# Spectral & Radiative Meson Physics of GlueX & CLEO-c

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The use of radiative meson couplings as a tool for spectroscopy is a topic which spans nuclear and high-energy physics, from the forthcoming photoproduction efforts of the GlueX project to the radiative charmonium processes measured at CLEO-c. This proposal continues previous work studying such quantities using lattice QCD methods. Herein we propose to compute radiative matrix elements between mesons of various $J^{PC}$, including excited states and exotics, in both the charm-quark and light-quark sectors.

Since addressing key questions in hadronic physics is a strategic goal of USQCD, this proposal satisfies a criterion for a class-A proposal. We request 1.5M 6n proc-hours on the JLab clusters.

## I. PHYSICS GOALS

Jefferson Lab's 12 GeV upgrade has as its flagship experiment the GlueX program which will use a custom-designed detector to investigate the light meson spectrum with unprecedented statistics. The production mechanism is rather novel, using 9 GeV real photons incident on proton and nuclear targets to photoproduce meson resonances, and is partly motivated by phenomenological expectations that this will enhance production of exotic mesons. These mesons, having $J^{PC}$ outside the set $(0^{\pm+}, 1^{\pm-}, 1^{++}, 2^{\pm+}, 2^{--} \ldots)$ allowed to a fermion-antifermion bound state, are believed to arise from excitations of the gluonic field.

In a production diagram like that shown in figure 1, one can model using existing data (largely pion-beam data) every feature except the photon-(exchange meson)-(produced meson) coupling. This photocoupling can be extracted from vector current three-point functions calculated in lattice QCD. Computation of these quantities thus admits a prediction for the production rate of various meson species at GlueX. Such predictions would be of use immediately to experimentalists developing Monte Carlo simulations of detector performance ahead of the experiment.

Photocouplings also play a role in data from CLEO-c, where radiative transitions between charmonium states are being measured with world-beating precision. There is now, or will soon be, good measurements of nearly all sub-$D\bar{D}$ charmonium radiative transitions. This runs alongside the startling growth in the number of observed states above threshold in the charmonium region, many of which were not expected in the otherwise successful quark-potential models. Despite the retirement of CLEO-c, spectroscopy in the charmonium region retains a bright future with BES III and PANDA having program elements of relevance.

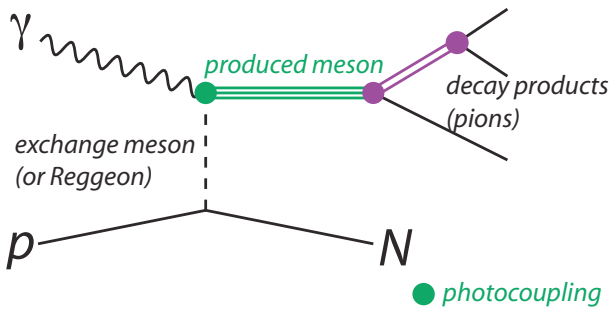


FIG. 1: Photoproduction diagram with $t$-channel meson exchange. An overall magnitude scale of the amplitude is determined by the photocoupling - these numbers are unknown even for most conventional mesons.

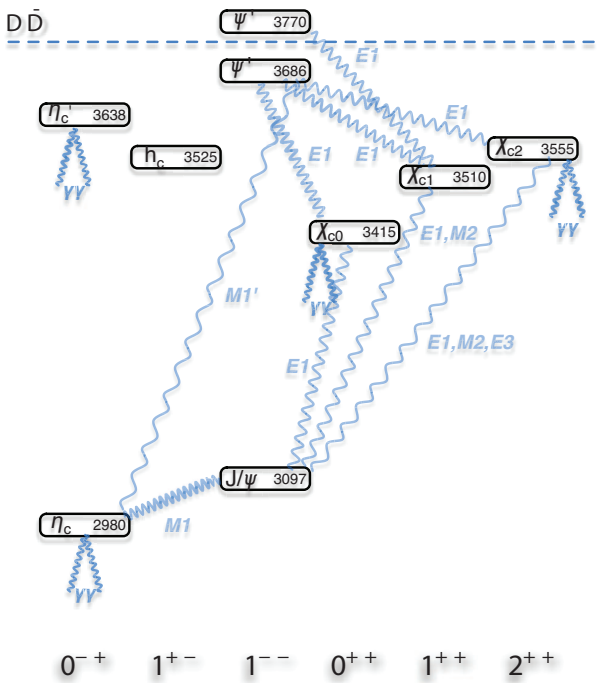


FIG. 2: Measured radiative transitions between charmonium states.

### A. Progress to date

Over the past three years, the JLab lattice group has produced a body of work aiming towards the realistic computation of radiative meson physics quantities. In [1], the first computation of radiative transition matrix elements between charmonia was performed with domain wall fermions on anisotropic quenched lattices. The results were promising (see figure 3), agreeing with experimental values and quark-model momentum dependencies within statistical errors. Indeed the work had quite an impact in the CLEO-c experimental community, with analyses of $\psi' \to \eta_c\gamma$, $\psi \to \eta_c\gamma$[2] and $\chi_{cJ} \to J/\psi\gamma$ multipoles[3] being directly inspired. Additionally, within the phenomenological community, our results for form-factors as a function of photon virtuality (something not available from experiment) immediately motivated calculations in quark-potential models [4] and Dyson-Schwinger models [5].

Our first study was limited in scope however - neither higher spins nor exotics could be studied since meson interpolators were limited to the local fermion bilinears. Additionally, the use of domain

wall fermions with their lack of a four-dimensional transfer-matrix, introduced oscillatory states which obscured the contribution of excited states to the three-point correlators, admitting extraction of only the ground-state transitions.

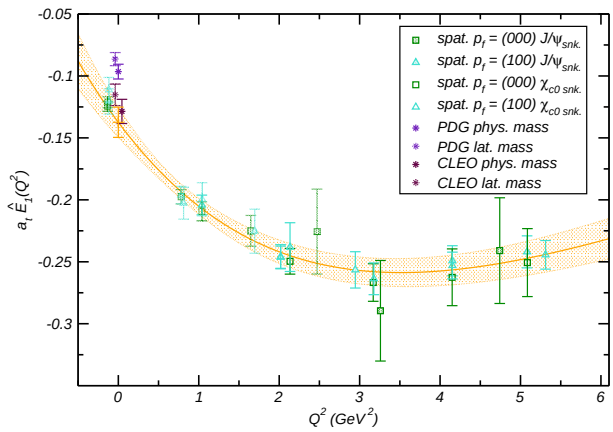


FIG. 3: Electric dipole radiative transition between $\chi_{c0}$ and $J/\psi$ computed using DWF on anisotropic quenched lattice

Anisotropic tree-level tadpole improved Clover was then investigated as a suitable action, removing the oscillatory behaviour and speeding up the propagator inversions (allowing a much larger number of configurations to be considered), the downside being the loss of near-exact $\mathcal{O}(a)$ improvement. For heavy quarks, even on an anisotropic lattice, there is the worry that $\mathcal{O}(ma_s)$ errors may be large. It was found that implementing the anisotropic improvement scheme of [6] on the vector current one obtained clover matrix elements in good agreement with the DWF matrix elements of the previous study, see figure 4.

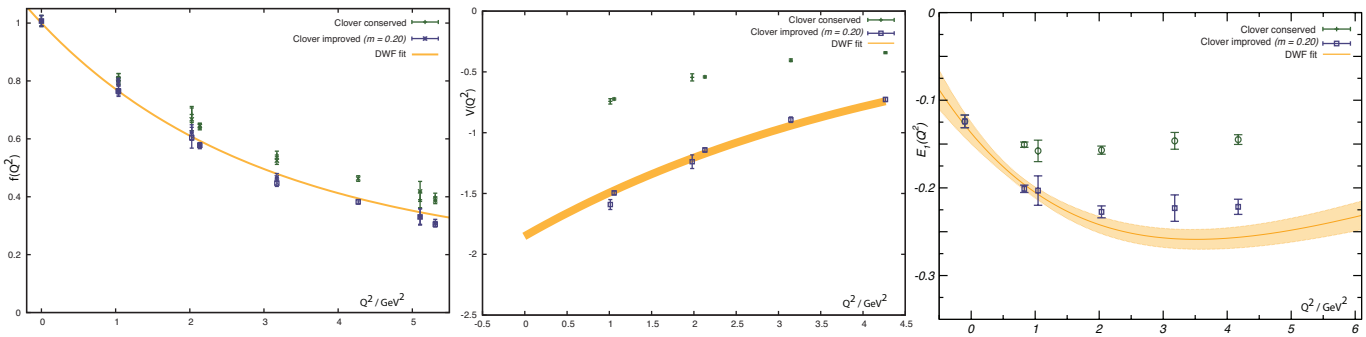


FIG. 4: Vector current matrix elements. The green data points are unimproved, conserved current clover results, the purple data points are the *improved* conserved current clover results and the orange curves are the results of fits to the DWF data of [1]. To the extent that DWF can be considered an improved action, it appears that the improved Clover has only small scaling violations.

Our basis of interpolators for mesons is now much broader. In [7], an operator basis was constructed based upon operators that in the continuum would have the structure of fermion bilinears with a number of symmetric covariant derivatives

$$\mathcal{O}_{\mu\nu\rho\cdots} = \bar{\psi}(x)\Gamma_\mu \overleftrightarrow{D}_\nu \overleftrightarrow{D}_\rho \cdots \psi(x).$$

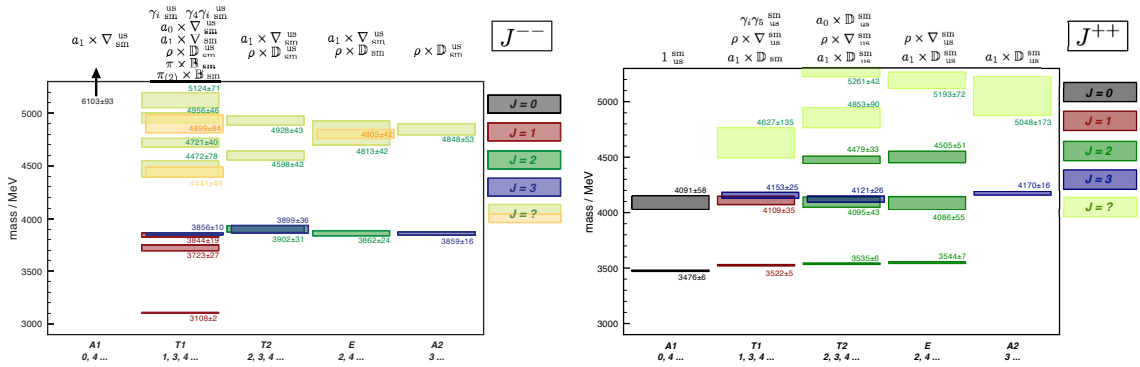


FIG. 5: Extracted quenched charmonium mass spectrum for $PC = --, ++$ listed by lattice irreducible representation. Operator labels listed in [7]

Including up to two derivatives, these operators give access to almost all continuum $J^{PC}$ with $J \leq 3$. Suitable linear combinations of these operators can be constructed that transform as the irreducible representations of the lattice cubic group. These are related to the operators used in [8], extended, corrected and modified to be eigenoperators of charge-conjugation at finite three-momentum.

These interpolators were used to measure meson two-point functions using Clover quarks on anisotropic quenched lattices in [7]. Matrices of correlators were constructed within a given lattice irrep and a variational solution found via a generalised eigensystem, yielding both a mass spectrum (from the eigenvalues) and the overlap of the states on to the set of interpolators (from the eigenvectors). As an example of the quality of the results we show in figure 5, the extracted spectrum in the $PC = --$ and $PC = ++$ channels.

Note that the $T_1^{--}$ channel has three very closely spaced excited levels above the ground state - that we were able to extract these states at all testifies to the power of the variational method with its in-built orthogonality of states. This structure is actually what one would expect: experimentally above the $J/\psi$ one has the $\psi(3686)$ and the nearby $\psi(3770)$, naturally explained in potential models as $2^3S_1$ and $^3D_1$ states. To explain the remaining state we recall that in the continuum $T_1$ resolves into not only spin-1, but also spin-3 and higher and that one expects a $3^{--}(^3D_3)$ roughly degenerate with the $^3D_1$. If we look across the remaining lattice irreps we see states which appear to make up the full $^3D_{J=1,2,3}$ family. Close study of the overlap factors for states in different irreps add support to the spin identification made in the figure, we refer the reader to [7] for details of this powerful method. Since considerable success in spin assignment has arisen from use of these operators, we will continue to use them in what follows.

Since these results are on quenched lattices we do not expect to be able to trust the precision of the spectrum extracted. Nevertheless we are now confident that we have a sound technique for extracting spectral information from two-point correlators.

The derivative-based operators have been implemented also as sequential sources into Chroma allowing computation of three-point functions with these operators at the sink. We show in figure 6, three-point correlators for a pseudoscalar-pseudoscalar vector-current transition with a smeared $\bar{\psi}\gamma_5\psi$ source and a range of sink operators. The time-dependence of the ground state - ground state transition has been divided out so that there can be a plateau in the middle of the lattice if this transition dominates. It appears that the correlators agree, but have differing degrees of excited-state contamination which we intend to utilise to determine excited-state transitions taking advantage of the precise spectral information gleaned from the two-point function analysis. The need to include multiple excited-states in this analysis is indicated by the results of the two-point function analysis shown in figure 7 where the contribution of each state to a given correlator is shown.

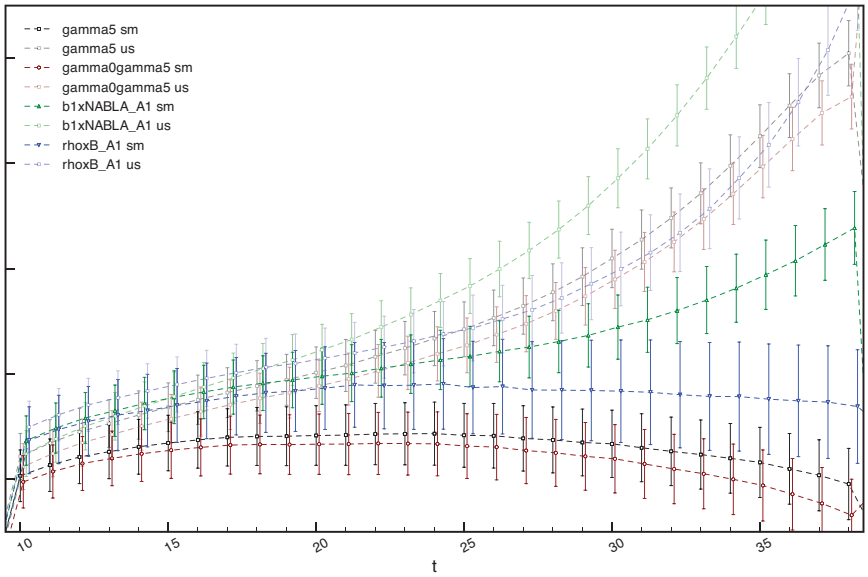


FIG. 6: Pseudoscalar-pseudoscalar three-point function with vector current insertion. Range of sink operators shown. The differences, combined with accurate knowledge of the overlaps and masses from the two-point functions is a strong lever in extraction of excited state transitions.

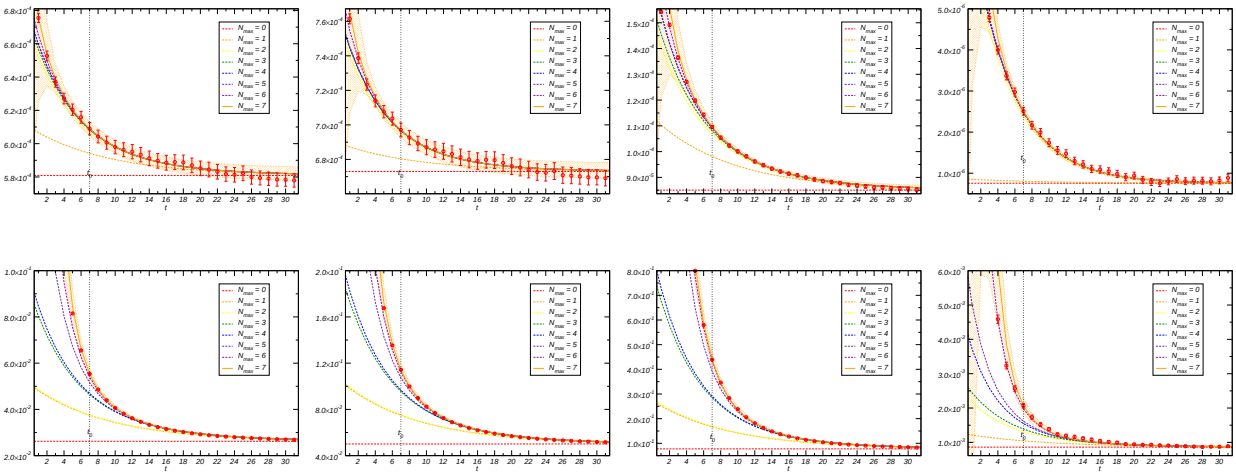

FIG. 7: Diagonal two-point correlators and variational solution reconstructions (ground state exponential divided out) for $A_1^{-+}$ irrep. Left to right operators are $\gamma^5$, $\gamma^0\gamma^5$, $b_1 \times \nabla_{A_1}$, $\rho \times B_{A_1}$. Upper row smeared, lower row unsmeared. Cumulative state contributions are shown by the dashed lines.

Analysis of these quenched three-point correlators is underway and will determine the degree of statistical precision we can expect for excited state transitions.

### B. This proposal

In this proposal we intend to work on the dynamical anisotropic clover gauge fields produced by the proposal of Edwards et al. In table I we present the computations we propose to perform on these

lattices.

| lat. | charmonium | light meson | $D$-meson |
|---|---|---|---|
| $N_F = 3$, $m_\pi = 880$ MeV, $16^3 \times 128$ | - | spectr. & rad. trans | - |
| $N_F = 2+1$, $m_\pi = 580$ MeV, $16^3 \times 128$ | spectr. & rad. trans. | spectr. | spectr. |
| $N_F = 2+1$, $m_\pi = 315$ MeV, $20^3 \times 128$ | spectr. & rad. trans. | spectr. | spectr. |

TABLE I: Computation array. "spectr." indicates a calculation of the meson spectrum using derivative operators. "rad. trans." indicates a computation of all relevant radiative transitions as detailed in the text.

In support of GlueX we will compute the spectrum and radiative transitions between light mesons using the same action for valence quarks as was used in the dynamical generation. Initially we will work with valence quarks at close to the strange quark mass - as shown in figure 8, previous lattice studies appear to indicate that in this mass region, the exotic $1^{-+}$ state is lighter than the $\pi b_1$ $S$-wave multihadron state. This is a benchmark calculation that will determine if extraction of light-meson radiative transitions is feasible under rather favourable conditions.[1]

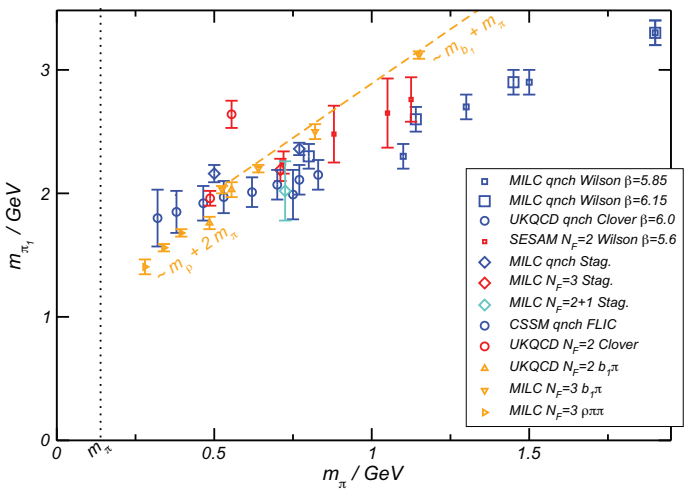


FIG. 8: Lightest $1^{-+}$ state as a function of pion mass from various lattice QCD calculations using assorted actions. Finer lattices are denoted by larger symbols. Also shown is a crude estimate of the nearest $S$-wave threshold mass $m_\pi + m_{b_1}$ extracted from similar lattice simulations

In order to determine what chance future radiative transition calculations have of succeeding at light quark masses we will survey the meson spectrum using our derivative-based operator set at pion masses near 580 and 315 MeV. From this we will have an idea of which mesons have become decaying resonances and to what extent we will need methods dealing with this in the short term. The spectrum for $I = 1$ mesons, kaons and $s\bar{s}$ will be computed (without disconnected contributions).

More complete calculations using interpolating fields with large anticipated overlap onto multi-meson states will follow in future proposals - these will likely require stochastic technology which is under development within USQCD proposals.

Using charm-mass clover valence (see [7] for more details of the action) on lattices with pion masses 580 and 315 MeV we will compute the spectrum and all relevant radiative transitions below $D\bar{D}$ thresholds. The positions of these thresholds will be determined from an extraction of the $D$-meson spectrum that will follow from our computation of both charm and light-quark propagators on

[1] We use the $N_F = 3$ lattice initially to avoid the possibility of a $KK_1$ $S$-wave state being lighter than the strange-valence exotic state

the same lattices. The extraction of excited states above $D\bar{D}$ threshold is naturally complicated by the presence of discrete di-meson energy levels. The quasi-local operators we propose using will likely have limited overlap on these and again future proposals will need to consider multi-meson operators[2].

It looks unlikely that $a_s = 0.1\,\text{fm}$ or finer lattices will become available during the proposal period, so estimation of the scaling dependence will have to wait until future proposals. We refer the reader to the previous section for discussion of improvement designed to reduce the scaling.

Note that in the radiative transition computations we will only compute vector current insertions on the connected propagator lines and not any effects due to disconnected loops.

As well as the personnel listed as investigators on this page, JLab has expectations to hire a postdoc for FY09 who will work mainly on this project.

## II. COMPUTATION, SOFTWARE & RESOURCES

Since last year's proposal we have found methods which we believe can remove much of the non-propagator time from our computations. However we were somewhat optimistic about the number of propagators required to compute all the radiative transitions of interest and in fact we need more than previously suggested.

We have determined that with 70 propagators (10 forward and 60 backward from sequential sources) we can compute

$$\eta_c \leftrightarrow \psi^{(N)},\ \chi_{c0,1} \leftrightarrow \psi^{(N)},\ J/\psi \leftrightarrow \chi_{c2}^{(N)},\ J/\psi \leftrightarrow \eta_c^{(N)} \tag{1}$$

plus transitions between the conventional mesons and the exotic $J^{PC}$ states, although these may be difficult to extract owing to di-meson states being lightest in these channels. The superscript $(N)$ indicates that we should be able to extract transitions involving excited states of this $J^{PC}$. The analogous set in the light meson sector can be computed with the same number of propagators. Depending upon the results of these runs it may prove possible in future to use fewer backward propagators.

For the light quark spectral investigations we will limit ourselves to 4 forward propagators for each of valence light and strange quarks. Here we are giving up on rotational redundancy and equating propagator contractions that are body rotations of each other. This can be done if we are only computing two-point functions, but is not so easily achieved for three-point functions computed using sequential-sources.

Propagator inversion times are based upon estimates outlined in the proposal of Edwards et al. There are time overheads associated with constructing sources, sequential sources and performing propagator contractions. We have estimated these on the basis of work done on quenched lattices including a number of improvements to speed them up.

Table II lists our computing requirements.

| lat. | charmonium | | light meson | | | $D$-meson |
|---|---|---|---|---|---|---|
| | prop. time *(cfgs)* | overhead | light prop. time *(cfgs)* | strange prop. time | overhead | overhead |
| $m_\pi = 880$ MeV, $16^3 \times 128$ | - | - | - | 325K *(1000)* | 62K | - |
| $m_\pi = 580$ MeV, $16^3 \times 128$ | 35K *(1000)* | 62K | 74K *(2000)* | 47K | 36K | 24K |
| $m_\pi = 315$ MeV, $20^3 \times 128$ | 70K *(1000)* | 124K | 390K *(2000)* | 92K | 72K | 72K |

TABLE II: Computing time requirements. Units are 6n proc-hours.

[2] A Lüscher-style analysis of the $\chi'_{c0}$ as a resonance in $D\bar{D}$ would be possible on a $20^3$ lattice with $a_s = 0.12\,\text{fm}$ and a reasonably light pion mass if mass shifts on the scale of 30 MeV could be resolved. This is of the order of 1% on an excited state mass which is the level of statistical precision attained in [7]

Our quenched studies indicate that 1000 configurations is a reasonable scale of statistics in charmonium where we were able to extract 1% statistical precision on excited state masses. If the dynamical lattices prove to provide signals that are more noisy, we may be able to utilise multiple sources spread over the long (for charmonium) time-extent of the lattice. This needs to be investigated to ensure that it does not interefere with the extraction of excited state transitions from sub-leading time-dependence.

For the light-quark spectrum studies we will use 2000 configurations in an attempt to overcome the inevitable reduction in signal-to-noise.

At the lightest mass where propagator construction is most expensive we will save the propagators. They will be of use in future radiative transition computations. Note that we will carefully tune the smearing used in the derivative-based sources for these propagators to minimise noise on meson correlators, in particular the exotic meson correlators. Although this may limit their usefulness in other projects where rather different smearing may be required, we are happy to release them to any project not computing the excited state meson spectrum (until our results are published).

The grand total for all the above is roughly 1.5M 6n-proc-hours which we request on the JLab cluster for rapid file I/O. Chroma will be used throughout.

We require storage space for two-point correlator data, three-point correlator data and, for the lightest pion mass, the propagators. We estimate a tape requirement of 7.6 Tb for two-point data, 15 Tb for three-point data and 2.1 Tb for propagators - a total of 24.7 Tb ($\approx$ 100K 6n-equiv. node-hours). Immediate access disk space of 5 Tb is required ($\approx$ 100K 6n-equiv. node-hours). We are currently using storage space at JLab on tape and disk for quenched data sets which we hope to have freed up very early in the proposal time.

Should additional resources become available we would look to consider the spectrum at the lightest quark mass on the planned, larger $24^3$ volume, and would, if the spectrum data indicated it feasible, consider computing radiative transitions on the 580 MeV pion mass lattice.

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