THE UNIVERSITY OF CHICAGO

Nucleon and Omega Masses with All HISQ Fermions

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- Fermilab Lattice Collaboration
- MILC Collaboration

Outline

- The importance of baryon masses
- Interpolators and simulation details
- Preliminary data and results
    - Nucleon correlators
    - Omega baryon correlators
- Conclusion

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Why Nucleon and Omega Masses?

$$M_{proton} = 938.272081 \pm 0.000006\ MeV$$

$$M_{\Omega^-} = 1672.45 \pm 0.29\ MeV$$

[2019 Particle Data Group]

~10^{-7}% uncertainty!

~0.017% uncertainty!

Why Nucleon and Omega Masses?

- **Nucleon mass as the first step towards nucleon matrix element (neutrino physics)**
- **Omega baryon mass for absolute lattice scale setting (precision physics such as muon HVP)**
- **Omega baryon as a test bed for staggered fermion formalism**

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Simulation Details

Set	β	a (fm)	am_l	am_s	am_c	$N_s \times N_T$	$n_{\rm cfg}$
1	5.8	0.1529(4)	0.002426	0.06730	0.8447	32×48	3500
2	6.0	0.1222(3)	0.001907	0.05252	0.6382	48×64	1000
3	6.3	0.0879(3)	0.001200	0.03630	0.4320	64×96	1047

[MILC collaboration, arxiv: 1212.4768]

- **2+1+1 HISQ ensembles at physical pion masses generated by the MILC collaboration for both valence and sea quarks**
- **Coulomb gauge fixed**
- **Wall sources**

Staggered Nucleon Operators

Finite Lattice symmetry: $SU_I(2) \times GTS$

GTS Irrep	$I = 3/2$	$I = 1/2$
8	$3N + 2\Delta$	$5N + 1\Delta$
$8'$	$0N + 2\Delta$	$0N + 1\Delta$
16	$\boxed{1N + 3\Delta}$	$3N + 4\Delta$

[Jon A. Bailey, hep-lat/0611023]

Use 16 irrep with isospin 3/2 to extract nucleon mass without any taste complications

Staggered Omega Baryon Operators

GTS Irrep	$"I" = 3/2$	$"I" = 1/2$
8	$3N_s + 2\Omega$	$5N_s + 1\Omega$
8′	$0N_s + 2\Omega$	$\boxed{0N_s + 1\Omega}$
16	$1N_s + 3\Omega$	$3N_s + 4\Omega$

[Jon A. Bailey, hep-lat/0611023]

$$\Omega\text{: } 3/2^+ \ (J^P),\ sss, \cdots$$

$$N_s\text{: } 1/2^+ \ (J^P),\ sss^*, \cdots$$

Use 8' irrep with "isospin" 1/2 to extract omega baryon mass without any taste complications

Staggered Omega Baryon Operators

GTS Irrep	$"I" = 3/2$	$"I" = 1/2$
8	$3N_s + 2\Omega$	$5N_s + 1\Omega$
$8'$	$0N_s + 2\Omega$	$0N_s + 1\Omega$
16	$1N_s + 3\Omega$	$\boxed{3N_s + 4\Omega}$

[Jon A. Bailey, hep-lat/0611023]

For a given operator irrep and isospin,
total number of operators used = total number of states

Question: Can we resolve different baryon tastes?

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Nucleon Correlators

- **Perform GEVP on the three by three correlator matrix for 16 irrep, isospin 3/2**

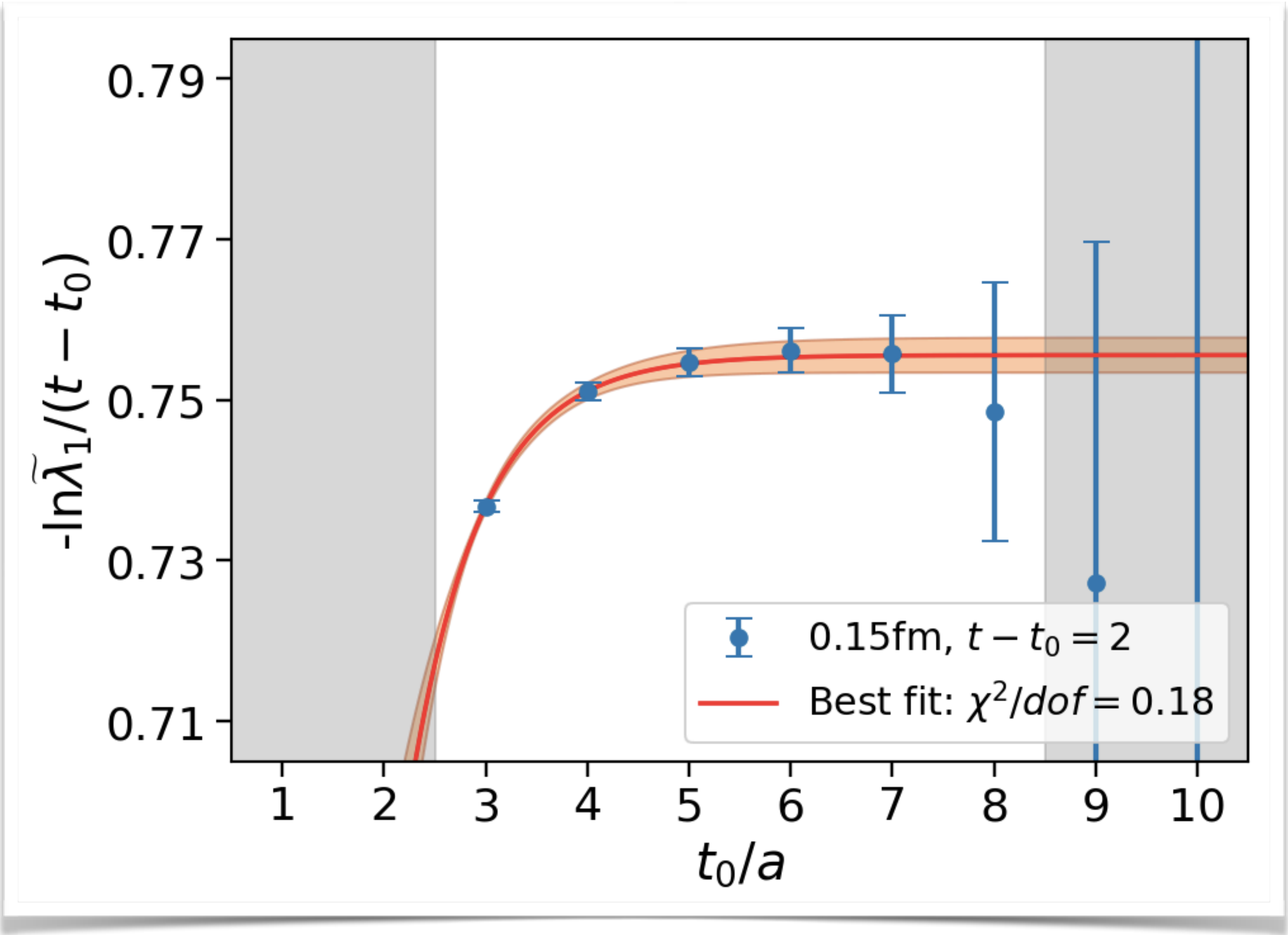
- **We solve the equation**

$$\frac{1}{4}\Big\{[\mathbf{C}(t_0-1)]^{-1}\mathbf{C}(t-1)+2[\mathbf{C}(t_0)]^{-1}\mathbf{C}(t)$$
$$+[\mathbf{C}(t_0+1)]^{-1}\mathbf{C}(t+1)\Big\}\widetilde{v}_1^R(t)=\widetilde{\lambda}_1(t,t_0)\widetilde{v}_1^R(t)$$

- **Perform unconstrained plateau fits (plus an excited state exponential term) to the eigenvalues**

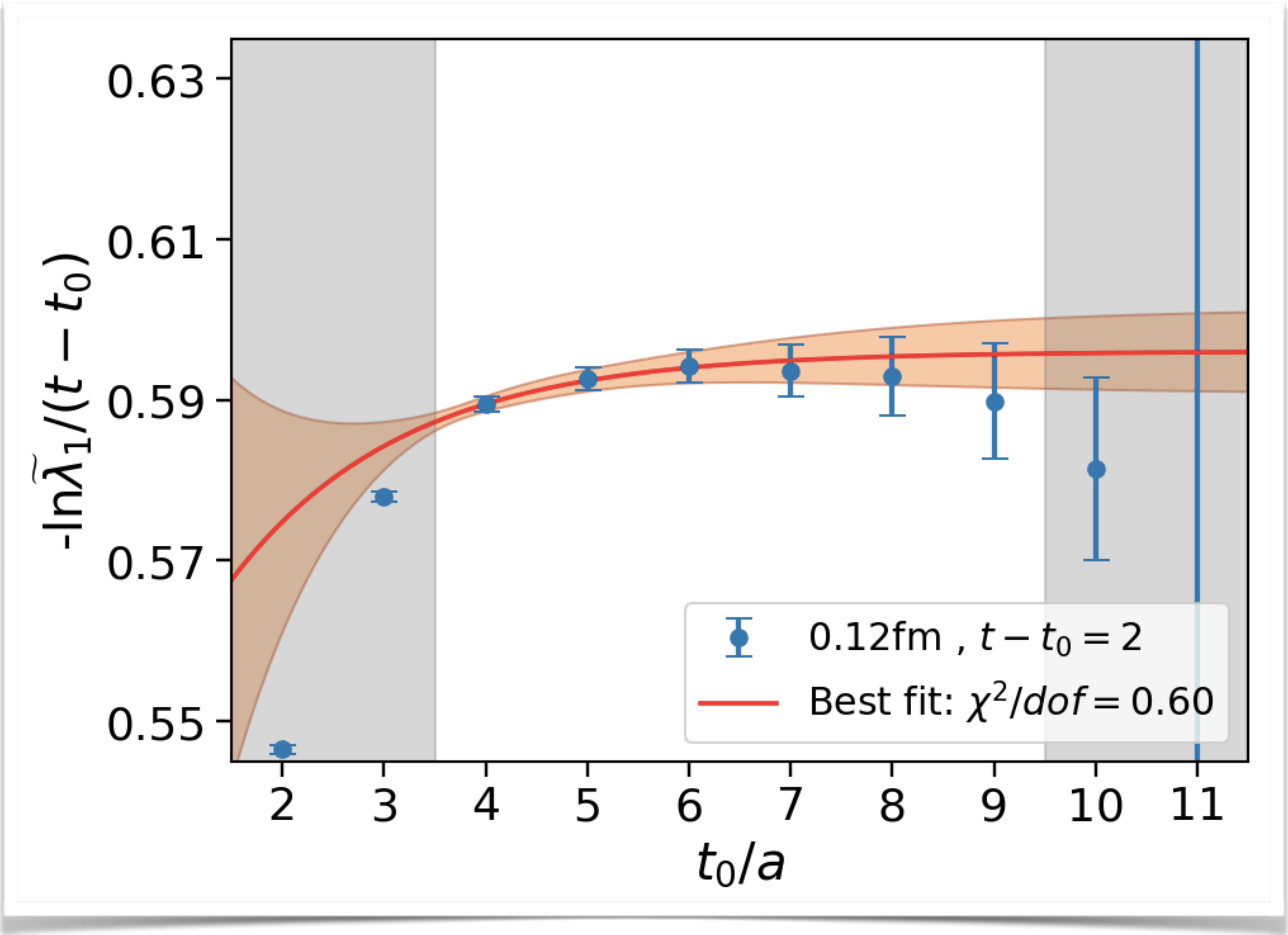
- **Bayesian fits gave the same posterior masses**

Nucleon Correlator: 0.15fm



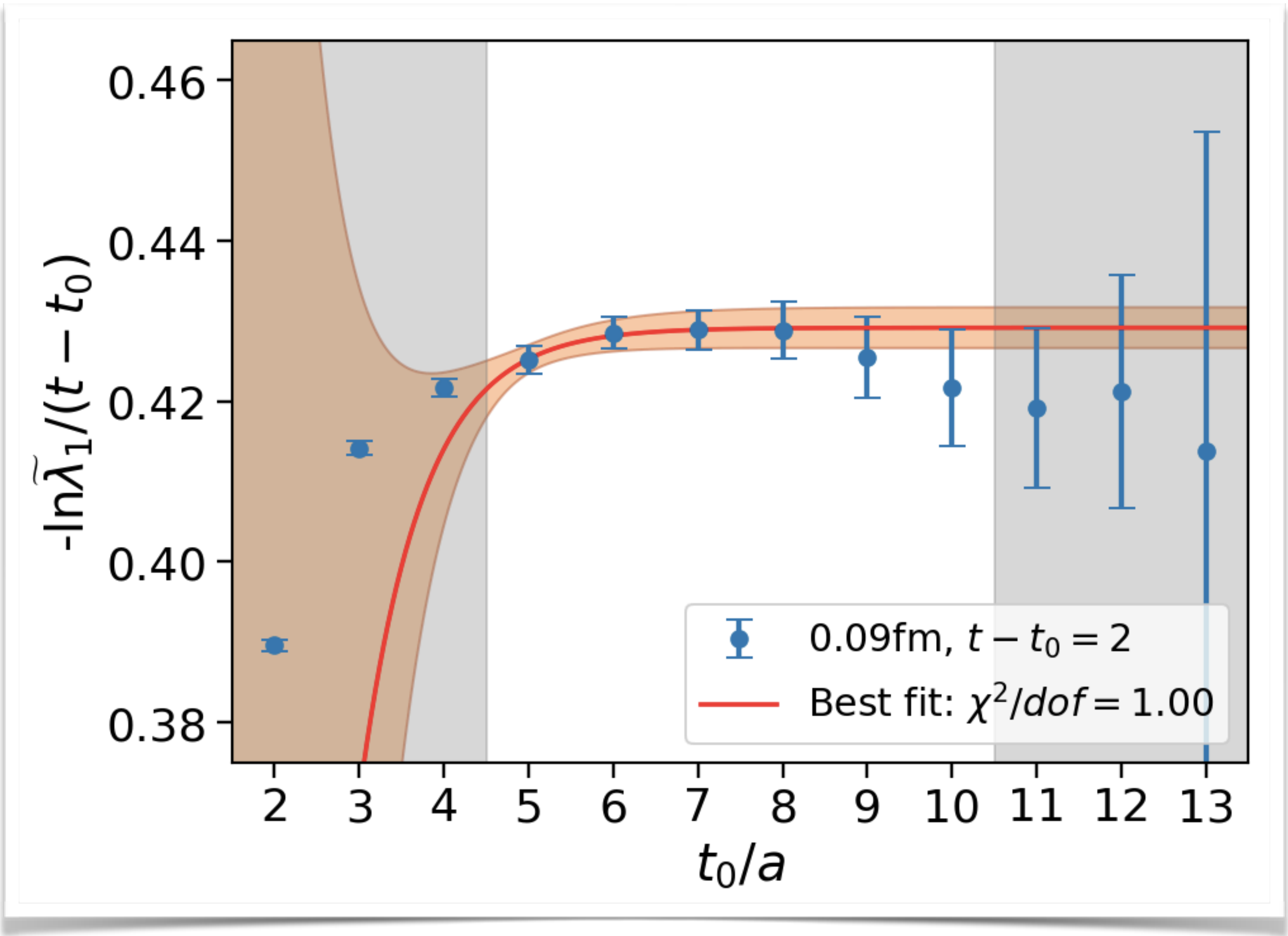
$$aM_N = 0.7556(59)_{fit}(22)_{stat}$$

Nucleon Correlator: 0.12fm



$$aM_N = 0.5946(22)_{fit}(48)_{stat}$$

Nucleon Correlator: 0.09fm



$$aM_N = 0.4295(8)_{fit}(26)_{stat}$$

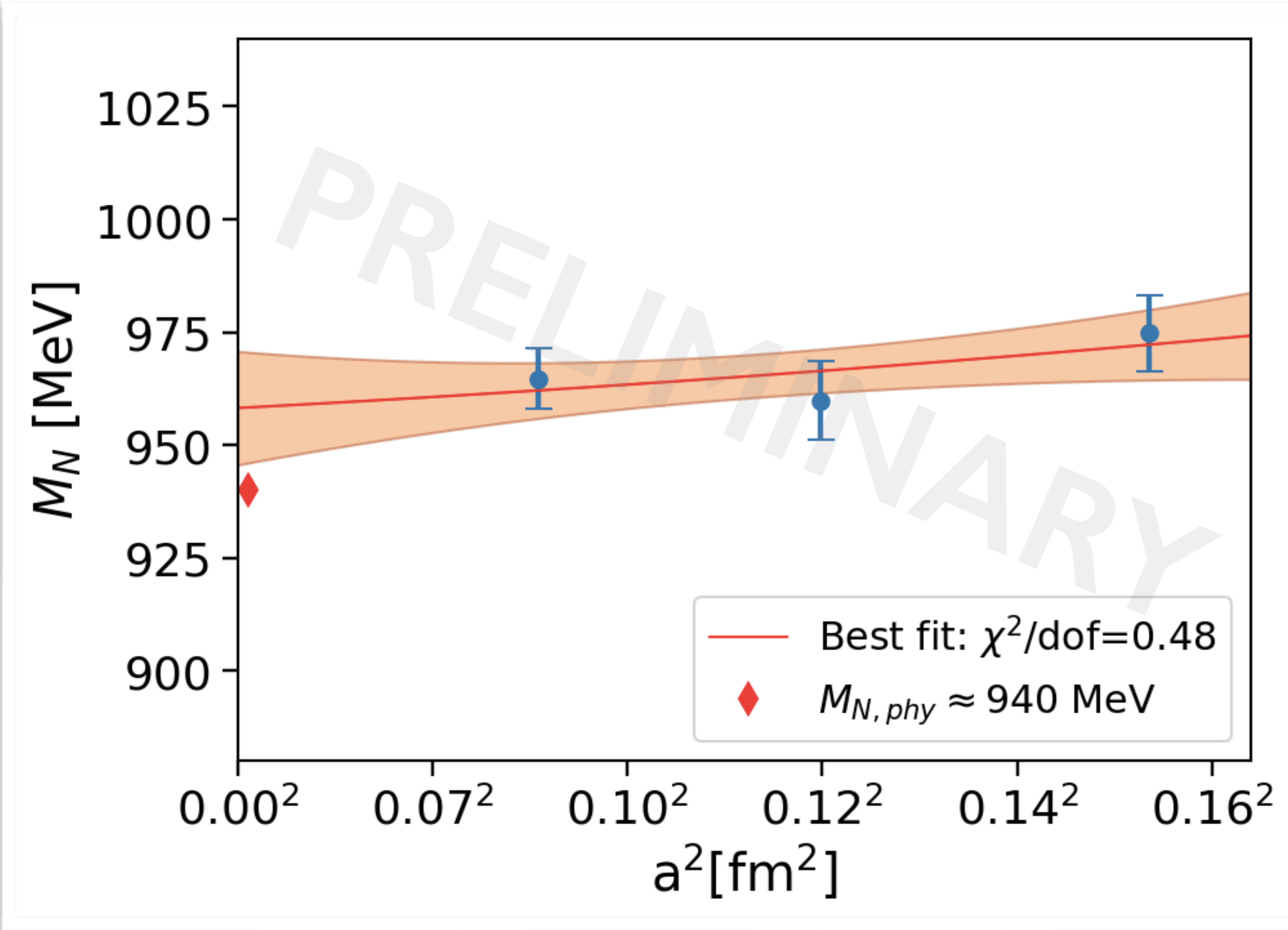
Nucleon Continuum Extrapolation

We perform Bayesian fit to $(\Lambda_{QCD} = 500\ MeV)$

$$M_N(a) = M_{N,phy}\left\{1 + o_2\left(\Lambda_{QCD}a\right)^2 + o_4\left(\Lambda_{QCD}a\right)^4\right\}$$

Parameter	Prior	Posterior
$M_{N,\mathrm{phy}}$ [MeV]	940(50)	957(10)
o_2	unconstrained	0.07(22)
o_4	0.0(1.0)	0.15(96)

Nucleon Continuum Extrapolation



$$M_N = 958(13)\ MeV$$

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Omega Baryon Correlators

- **Only one correlator for 8' irrep, "isospin" 3/2 operator**
- **Two types of effective masses**

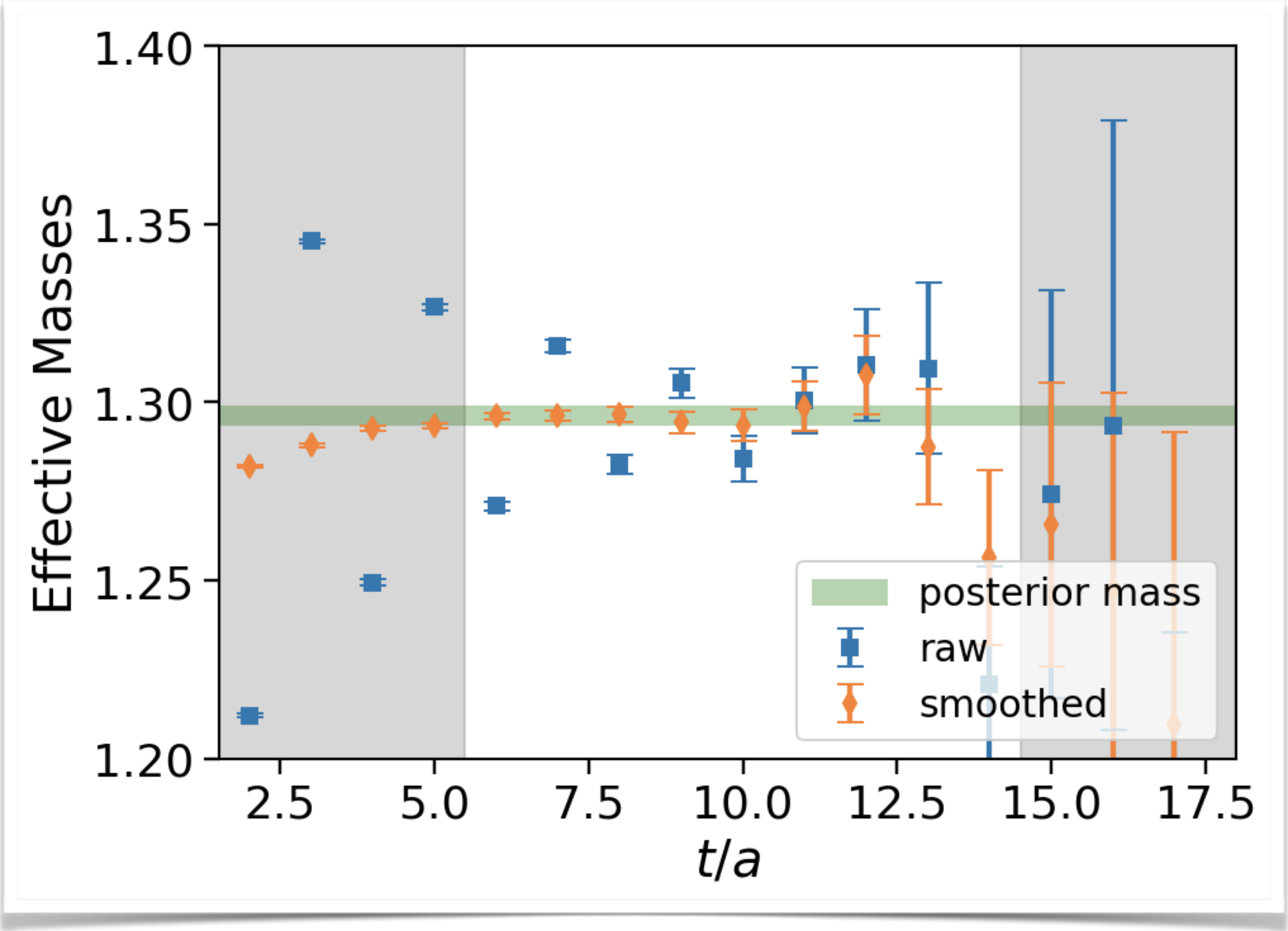
$$M_{raw} \equiv \frac{1}{2} \ln \left(\frac{C(t)}{C(t+2)} \right)$$

$$M_{smoothed} \equiv \frac{1}{4} \Big(M_{eff}(t-1) + 2M_{eff}(t) + M_{eff}(t+1) \Big)$$

[Carleton DeTar and Song-Haeng Lee, arxiv: 1411.4676]

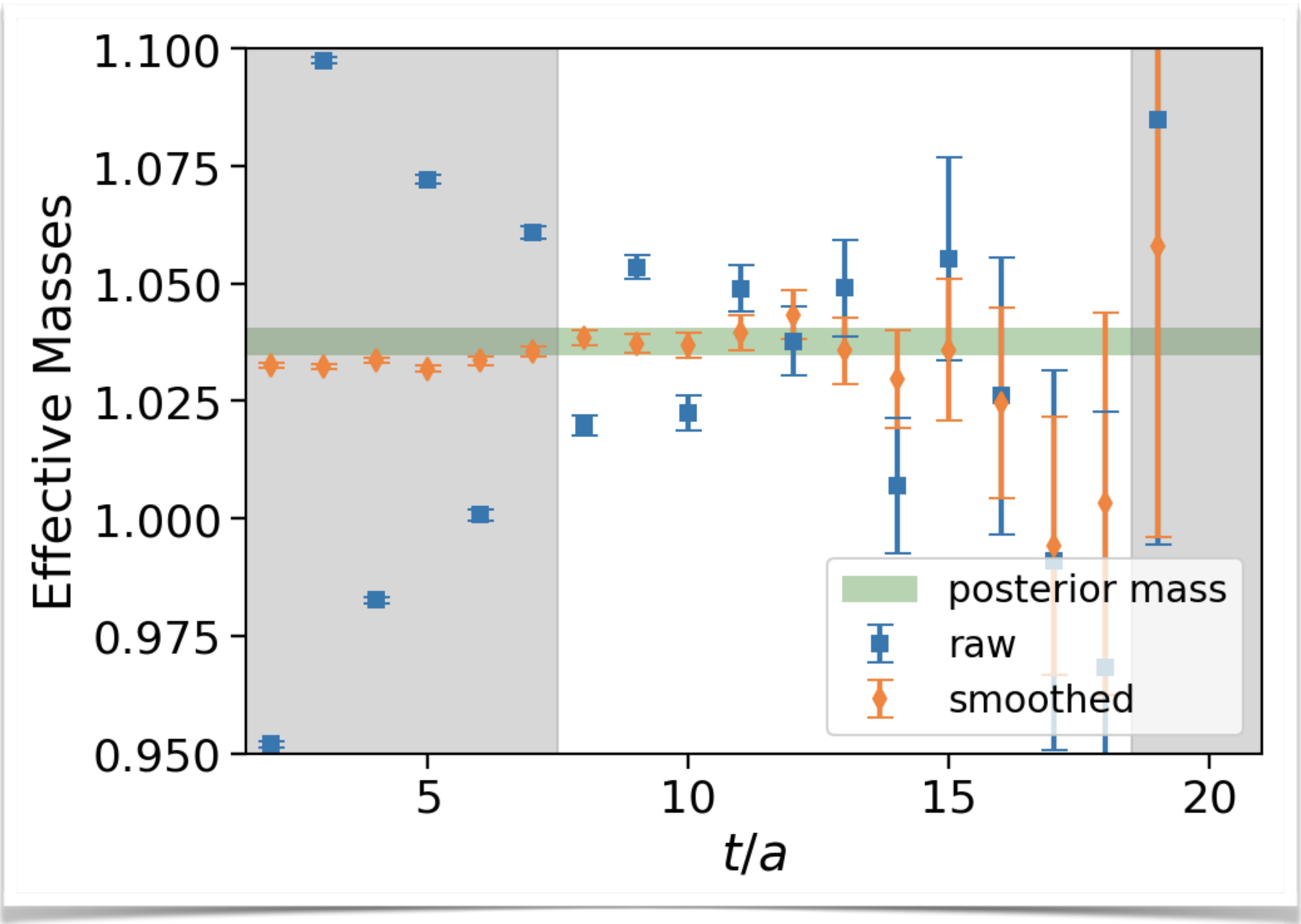
- **We perform Bayesian fits (only set priors on the masses) to the single correlator with two even and one odd parity states**

Omega Baryon Correlator: 0.15fm



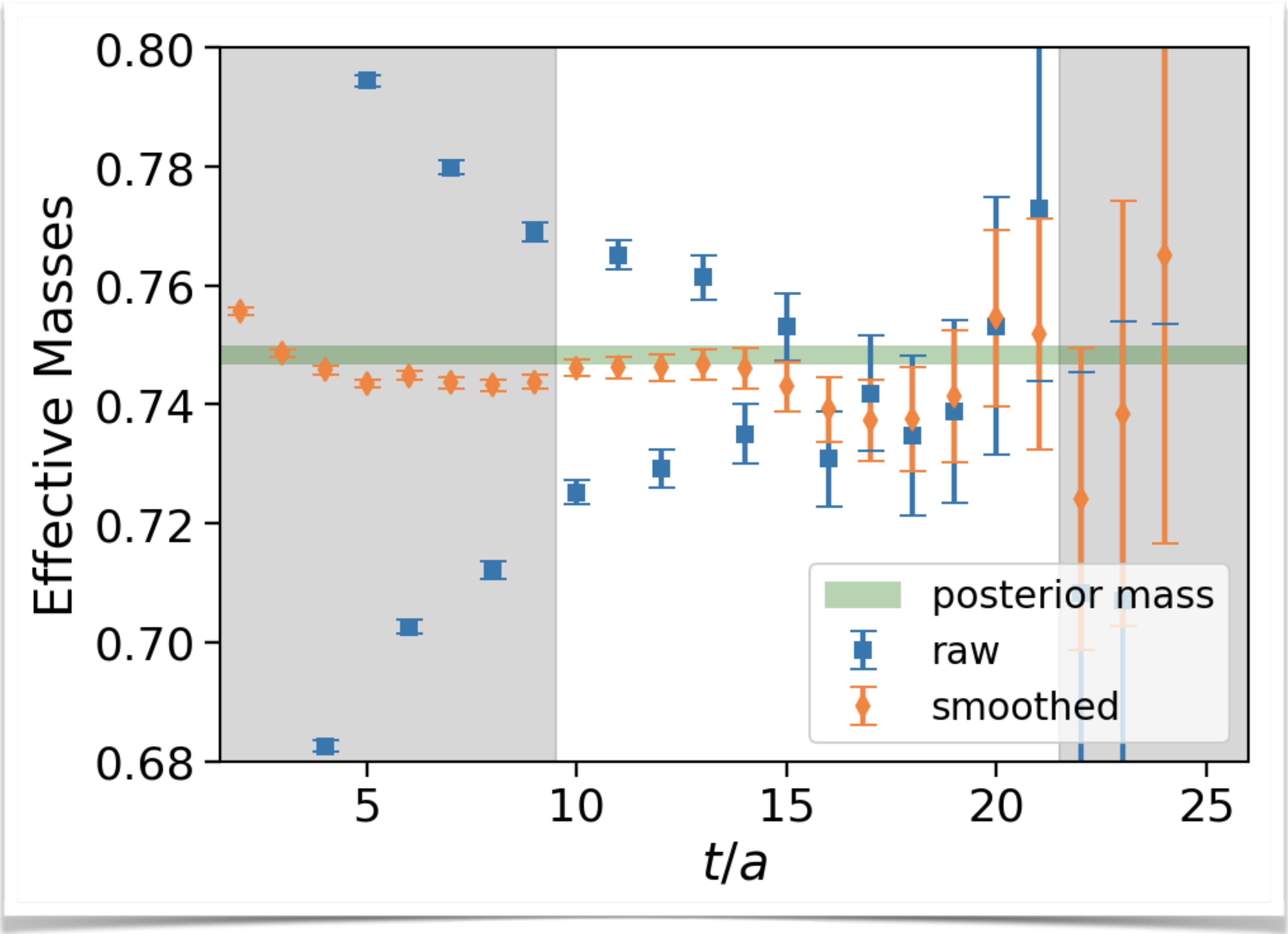
$$aM_{\Omega} = 1.296(3)_{stat}$$

Omega Baryon Correlator: 0.12fm



$$aM_{\Omega} = 1.038(3)_{stat}$$

Omega Baryon Correlator: 0.09fm



$$aM_{\Omega} = 0.748(2)_{stat}$$

Omega Baryon Correlators

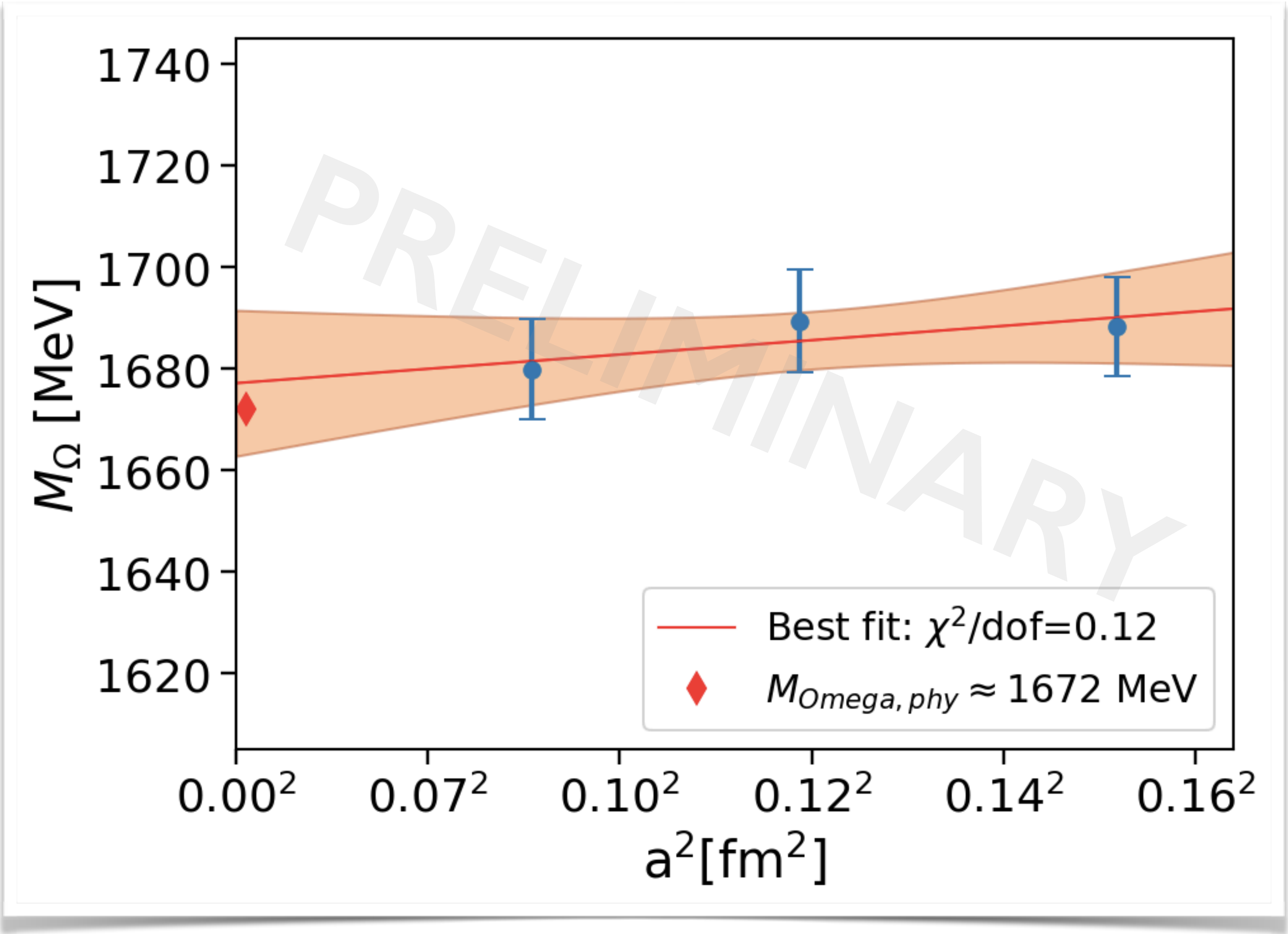
- **We perform the same Bayesian fits as nucleon using the lattice spacings determined by the gradient flow, w_0** [MILC Collaboration, arxiv:1503.02769]

- **We also illustrate the potential of using omega baryon to set the scale by plotting $w_0 M_\Omega$ and compare it to the current value of**

$$w_{0,phy} = 0.1715(9)\ fm,\ w_0 M_\Omega = 1.454(8)$$

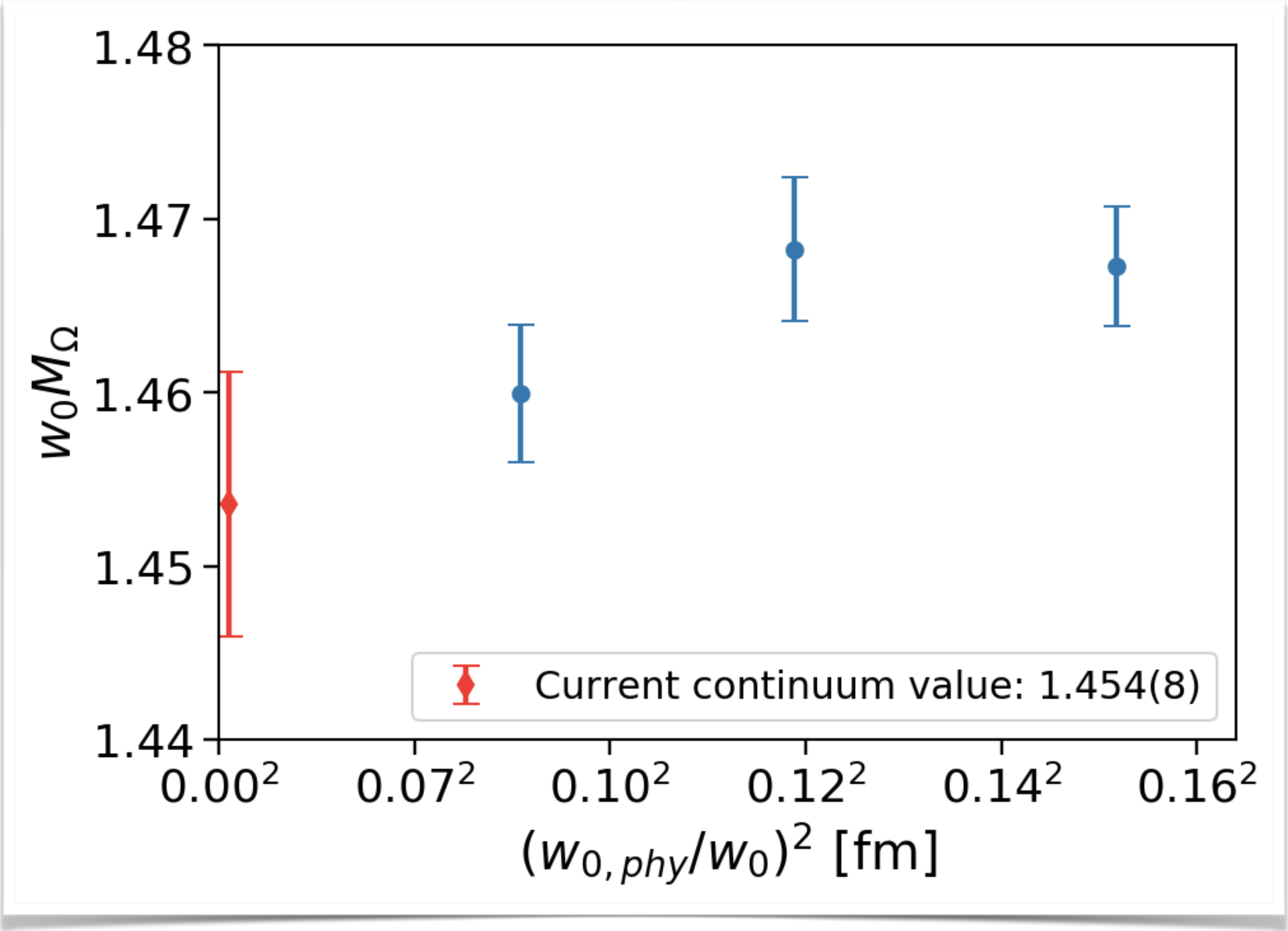
[HPQCD Collaboration, arxiv:1303.1670]

Omega Continuum Extrapolation



$$M_\Omega = 1677(14)_{stat}\ MeV$$

Scale Setting with w_0 and M_Ω



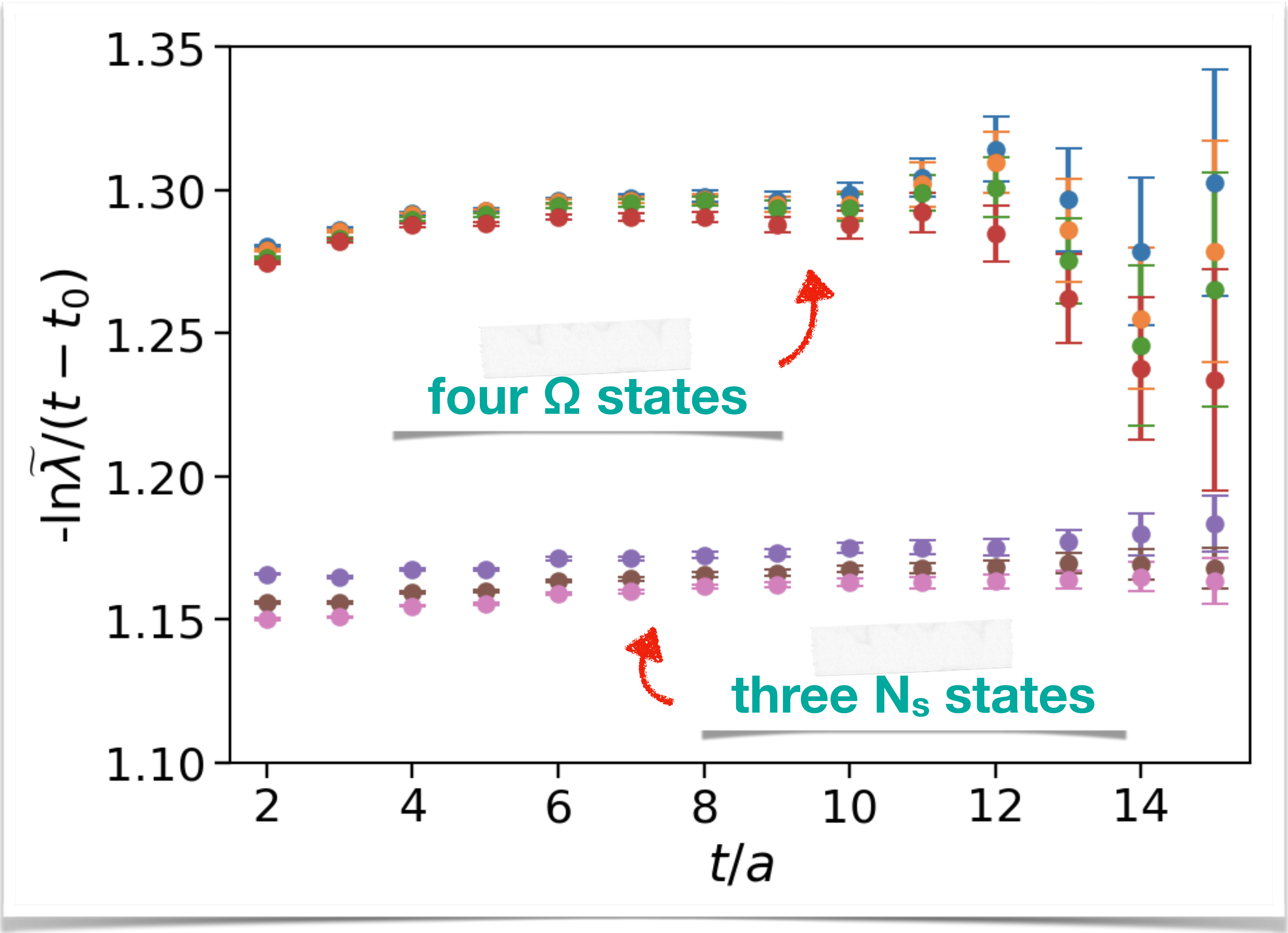
Tastes of Omega Baryon

- **Lastly, we are interested in the taste-breaking pattern for staggered baryons**
- **We will solve the same GEVP equation as nucleon for 16 irrep with “isospin” 3/2**

Recall the spectrum:

GTS Irrep	$"I" = 3/2$	$"I" = 1/2$
8	$3N_s + 2\Omega$	$5N_s + 1\Omega$
$8'$	$0N_s + 2\Omega$	$0N_s + 1\Omega$
16	$1N_s + 3\Omega$	$3N_s + 4\Omega$

Tastes of Omega Baryon: 0.15fm



In Conclusion…

- **We have successfully extract both nucleon and omega baryon masses and extrapolate them continuum**

- **We have demonstrated the potential of using omega baryon to set the scale**

- **We might be able to extract the masses of all entangled tastes if we use all operators. But this needs further studies**