive definite matrix of correlators [C. Michael, '85; Luscher&Wolf '90; ...]
- Prony methods: [Fleming '04; NPLQCD '08; Fleming et.al. '09]
- Matrix Prony [NPLQCD '08]

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Generalized Pensile of Matrix

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Generalized Pensile of Matrix

GPOF

Y. Hua and T. Sarkar

IEEE Transactions of Antennas and Propagation

Vol. 37 No. 2 p.229 '89

Consider

$$G_{ij}(t) = \langle \mathcal{O}_i(t)\mathcal{O}_j^\dagger(0)\rangle$$

$$K_{ij}^{lm}(t) = \langle \mathcal{O}_i(t+l\tau)\mathcal{O}_j^\dagger(-m\tau)\rangle = G_{ij}(t+(l+m)\tau)$$

Organized into a matrix

$$K(t) = \begin{pmatrix} G(t) & G(t+\tau) & G(t+2\tau) & G(t+3\tau) & \cdots \\ G(t+\tau) & G(t+2\tau) & G(t+3\tau) & G(t+4\tau) & \cdots \\ G(t+2\tau) & G(t+3\tau) & G(t+4\tau) & G(t+5\tau) & \cdots \\ \vdots & \vdots & \vdots & \vdots & \cdots \end{pmatrix}$$

If N operators and M shifts are used then K is an NMxNM matrix

$$G_{ij}(t) = \sum_n \langle 0|e^{Ht}\mathcal{O}_i e^{-Ht}|n\rangle\langle n|\tilde{\mathcal{O}}_j^\dagger|0\rangle$$

Using the operators $\mathcal{O}_i(t)$ $\tilde{\mathcal{O}}_i^\dagger(t)$ and

$$\mathcal{O}(t+m\tau) = e^{m\tau H}\mathcal{O}(t)e^{-m\tau H}$$
$$\mathcal{O}^\dagger(t-m\tau) = e^{-m\tau H}\mathcal{O}^\dagger(t)e^{m\tau H}$$

The K(t) is the matrix of correlators resulting from

$\tilde{\mathcal{O}}_i^\dagger(t-m\tau)$ creation operators

and

$\mathcal{O}_i(t+m\tau)$ annihilation operators

In general K(t) is:

- A positive definite and symmetric if G(t) is positive definite and symmetric
- A rectangular matrix if the basic creation and annihilation operators are not the same set
- An $(M_1 N_1) \times (M_2 N_2)$ matrix if M_1 shifts with N_1 basic annihilation operators and M_2 shifts with N_2 basic creation operators are used

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From now on I consider K(t) an NxM matrix

Estimating Energies

Assuming finite number (S) of states contributing to the correlators with S < min(N,M)

$$K_{ij}(t) = \sum_n Z_i^n (\tilde{Z}_j^n)^* e^{-E_n t}$$

Look for vectors ω^n and $\tilde{\omega}^n$ that

$$\omega^{n\dagger} Z^m = \sum_{i=1}^{N} \omega_i^{n*} Z_i^m = \delta_{nm} \qquad \tilde{Z}^{n\dagger} \tilde{\omega}^m = \sum_{i=1}^{M} \tilde{Z}_i^{n*} \tilde{\omega}_i^m = \delta_{nm}$$

$$K(t)\tilde{\omega}^n = Z^n e^{-E_n t} = e^{-E_n (t-t_0)} K(t_0)\tilde{\omega}^n$$

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$$K(t)\tilde{\omega}^n = \lambda K(t_0)\tilde{\omega}^n$$

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$$K(t)\tilde{\omega}^n = \lambda K(t_0)\tilde{\omega}^n$$

$$\lambda = e^{-E_n (t-t_0)}$$

$$K(t)\tilde{\omega}^n = \lambda K(t_0)\tilde{\omega}^n$$

$$\omega^{n\dagger} K(t) = \lambda \omega^{n\dagger} K(t_0)$$

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Generalized eigenvalue problem but K is not symmetric and not positive

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$$\omega^{n\dagger} K(t) = \lambda \omega^{n\dagger} K(t_0)$$

Generalized eigenvalue problem but K is not symmetric and not positive

Consider the singular value decomposition

$$K(t_0) = U \Sigma V^\dagger$$

$$K(t)\tilde{\omega}^n = \lambda K(t_0)\tilde{\omega}^n$$

$$\omega^{n\dagger} K(t) = \lambda \omega^{n\dagger} K(t_0)$$

Generalized eigenvalue problem but K is not symmetric and not positive

Consider the singular value decomposition

$$K(t_0) = U\Sigma V^\dagger$$

Let M<N Then we have M singular values

But only S (the number of states contributing to the correlator) of them are non-zero

$$K(t) = \begin{pmatrix} G(t) & G(t+\tau) & G(t+2\tau) & G(t+3\tau) & \cdots \\ G(t+\tau) & G(t+2\tau) & G(t+3\tau) & G(t+4\tau) & \cdots \\ G(t+2\tau) & G(t+3\tau) & G(t+4\tau) & G(t+5\tau) & \cdots \\ \vdots & \vdots & \vdots & \vdots & \cdots \end{pmatrix}$$

The S+1 column is a linear combination for the first S columns given that the signal is a sum of exponentials

Let σ_i be the non-zero singular values of $K(t_0)$

$$\Sigma' = \begin{pmatrix} \sigma_1 & 0 & \cdots \\ 0 & \sigma_2 & \cdots \\ \vdots & \vdots & \ddots \end{pmatrix}$$

SxS matrix

$U' = U(:, 1:S)$ NxS matrix

$V' = V(:, 1:S)$ MxS matrix

$$K(t_0) = U'\Sigma'V'^{\dagger}$$

$$V'^{\dagger}V' = \mathbf{1}_{S\times S} \qquad U'^{\dagger}U' = \mathbf{1}_{S\times S}$$

Let $A = \Sigma'^{-\frac{1}{2}}\, U'\, K(t)\, V'\, \Sigma'^{-\frac{1}{2}}$ SxS matrix

Then $A\tilde{q}^n = \lambda_n \tilde{q}^n$ $q^{n\dagger} A = \lambda_n q^{n\dagger}$ $q^{n\dagger}\tilde{q}^m = \delta_{nm}$

with $\tilde{\omega}^n = V'\Sigma'^{-\frac{1}{2}}\, \tilde{q}^n$ $\omega^{n\dagger} = q^{n\dagger}\, \Sigma'^{-\frac{1}{2}}\, U'^\dagger$

is an eigenvalue problem of a non-symmetric matrix

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is an eigenvalue problem of a non-symmetric matrix

Z factor reconstruction

$$\tilde{Z}^{\dagger} = Q^{\dagger}\Sigma'^{\frac{1}{2}}V'^{\dagger} \quad Z = U'\Sigma'^{\frac{1}{2}}\tilde{Q}$$

In practice...

Keep singular values that $$\frac{\sigma_k}{\max(\sigma_i)} > tol$$

The tolerance can be taken to be of the order of the signal to noise ratio

$$tol \sim \frac{\mathrm{err}[G(t_0)]}{\bar{G}(t_0)}$$

Typical tolerance values 10^{-2} to 10^{-3}

In practice...

$$A(t) = \Sigma'^{-\frac{1}{2}} \, U' \, K(t) \, V' \, \Sigma'^{-\frac{1}{2}}$$

$$A(t)\tilde{q}^n = \lambda_n(t)\tilde{q}^n$$

$$\lambda_n(t) = \left(1 - \sum_i z_i\right) e^{-E_n(t-t_0)} + \sum_i z_i e^{-E'_i(t-t_0)}$$

In practice...

$$A(t) = \Sigma'^{-\frac{1}{2}}\, U'\, K(t)\, V'\, \Sigma'^{-\frac{1}{2}}$$

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$$\lambda_n(t) = \left(1 - \sum_i z_i\right) e^{-E_n(t-t_0)} + \sum_i z_i e^{-E_i'(t-t_0)}$$

principal correlator

In practice...

- Scan over several t_0 values
- Chose tolerance based on signal to noise ratio
- Fit the principal correlators in (t_0+1, t_{max})

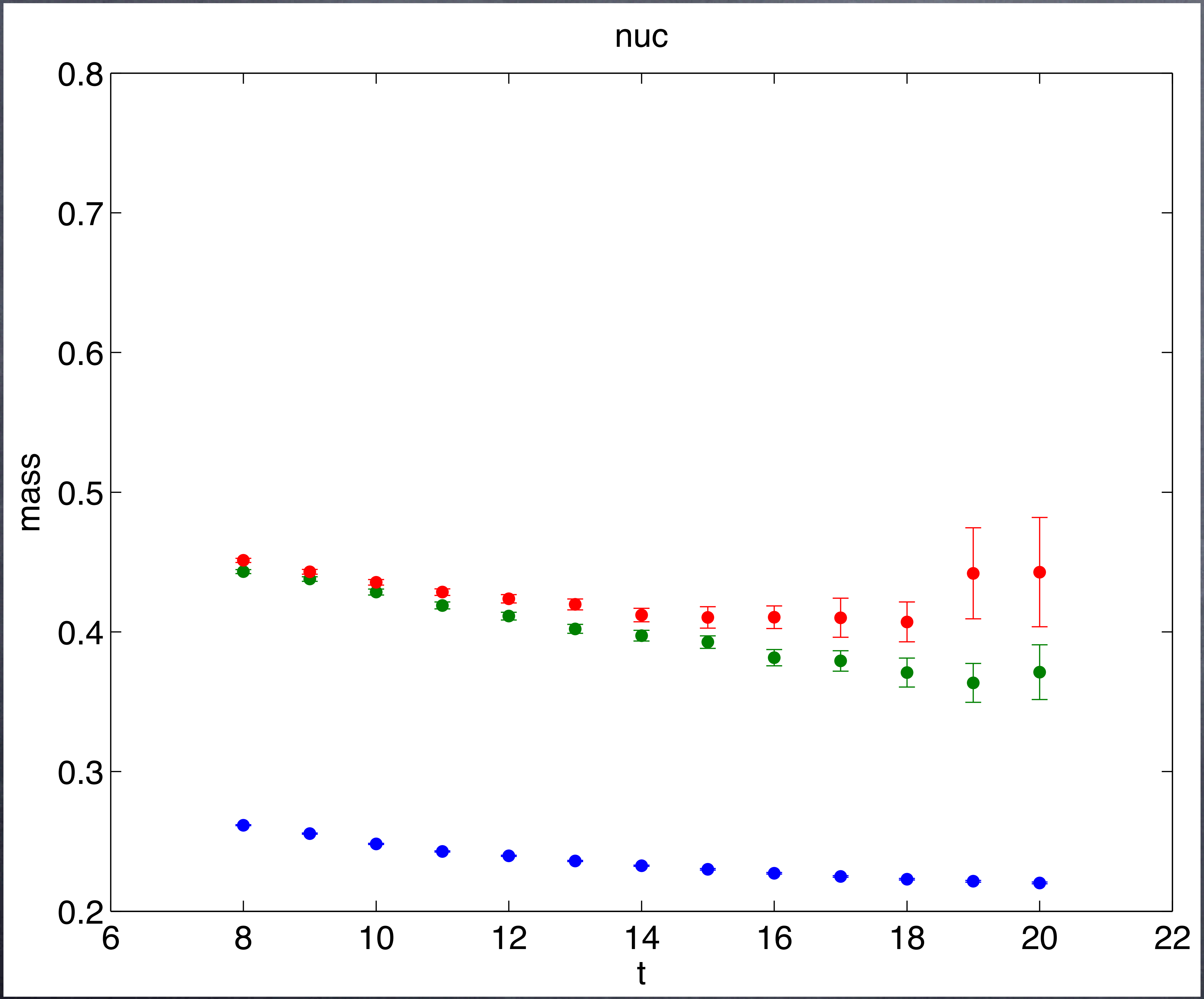
$$\lambda_n(t) = e^{-E_n(t-t_0)}$$

- t_{max} as large possible with $\lambda(t)$ resolved
- Confidence level is checked

Single Baryon spectrum

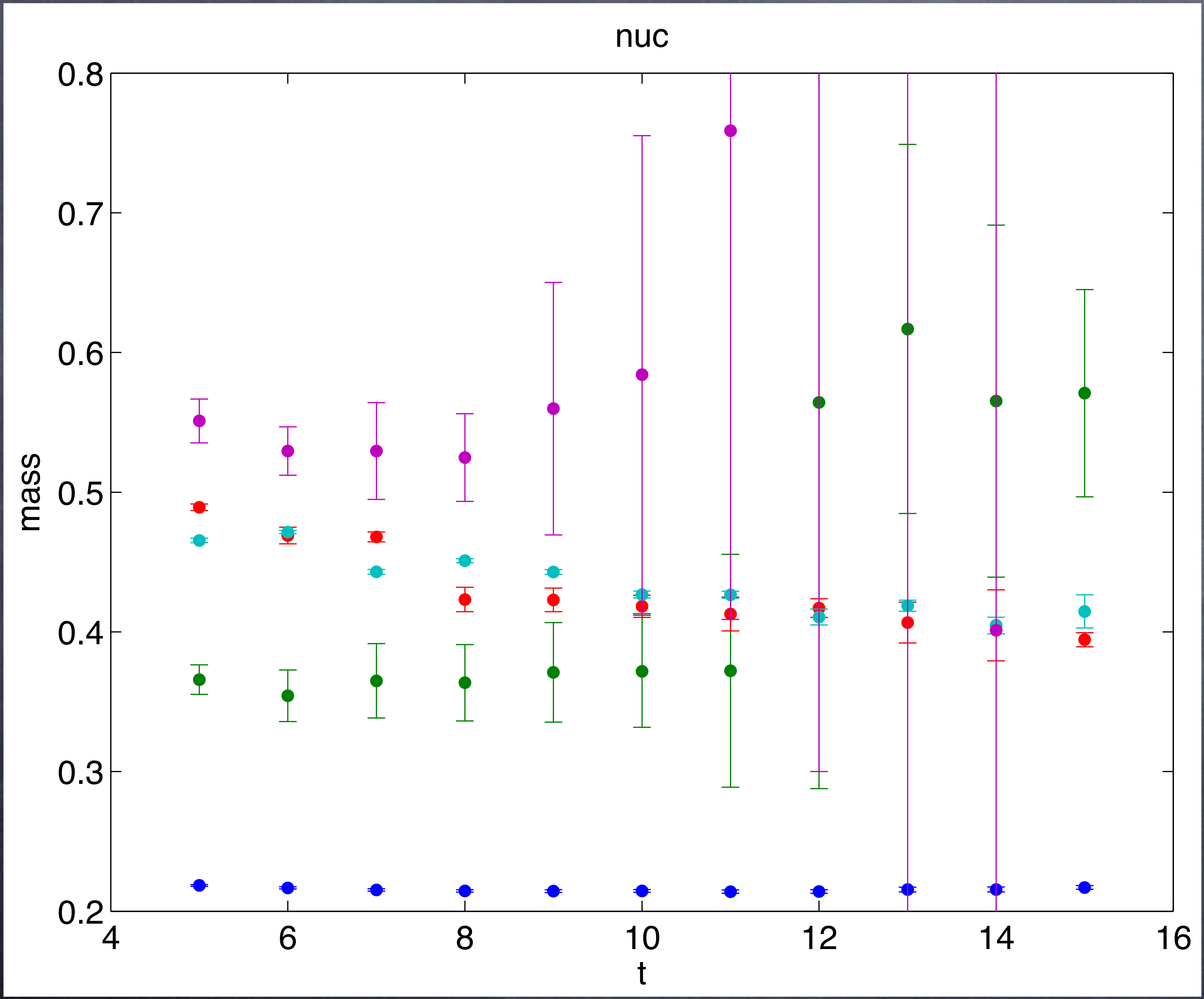
- Use smeared-smeared correlation functions
- Use a basis of all local independent interpolating fields
- JLab anisotropic lattices at 390MeV pion mass
- Compare GPOF with regular "variational"

Nucleon Mass



$16^3 \times 128$

Nucleon Mass



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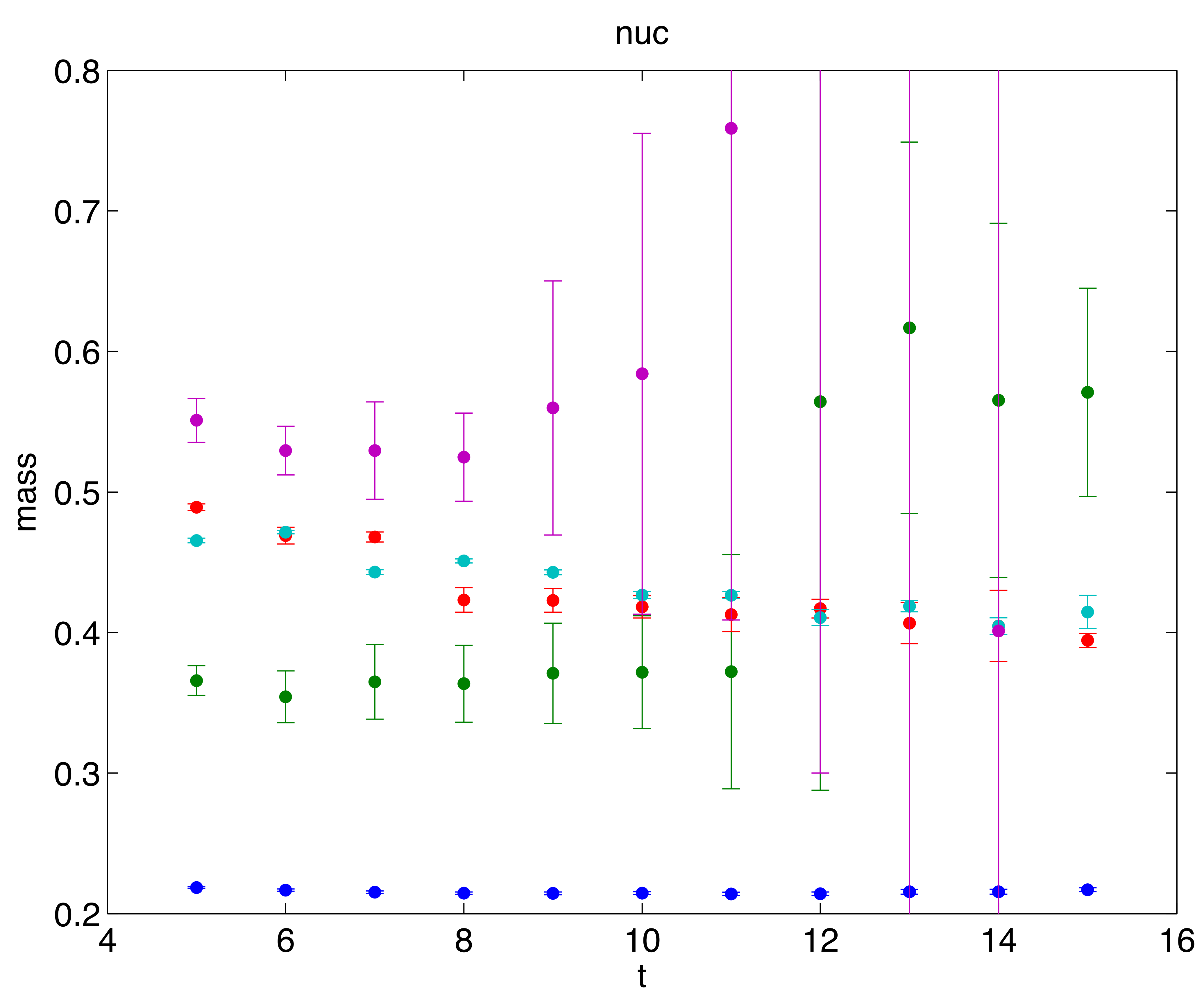
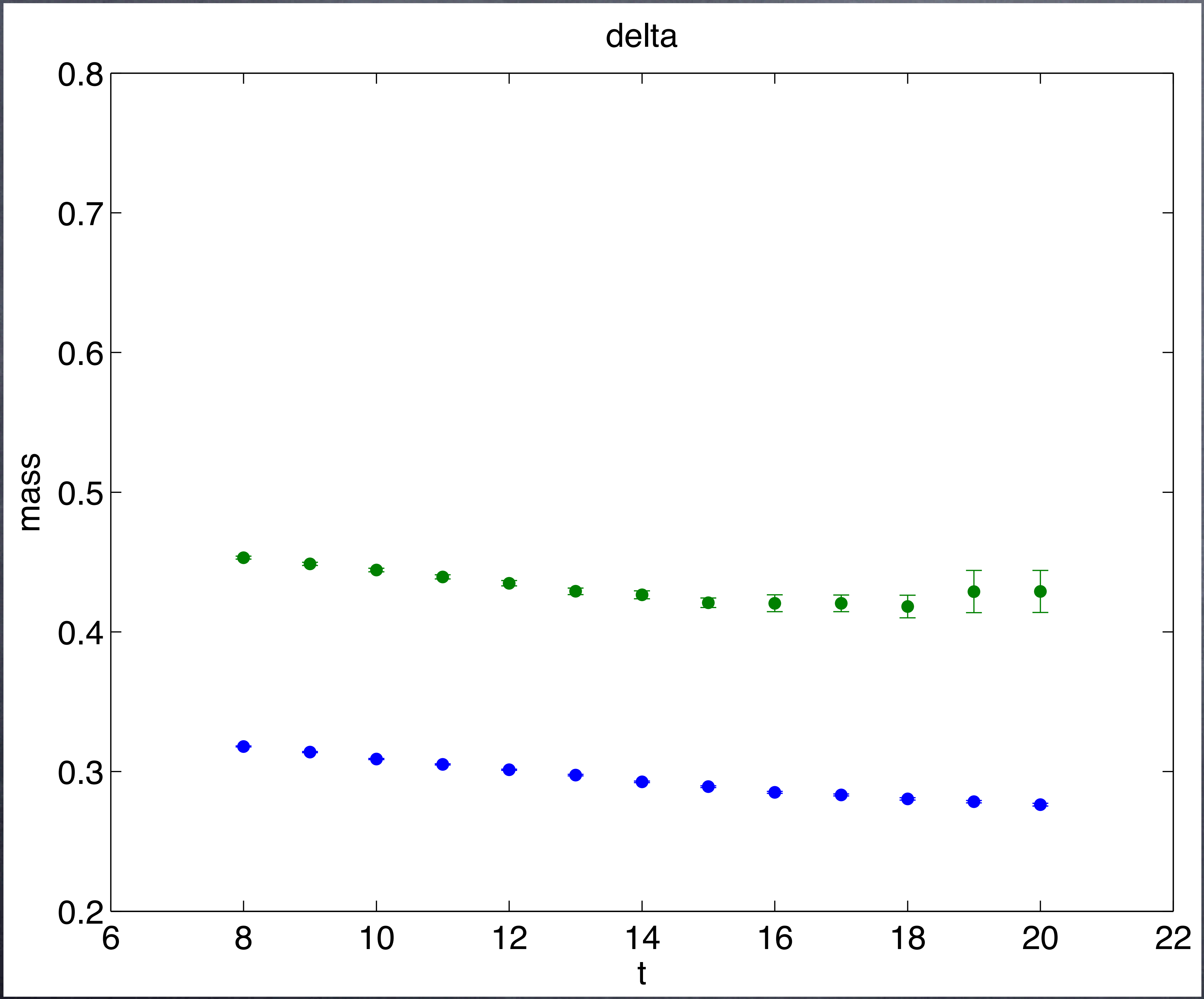


16^3x128

2 source shifts
2 sink shifts
3 local operators

6x6 matrix

Delta Mass



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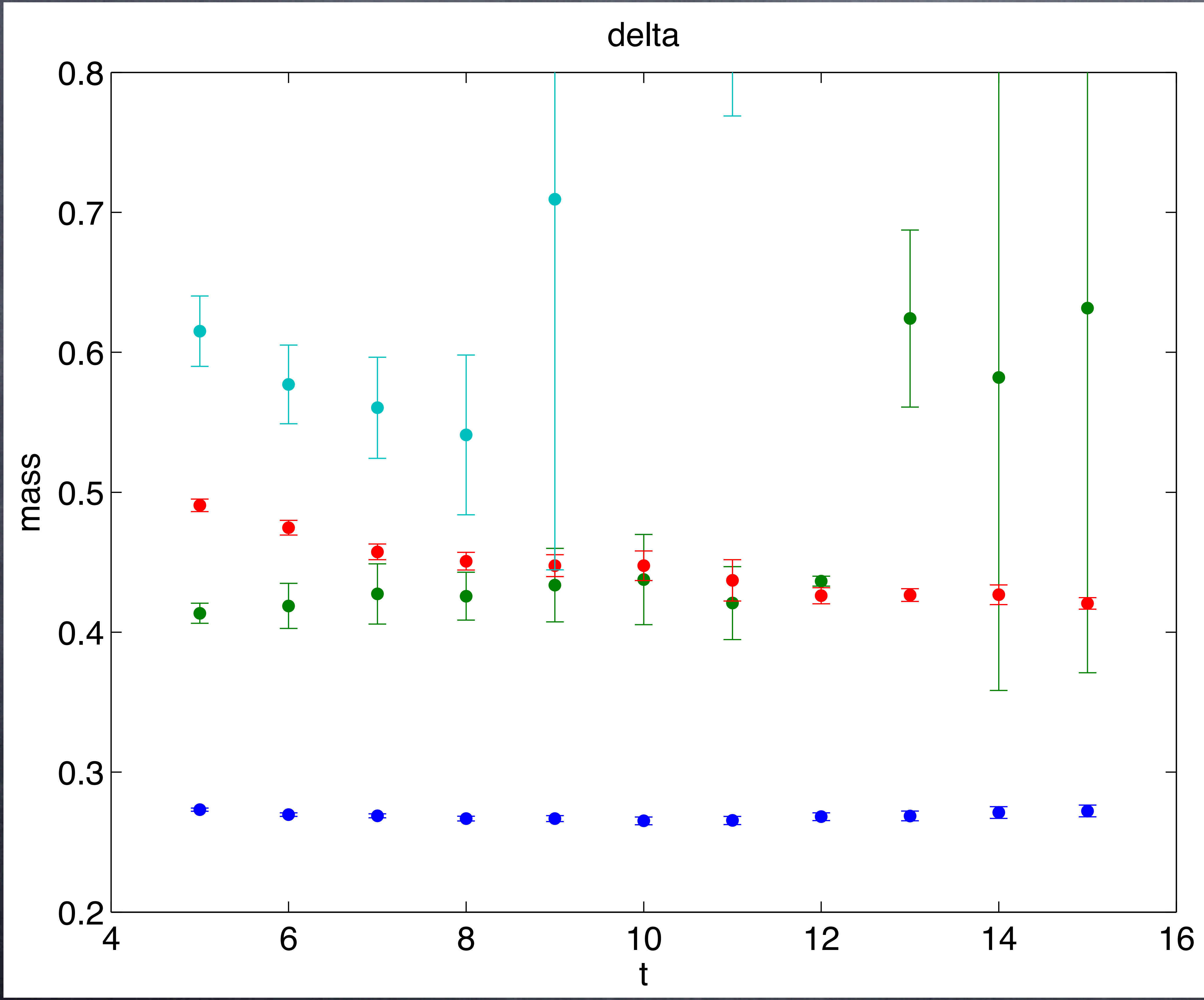

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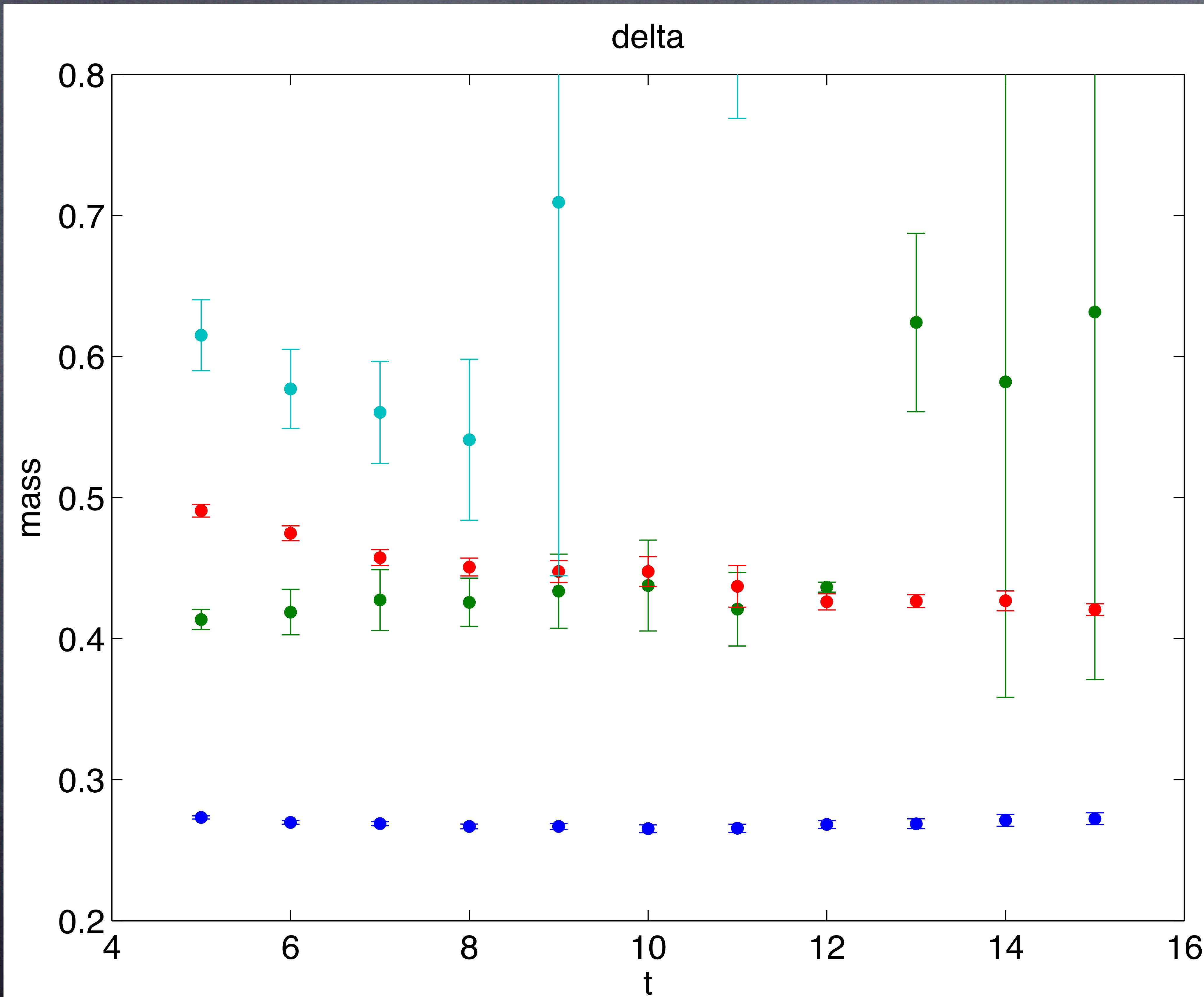


16^3x128

2 source shifts
2 sink shifts
2 local operators

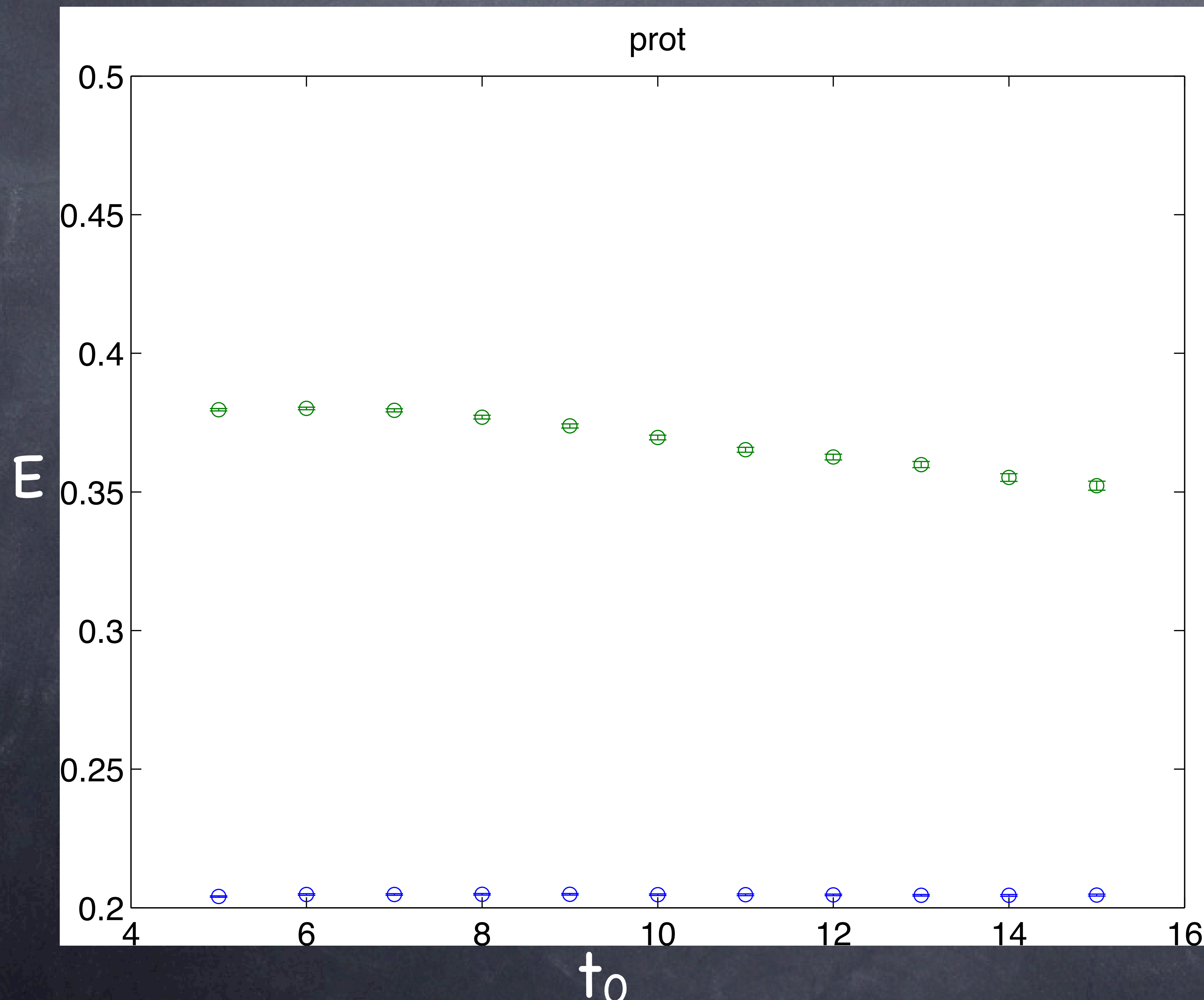
4x4 matrix

Two Baryon Correlation functions

- Single smeared quark source
- Multiple sink interpolating fields
  - Smeared, Point and Smeared-Point
- Resulting G is a 3x1 matrix
- No-need for all-to-all propagators
- Very high statistics (300K correlation functions on 2K lattices)

NPLQCD data

Single Baryon



NPLQCD data

single operator

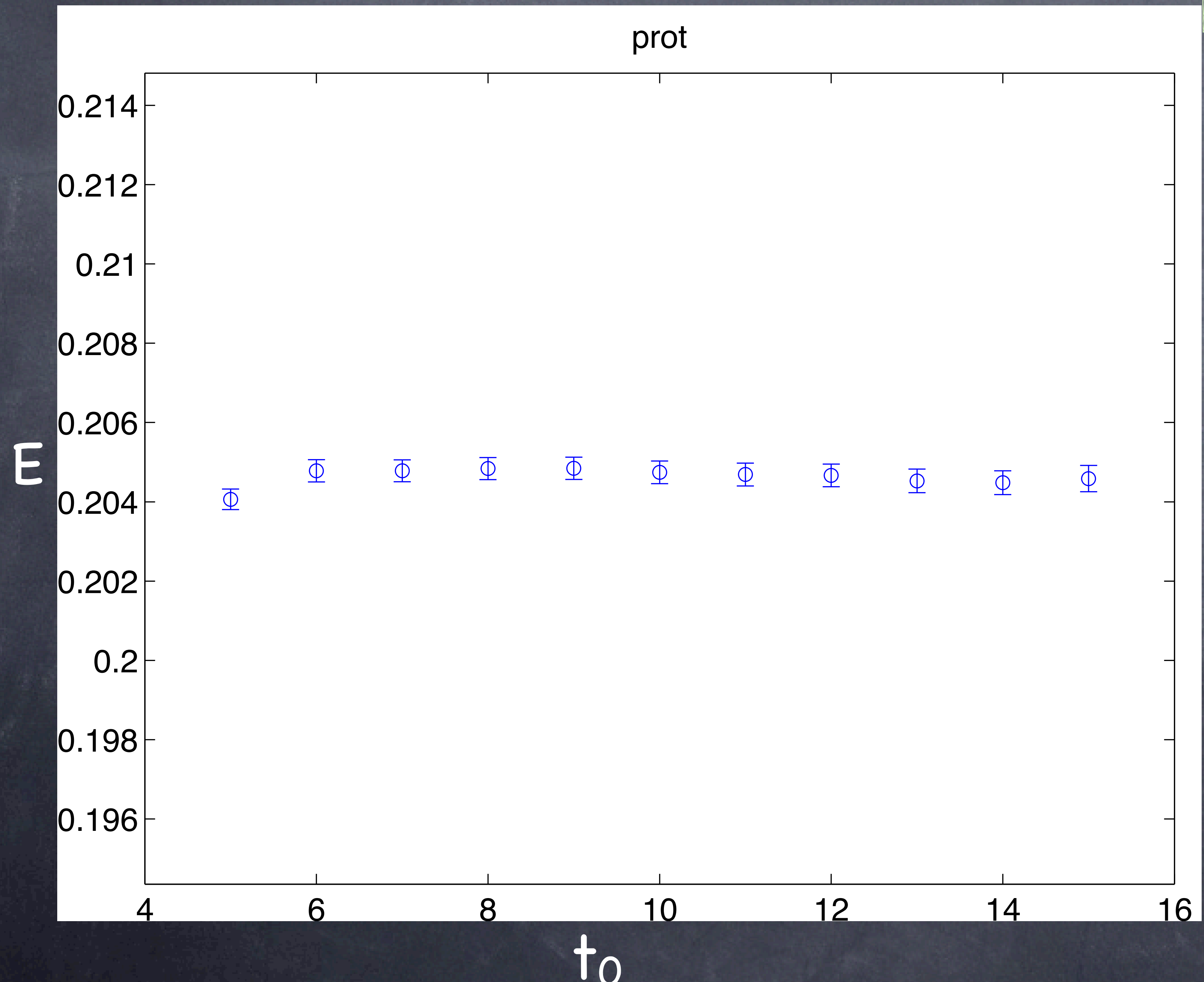
one source smearing

smeared and point sink

two source shifts

2x2 matrix

Single Baryon



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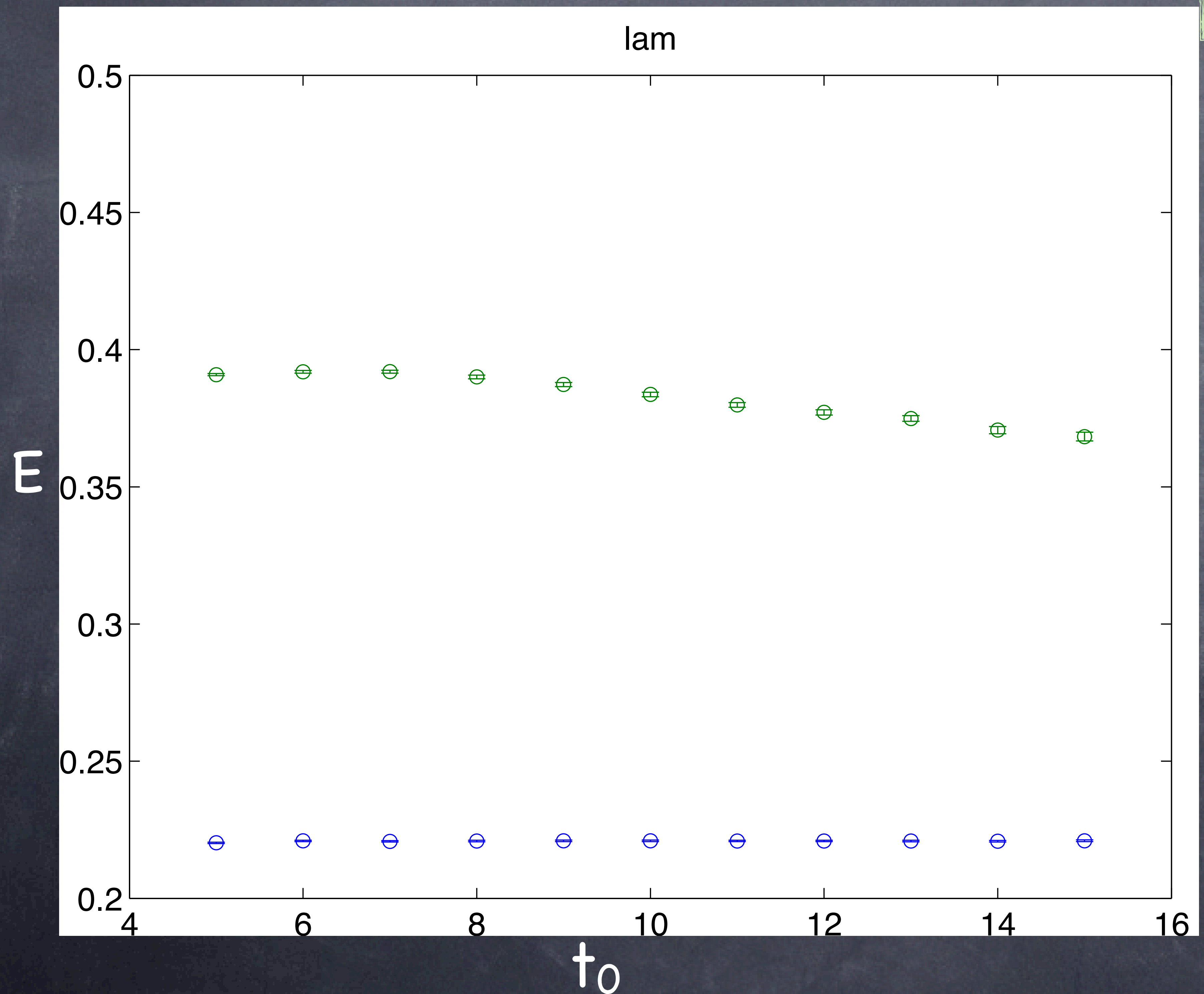

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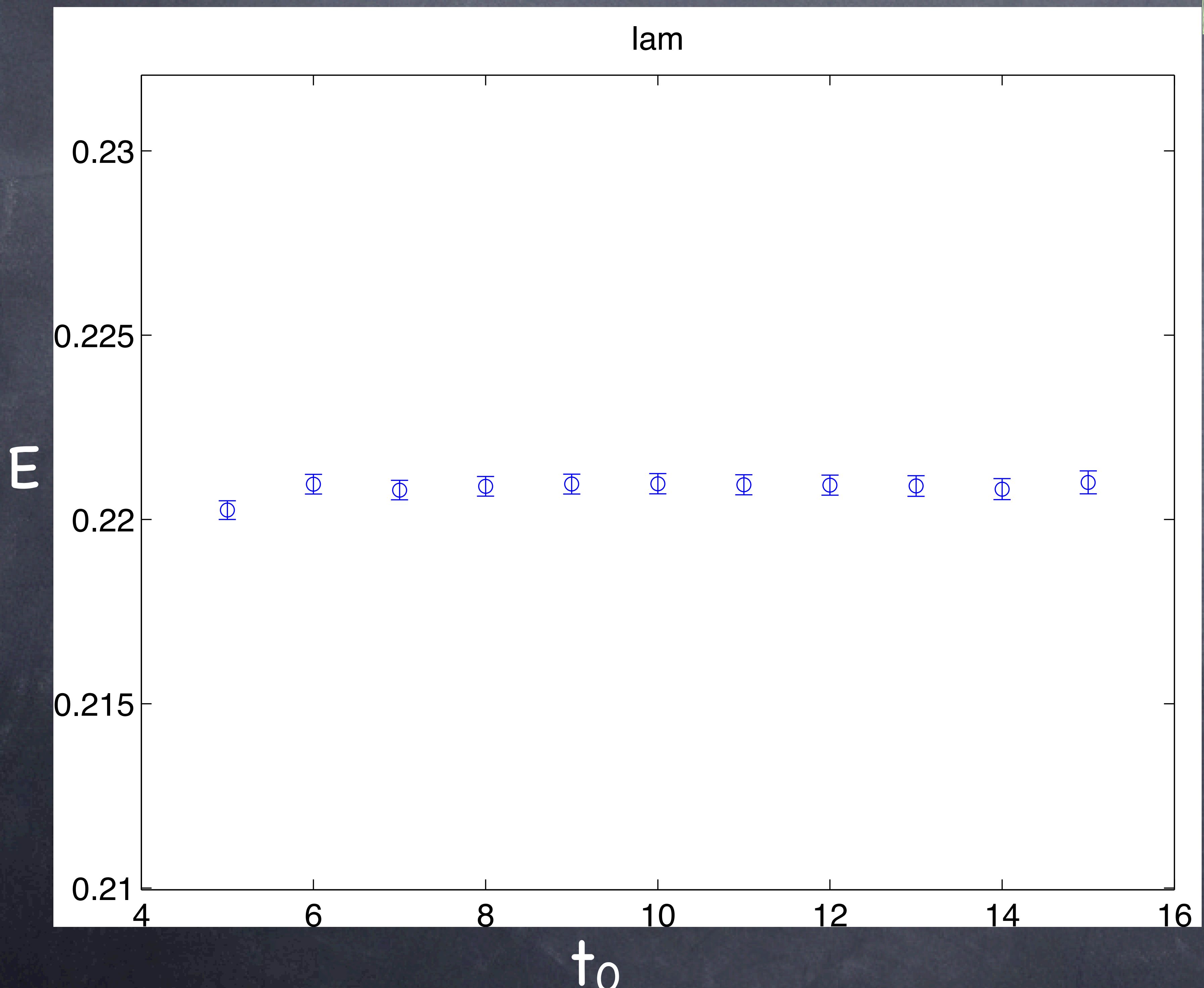

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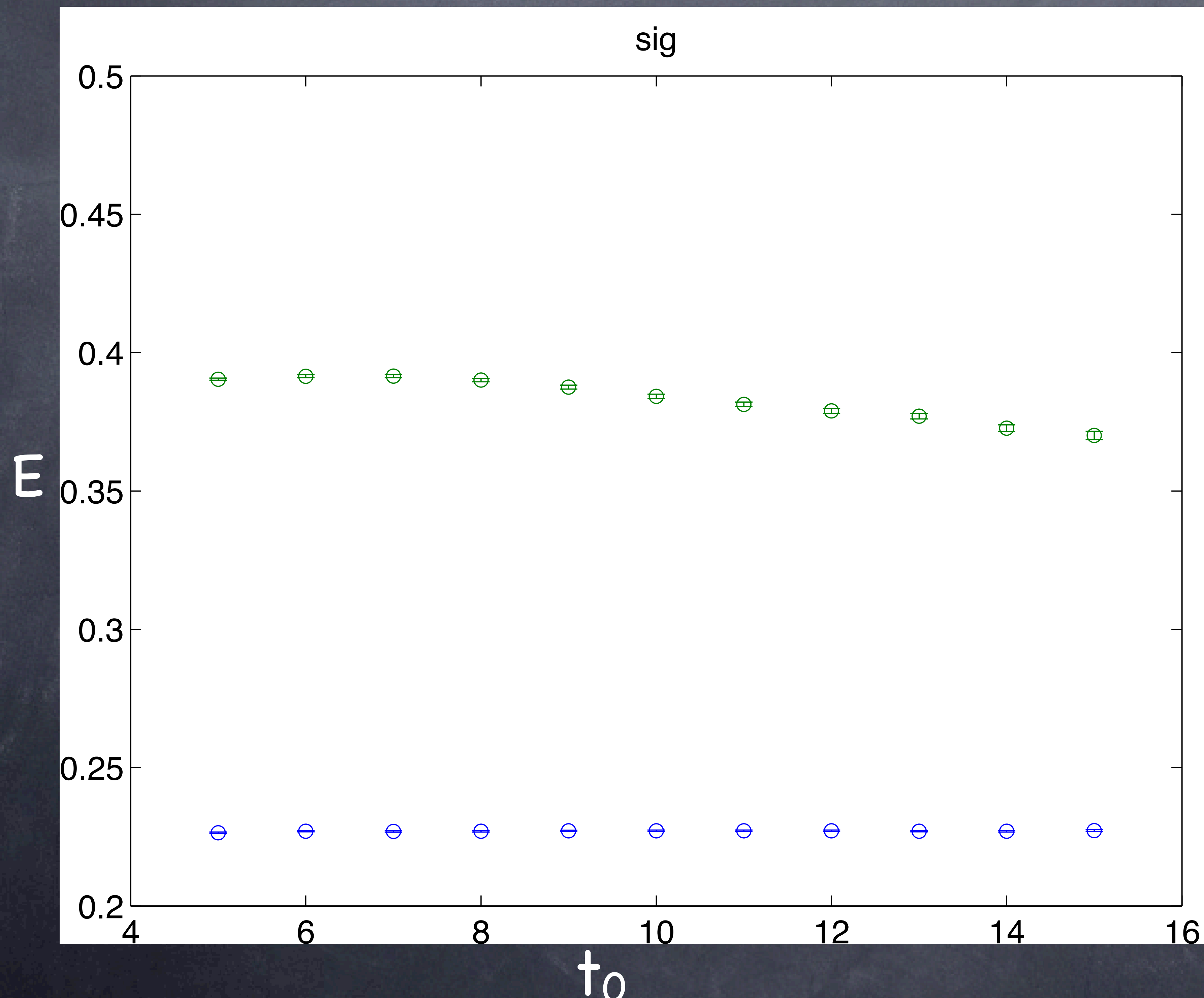

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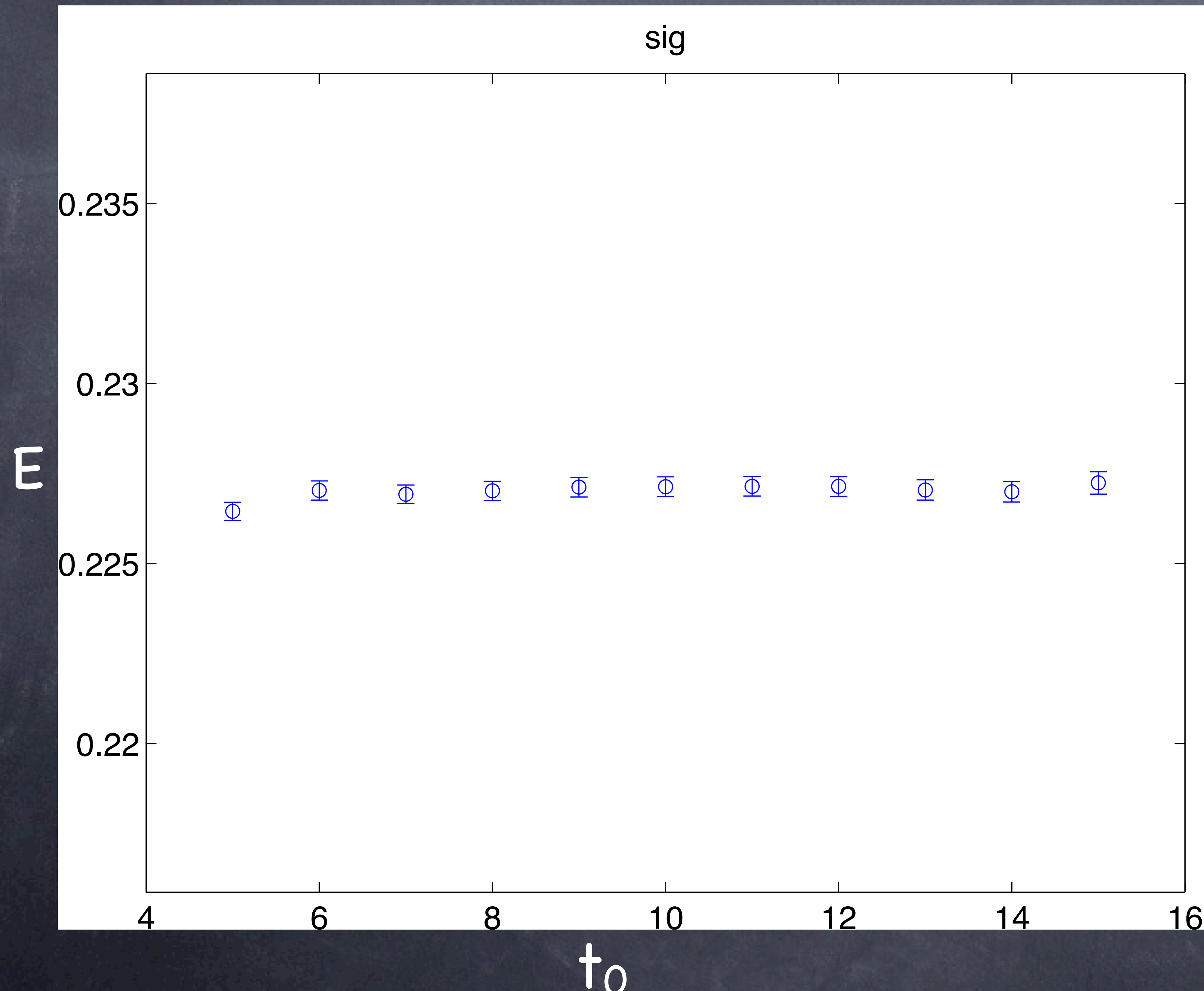

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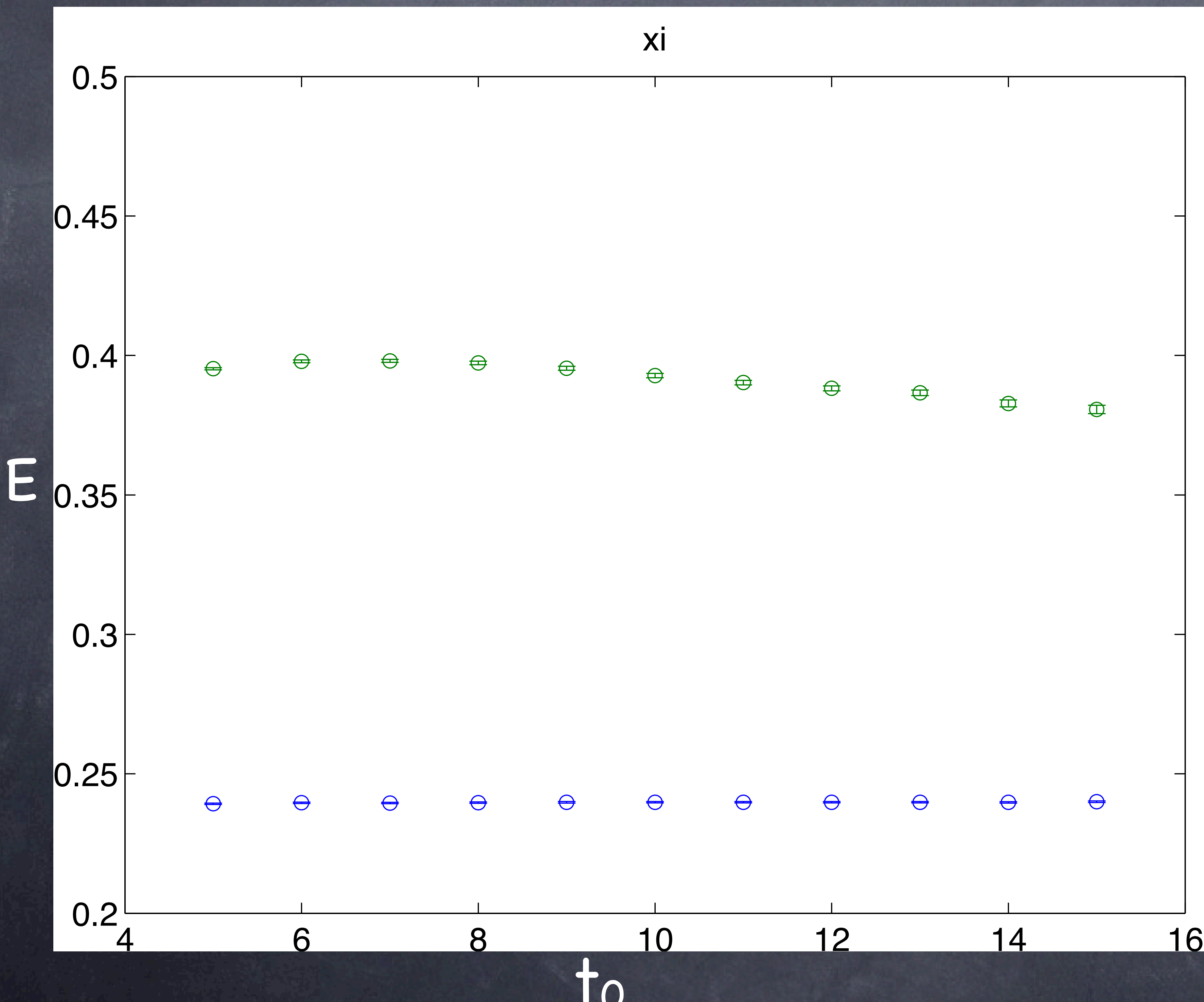
Single Baryon



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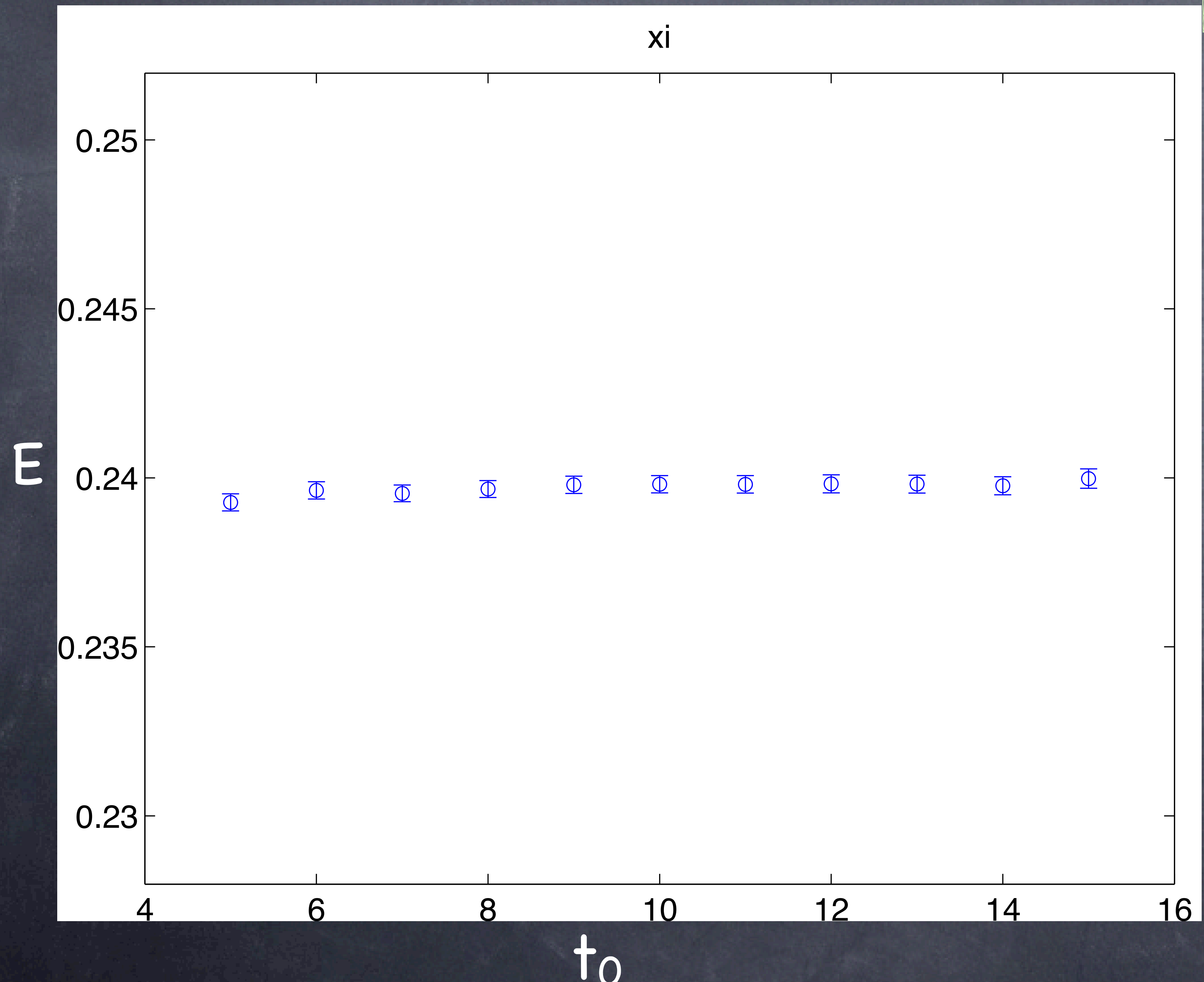

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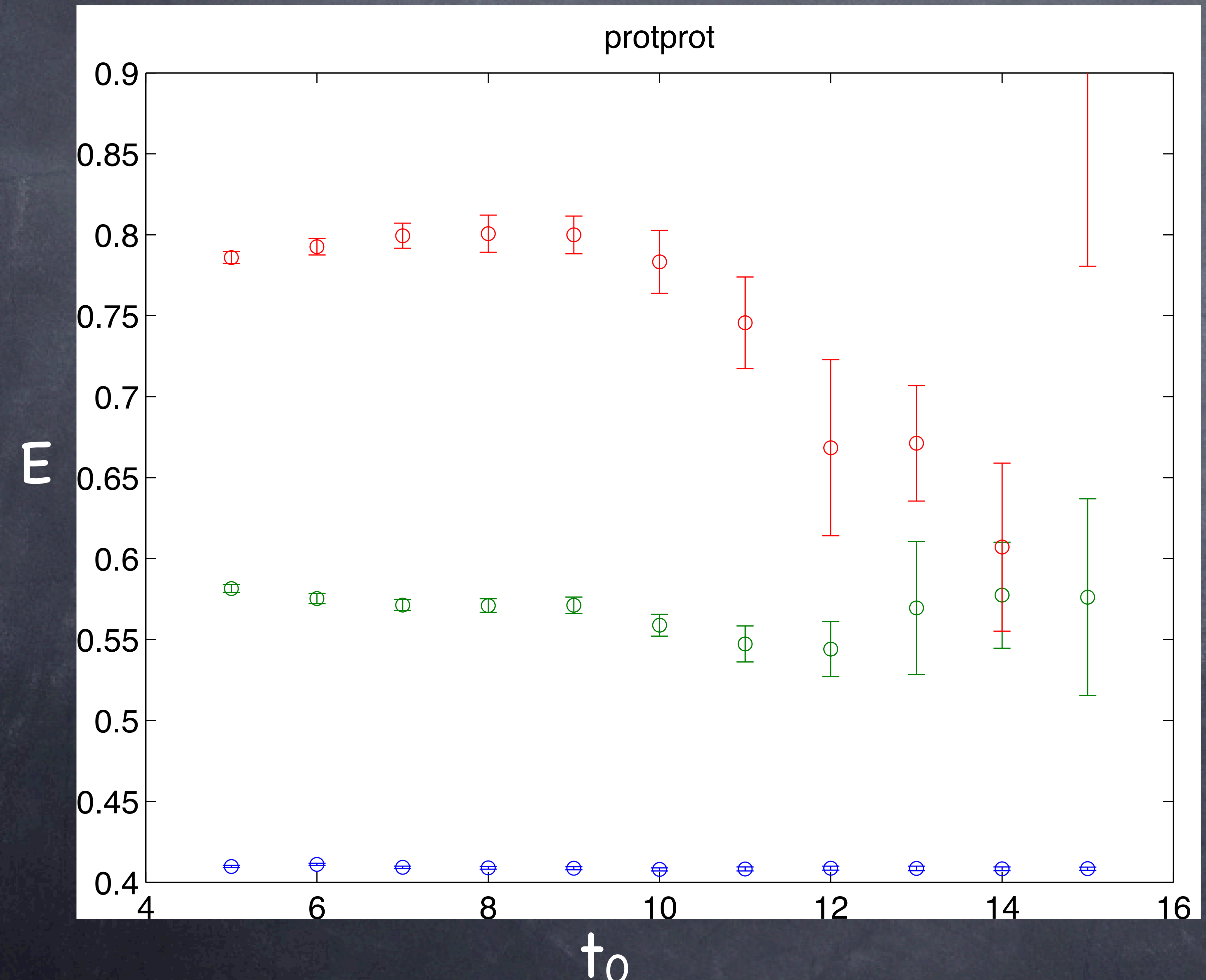


NPLQCD data

single operator

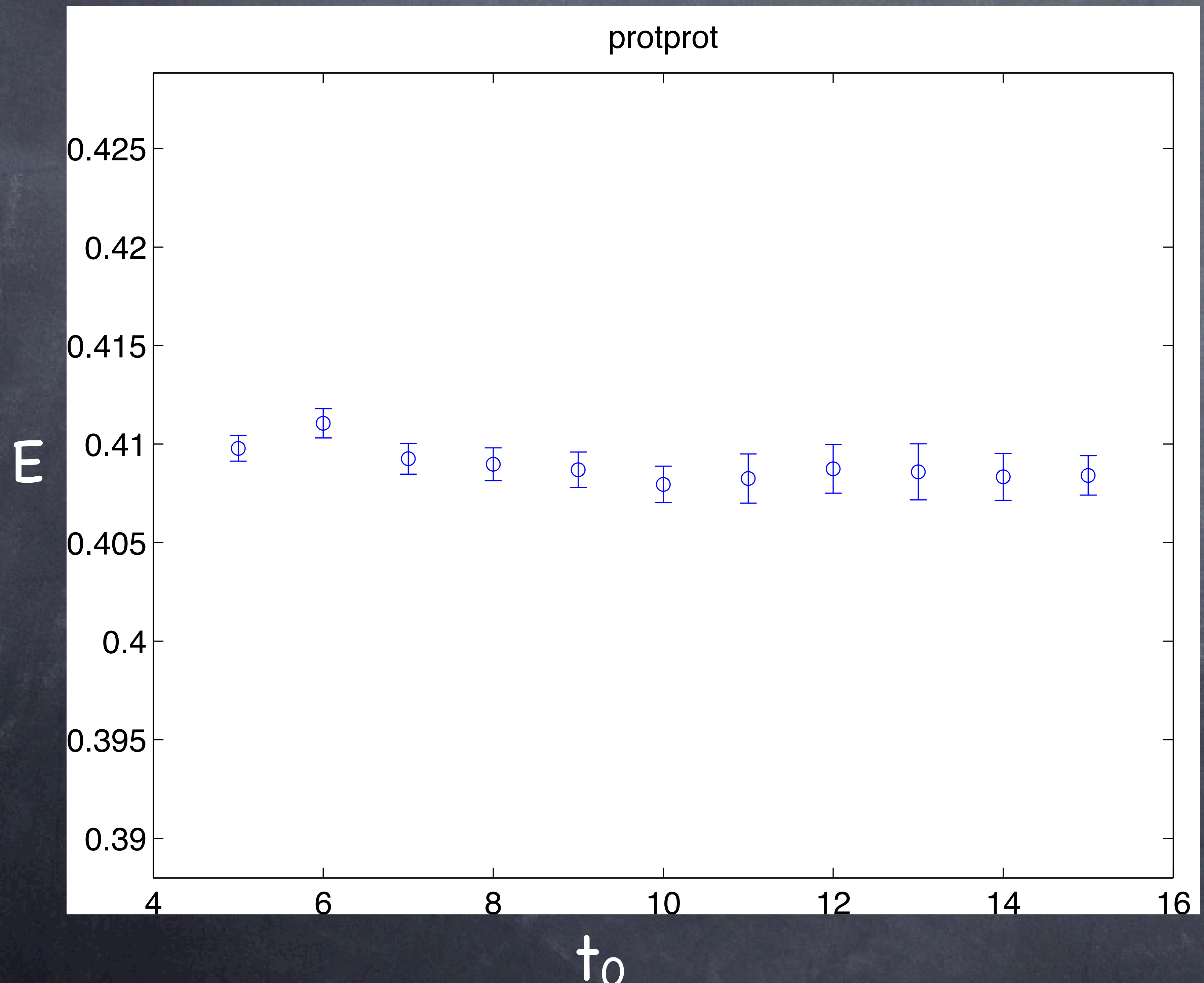
one source smearing

smeared, point and smeared-point sink

three source shifts

3x3 matrix

Two Baryons



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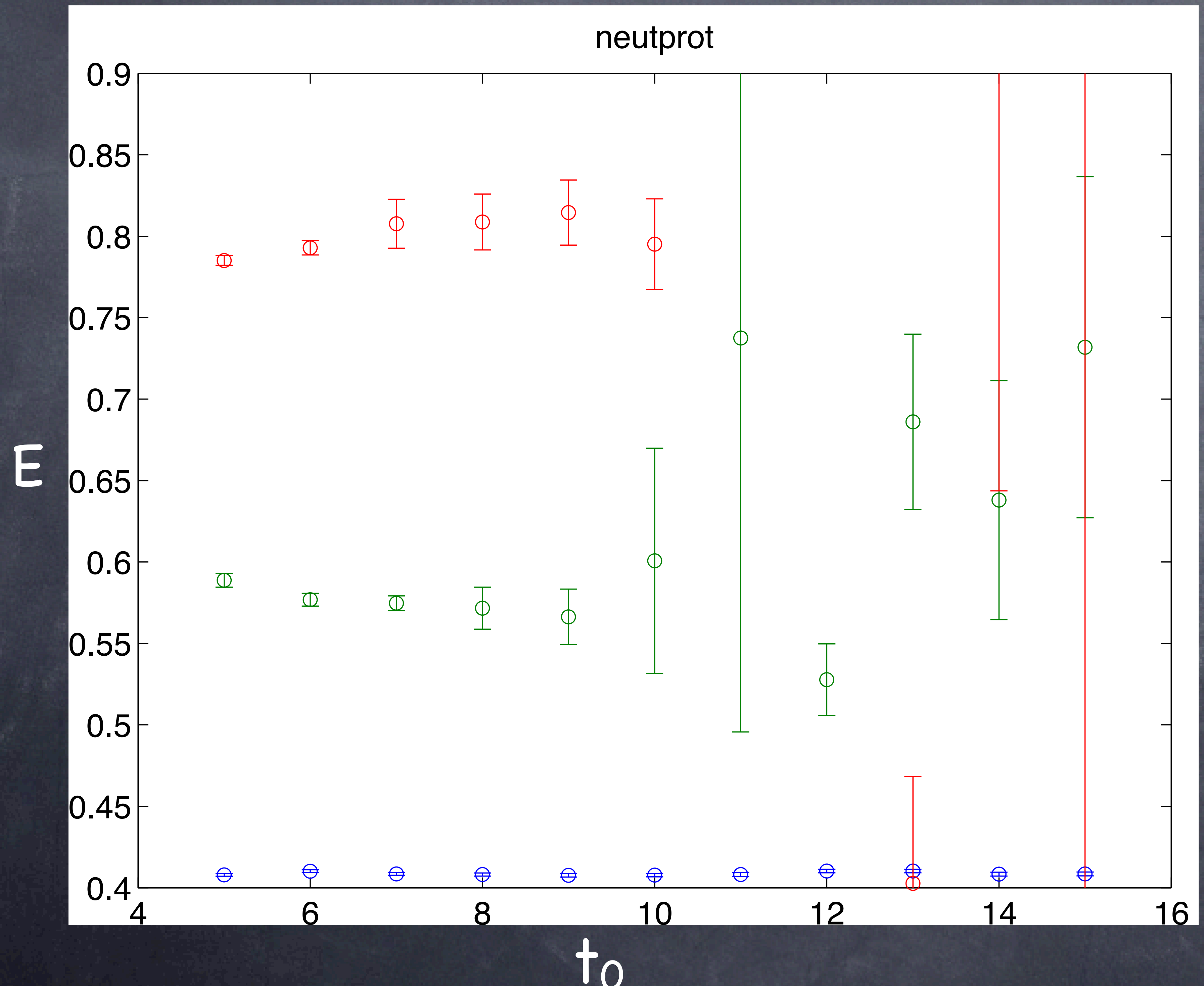

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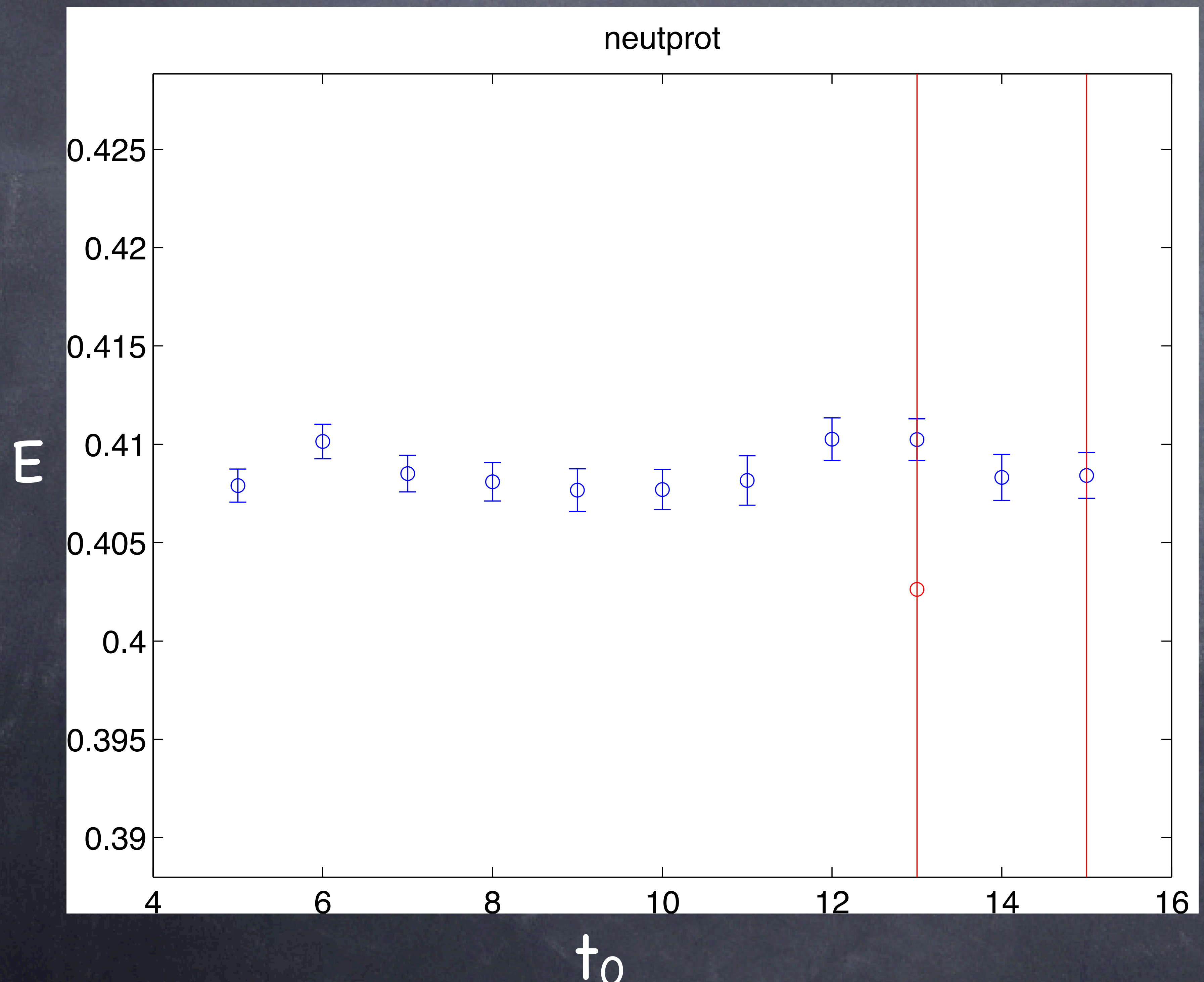

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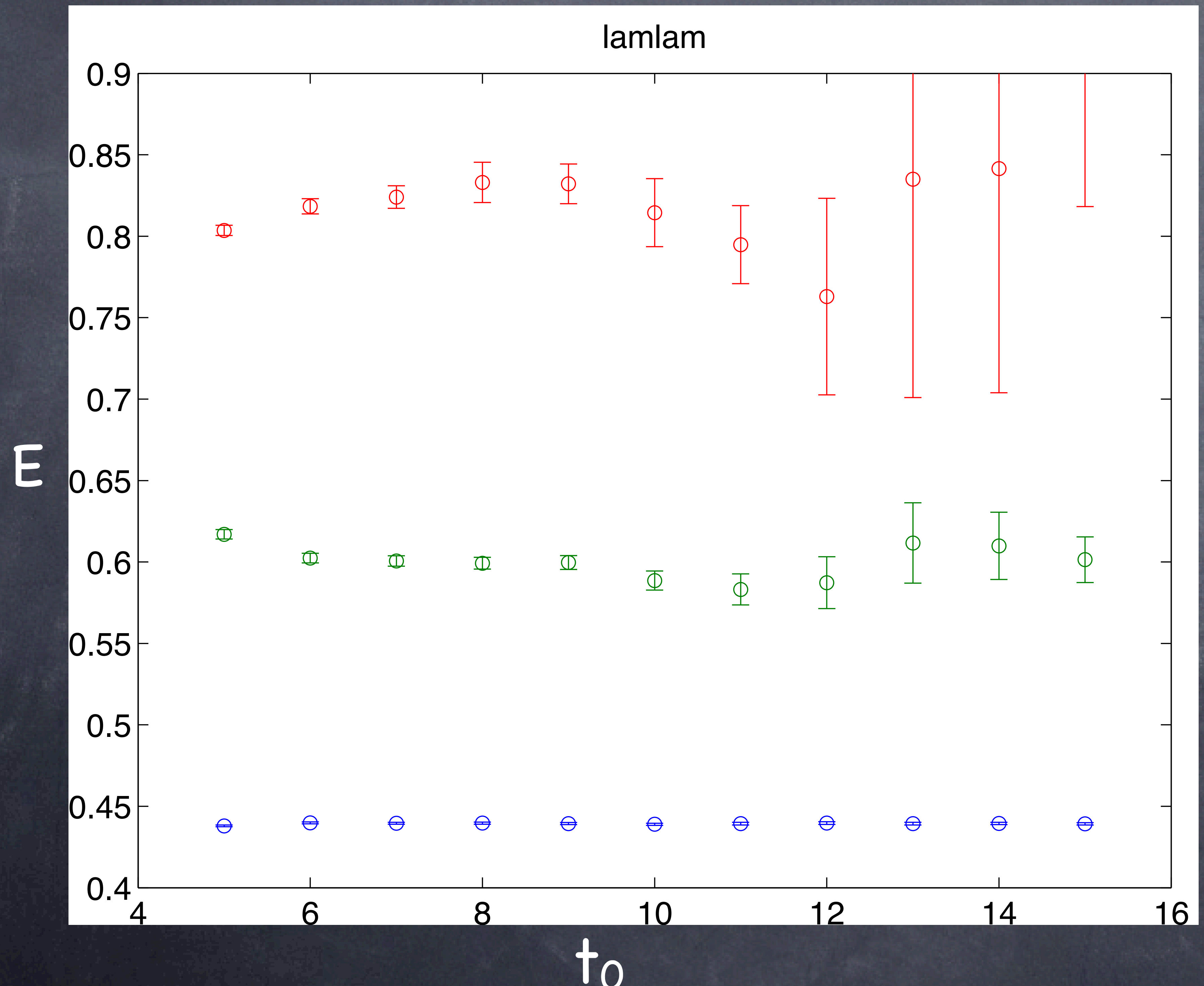

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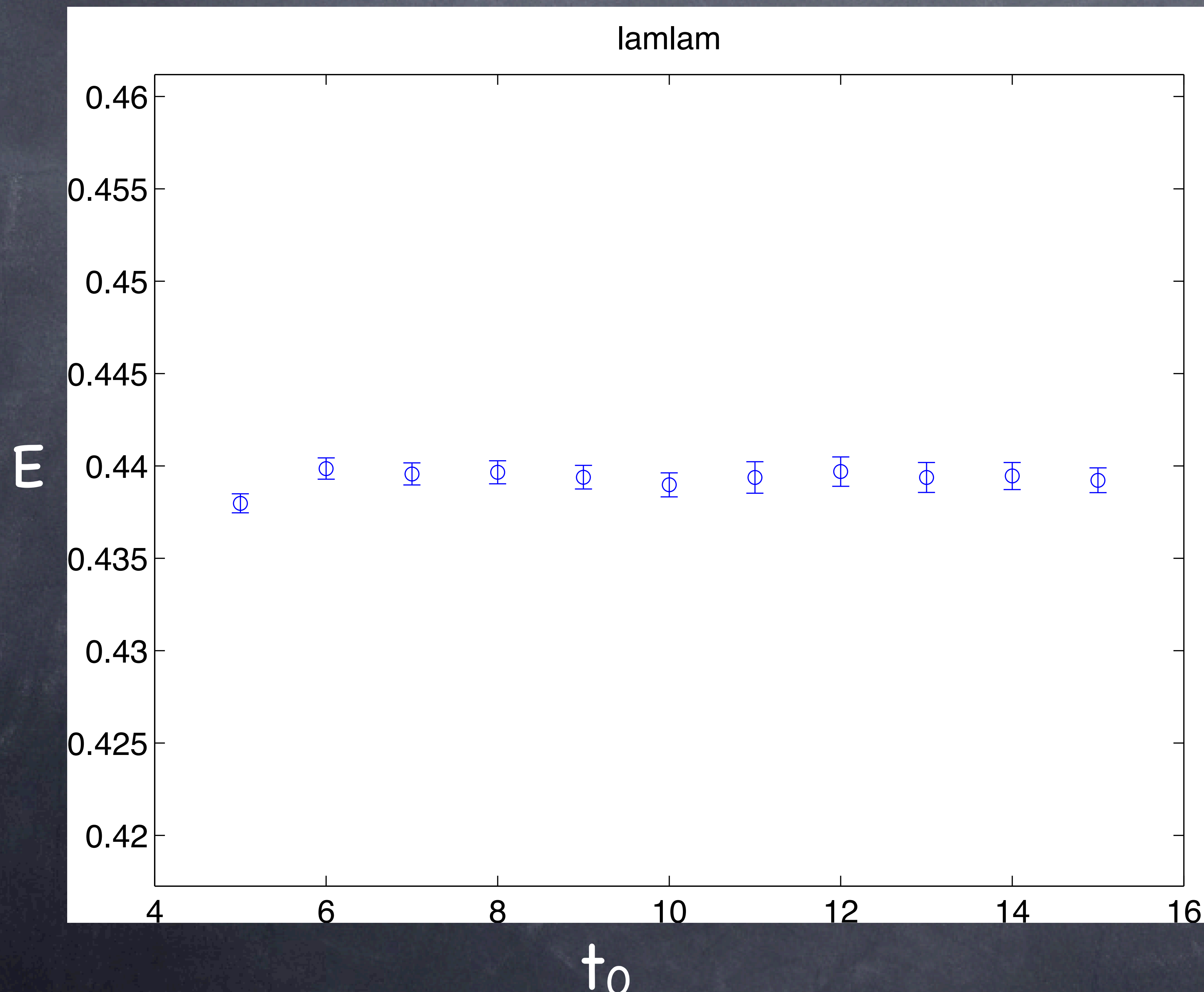

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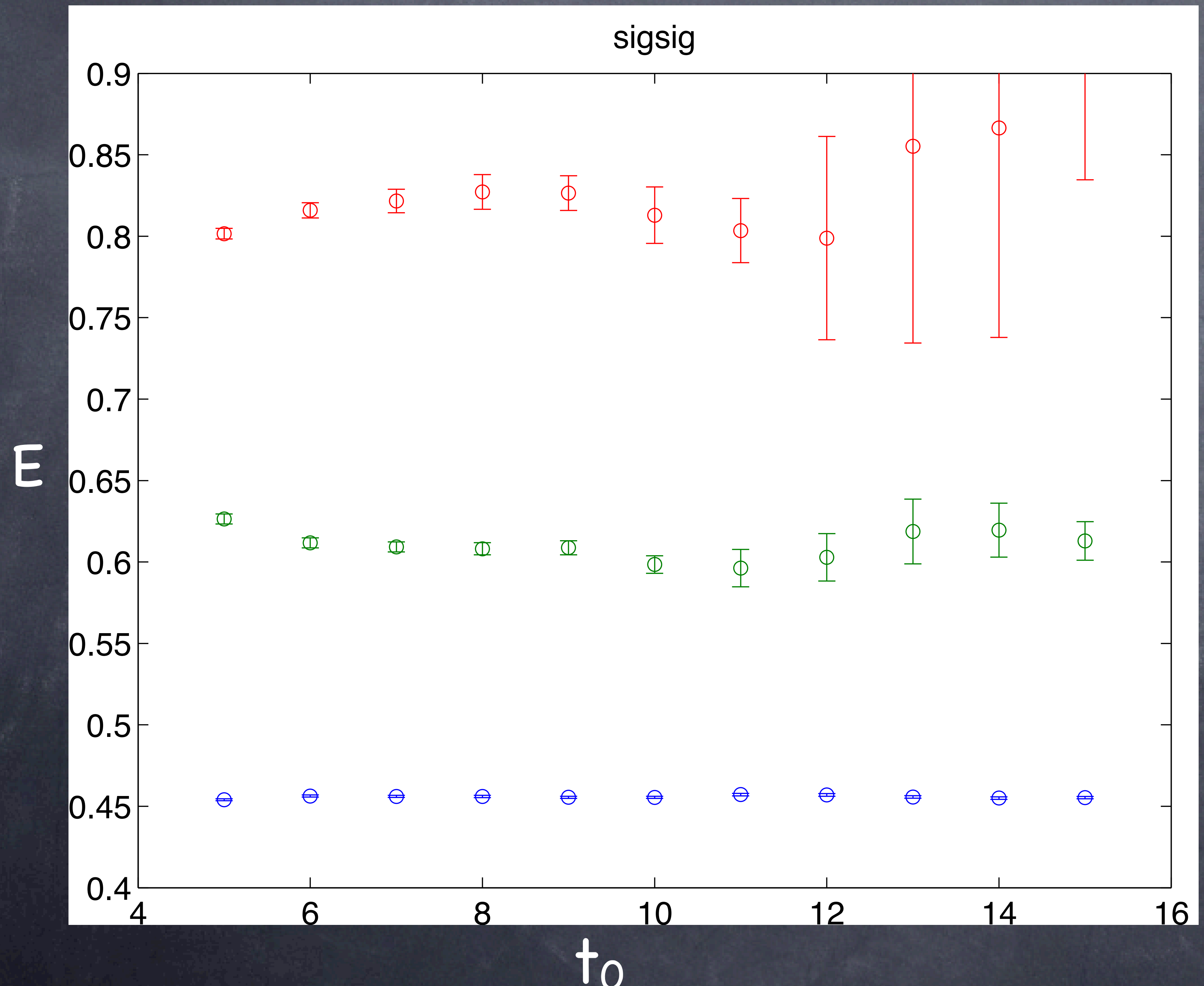

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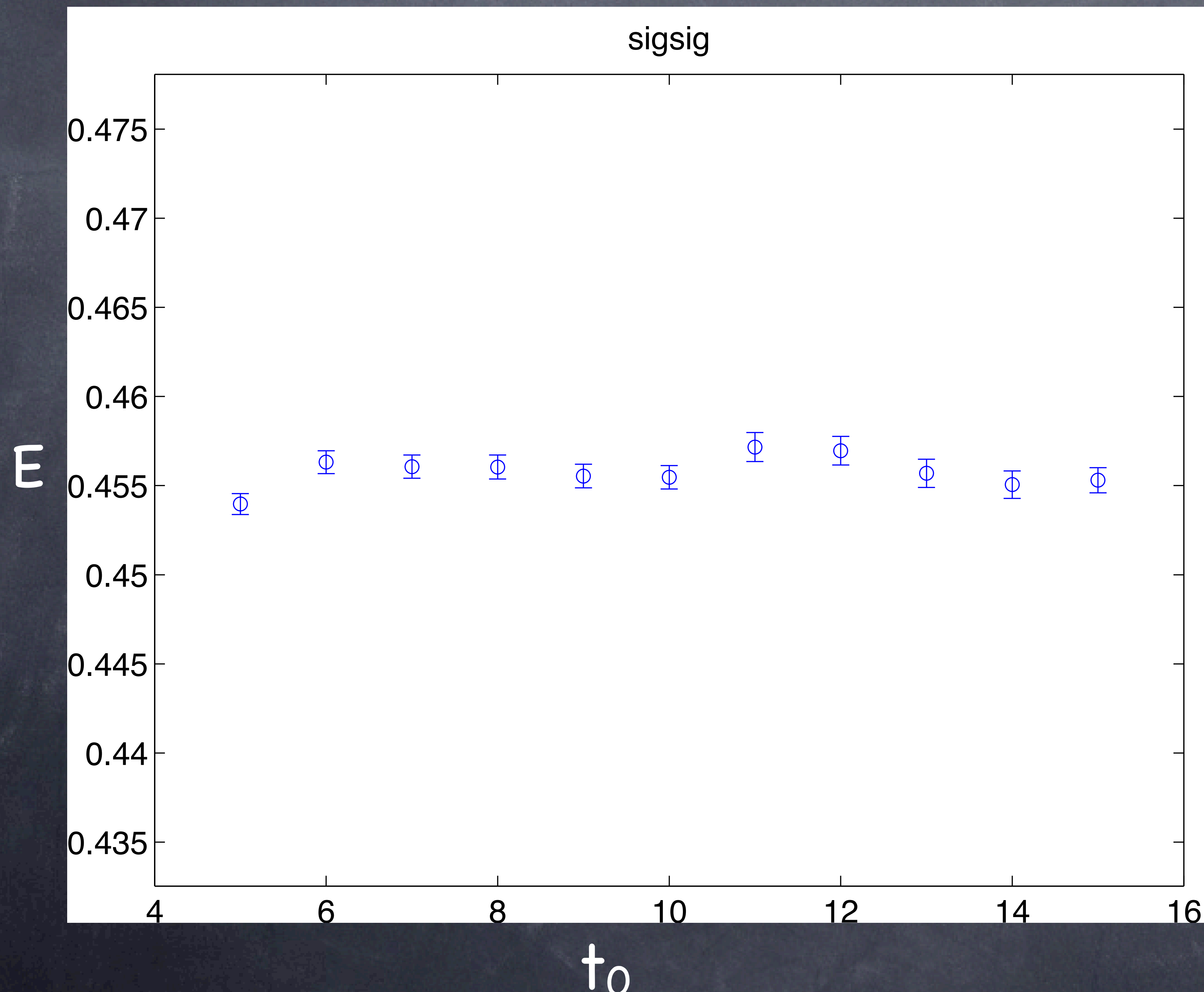
3x3 matrix

Two Baryons



NPLQCD data

single operator

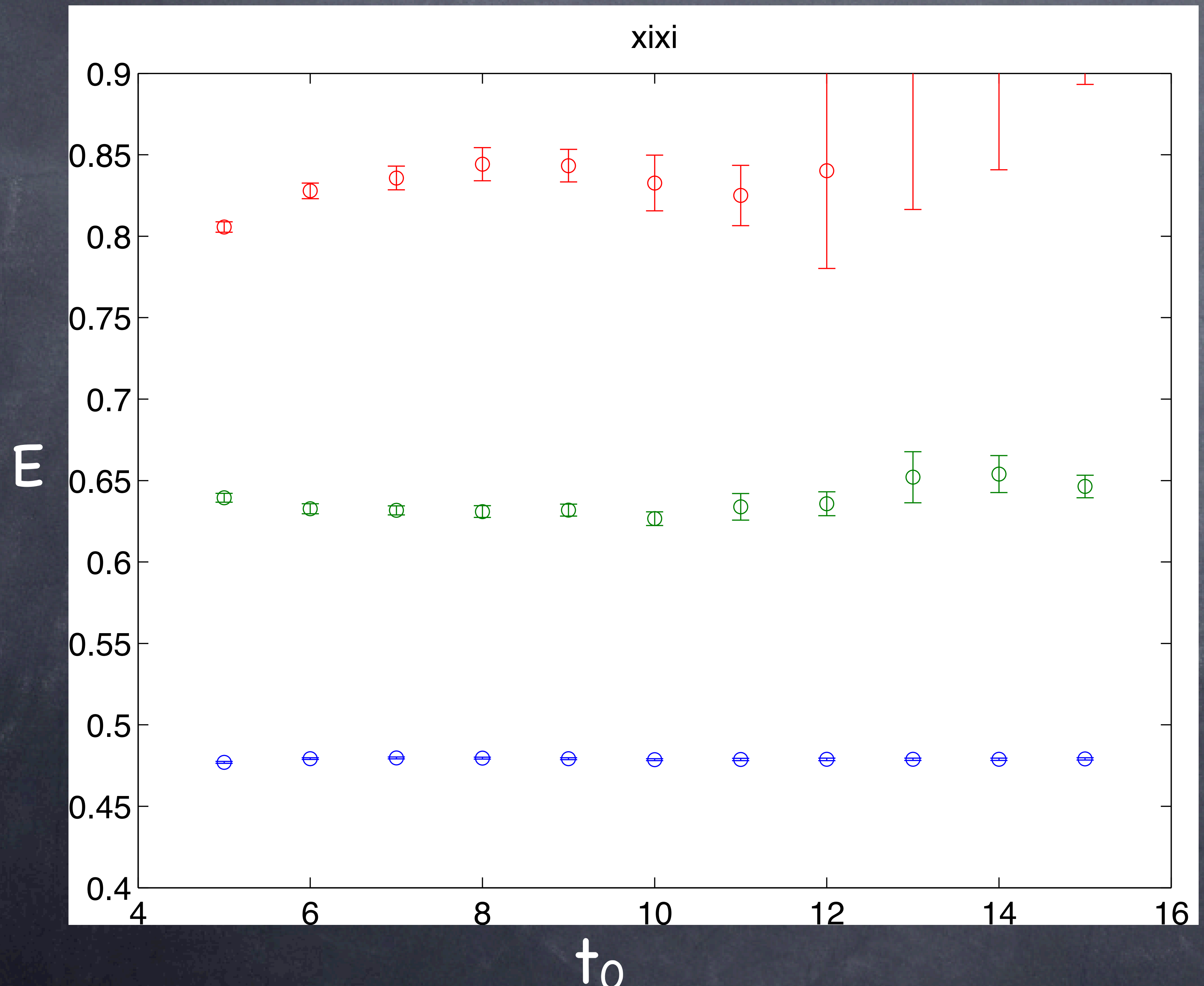
one source smearing

smeared, point and smeared-point sink

three source shifts

3x3 matrix

Two Baryons



NPLQCD data

single operator

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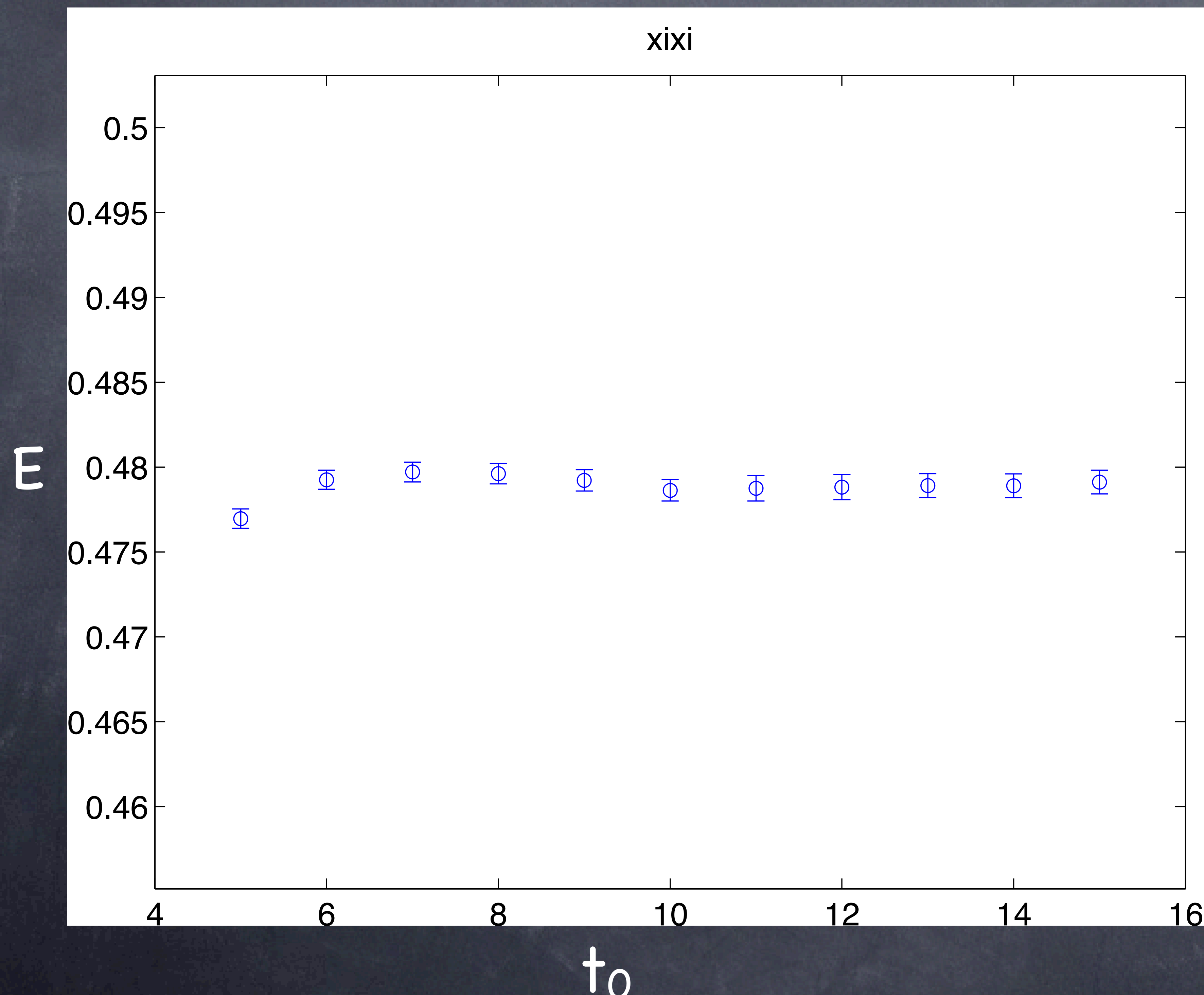
smeared, point and smeared-point sink

three source shifts

3x3 matrix

Two Baryons



NPLQCD data

single operator

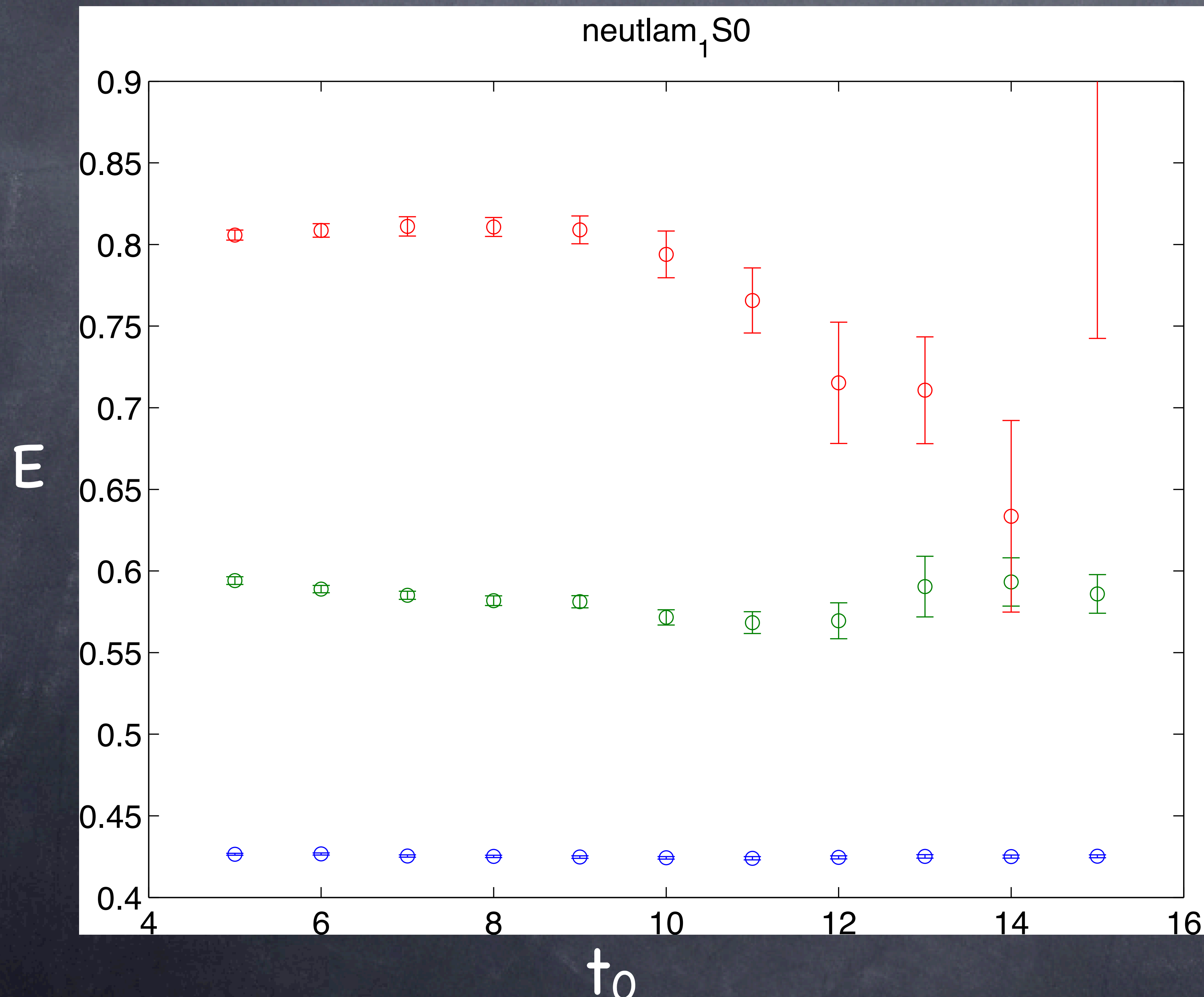
one source smearing

smeared, point and smeared-point sink

three source shifts

3x3 matrix

Two Baryons



NPLQCD data

single operator

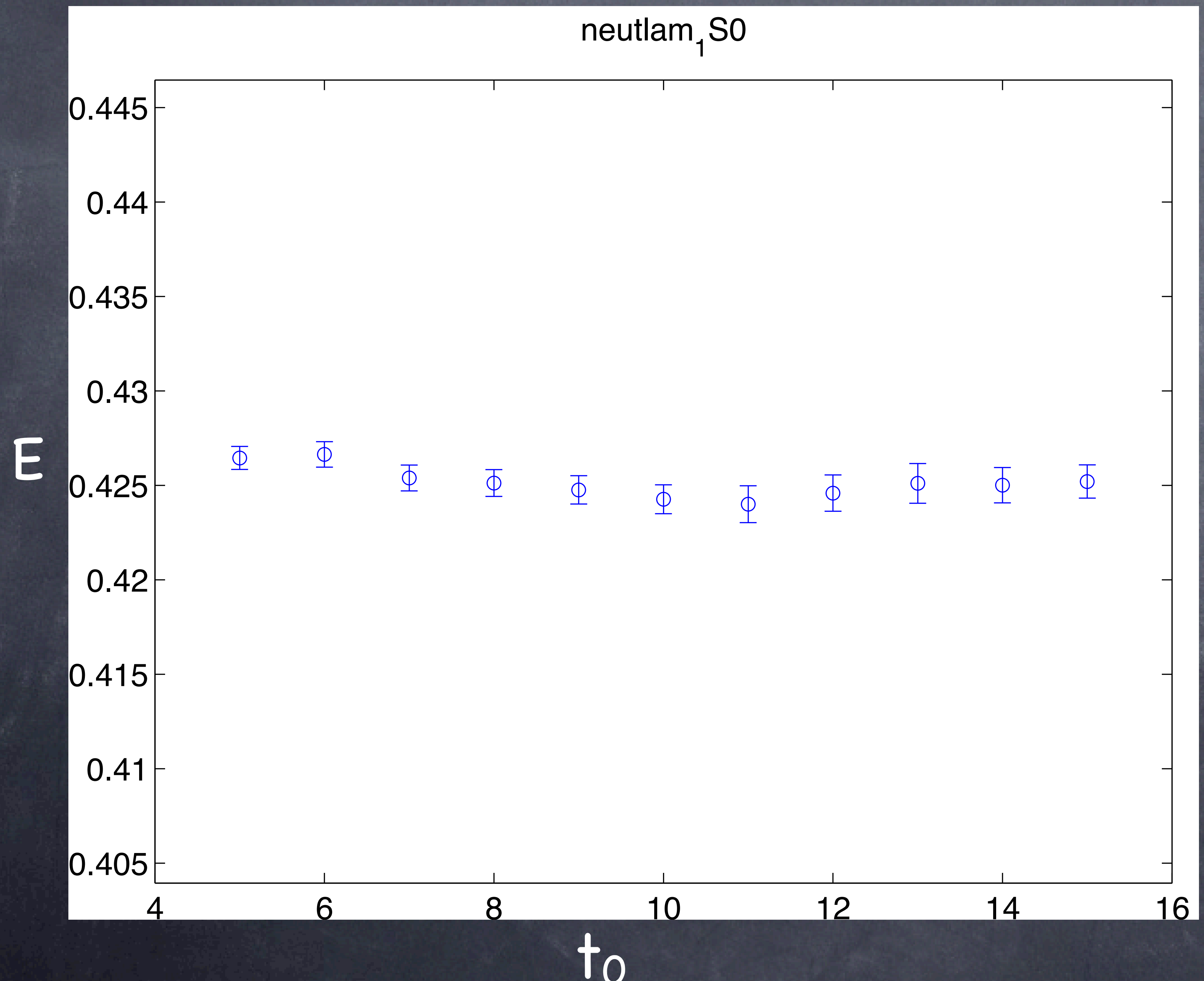
one source smearing

smeared, point and smeared-point sink

three source shifts

3x3 matrix

Two Baryons



NPLQCD data

single operator

one source smearing

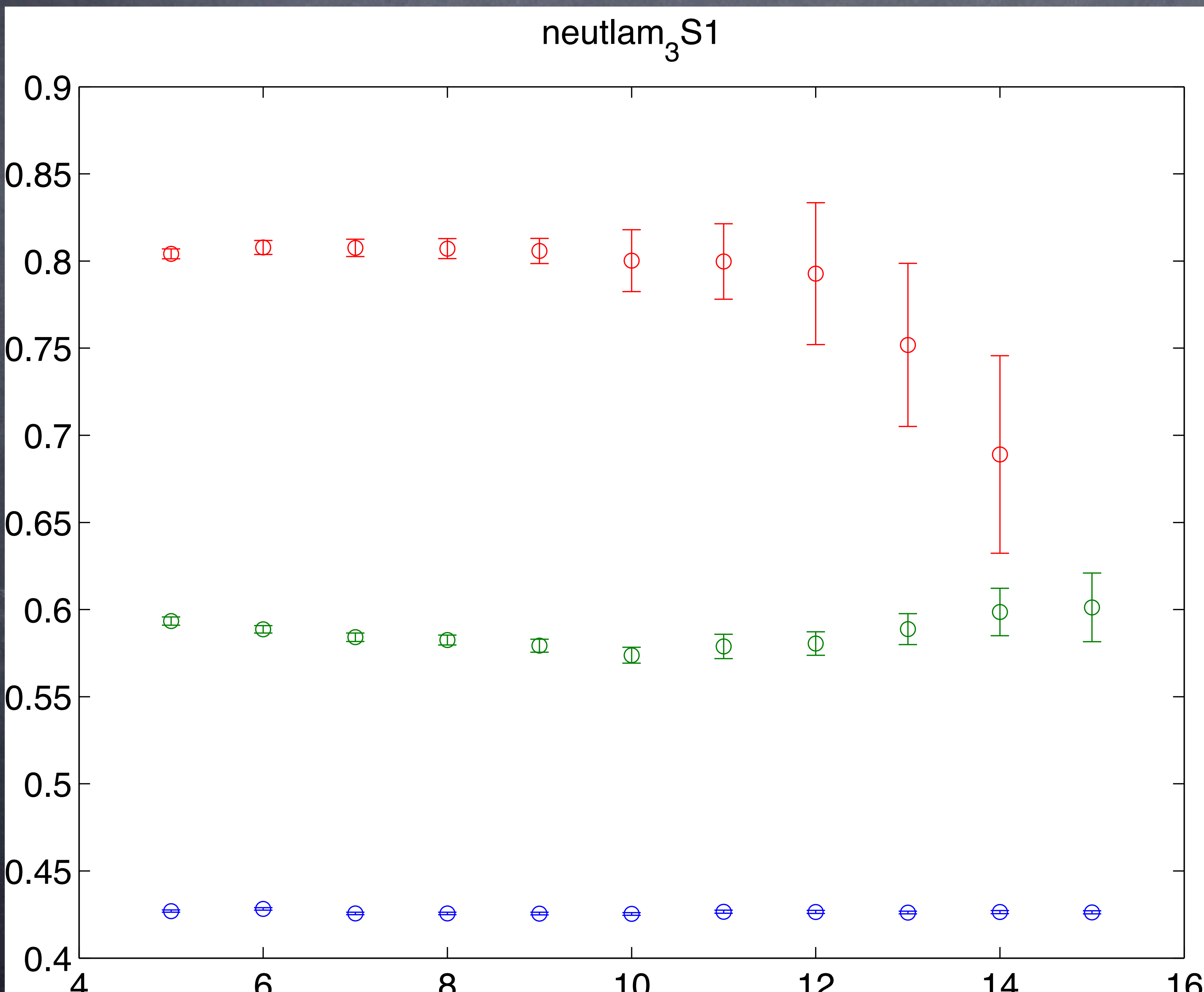
smeared, point and smeared-point sink

three source shifts

3x3 matrix

Two Baryons

E



t_0

NPLQCD data

single operator

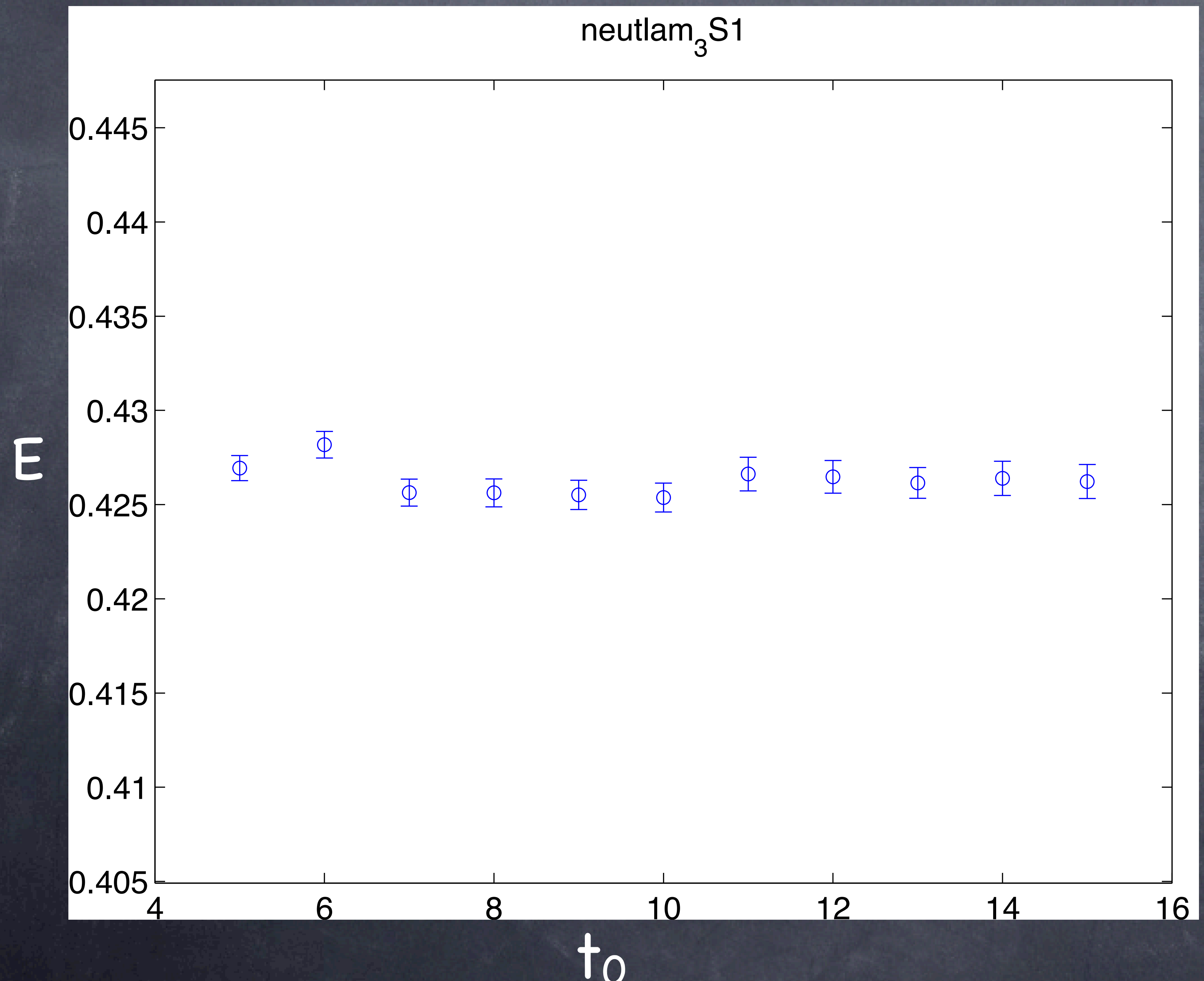
one source smearing

smeared, point and smeared-point sink

three source shifts

3x3 matrix

Two Baryons



NPLQCD data

single operator

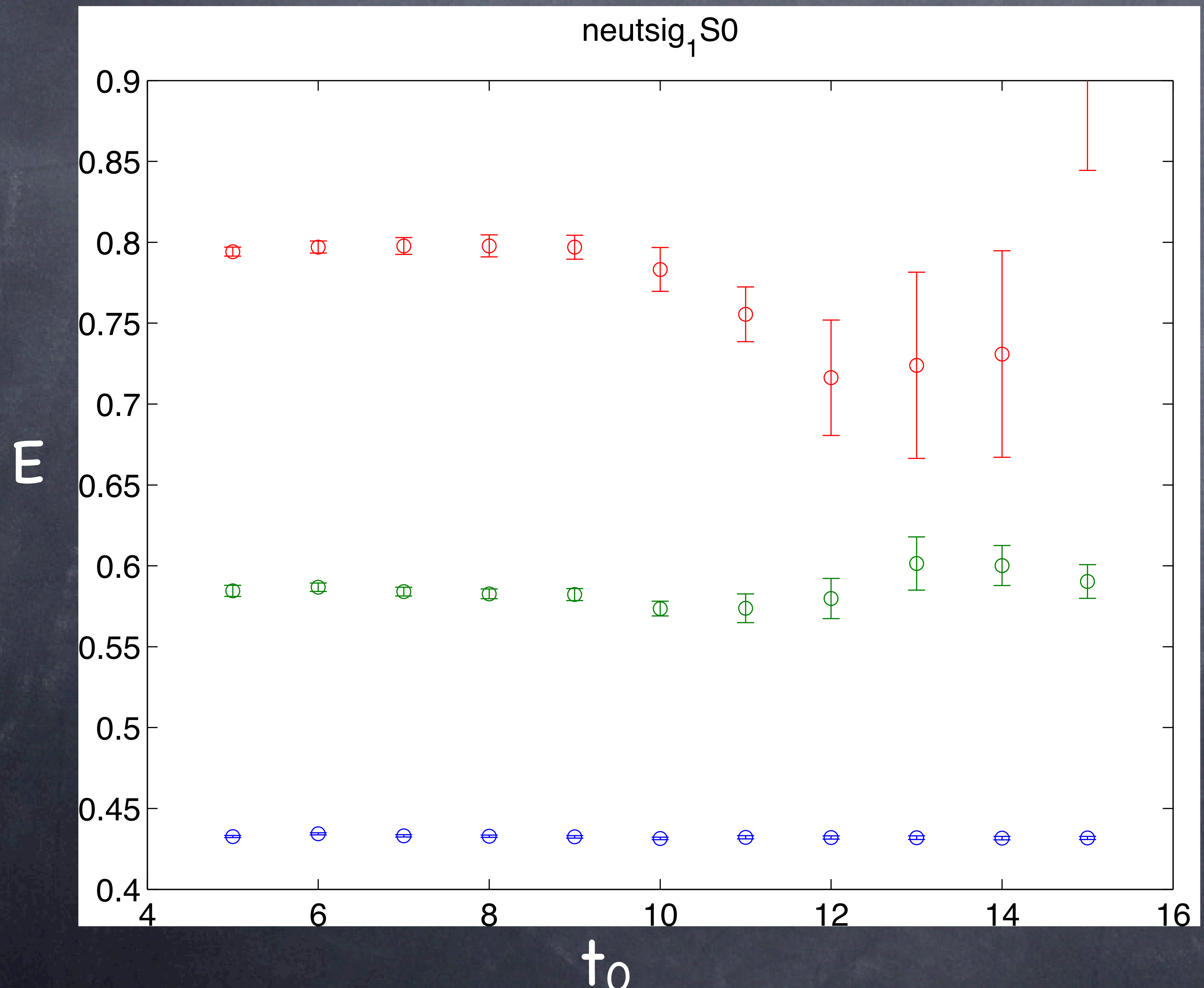
one source smearing

smeared, point and smeared-point sink

three source shifts

3x3 matrix

Two Baryons



NPLQCD data

single operator

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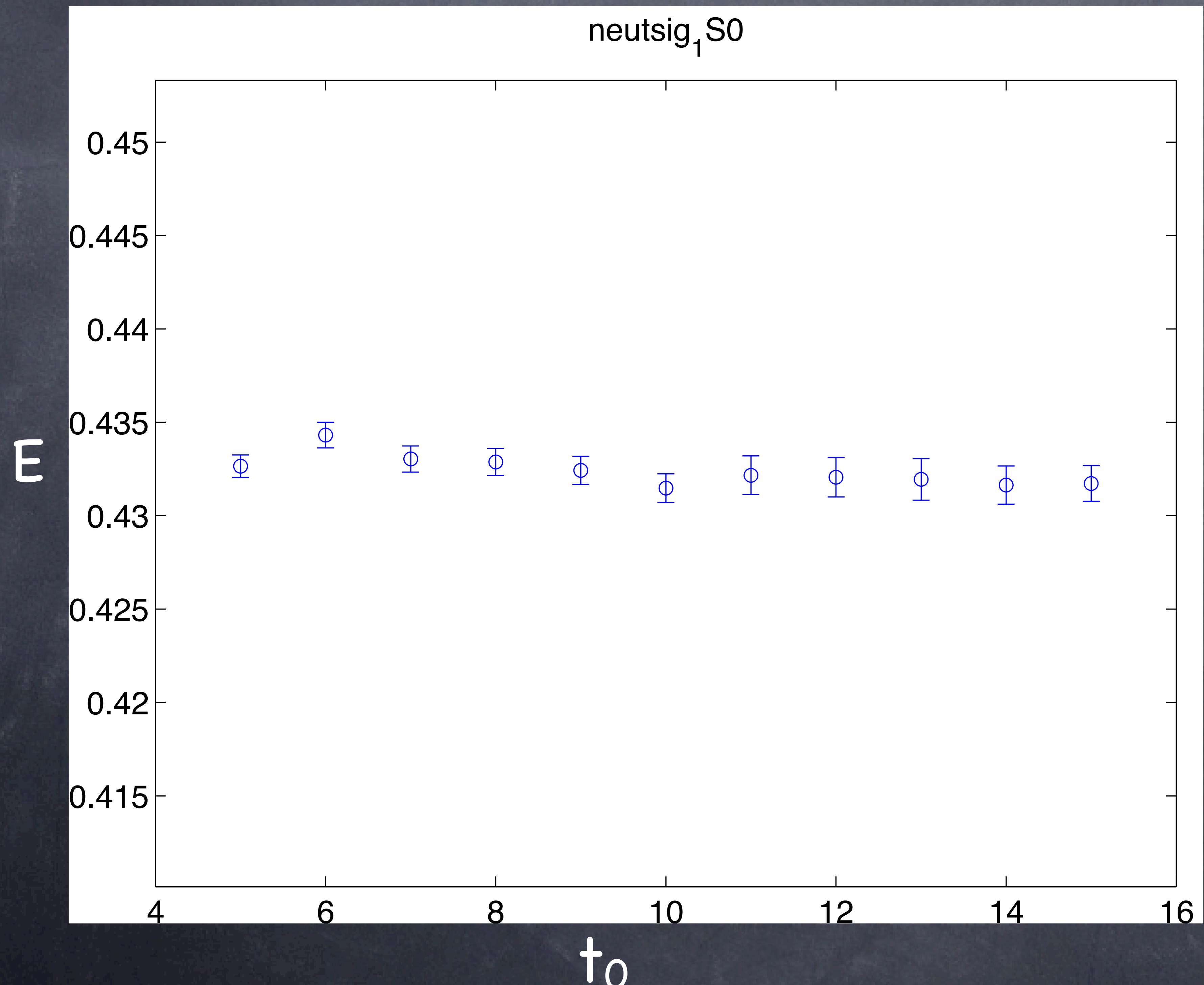
smeared, point and smeared-point sink

three source shifts

3x3 matrix

Two Baryons



NPLQCD data

single operator

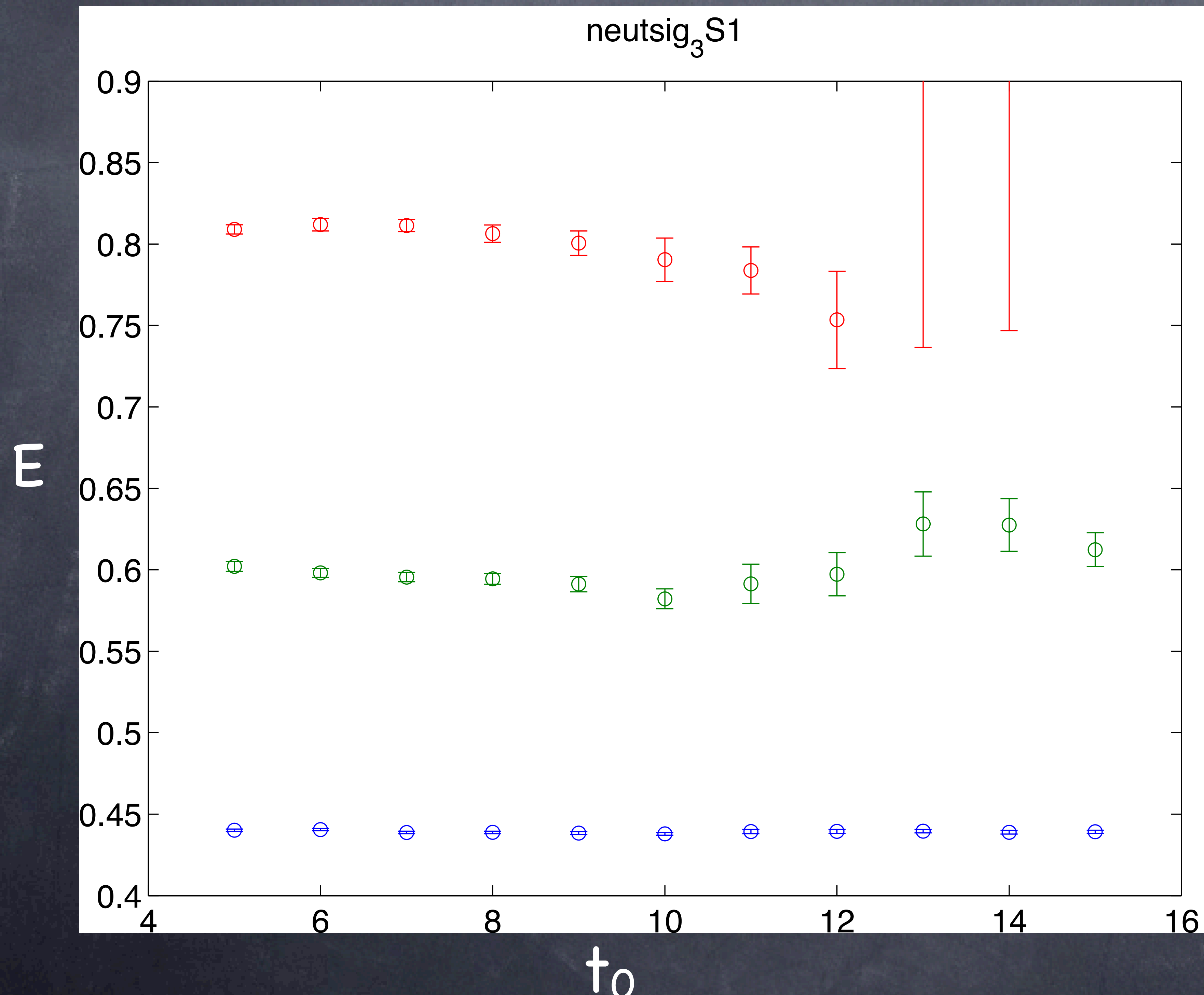
one source smearing

smeared, point and smeared-point sink

three source shifts

3x3 matrix

Two Baryons



NPLQCD data

single operator

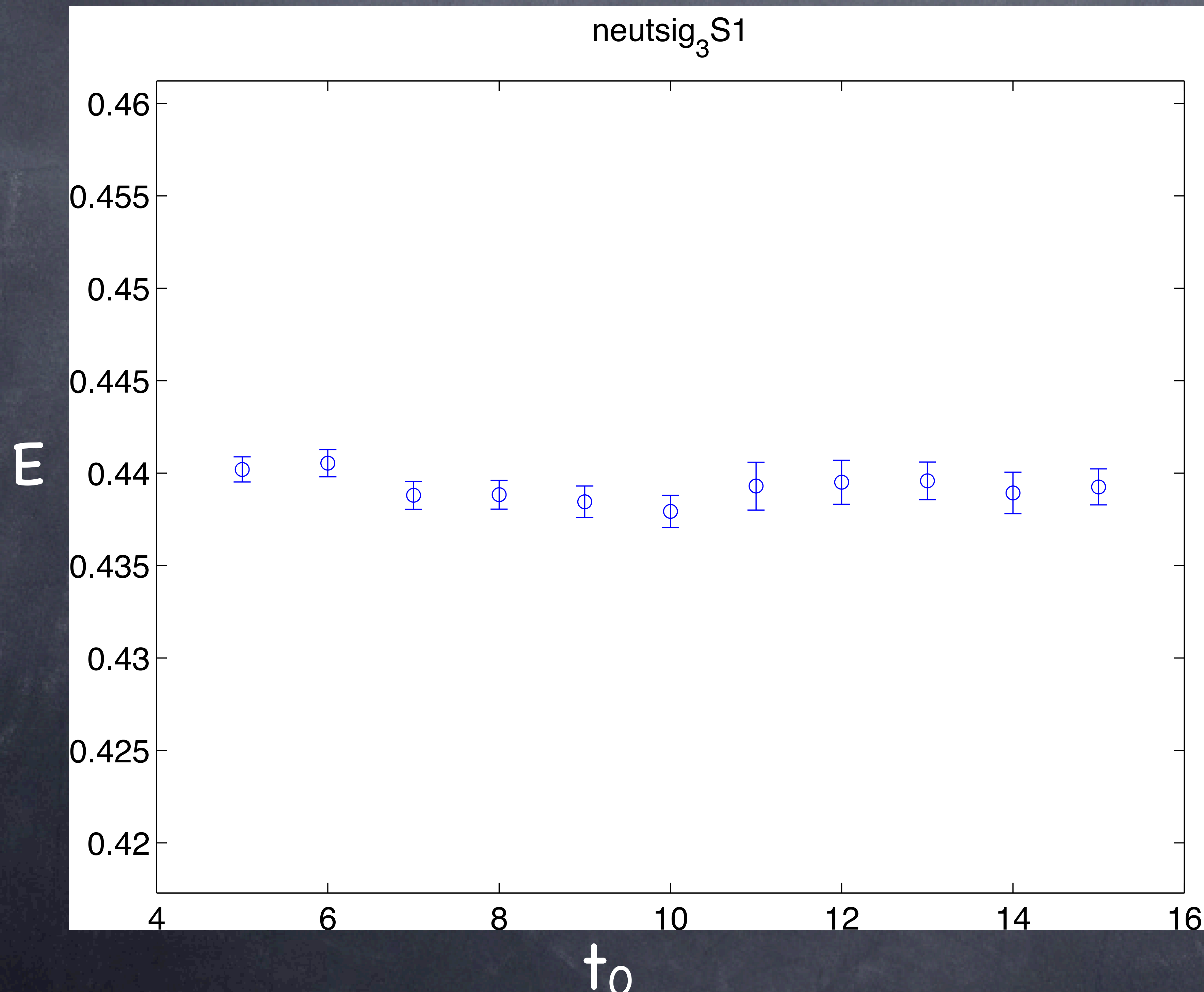
one source smearing

smeared, point and smeared-point sink

three source shifts

3x3 matrix

Two Baryons



NPLQCD data

single operator

one source smearing

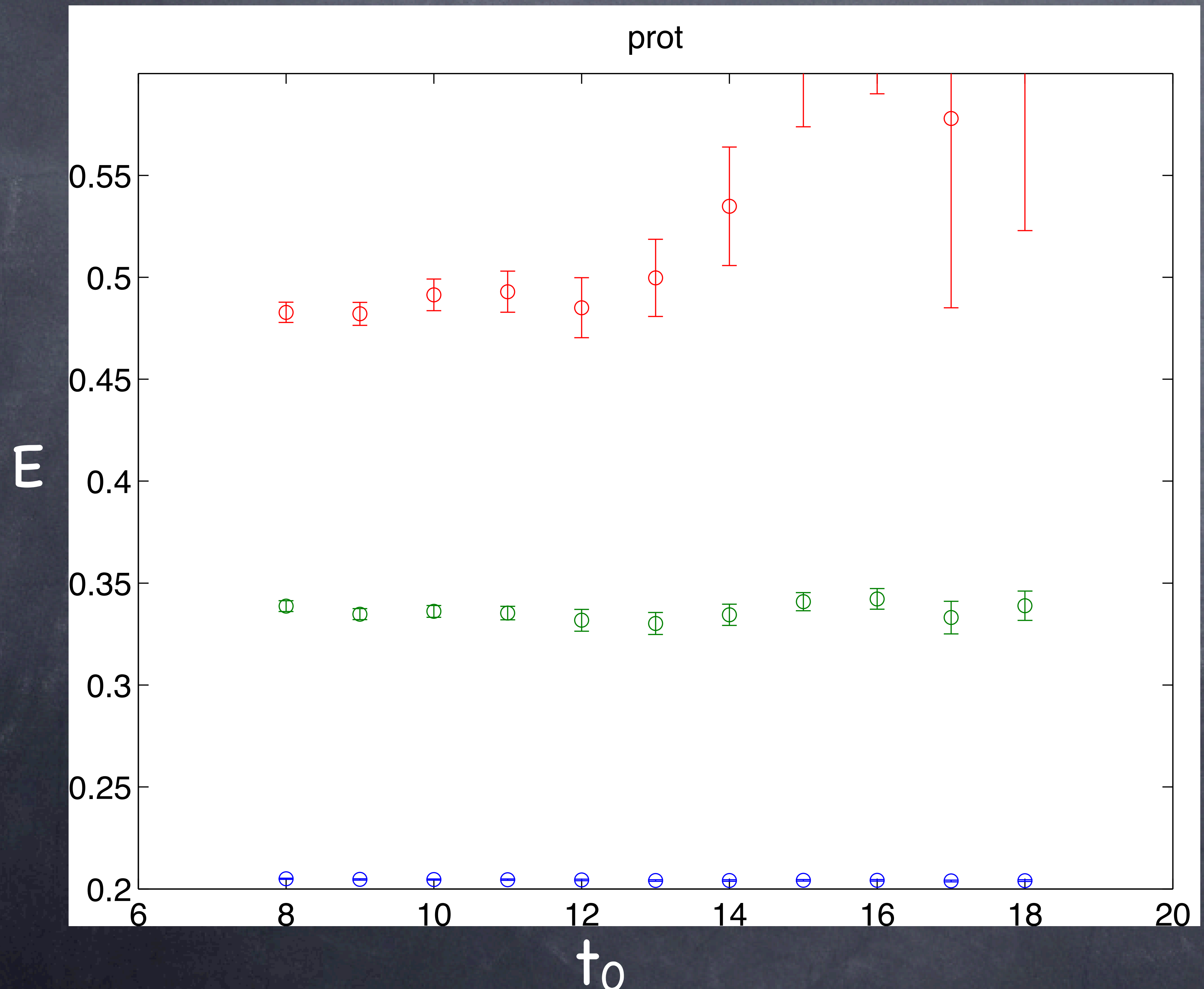
smeared, point and smeared-point sink

three source shifts

3x3 matrix

Single Baryon

NPLQCD data



single operator

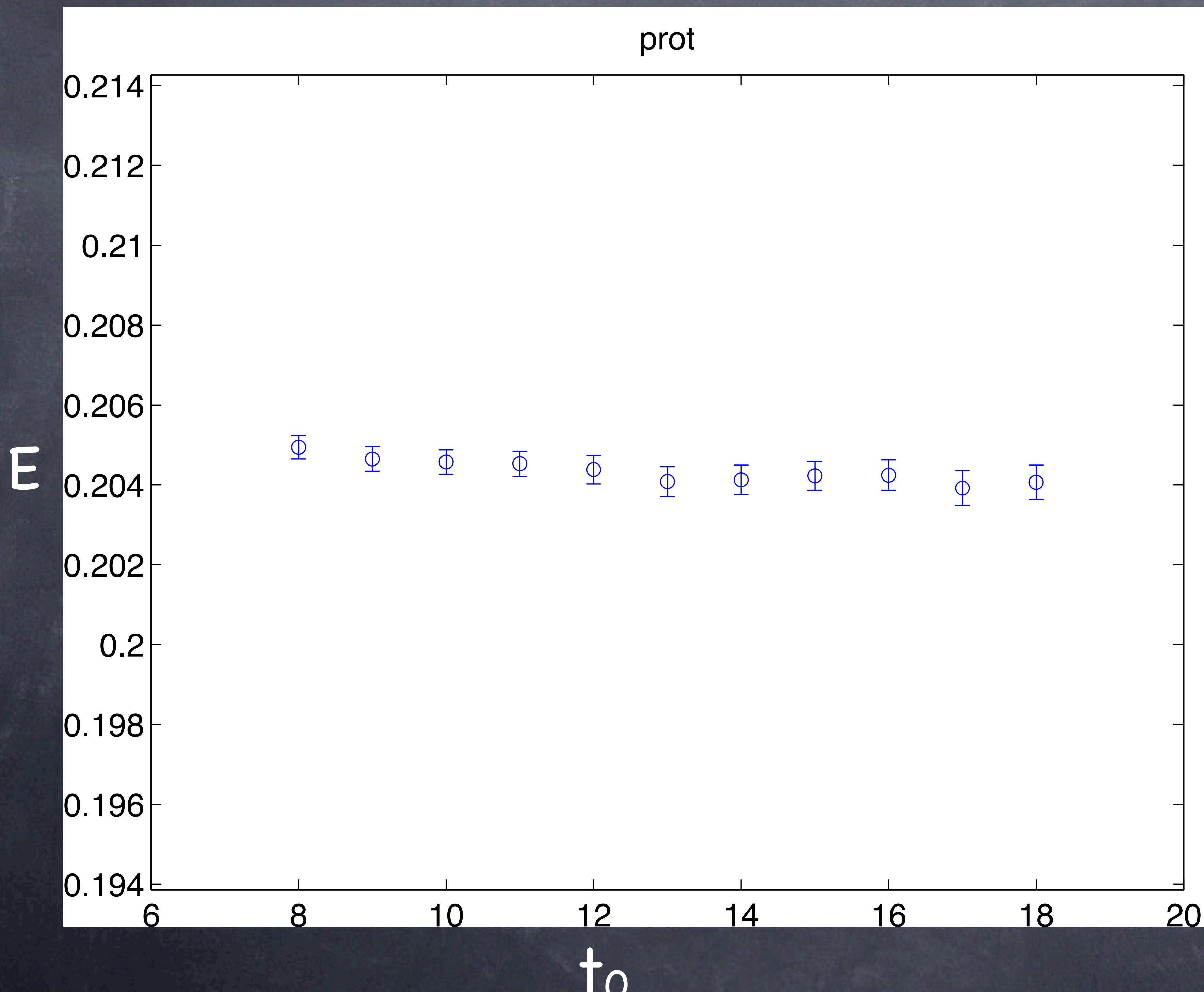
one source smearing

smeared and point sink

VarPro 3 state fits

Single Baryon

NPLQCD data



single operator

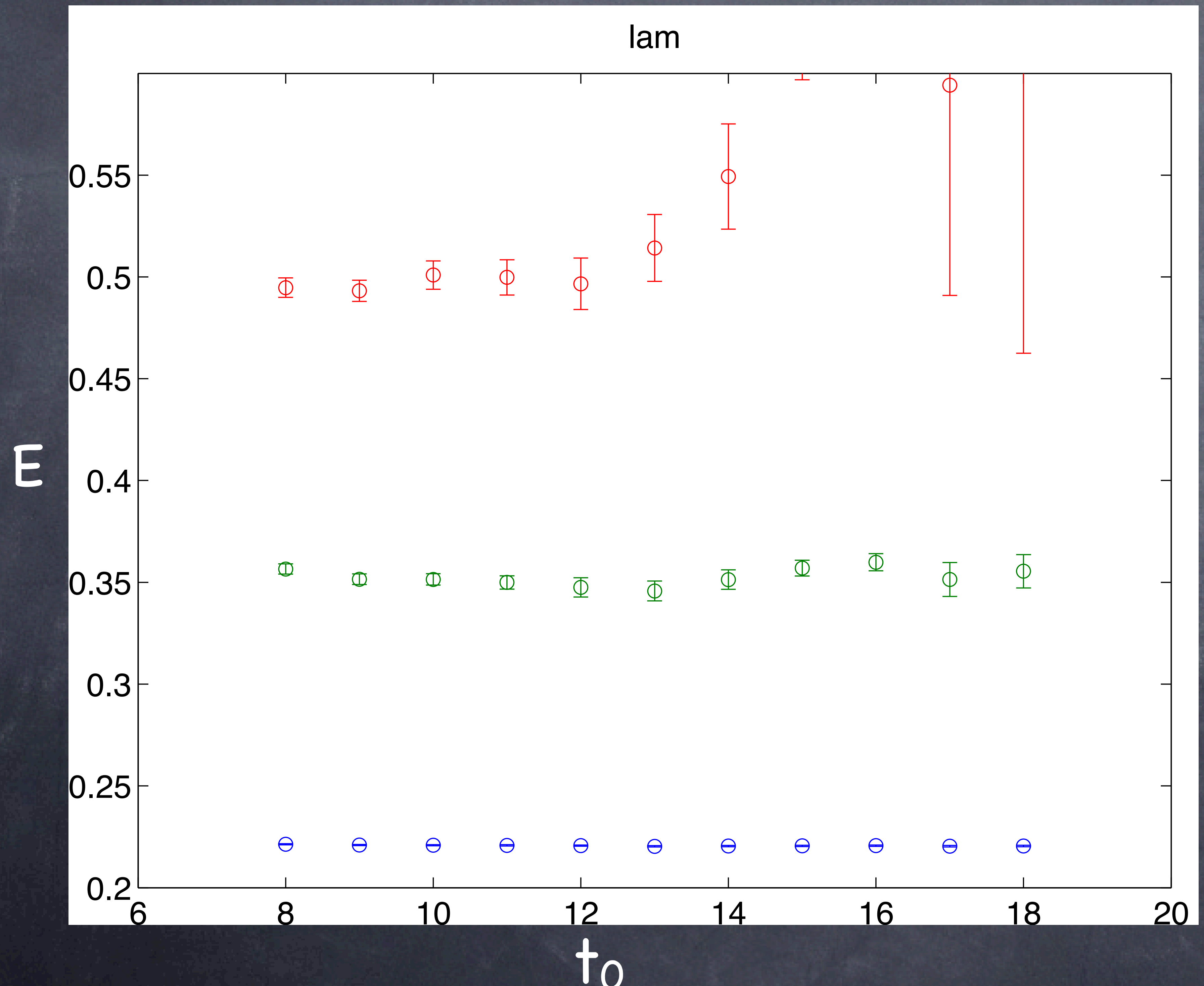
one source smearing

smeared and point sink

VarPro 3 state fits

Single Baryon

NPLQCD data



single operator

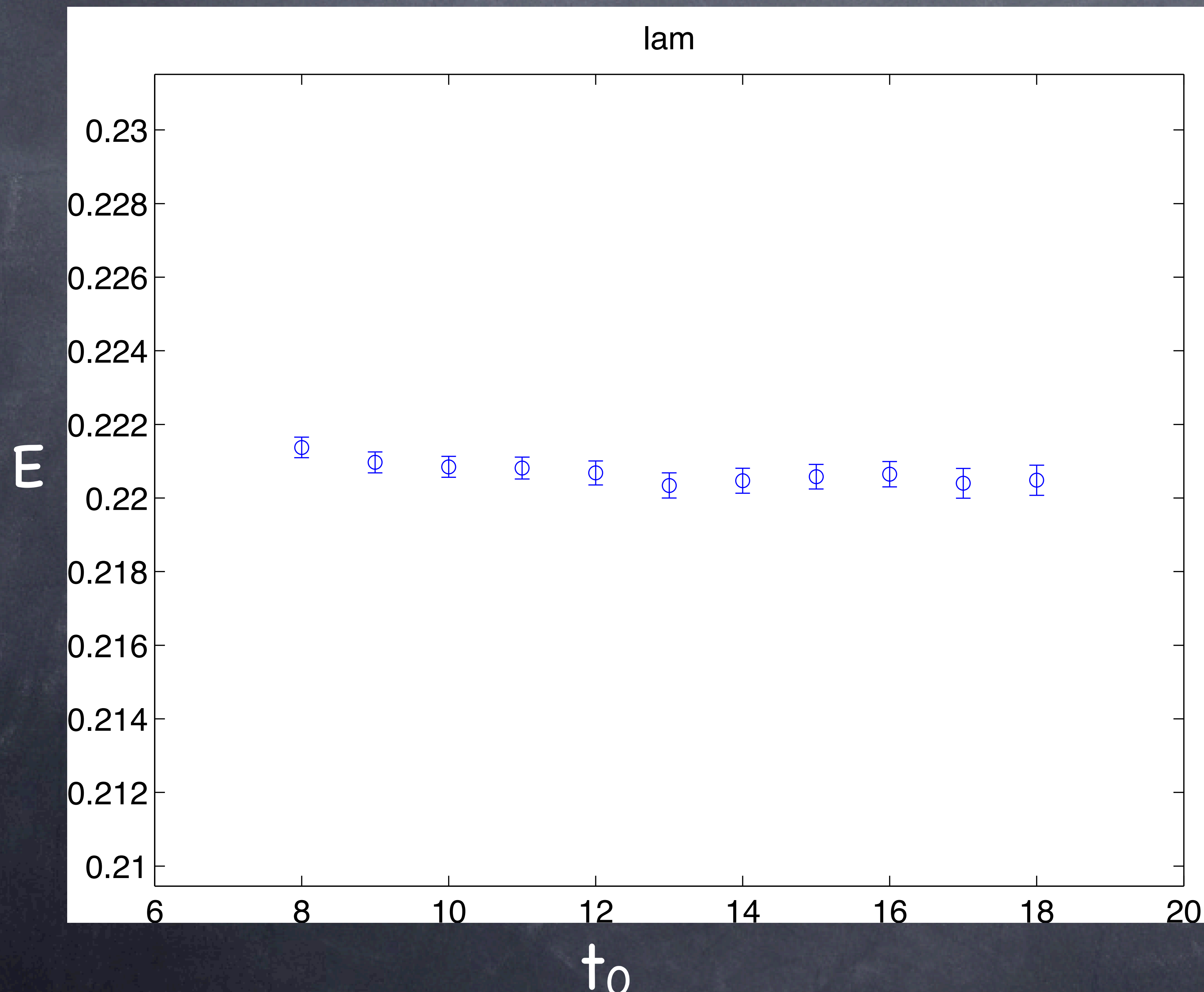
one source smearing

smeared and point sink

VarPro 3 state fits

Single Baryon

NPLQCD data



single operator

one source smearing

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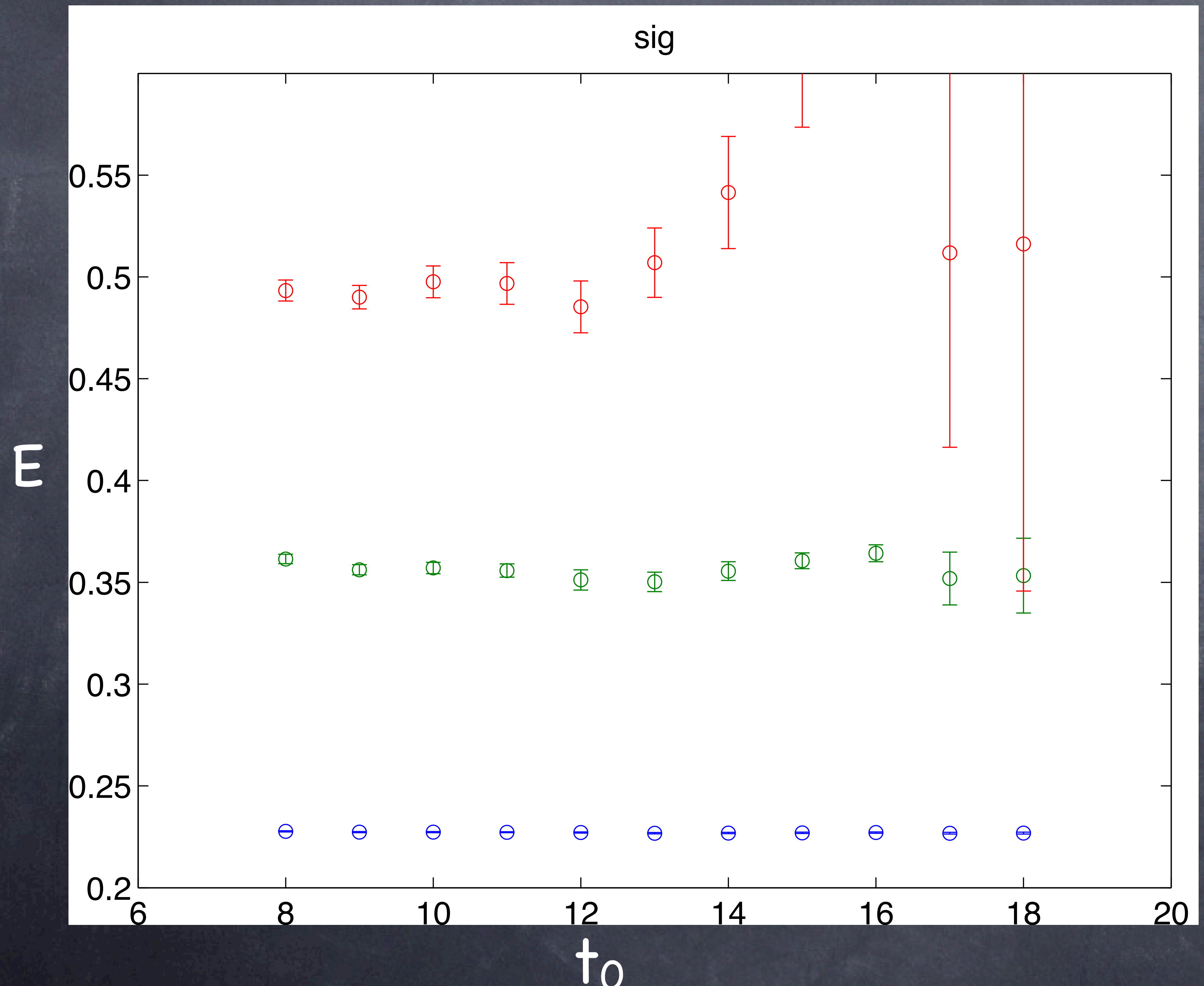
VarPro 3 state fits

Single Baryon

NPLQCD data



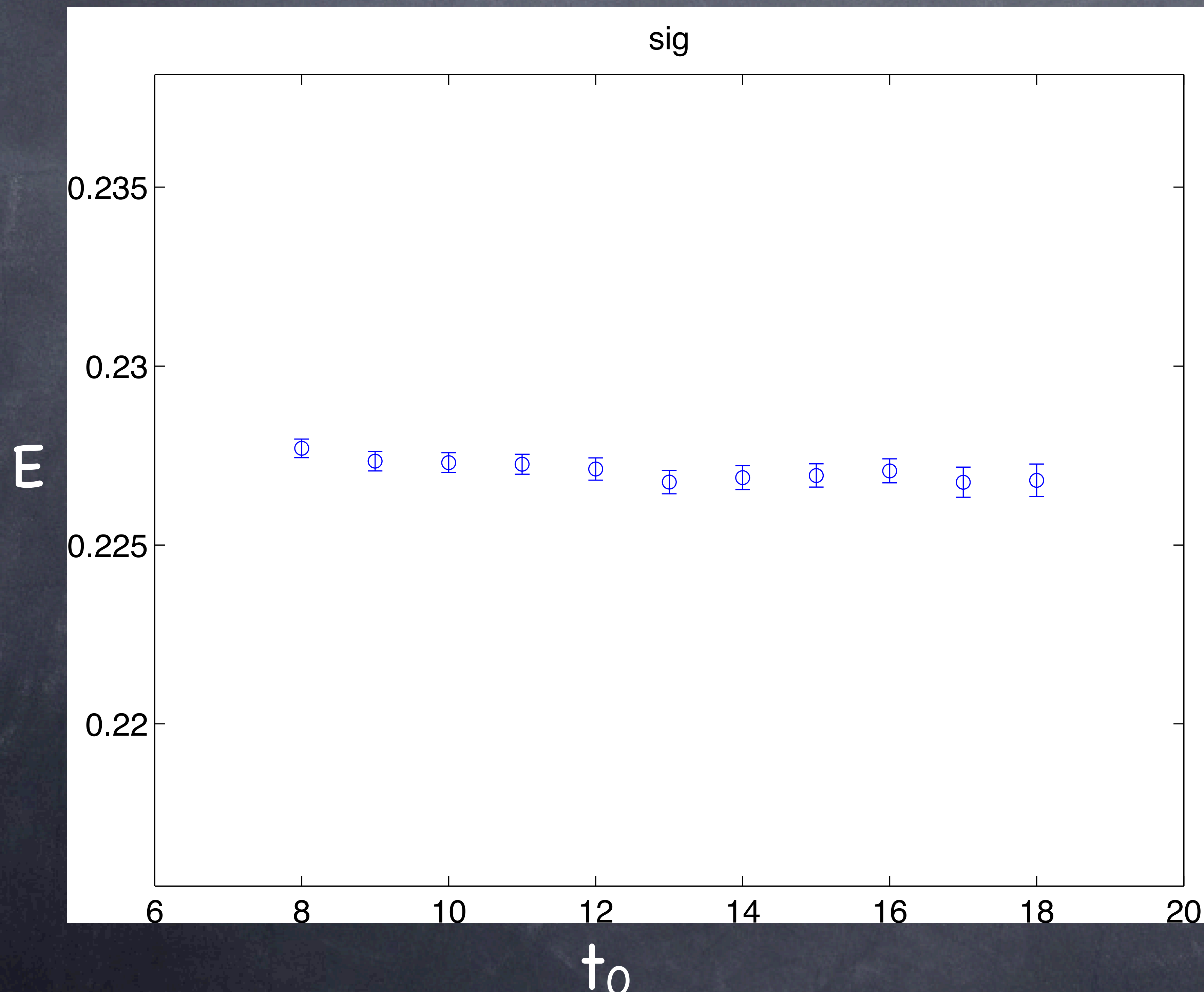
single operator

one source smearing

smeared and point sink

VarPro 3 state fits

Single Baryon



NPLQCD data

single operator

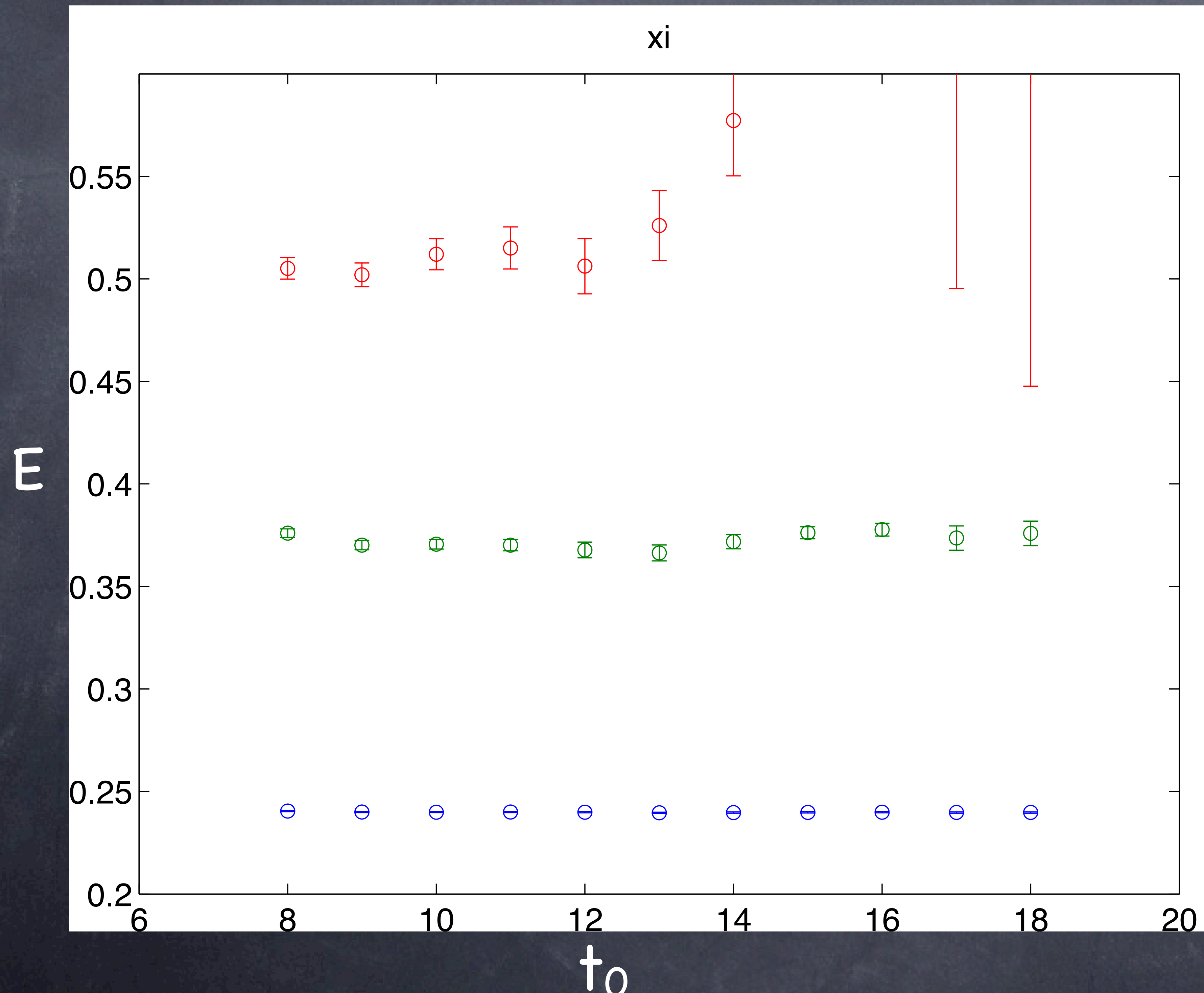
one source smearing

smeared and point sink

VarPro 3 state fits

Single Baryon

NPLQCD data



single operator

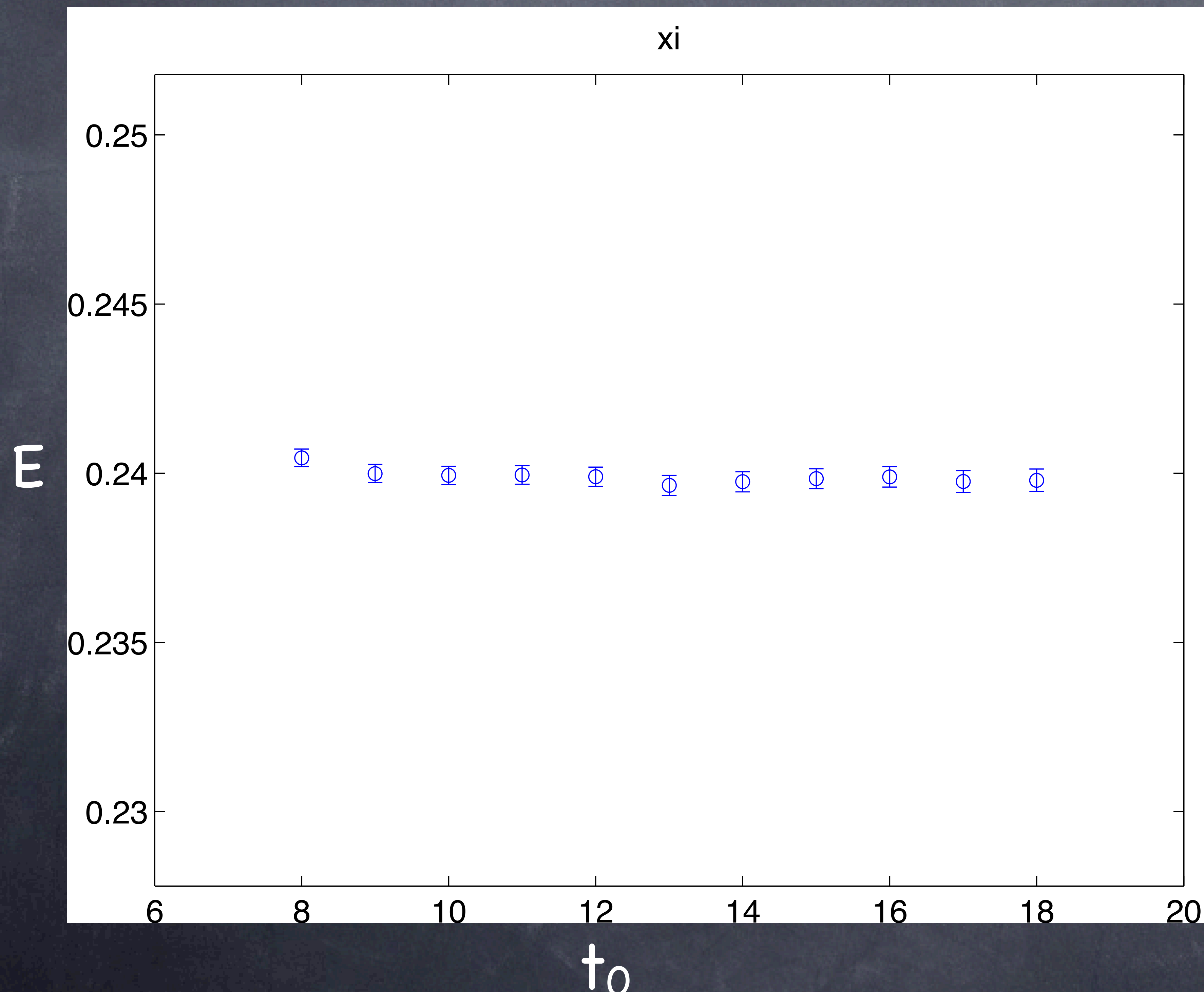
one source smearing

smeared and point sink

VarPro 3 state fits

Single Baryon

NPLQCD data



single operator

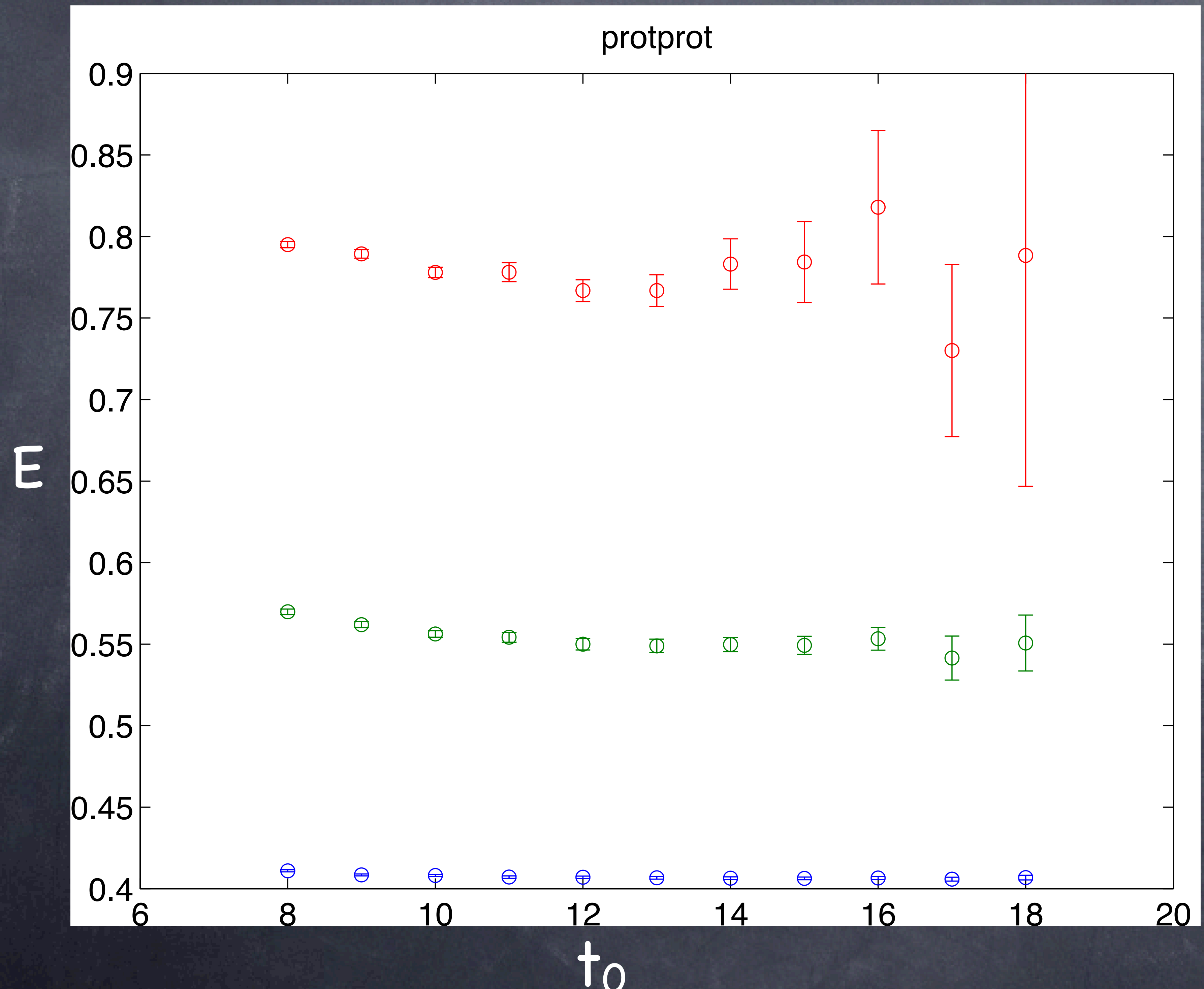
one source smearing

smeared and point sink

VarPro 3 state fits

Two Baryons

NPLQCD data



single operator

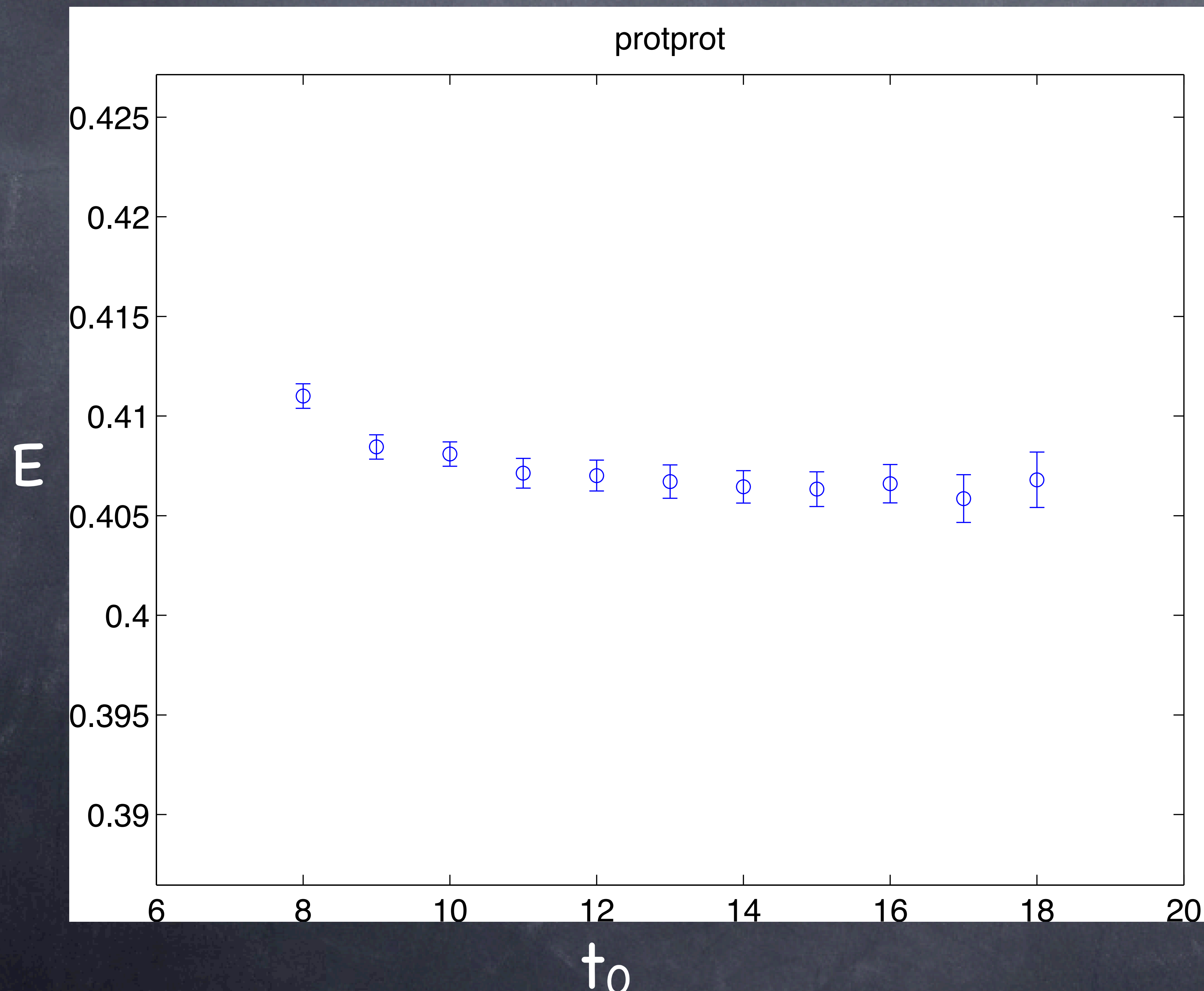
one source smearing

smeared, point and smeared-point sink

VarPro 3 state fits

Two Baryons

NPLQCD data



single operator

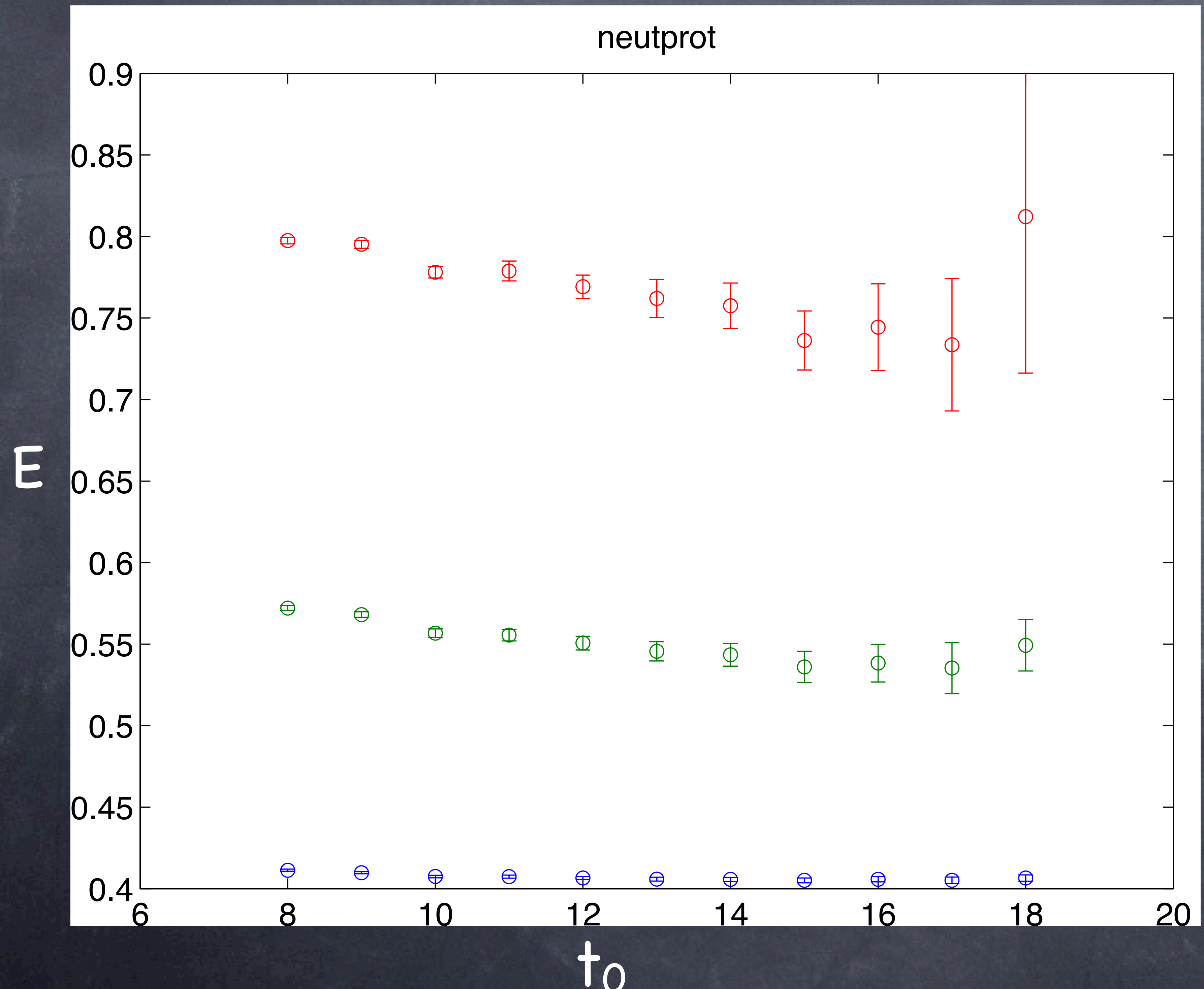
one source smearing

smeared, point and smeared-point sink

VarPro 3 state fits

Two Baryons

NPLQCD data



single operator

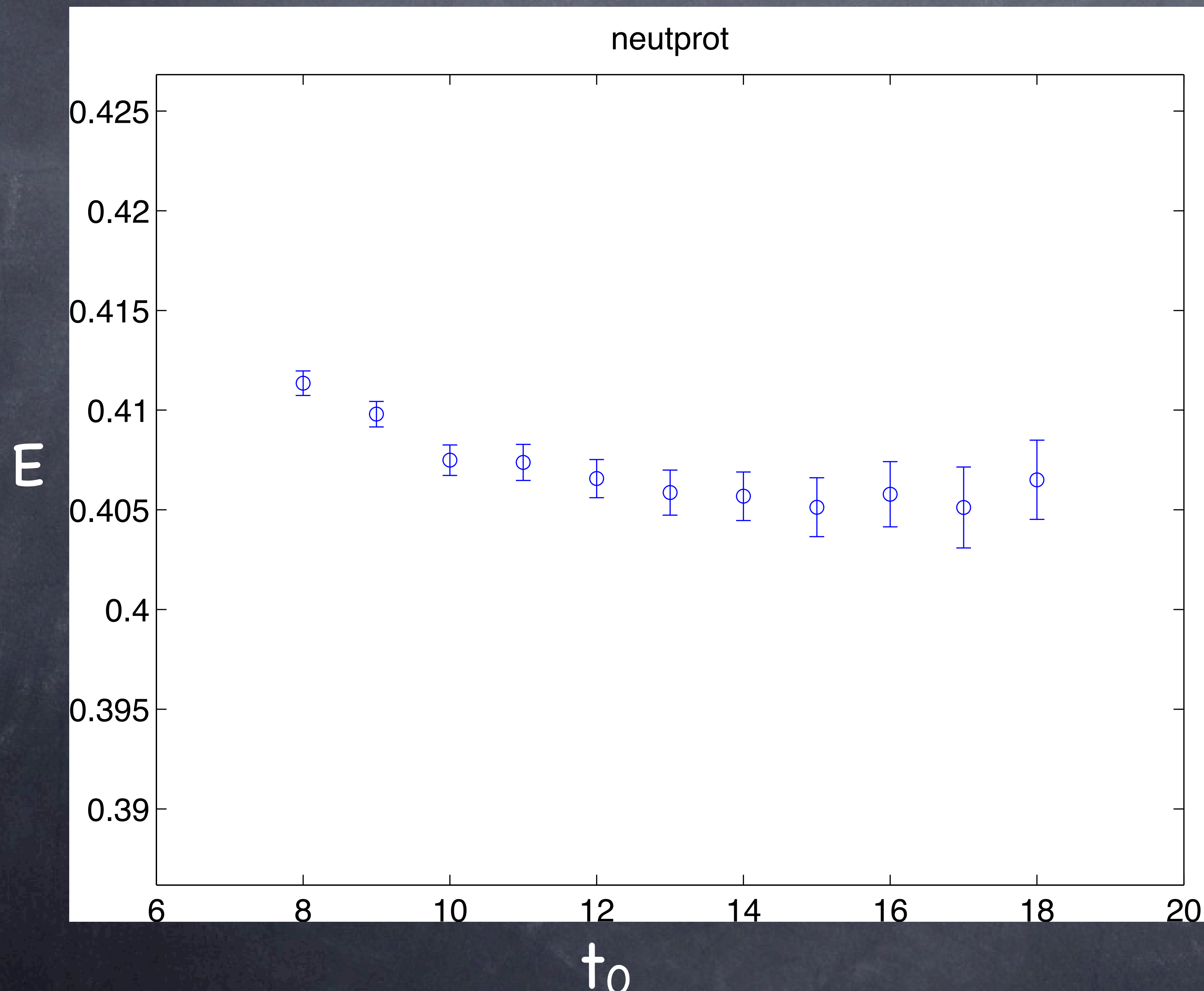
one source smearing

smeared, point and smeared-point sink

VarPro 3 state fits

Two Baryons

NPLQCD data



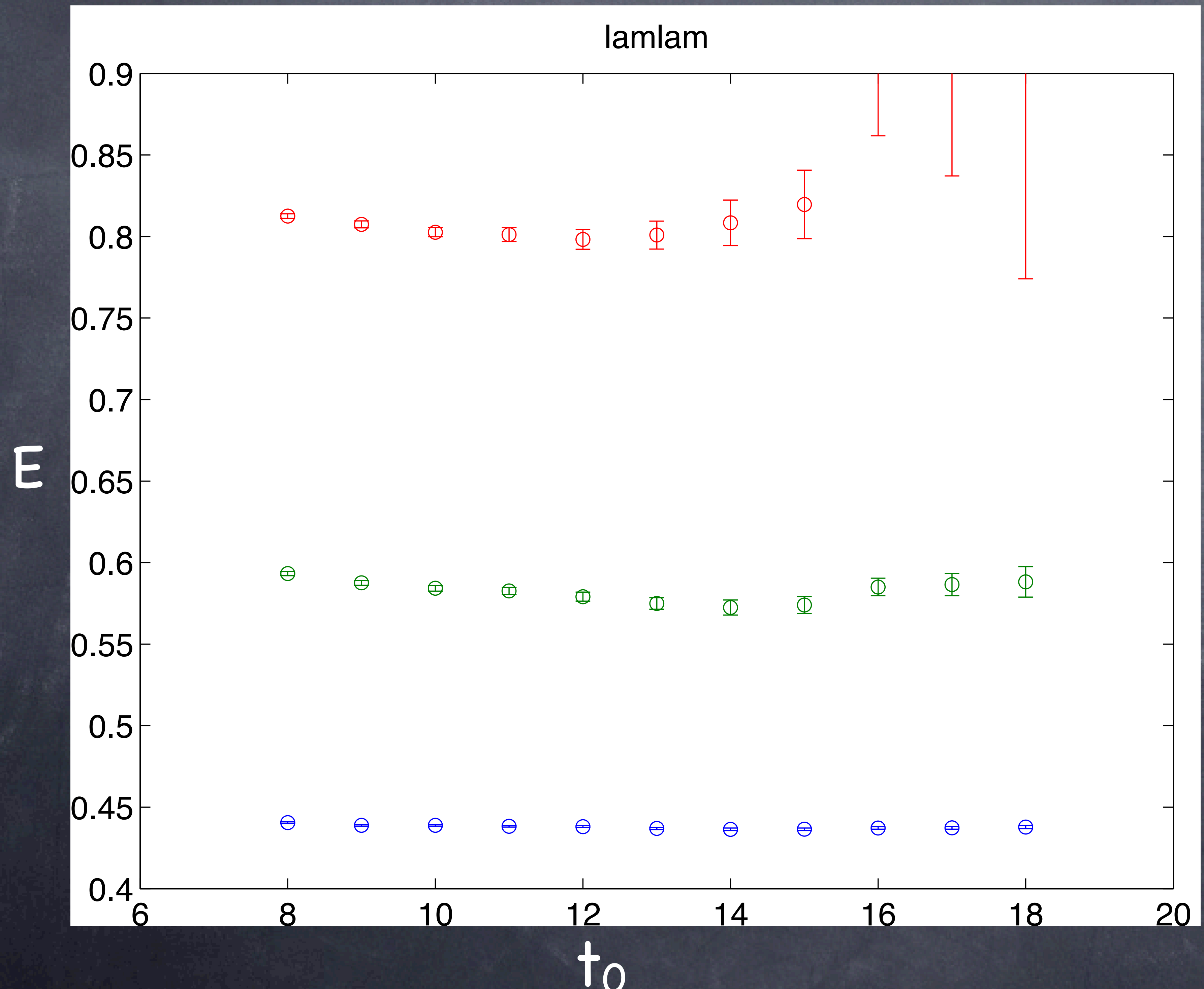
single operator

one source smearing

smeared, point and smeared-point sink

VarPro 3 state fits

Two Baryons



NPLQCD data

single operator

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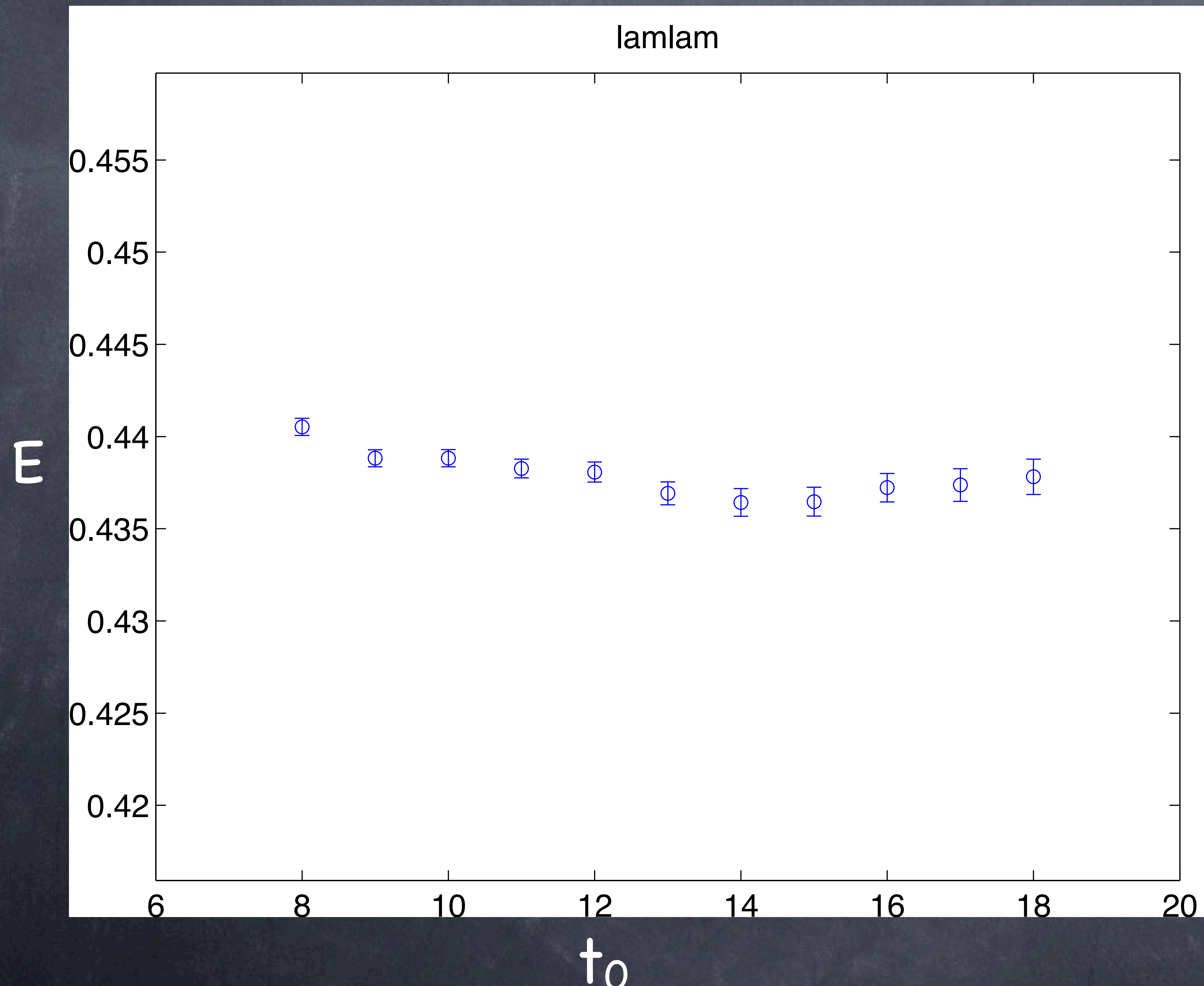
VarPro 3 state fits

Two Baryons



NPLQCD data

single operator

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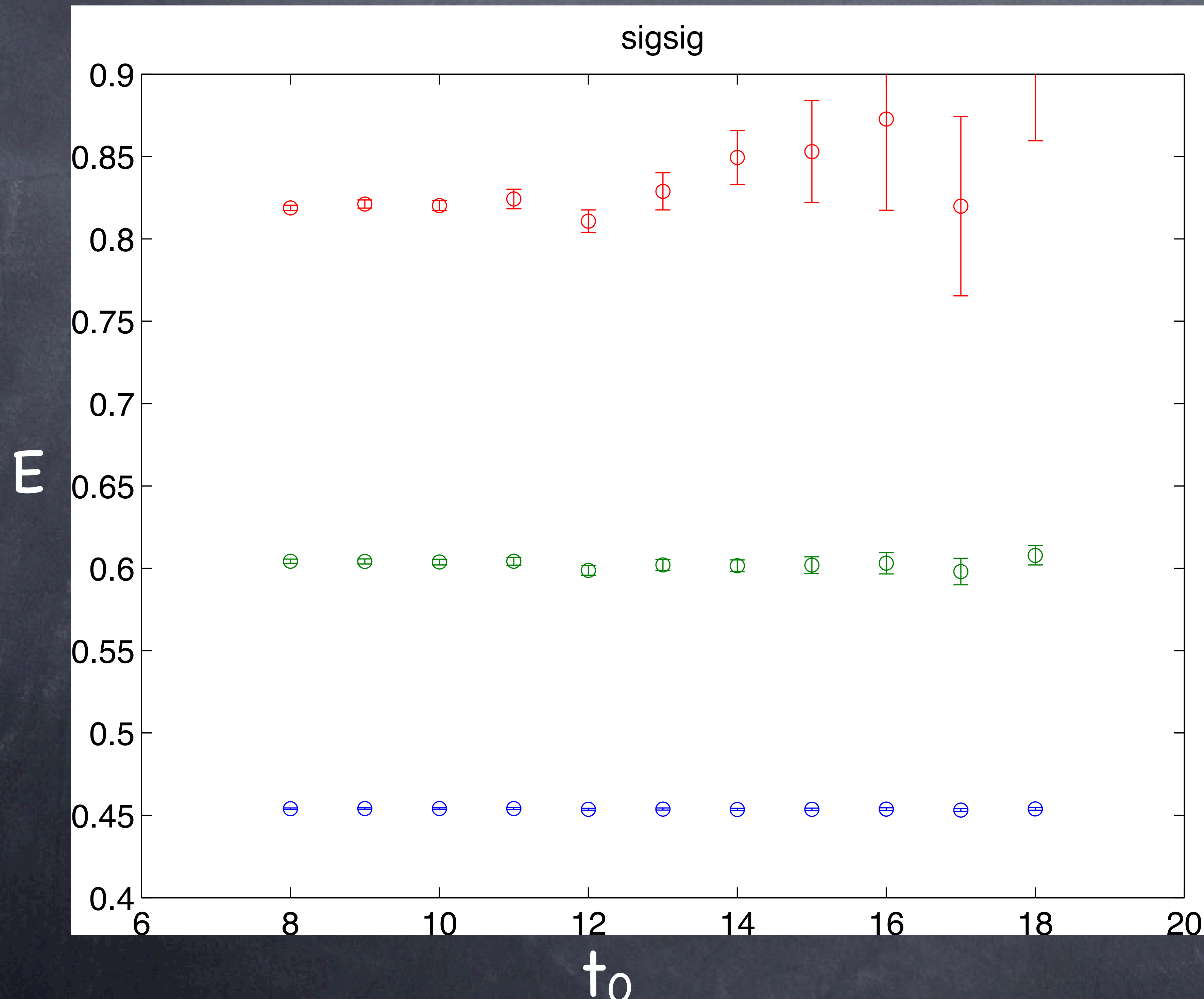
VarPro 3 state fits

Two Baryons

NPLQCD data



single operator

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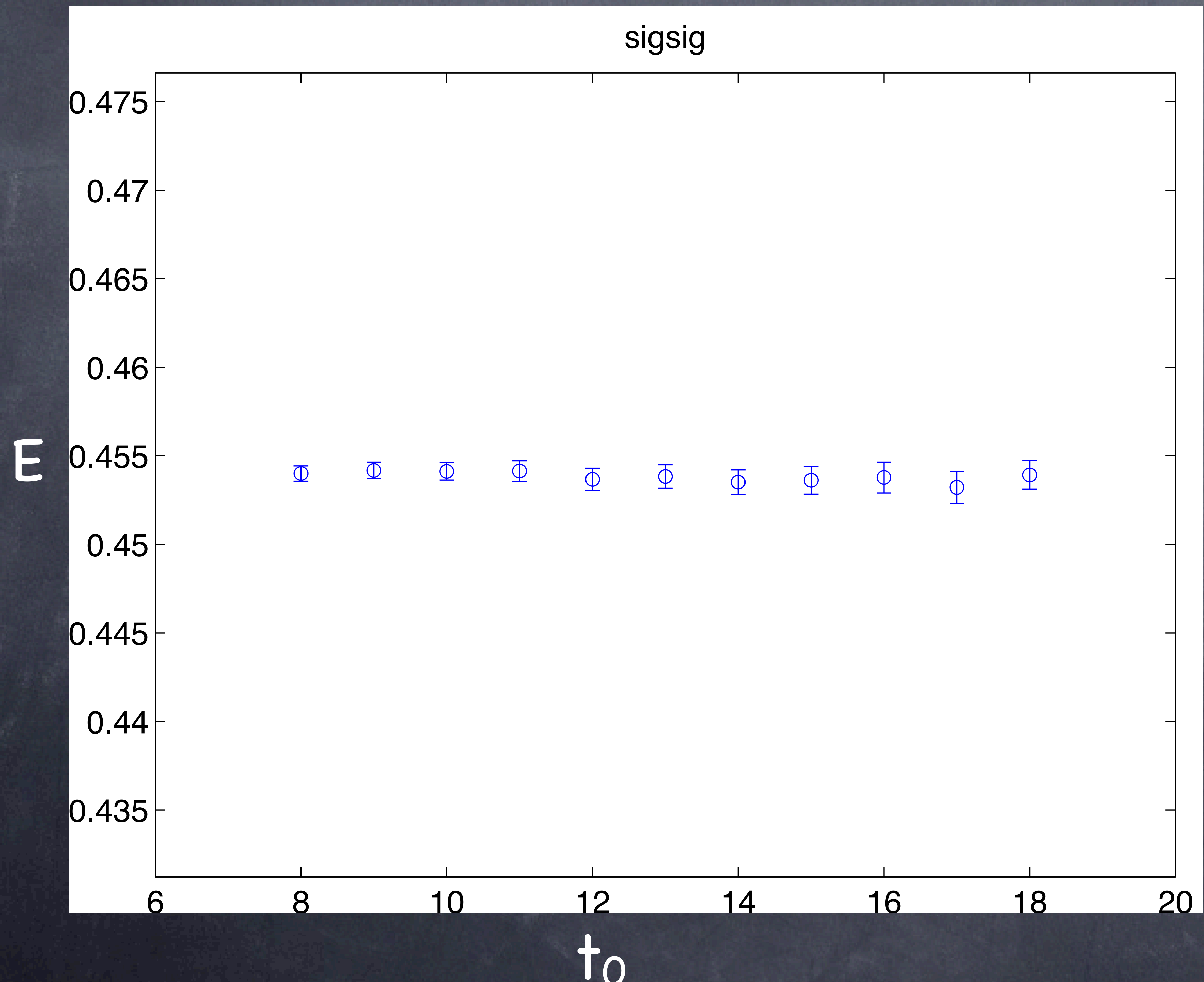
VarPro 3 state fits

Two Baryons

NPLQCD data



single operator

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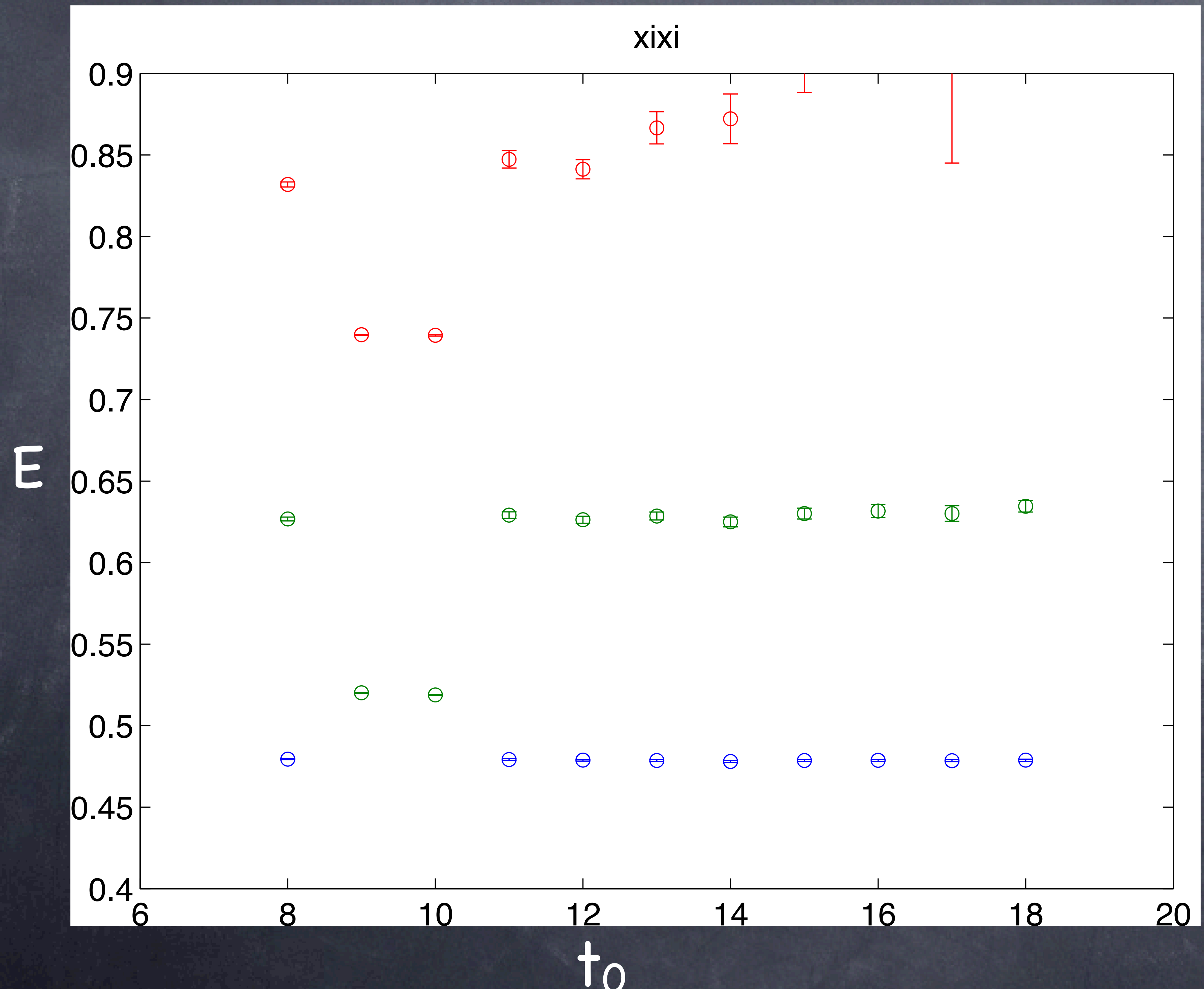
VarPro 3 state fits

Two Baryons

NPLQCD data



single operator

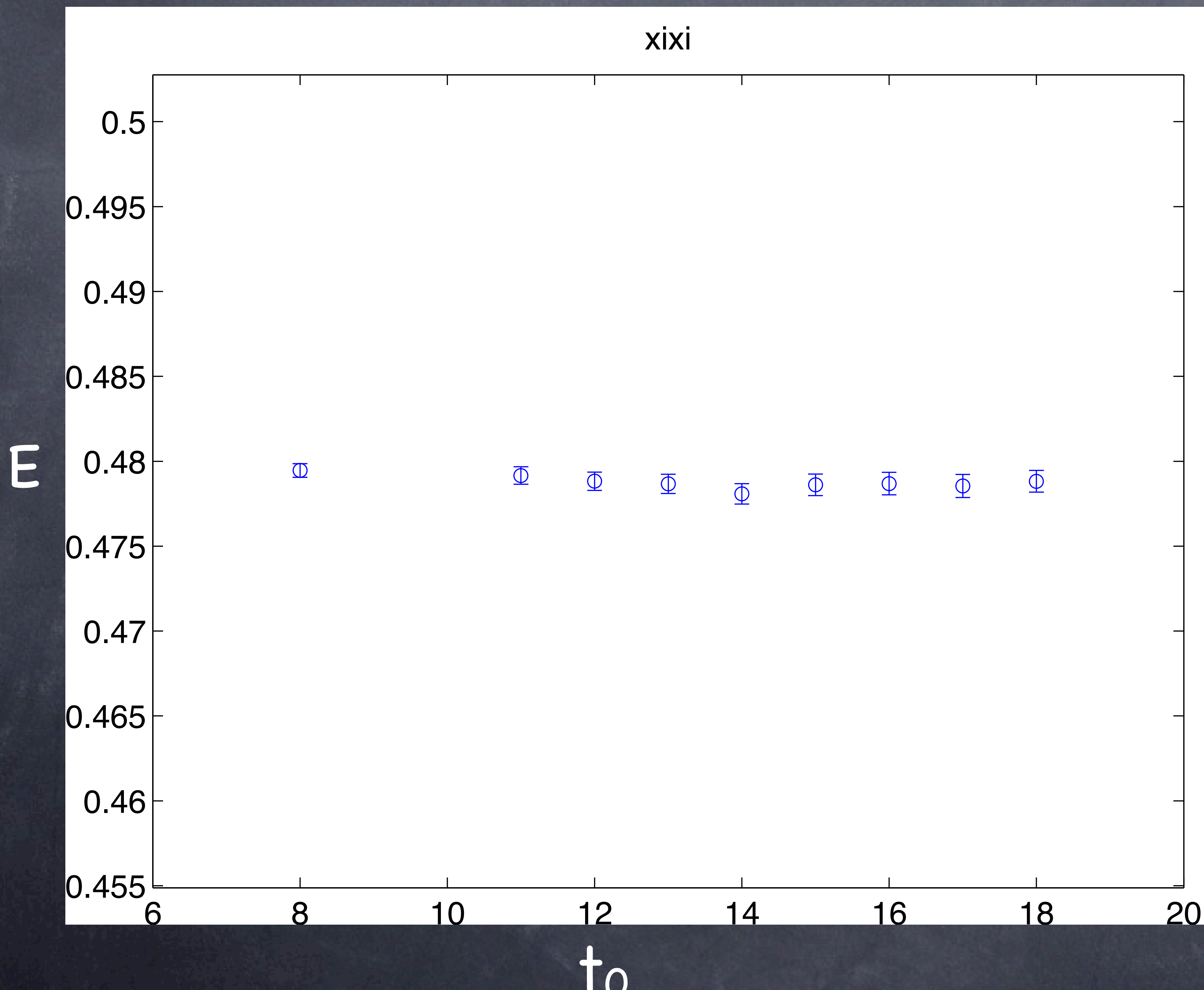
one source smearing

smeared, point and smeared-point sink

VarPro 3 state fits

Two Baryons

NPLQCD data



single operator

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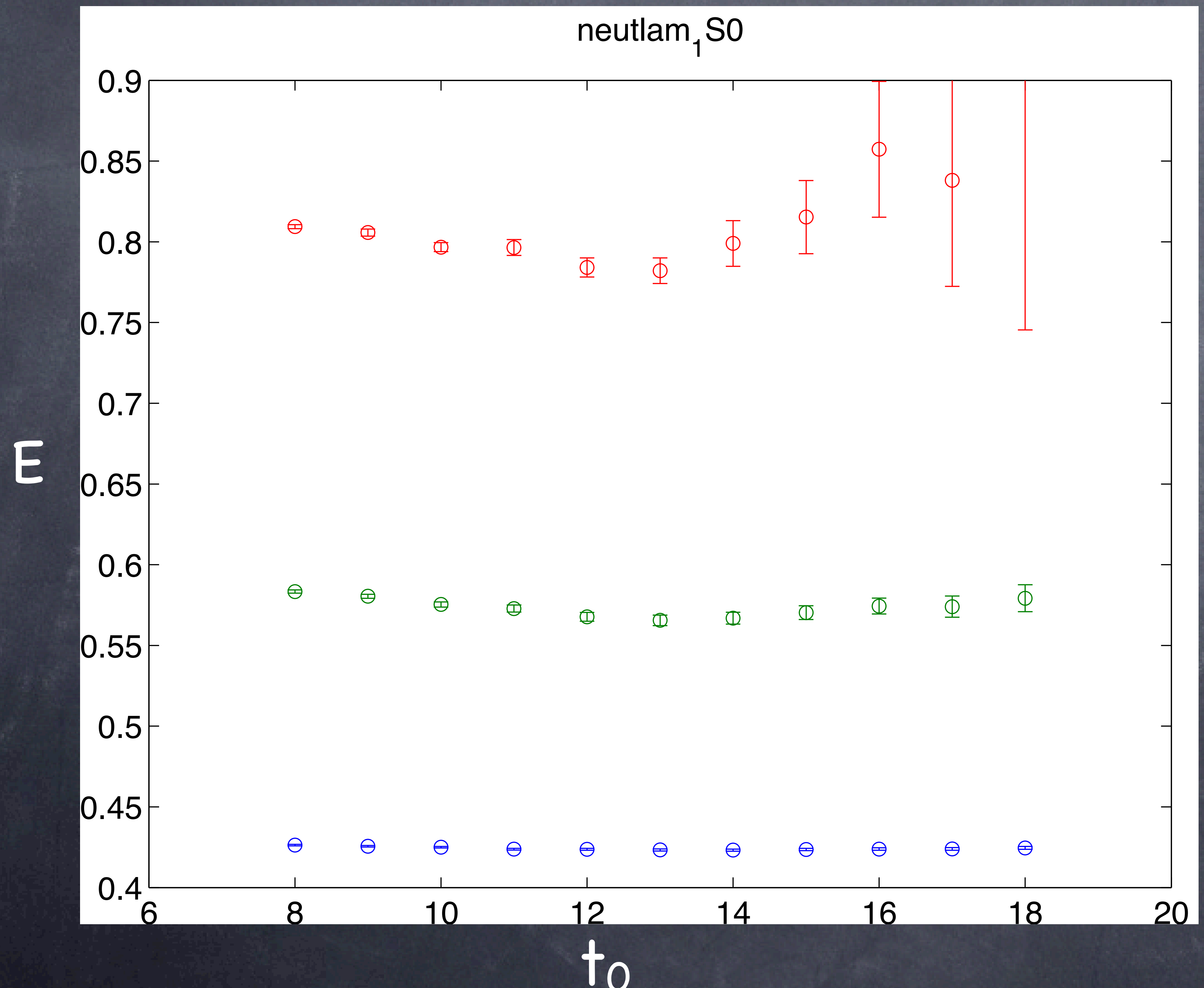
Two Baryons



NPLQCD data

single operator

one source smearing

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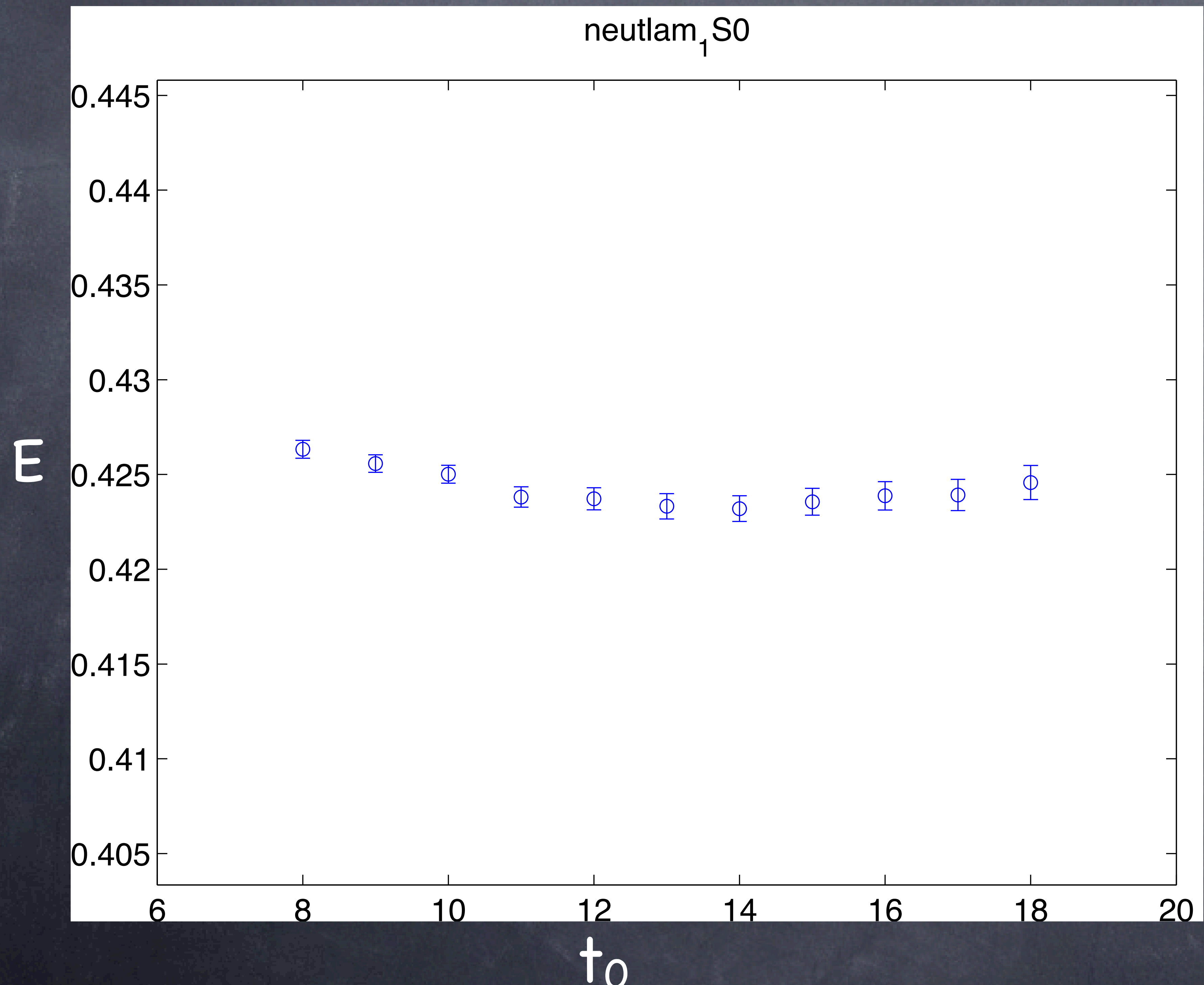
VarPro 3 state fits

Two Baryons

NPLQCD data



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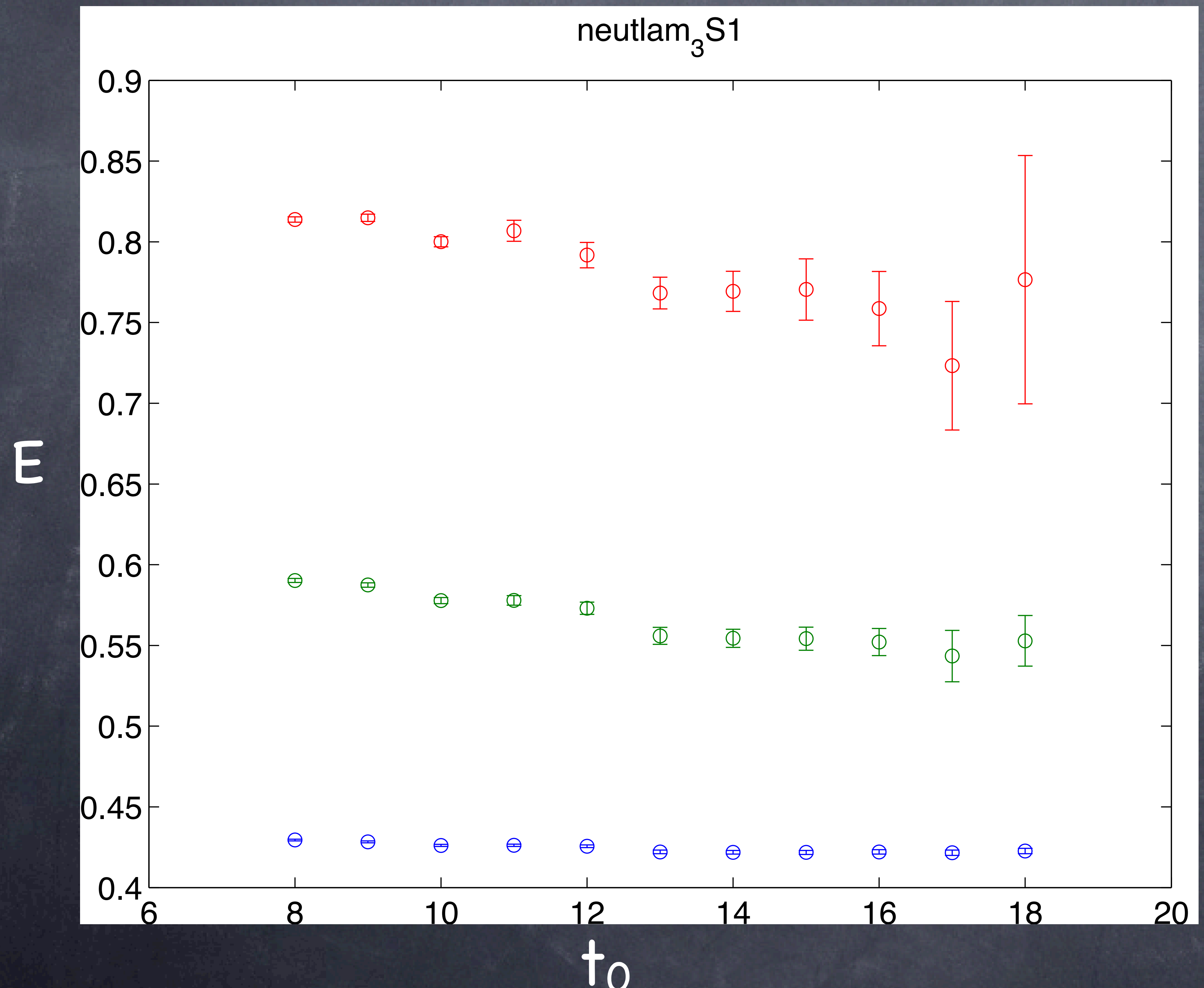
Two Baryons

NPLQCD data



single operator

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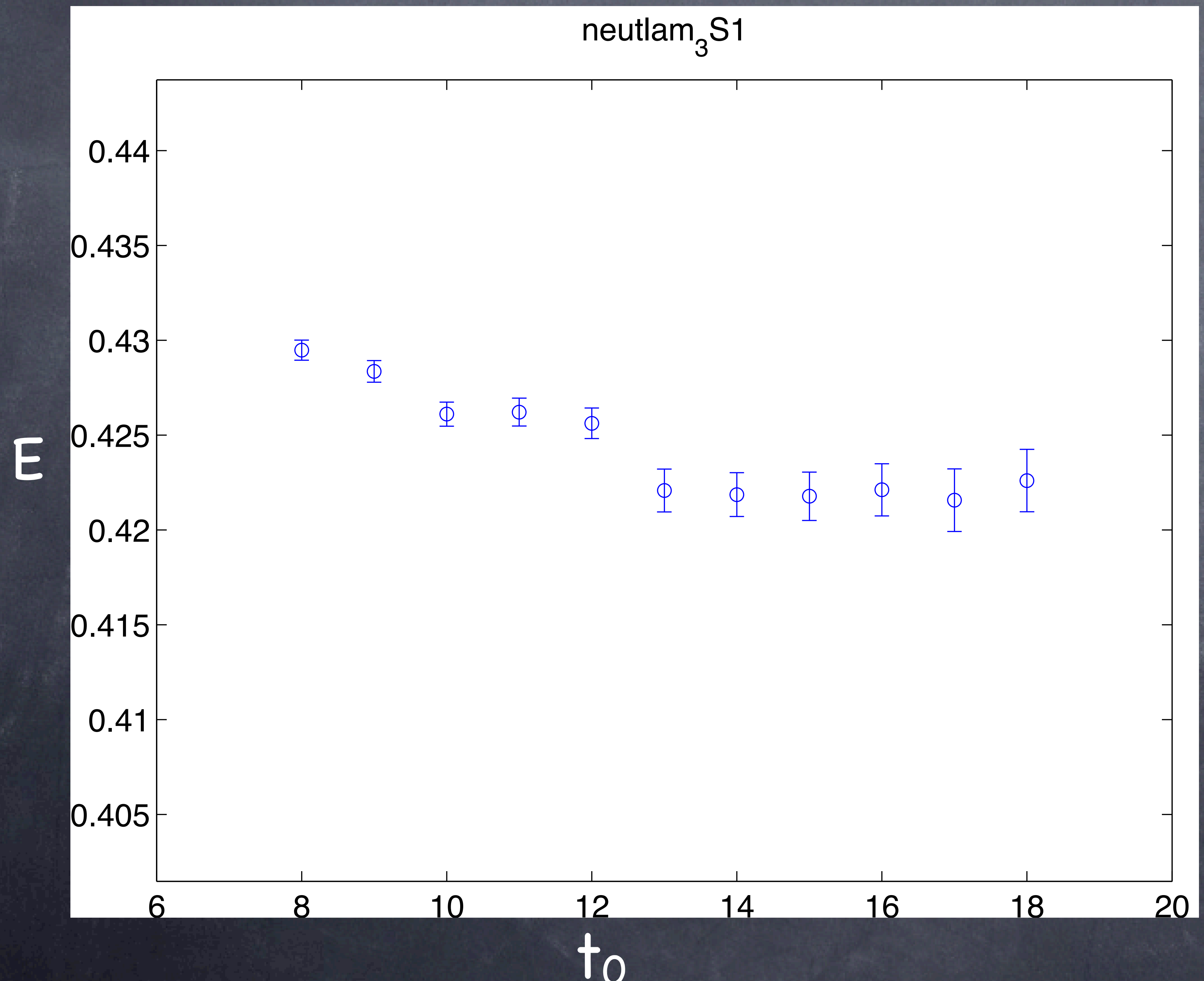

single operator

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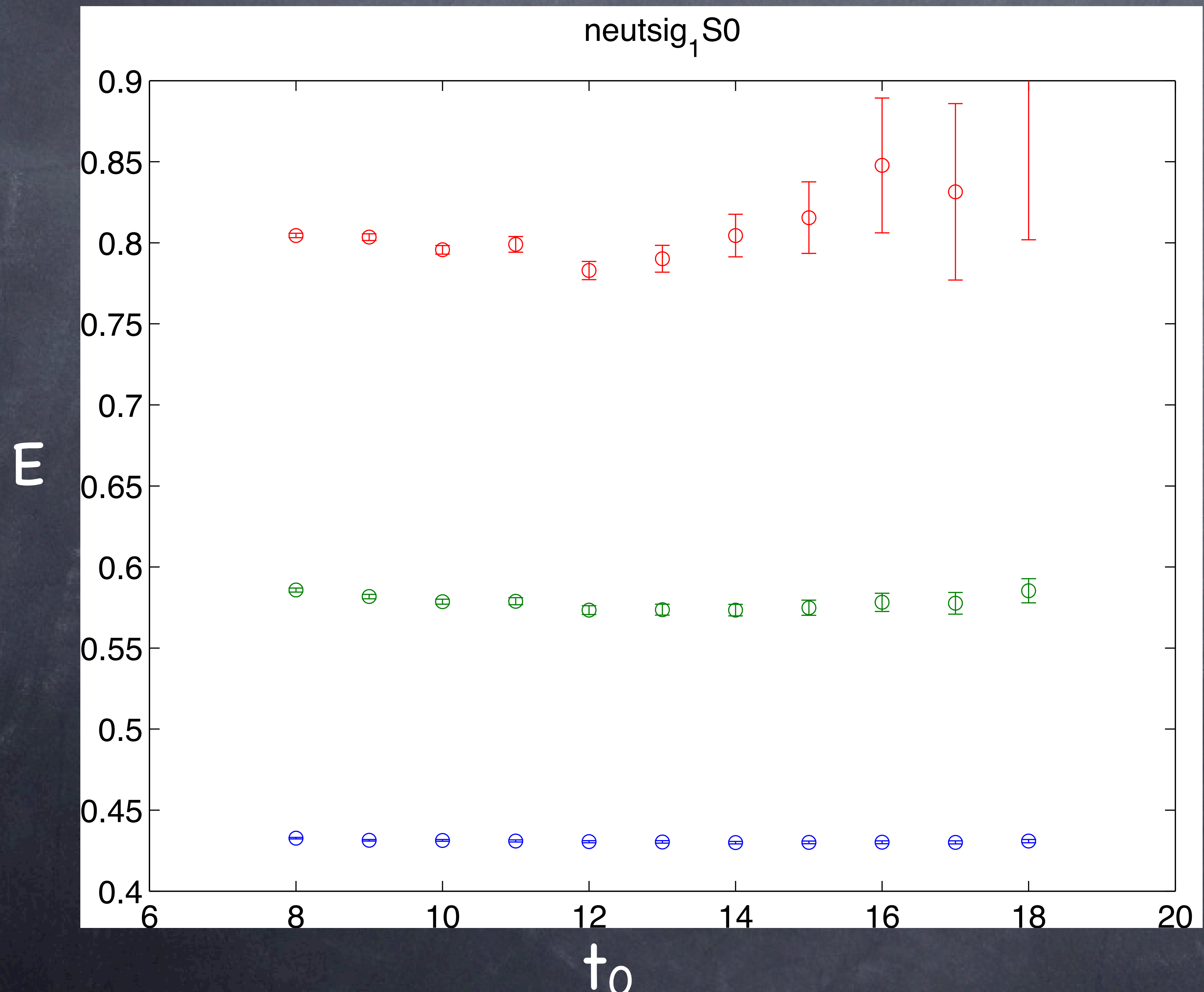
VarPro 3 state fits

Two Baryons



NPLQCD data

single operator

one source smearing

smeared, point and
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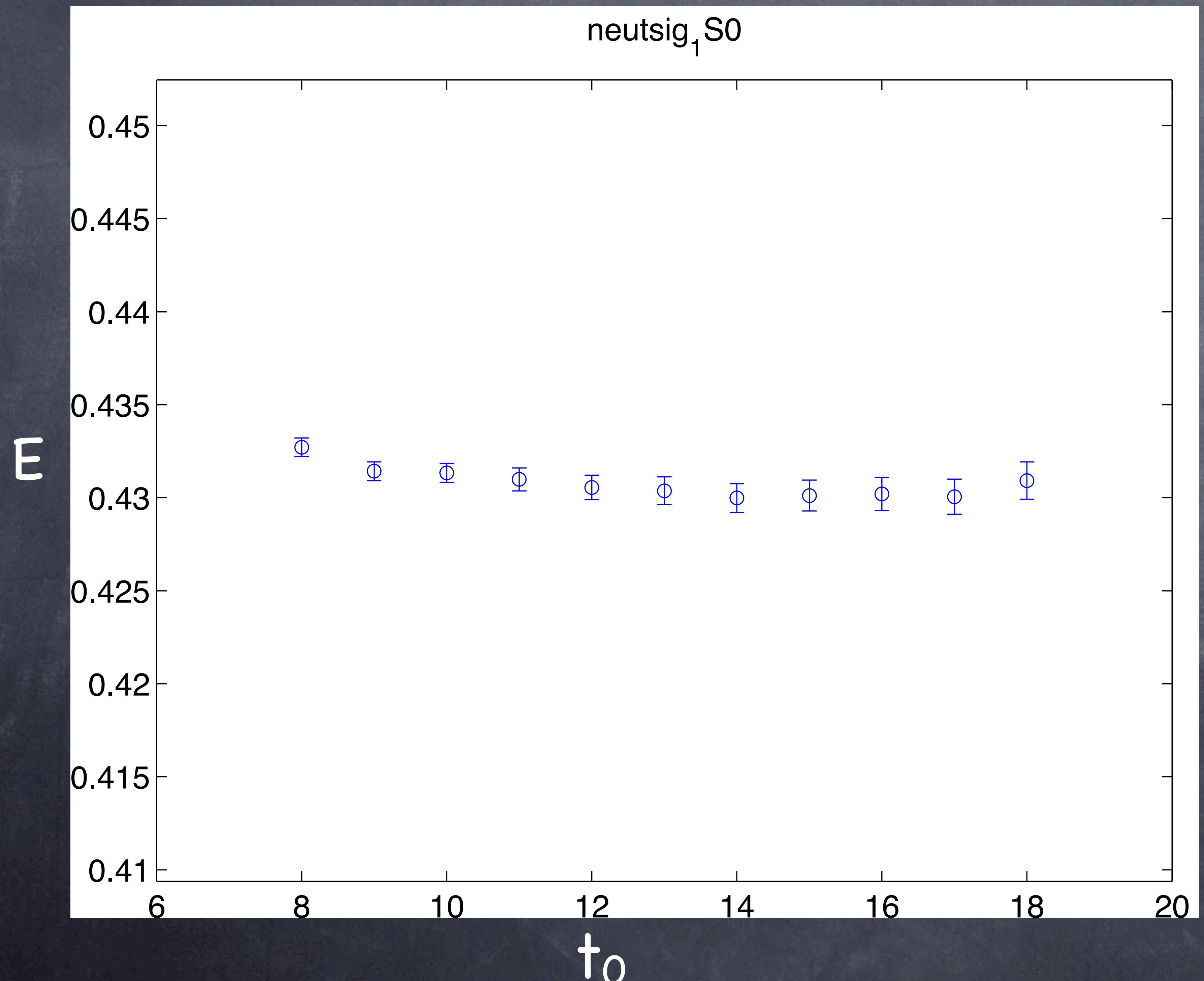
VarPro 3 state fits

Two Baryons

NPLQCD data



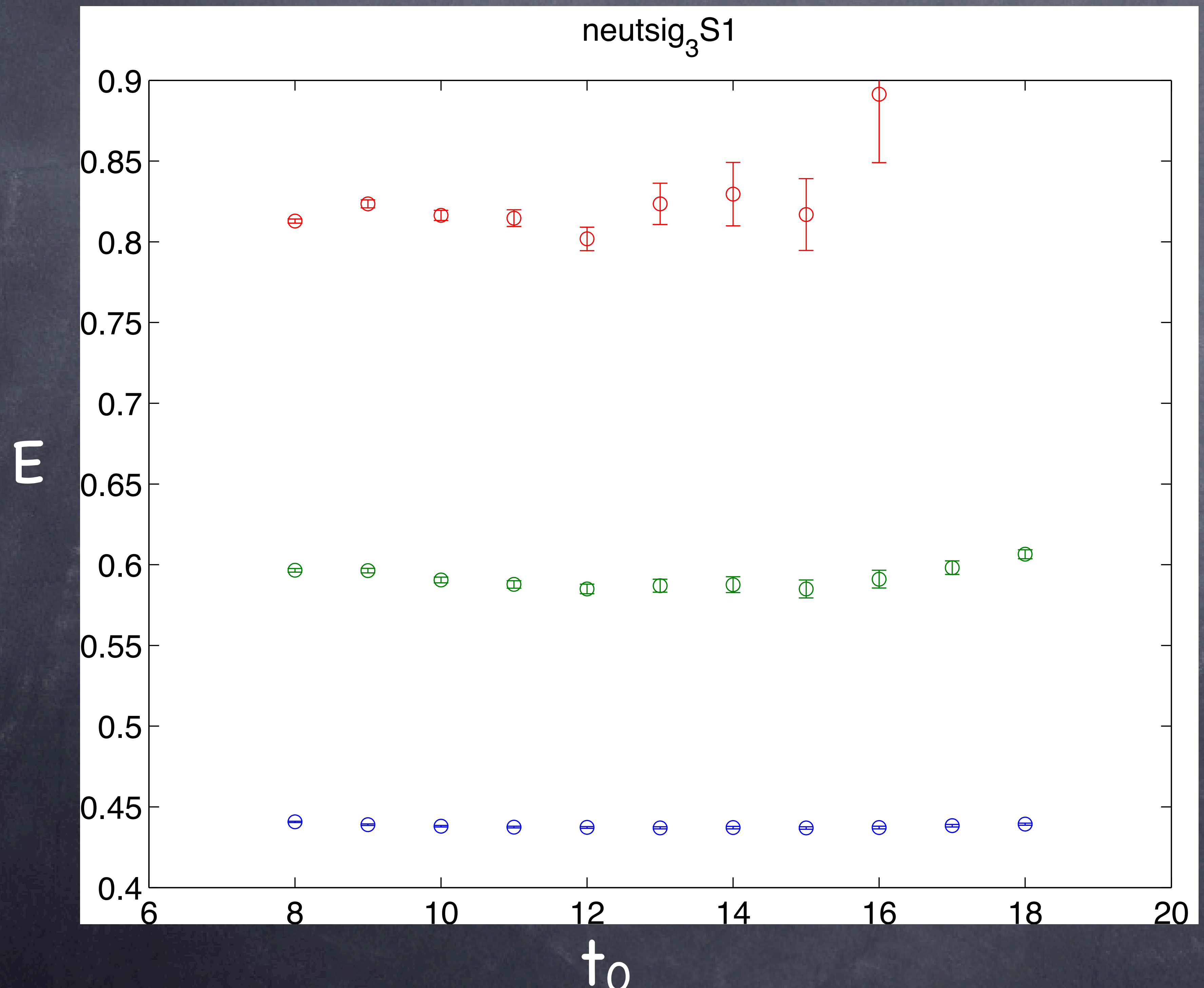
single operator

one source smearing

smeared, point and smeared-point sink

VarPro 3 state fits

Two Baryons



NPLQCD data

single operator

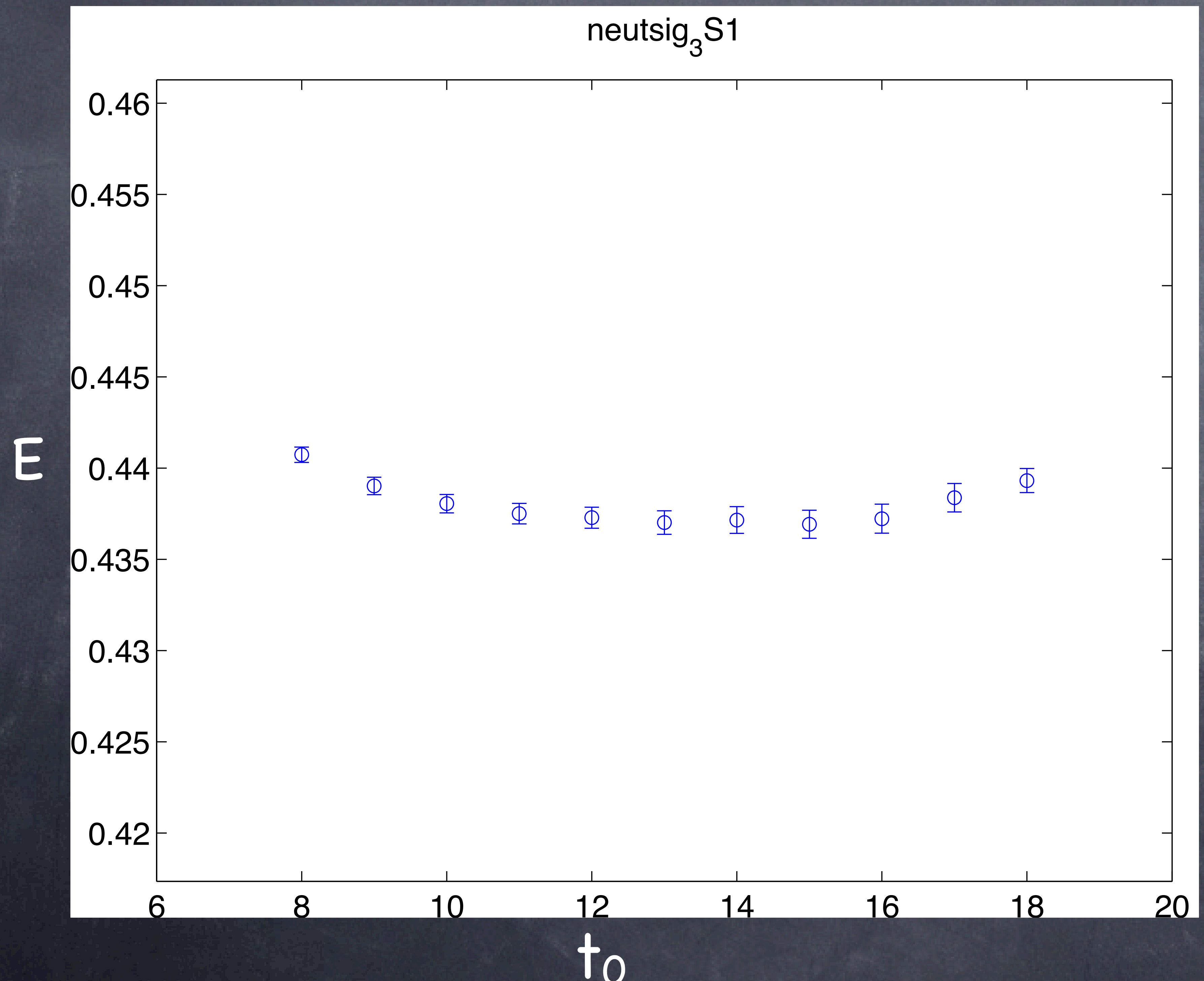
one source smearing

smeared, point and smeared-point sink

VarPro 3 state fits

Two Baryons

NPLQCD data



single operator

one source smearing

smeared, point and smeared-point sink

VarPro 3 state fits

Conclusions

- The Generalized Pencil of Matrix provides an alternative "diagonalization" method for correlator matrices
- "Shifting" is not a substitute for a good set of interpolating fields
- Non-symmetric correlator matrices can be treated
- Symmetric positive definite correlator matrices are preferable
- Could be useful for variational approach to Form Factor calculations