# The Nucleon Axial-Vector Form Factor at the Physical Point with the HISQ Ensembles

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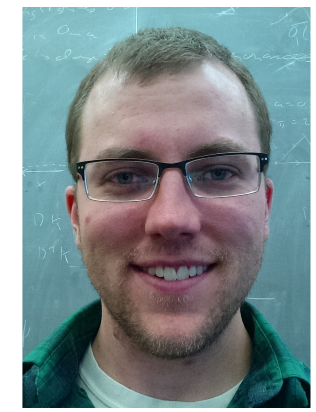
# Collaborators

- Richard Hill (U. Chicago, TRIUMF, Perimeter I.),
  Aaron Meyer (U. Chicago)

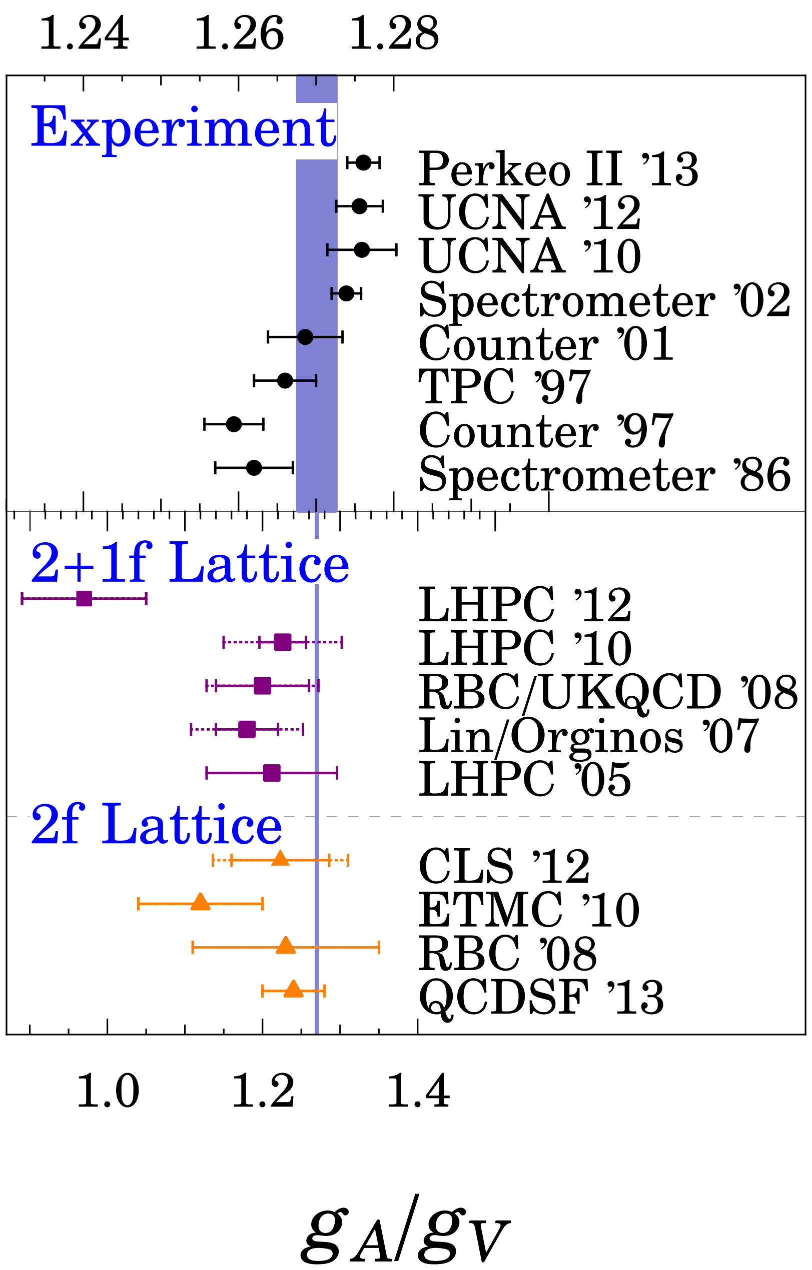


- Fermilab Lattice and MILC Collaborations:
    - A. Bazavov, C. Bernard, N. Brown, C. DeTar, Daping Du, A.X. El-Khadra, E.D. Freeland, E. Gámiz, Steven Gottlieb, U.M. Heller, J. Laiho, Ruizi Li, P. B. Mackenzie, D. Mohler, C. Monahan, E. T. Neil, J. Osborn, T. Primer, J. Simone, R. Sugar, D. Toussaint, R. S. Van de Water, A. Veernala, Ran Zhou

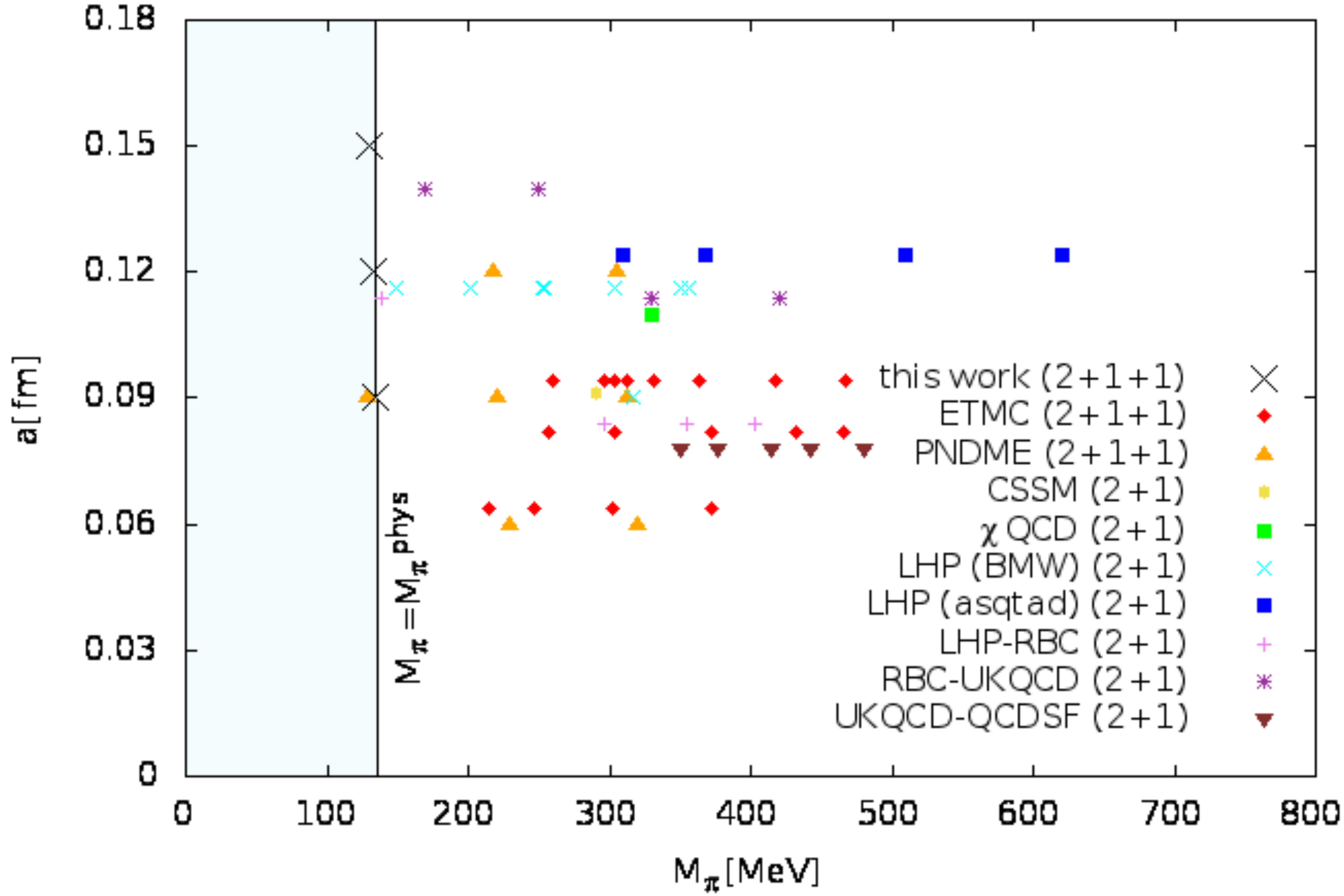
# The Calculation

- One of several projects (around the world) aiming to calculate $g_A = F_A(0)$.
- One of a few aiming to calculate the shape of the axial vector form factor, $F_A(q^2)$.
- How is our proposal unique?
    - All staggered on 2+1+1 HISQ ensembles;
    - physical light-quark masses;
    - large volumes;
    - many operators.

plot by PNDME

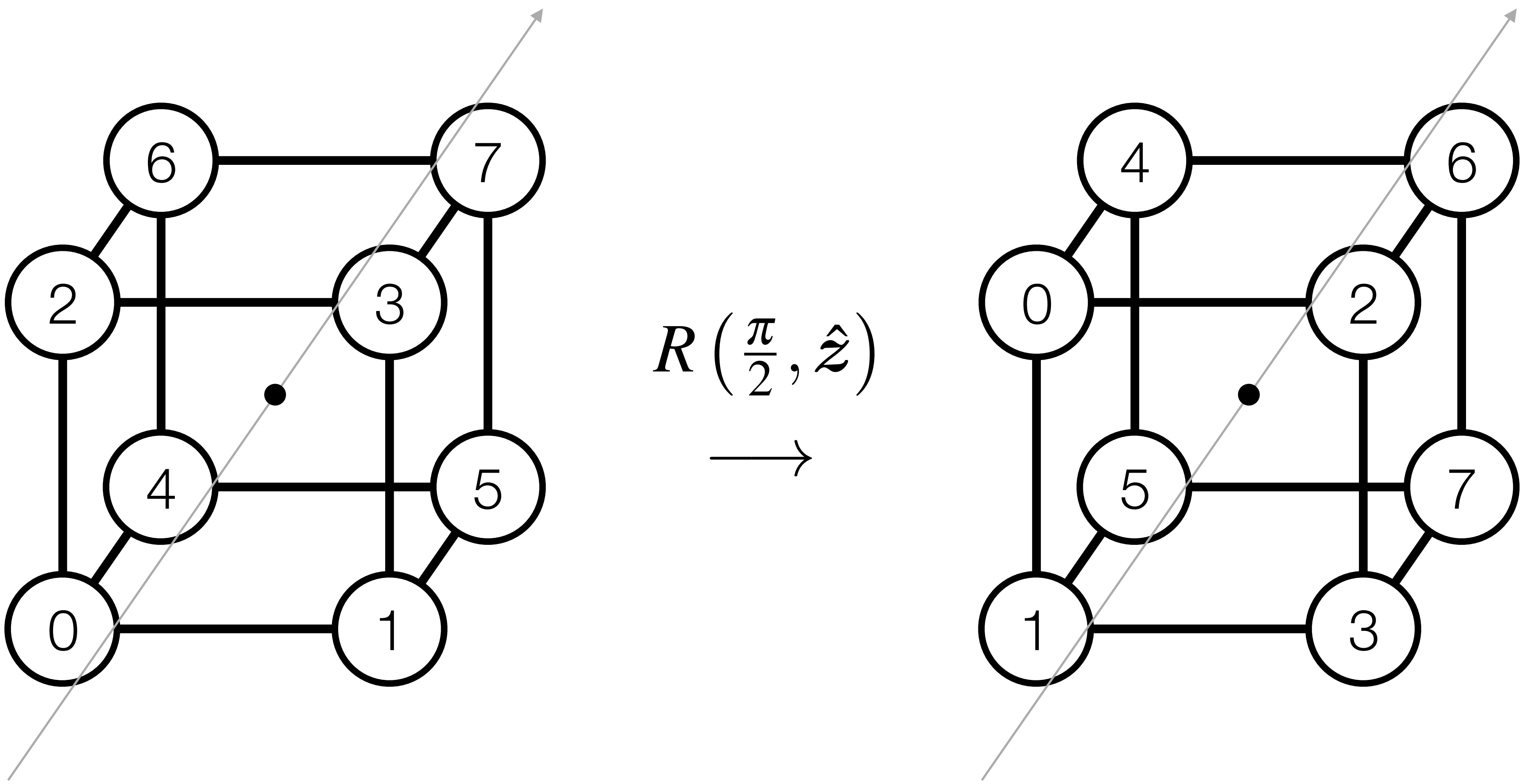


# Lattice Status: Axial Charge $g_A = F_A(0)$



# Staggered Baryons

- Useful to think of the staggered field as an 8-component object associated with (spatial) cubes in a timeslice $\psi^a_{iA}(y) = \chi^a_i(y+A)$:




- Baryon irreps: $\underline{8} \otimes \underline{8} \otimes \underline{8} = 20 \cdot \underline{8} \oplus 4 \cdot \underline{8}' \oplus 20 \cdot \underline{16}$.

# Staggered Baryons

- The group theory yields [Bailey, arXiv:hep-lat/0611023] numerical tensors for contracting the quark propagators in the baryon.

- Adding in isospin yields operators than create both $N$-like and $\Delta$-like baryons:

| GTS/$I$ | $\frac{3}{2}$ | $\frac{1}{2}$ |
|---|---|---|
| $\underline{8}$ | $3N, 2\Delta$ | $5N, 1\Delta$ |
| $\underline{8}'$ | $0N, 2\Delta$ | $0N, 1\Delta$ |
| $\underline{16}$ | $1N, 3\Delta$ | $3N, 4\Delta$ |

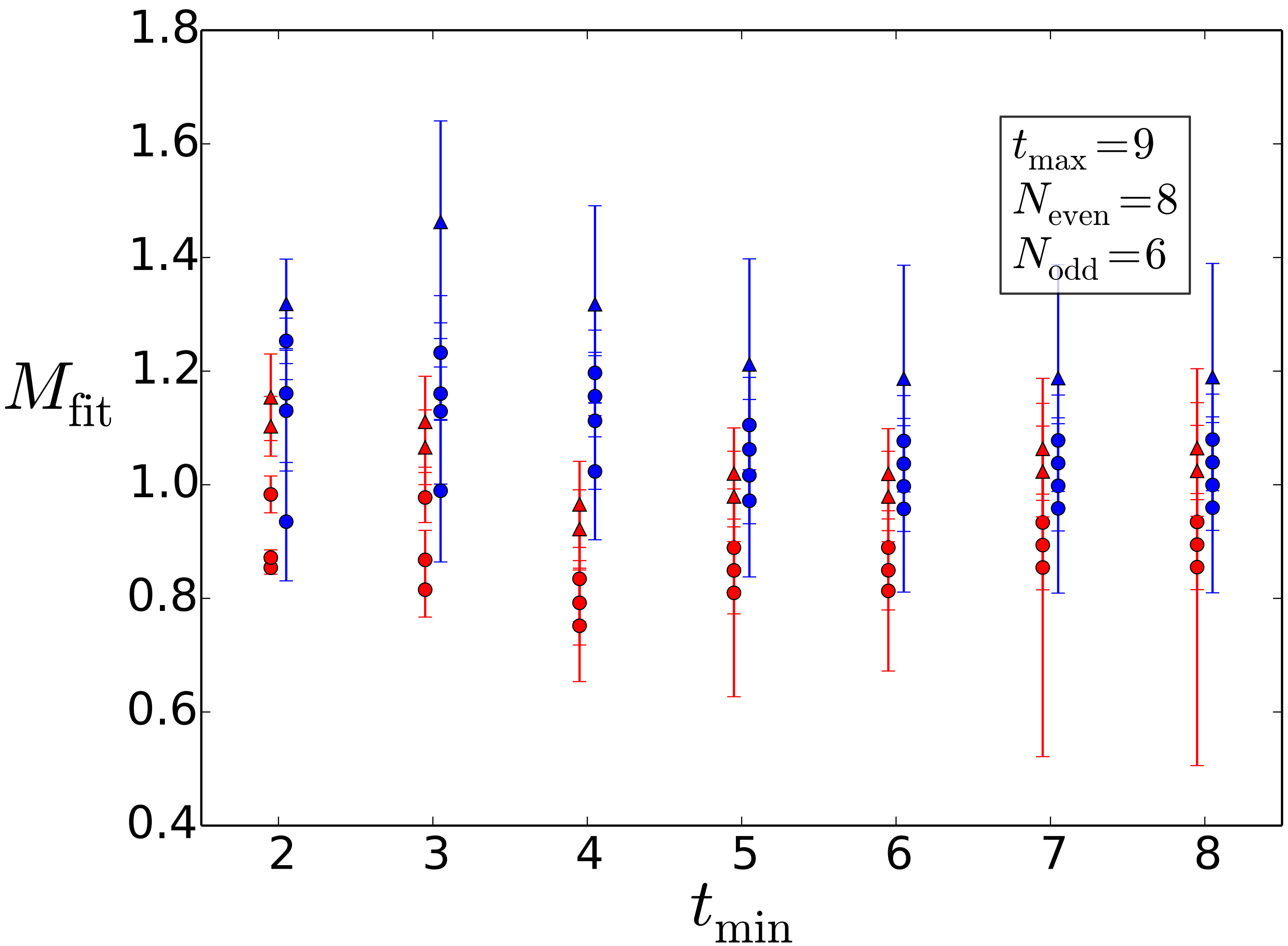
  baryons of different "taste".

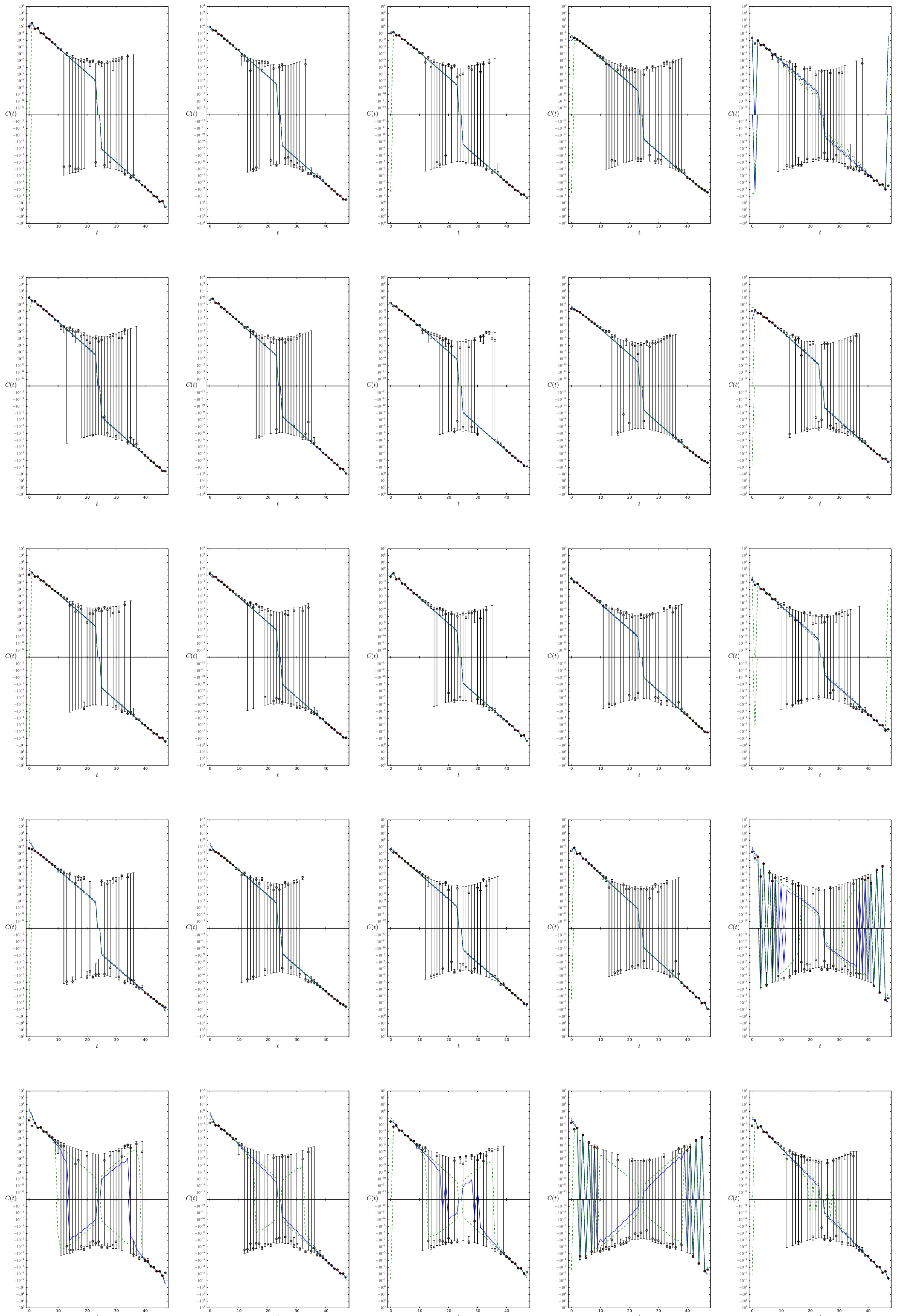
- Use $\underline{8}'$ to get $\Delta$ mass and its typical taste splitting; then use $\underline{8}$ to get $N$ mass and its typical taste splitting; then use $\underline{16}$ to home in on $N$.

# Status: 2-point functions

working on a $16^3 \times 32$ lattice with $a = 0.15$ fm, $m_l = 0.2 m_s$

- Several operators in each irrep allow variational calculations (here 8).



- Errors on splittings < errors on masses.

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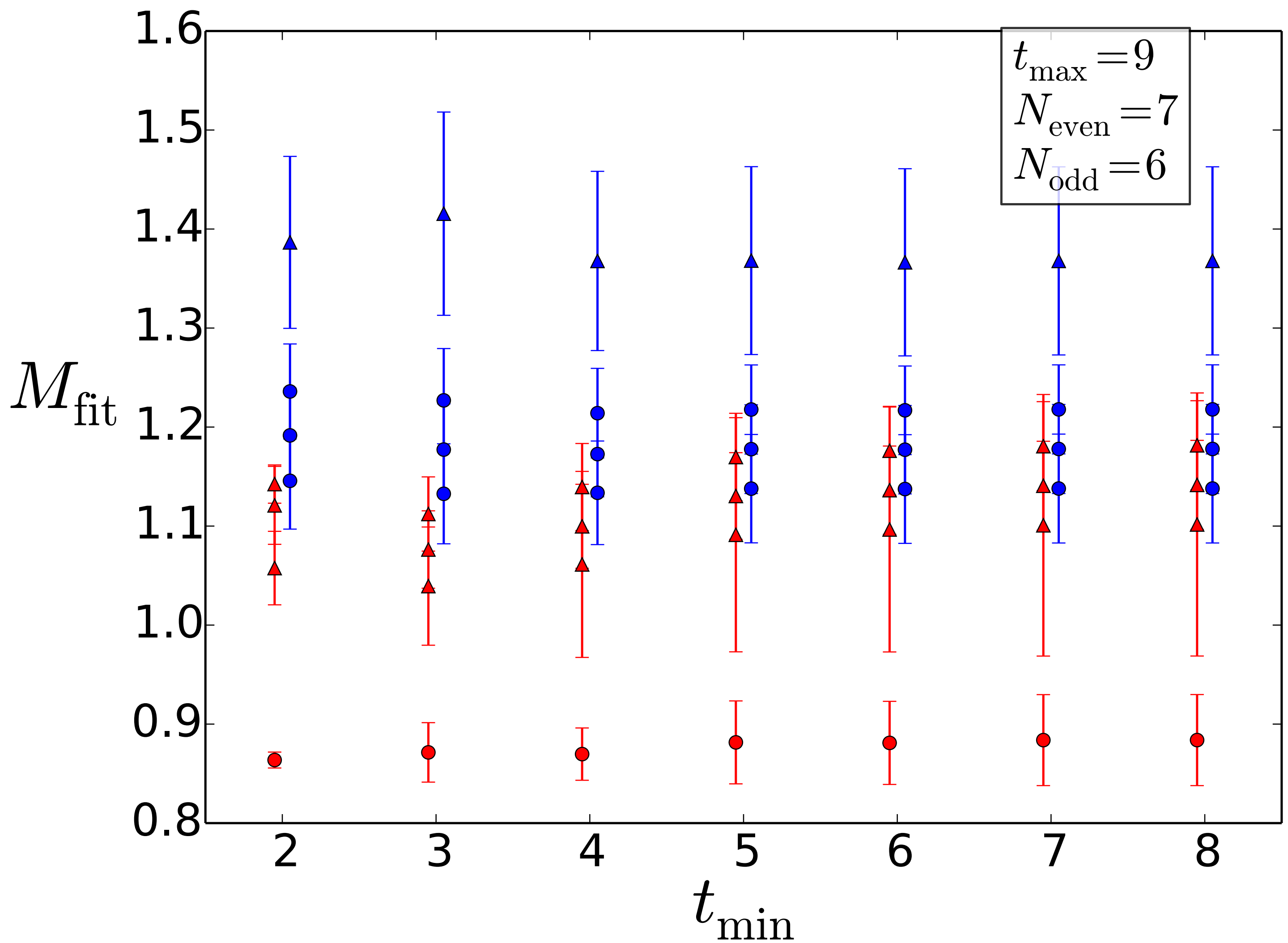
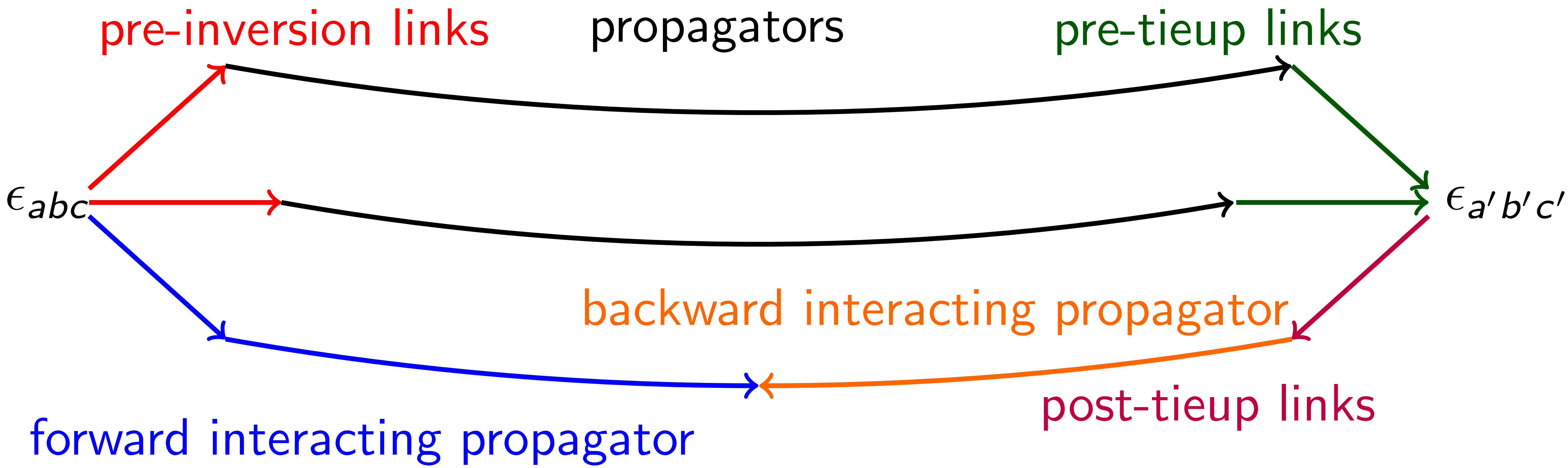



- Getting to this point forced us to abandon last year's proposed noise, in favor of Coulomb wall sources and 3-pt sinks with mesonic random noise.

# Status: 3-point functions

- Plots in proposal (to be revised) looked horrible but (fortunately) suffered from two bugs, which have been eliminated:
    - error in handling boundary conditions of lattice;
    - race condition (led to wrong results on multi-node jobs).
- Further improvements:
    - tweaks to the baryon operators (including link matrices within a cube improves 3-point signal-to-noise ratio);
    - pick linear combo of operators that optimizes signal-to-noise (rather than overlap with lowest-lying state).

# Anatomy: 3-point functions



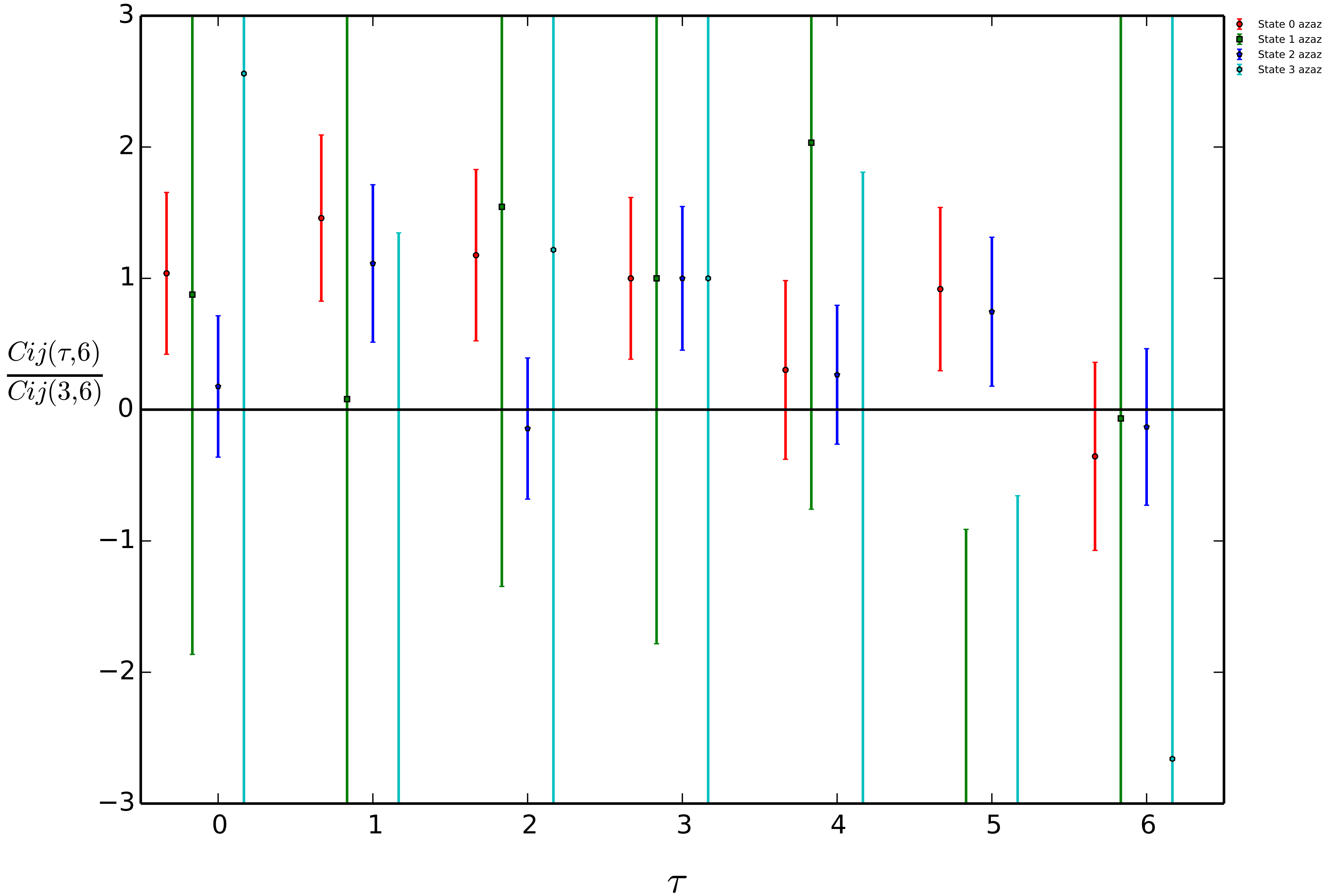

- Choose overlap-maximizing vectors from 2-point fits, or maximize

$$\frac{S^2}{N^2} = \frac{\sum_{ij} \sum_{\tau=1}^{5} (v_i C_{ij}(\tau, t=6) w_j^T)^2}{\delta[v_i C_{ij}(\tau, t=6) w_j^T]^2}$$

# Status: 3-point functions

working on a $16^3 \times 32$ lattice with $a = 0.15$ fm, $m_l = 0.2 m_s$

- Optimizing for the lowest-lying state (here <u>16</u>); 400 configs w/ 4 noises:



# Status: 3-point functions

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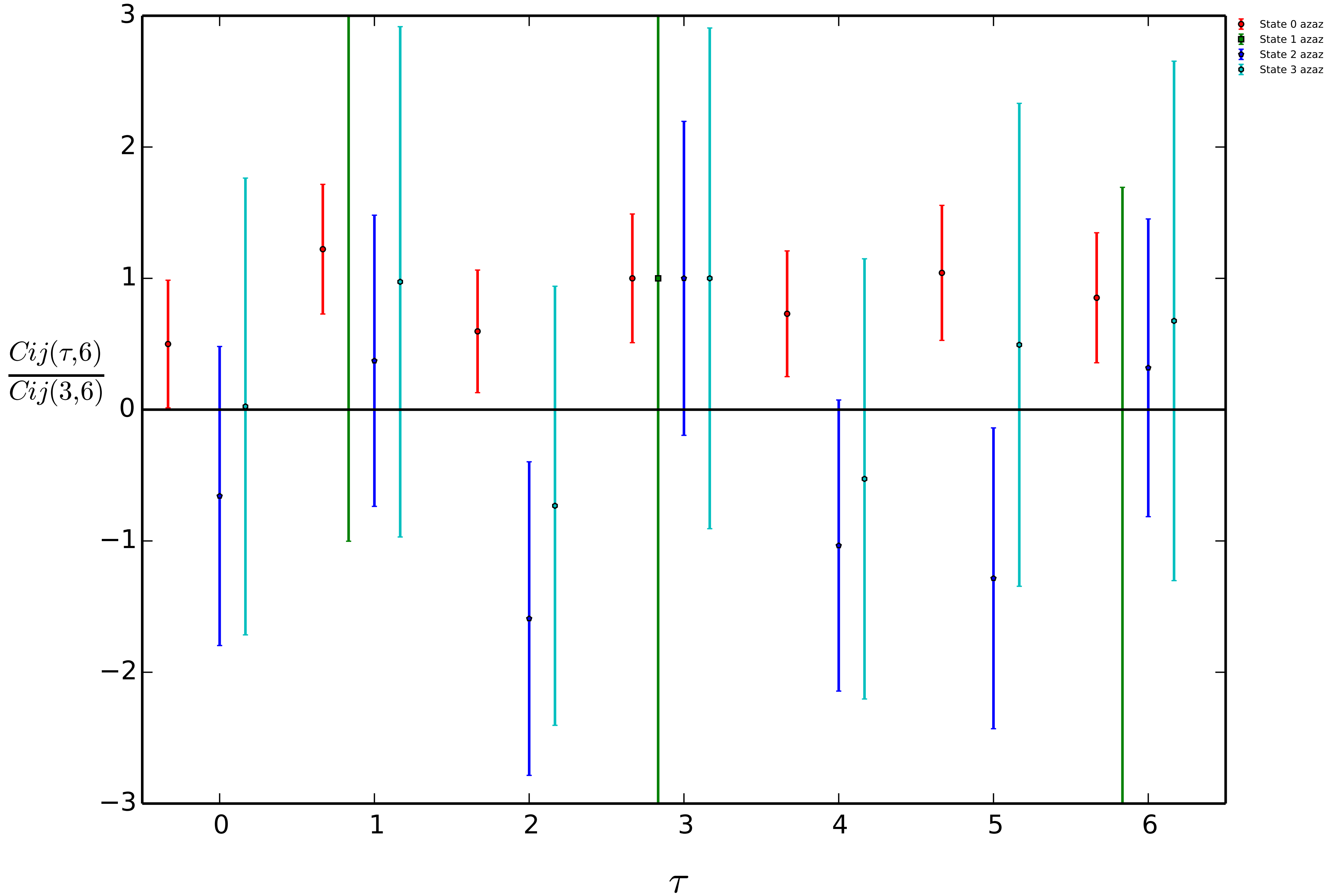
- Optimizing for signal/noise (here 16); 400 configs w/ 4 noises:



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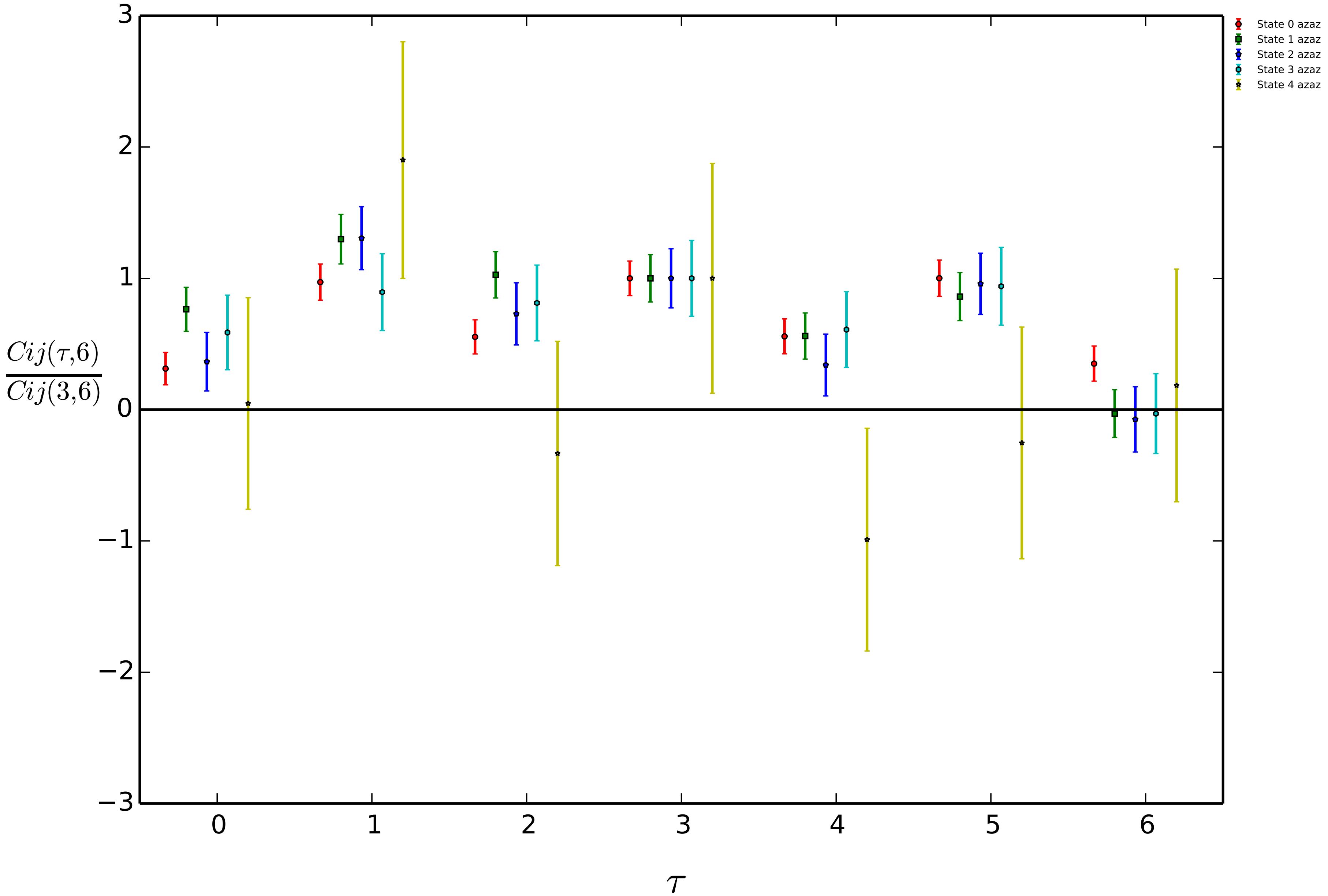

# Uniqueness Revisited

- All staggered on 2+1+1 HISQ ensembles, hence: large volumes;
  - physical light-quark masses ⇒ so χPT for FV correction;
  - many operators allow us to disentangle tastes of *N* and Δ.
- Further features:
  - $z$ expansion ⇒ model-independent description of shape;
  - blind analysis for $g_A$ planned;
  - motivation (for us) is neutrino physics ⇒ new allies among experimenters (*e.g.*, Meyer, Betancourt, Gran, Hill, arXiv:1603.03048).

# Resource Request

- Timings:

| $\approx a$ (fm) | $N_s^3 \times N_t$ | $N_{\text{confs}}$ | Inversions | 3-point tie-ups | Total |
|---|---|---|---|---|---|
| | | | | (M `Jpsi`-core-hours) | |
| 0.15 | $32^3 \times 48$ | 1000 | 1.17 | 2.94 | 4.11 |
| 0.12 | $48^3 \times 64$ | 1000 | 5.46 | 10.88 | 16.34 |
| 0.09 | $64^3 \times 96$ | 1047 | 27.52 | 35.17 | 62.69 |
| Total | | | 34.15 | 48.01 | 84.14 |

- We expect to find efficiencies (e.g., in contractions) before starting on the 0.09 fm ensemble, so we request 51 M Jpsi-core-hours (and some disk and tape storage). We will pursue further computing resources for finer HISQ ensembles.

- Wise of last year's SPC to keep us lean, but we now have an opportunity for USQCD to have first physical-point calculations of $F_A(q^2)$.

# Questions from the SPC

(1) Given the demand for resources and the number of groups doing this type of calculation, have you explored opportunities to share calculations or collaborate?

As we say in the proposal, we plan to store the propagators needed for staggered baryons for other projects, such as Lambda_b decays, should we or another group (possibly in collaboration) wish to pursue it.

Concerning collaboration on nucleon form factors, we do not know of another group with plans to use staggered baryons on the HISQ ensembles. If that were the case, we would be happy to share effort and resources. At this stage, we have made an investment in planning and coding a project that has several advantages over competing approaches. In particular, we aim to take full advantage of the physical-mass HISQ ensembles. USQCD has devoted considerable resources to generating these ensembles, and it behooves us (USQCD as well as Fermilab/MILC) to extract as much important physics as possible.

(2) In a related question to (1), there are several groups using the same MILC ensembles but doing different physics. Nevertheless there may be opportunities to share resources. Have you considered this?

The three projects proposed by the Fermilab Lattice and MILC collaborations have different needs. B- and D-meson analyses (Mackenzie) use the multi-mass inverter to generate partially quenched data, inject random noise at the source, and use a corner wall with support only on even sites. The HVP g-2 proposal (Laiho) uses full (not corner) walls and some special-purpose sources. For nucleons, we must generate propagators from all eight corners (not just the all-even corner), and our method for injecting momentum exploits noise at the sink.

The need for eight corner walls is linked intimately to the group theory for staggered fermions. It is useful to think of the staggered field residing on cubes on a timeslice, with eight taste/Dirac components on the corners of the cubes. From the B- and D-meson proposal we could, in principle, use the physical-mass all-even random corner-wall propagators, by placing one of the (two or three) nucleon sinks at the heavy-light source. This would save one out of 24–48 propagator calculations. We can investigate whether the costs of I/O and medium-term storage are less than the computing savings.

(3) The relative cost of doing contractions for this project is high in comparison to the light quark propagator calculations. Can you please explain the origin of this cost and what steps you have taken to optimize this part of the calculation?

Our priority so far has been to write a working and correct code. We expect that the contractions can be made much more efficient, and have already identified a couple pathways to optimization. We will look for further optimizations before moving to the larger lattices in the proposal.

(4) Since you are still in the process of developing a new method, would it make sense to do tests using the coarser ensembles this year before embarking on the expensive calculations on the 0.09 fm ensembles in the future?

We have already spent a year developing and testing code, and it is important for physics and the student's career to get a paper out in another year's time.

(5) With the new resources at JLab being as yet unspecified, we would like to know if you are in a position to use them efficiently if they are a) cpu, b) GPU, c) KNL. If you are not, that is fine, but it will help in our allocation decisions to know this information from every proposal.

If the new hardware is CPU based, we expect to be able to make efficient use of it using the MILC code as it should be possible to run benchmarks prior to acquisition and we presume that will have been done.

If the new hardware is GPU based, we expect to be able to make efficient use for propagator solvers as the QUDA code runs well for both staggered and Wilson/Clover. Codes that require many contractions might require additional work and we have sometimes run in a mixed environment where propagators are saved and contractions are done on separate CPU resources. Depending on our success at reducing the number of contractions, this may be a special concern here.

If the new hardware is KNL based, we cannot predict how efficient our usage will be. We have been working for quite some time to produce efficient Xeon Phi code; however, on KNC we were never able to run successfully on multiple chips because of MPI issues. KNL has not been released and it might have a good MPI implementation particularly on a machine that does not rely on host processors, e.g., one in which the KNLs are connected via Omnipath. However, we have no direct experience with such a system and could not promise any baseline level of performance from which we could start out tuning efforts. We will continue efforts to explore and improve performance on Xeon Phi, but without experience on a multichip system, we would have to say the we do not know if we are in a position to make efficient use of such a system.

# Further Calculations of Interest