Golden Probe of the di-ϒ Threshold

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Recent studies indicate that the ground state of a QCD four bottom quark system may form a resonance in the range $\sim 18 - 19$ GeV, near the di-ϒ threshold, which may be observable at the LHC in the four lepton final state. These studies also predict a variety of possible resonances associated with the various excited states and allow for a number of possible spin and CP quantum numbers. Of course, even if a resonance is observed in four leptons in the predicted mass range, it will be prudent to experimentally confirm its four bottom quark QCD nature or whether it is perhaps something more exotic. We initiate an investigation in this direction by exploring the ability of the normalized fully differential decay width for decays to four leptons to probe the underlying nature of a putative resonance including CP and tensor properties. We assume the first observed state is a spin-0 boson decaying to at least one on-shell ϒ, but allow for decays to four leptons through ϒϒ, $\Upsilon \gamma$, and $\Upsilon Z$ boson pairs. We consider a range of resonance masses around the di-ϒ threshold and find excellent prospects at the LHC for establishing its CP and tensor properties, perhaps not long after a discovery depending on (unknown) production cross sections and the exact resonance mass.

INTRODUCTION

Recent studies indicate \cite{10} that a QCD bound state composed of four bottom quarks, a so-called ‘beauty-full’ tetraquark \cite{6}, may be observable as a resonance at the LHC in the mass range $\sim 18 - 19$ GeV.\footnote{Tantalizingly, a recent (not yet approved) CMS analysis \cite{14} hints at a potential four lepton excess just in this mass range.} In particular it has been pointed out that decays to an on-shell ϒ and a pair of leptons with ϒ also decaying to leptons allows for the possibility of a striking signal at the LHC in the invariant mass distribution of $\Upsilon (1S) \ell^+ \ell^-$ events ($\ell = e, \mu$). These studies predict a plethora of bound states around, but just below, the di-ϒ $\Upsilon / \eta_b$ thresholds \cite{3}, thus implying a bottom tetraquark bound state. This includes bound states of spin 0, 1, or 2 carrying different combinations of CP quantum numbers, potentially including admixtures. While progress on computing the ground state energy of a tetraquark bound state (or effective mass) has been made, studies of their decays are still in the preliminary \cite{11} stages.\footnote{We comment that the authors in \cite{13} studied 4b tetraquark bound states and found it would not have a narrow width.} These studies of potential tetraquark systems are based on theoretical calculations utilizing various sum rules or \textit{ad hoc} bound state potentials to compute the 4b ground state. Generically these calculations have found the ground state to lie below the di-ϒ threshold. However, recent lattice QCD calculations based on first principles \cite{12} indicate that no 4b bound state is expected below the di-ϒ threshold. Instead the ground state is found to be on threshold, implying a di-meson system and not a tetraquark bound state. Regardless, whether a putative 4b resonance appears above or below the di-ϒ threshold there is the possibility for a striking four lepton signal which could be observable at the LHC.

The fact that a potentially narrow resonance\cite{3} can be observed in the precisely measured four lepton channel offers a unique opportunity to study its detailed properties utilizing the differential spectra of the many observables in the final state. Furthermore, even if a resonance is observed in four leptons in the predicted mass range, it will be prudent to experimentally confirm its four bottom quark QCD nature or whether it is perhaps something more exotic. We initiate an investigation\cite{7} of this possibility assuming at least one on-shell ϒ, but making minimal assumptions of how the effective couplings to $\Upsilon \ell^+ \ell^-$ are generated since these couplings can depend on both perturbative and non-perturbative effects \cite{9} as well as in principle beyond the SM (BSM) physics.

To this end we utilize a generic effective theory framework to analyze these (potential) tetraquark decays. In particular, we explore the possibility that the ‘off-shell’ lepton pair can come from either an $\Upsilon$, $Z$, or $\gamma$ boson. While in the SM we expect the $\Upsilon$ contribution to dominate \cite{6} \cite{10}, we examine whether the fully differential decay width for decays to four leptons can be used to establish this directly. Should the $\gamma$ or $Z$ be found to dominate or contribute significantly, it would be a tantalizing hint that perhaps this is not a SM QCD state and instead something more exotic. As part of this analysis we explore the possibility of probing the CP and tensor properties. We also briefly discuss various potential CP violating effects which, should a resonance be discovered, would be interesting to investigate further.

For this simplified study we assume the first observed

\footnote{Recently the authors in \cite{10} also examined the 4$\ell$ channel as well as discussed potential production mechanisms of a putative 4b bound state decaying through an intermediate $\Upsilon \Upsilon^*$ pair.}
resonance is a spin-0 scalar allowing for various CP and tensor structures in its couplings to \(\Upsilon\Upsilon, \Upsilon Z, \Upsilon \gamma\) pairs. We utilize the matrix element method (MEM) analysis framework developed in [14, 20] for scalar decays to four leptons which includes the tree level \(q\bar{q} \to 4\ell\) \((4\ell \equiv 2e2\mu, 4e, 4\mu)\) background. Motivated by the exciting possibility of a tetraquark bound state, we emphasize in our analysis a spin-0 resonance \(\sim 500\text{ MeV below}\) the di-\(\Upsilon\) threshold, but also examine resonance masses just below, at, and above the di-\(\Upsilon\) threshold.

We perform various hypothesis tests to examine the ability to directly establish the nature of the putative resonance including its CP and tensor properties. We find excellent prospects once \(\mathcal{O}(10 - 100)\) signal events have been observed at the LHC which may in principle be possible not long after discovery depending on (unknown) production cross sections and the exact mass of the putative resonance. We leave a study of spin-1 and known) production cross sections and the exact mass of the putative resonance. To gain intuition for the discriminating power to model the decays to four leptons of a putative scalar resonance including its ability to directly establish the nature of the putative resonance, we emphasize relative to \(\Upsilon\) by the required spin flip of the scalar mesons and subsequent decay into leptons are suppressed relative to \(\Upsilon\) by the required spin flip of the b-quark [1] as well as the negligible branching ratio into leptons [23]. We therefore neglect these contributions to the dilepton spectrum. We have also neglected contributions from the \(\Upsilon(2S)\) and \(\Upsilon(3S)\) excited states. However, including these various contributions may be necessary once many four lepton events have been collected.

Approximating electrons and muons to be massless we can write the tensor structure of a spin-0 particle which couples to two conserved lepton (pair) currents as,

\[
\Gamma_0^{\mu\nu} = C_1 g^{\mu\nu} + C_2 k_1^\mu k_2^\nu + C_3 \epsilon^{\mu\nu\alpha\beta} k_1^\alpha k_2^\beta, \quad (1)
\]

where the \(C_n\) are complex momentum dependent form factors which generically can contain multiple poles. Since an on-shell \(\Upsilon\) is required in each event, it always makes up one of the poles.

The invariant mass of the second lepton pair can be above or below the \(\Upsilon\) mass and there may be sizable contributions from off-shell photons especially at low dilepton invariant mass near the photon pole. There is in principle also an (highly) off-shell \(Z\) contribution which is expected to be suppressed by the large \(Z\) boson mass as compared to four lepton invariant mass. However, for something more exotic than a SM QCD state, these \(Z\) and \(\gamma\) contributions could in principle be enhanced by BSM effects. Thus for our study we assume the decay topology for the spin-0 resonance decaying to four leptons to be \(\varphi \to \Upsilon(1S)V \to 4\ell\) \((V = \Upsilon, Z, \gamma)\) and parametrize the \(\varphi\Upsilon V\) couplings with effective operators imposing only Lorentz and electromagnetic gauge invariance.

At dimension three this gives the ‘mass operators’ involving \(\Upsilon\Upsilon\) and \(\Upsilon Z\) vector boson pairs,

\[
\mathcal{L}_M \supset m_\varphi (A_1^{\Upsilon\Upsilon} \Upsilon^\mu \Upsilon_\mu + A_1^{\Upsilon Z} \Upsilon^\mu Z_\mu), \quad (2)
\]

where \(m_\varphi \equiv M_{4\ell}\) is the putative resonance mass and equivalent to the four lepton invariant mass assuming an on-shell \(\varphi\) decay. The form factors \(A_i\) can in principle be complex, but this will not affect our analysis below and we now neglect any momentum dependence. The momentum dependence of these form factors may be relevant, but this requires an analysis of both perturbative and non-perturbative effects which is beyond the scope of this study and left to future work.

Allowing for operators up to dimension five, including both \(CP\) odd and \(CP\) even, we consider the set,

\[
\mathcal{L}_{\Upsilon\Upsilon} \supset \frac{\varphi}{m_\varphi} (A_2^{\Upsilon\Upsilon} \Upsilon^\mu \Upsilon_\mu + A_3^{\Upsilon\Upsilon} \Upsilon^\mu \tilde{T}^{\mu\nu}),
\mathcal{L}_{\Upsilon Z} \supset \frac{\varphi}{m_\varphi} (A_2^{\Upsilon Z} \Upsilon^\mu Z_\mu + A_3^{\Upsilon Z} \Upsilon_\mu \tilde{Z}^{\mu\nu}),
\mathcal{L}_{\Upsilon \gamma} \supset \frac{\varphi}{m_\varphi} (A_2^{\Upsilon \gamma} \Upsilon^\mu F^{\mu\nu} + A_3^{\Upsilon \gamma} \Upsilon_\mu F^{\mu\nu}), \quad (3)
\]

where again we neglect any momentum dependence. While this list is not exhaustive, including the additional operators does not qualitatively affect our analysis or change our general conclusions. Note that the \(Z\) boson contribution effectively generates dimension five contact operators (e.g. \(\varphi \Upsilon^\mu \ell^- \ell^\nu\ell^\mu\)) though a more general analysis would include these separately. Thus our main assumption is that the operators in Eq. (2) and Eq. (3) capture the relevant momentum structure and poles.

We have implicitly assumed an expansion in \(m_\varphi^{-1}\) is valid, but since our analysis uses only shape decay information to conduct simple hypothesis tests, our results are independent of any normalization assumed. This also mitigates any dependence on non-perturbative QCD ef-
fects which might affect the overall normalization. The presence of additional poles appearing in the $A_n$ form factors due to either non perturbative or beyond the SM effects could invalidate this expansion as well as generate a complex phase. Though we do not examine this possibility here since our analysis is independent of whether they are complex, we will discuss it briefly below.

To model the $\Upsilon$ decays to leptons we follow closely the analysis of [24]. Assuming only SM contributions, we parameterize the $\Upsilon$ couplings to leptons as,

$$\mathcal{L} \supset \left( \frac{f_T}{m_\Upsilon} A_{\Upsilon}^{SM} \right) \Upsilon^\mu \ell_\mu \ell^\nu,$$

(4)

where $A_{\Upsilon}^{SM}$ is a dimensionless parameter which depends on both perturbative effects, and on non-perturbative meson-to-vacuum matrix elements. Since we are assuming only the SM in the $\Upsilon \to 2\ell$ decay we have [25] at leading order $A_{\Upsilon}^{SM} \approx -4\alpha \alpha Q_h$. There are small corrections [24] to this from various effects, but they can be safely neglected for our purposes. The form factor $f_T$ parameterizes the vacuum to meson transition amplitude and must be determined by measurements or lattice calculations. For purposes of the present study we simply treat the separate form factors as one effective coupling $g_T \equiv (f_T A_{\Upsilon}^{SM} / m_\Upsilon)$ in Eq. (4). We approximate $g_T$ numerically from the measured branching ratio of $\Upsilon$ decaying into muons ($\approx 2.5\%$) which gives $|g_T| \approx 0.00232$ assuming $m_\Upsilon = 9.46$ GeV and $\Gamma_\Upsilon = 54 \times 10^{-6}$ GeV [23]. Similarly to the $Z$ boson, the propagation of the intermediate $\Upsilon$s is modeled with a spin-1 massive vector boson propagator of the form,

$$\mathcal{P}_\Upsilon^{\mu\nu} \sim \frac{g_{\mu\nu} - k_\mu k_\nu/m_\Upsilon^2 + i m_\Upsilon \Gamma_\Upsilon}{k^2 - m_\Upsilon^2 + i m_\Upsilon \Gamma_\Upsilon},$$

(5)

where the $k_\mu k_\nu$ term drops out when dotted into the conserved currents associated with each pair of the final state (massless) charged leptons.

Fully differential decay width and integrated magnitudes

The basis for our analysis will be the $\varphi \to 4\ell$ fully differential decay width analytically computed and validated in [14, 15, 26] for Higgs decays, but adapted here to include an intermediate $\Upsilon$. All interference effects are computed including those from identical final state interference in the case of the $4\mu, 4e$ final state as well as interference between the operators in Eq. (2) and Eq. (3) though they will not be relevant for our results below.

The fully differential decay width for $\varphi \to 4\ell$ can be written as a sum over terms quadratic in the couplings which we can write schematically as,

$$\frac{d\Gamma_{\varphi \to 4\ell}}{dP} \sim \sum A_n^{ij} A_m^{ij*} \times \frac{d\Gamma_n^{ij}}{dP},$$

(6)

where the sum is over $n,m = 1,2,3$ and $i,j = \Upsilon\gamma, \Upsilon Z, \Upsilon \gamma$ (note $A_1^{\Upsilon \gamma} = 0$) and we have neglected any momentum dependence in the couplings as discussed above. Here $dP$ represents the differential volume element, or phase space. In the four lepton center of mass frame this can be parametrized in terms of two invariant masses formed out of the four vectors of the di-lepton pairs as well as five angular variables [15, 16].

In order to gain intuition on the potential to discriminate between the operators in Eq. (2) and Eq. (3) it is useful to examine what we call the integrated magnitudes [17] for each term in the sum of Eq. (6),

$$\Pi_{nm}^{ij} = \int \left| \frac{d\Gamma_{nm}^{ij}}{dP} \right| dP,$$

(7)

where the $\Pi_{nm}^{ij}$ are positive definite even in the case of CP violation. These integrated magnitudes contain information not only about the total phase space contribution of each combination of operators, but also about the differences in shape of the differential spectra. It is for this reason that one can have non-zero values even for combinations of operators which lead to CP violation.

We show in Fig. 1 the $\Pi_{nm}^{ij}$ for the $2e2\mu$ final state (with similar analysis for $4e, 4\mu$) assuming a resonance mass of $m_\varphi = 18.4$ GeV which corresponds approximately to the lightest predicted mass in [5]. We have also imposed cuts on the dilepton invariant mass as well as lepton transverse momentum and rapidity of $M_{ll} > 0.1$ GeV, $p_{Tl} > 2$ GeV, and $y_l < 2.4$ while normalizing to the $|A_1^{\Upsilon \gamma}|^2$ term, thus giving one for that entry. We see by examining the diagonal terms that the largest integrated magnitudes are for the $\Upsilon \gamma$ operators. This is due to a combination of the fact that in these cases both gauge bosons are kinematically allowed to be close to on-shell, as well as the larger coupling of photons to leptons relative to the $Z$ and $\Upsilon$. The next largest contributions come from the $|A_1^{\Upsilon Z}|^2$ term where the second $\Upsilon$ is kinematically restricted to be off-shell by around 500 MeV which is much larger than the $\Upsilon$ width.

As expected due to the large $Z$ boson mass, operators involving the $Z$ boson are very suppressed relative to the others. Thus any observable effects due to these operators would require extremely large couplings in comparison to $A_1^{\Upsilon \gamma}$ and $A_1^{Z\gamma}$. However, since we seek to be as agnostic as possible about any potential resonance and so little is known a priori about the possible form factors, we include them in our analysis. Furthermore, since we are not using rate information in the pure hypothesis tests conducted below, we can use only shape information to disfavor one operator for another independently of the size of the couplings. Of course the ultimate sensitivity

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4 We thank Ciaran Hughes for pointing this out.
and precision with which the form factors can be measured will depend on their numerical value (and potential momentum dependence). We also see that interference effects, especially in the case of \( \Upsilon \Upsilon \) and \( \Upsilon \gamma \) operators can be relevant and opens the possibility of using parameter extraction methods \[14, 15, 26\] to directly measure \( C_1 \). With strong phases present in the operators as well as \( \Upsilon \) and \( \Upsilon \gamma \) ‘diagonal’ terms in Eq. (6) with \( A_{ij}^2 \) defined above and in Fig. 1. We show distributions for the \( |A_{1}^{YY}|^2 \) (black), \( |A_{2}^{YY}|^2 \) (blue), \( |A_{3}^{YY}|^2 \) (turquoise), \( |A_{4}^{YY}|^2 \) (red), \( |A_{5}^{ZZ}|^2 \) (gold), and \( |A_{6}^{YY}|^2 \) (green) ‘diagonal’ terms in Eq. (6). There is also a polar angle for the lepton coming from the on-shell \( \Upsilon \) decay which has a very similar distribution to \( \theta_{\ell \ell} \) and also aids in discrimination. From these distributions it is clear that the differential spectra contain information about the pole structure of the operators as well as the \( CP \) and tensor properties.

Of course the fully differential decay width used in our MEM analysis contains more information than these projections and includes all correlations. Furthermore, utilizing all decay variables aids in discrimination against backgrounds regardless of if they help in signal discrimination. Strong momentum effects in the \( A_{ij}^2 \) form factors may distort these spectra, but unless there are additional poles they should not drastically change the overall shape of these distributions, particularly the angular ones.

**Opportunities for \( CP \) violation**

Here we briefly discuss some of the potential sources of \( CP \) violation which might be present in these decays. The possibility of additional poles entering in the form factors \( A_{ij}^2 \) and generating an imaginary component which can act as a ‘strong phase’ allows for additional sources of \( CP \) violation apart from those due to interference between \( CP \) even and \( CP \) odd operators in Eq. (6) with real coefficients. With strong phases present in the \( A_{ij}^2 \) form fac-
and Eq. (3) on how close the resonance mass is to the di-$\Upsilon$ threshold and whether it is above or below. Here we present results of our MEM analysis to assess the ability of the four lepton channel to probe the nature of a resonance around the di-$\Upsilon$ threshold. In particular we examine the sensitivity for distinguishing the different operators in Eq. (2) and Eq. (3) in order to establish its CP and tensor properties. Details of our analysis procedure based on utilizing the normalized fully differential $\varphi \to 4\ell$ decay width to construct the likelihood can be found in [15, 19, 31–33]. To generate events we have implemented the tensor structures in Eq. (2) and Eq. (3) into the Feynrules/Madgraph framework [34, 35].

Motivated by the interesting possibility of a bottom tetraquark bound state [1–9], for most of our MEM analysis we take the resonance mass to be $m_\varphi = 18.4$ GeV corresponding approximately to the lightest predicted mass in [7] and assume experimental cuts [22], including requiring an on-shell $\Upsilon$ mass, should greatly reduce the four lepton background. We therefore simply float the background fraction [15, 16] and assume during event generation that it is $\sim 50\%$ at the resonance mass.

We then perform a simplified study to assess how the ability to distinguish between the operators in Eq. (2) and Eq. (3) depends on how close the resonance mass is to the di-$\Upsilon$ threshold and whether it is above or below.

### Hypothesis testing

We use the hypothesis testing techniques developed in [38] and utilized in [19, 31, 33] to construct a test statistic that measures the separation power between pairs of operators in Eq. (2) and Eq. (3). We do this by constructing the ratio between two likelihoods assuming only one of the operators dominates at a time in each likelihood. Pseudoexperiments are then conducted to obtain a distribution of these likelihood ratios. This is first done assuming one operator as the ‘true’ hypothesis and then repeated assuming the second operator corre-
sponds to the true hypothesis. In each case, a distribution of likelihood ratios is obtained after conducting a large set of pseudoexperiments. The overlap (or lack thereof) between these two distributions can then be converted into a measure of the ability to discriminate between the two models. We follow closely the procedure in [31], but present our results in terms of \( p \)-values instead of \( \sigma \).

**Probing a beautiful tetraquark**

Motivated by the possible existence [11] of a four bottom quark bound state at \( m_\varphi = 18.4 \) GeV, we show in Fig. 4 the probability of mistaking the \( A_1^{\Upsilon \Upsilon} \) operator for \( A_2^{\Upsilon \Upsilon} \) (black), \( A_3^{\Upsilon \Upsilon} \) (blue), \( A_1^{\Upsilon Z} \) (red), \( A_2^{\Upsilon Z} \) (turquoise), \( A_3^{\Upsilon Z} \) (forest green), \( A_3^{\Upsilon \gamma} \) (dark green), \( A_3^{\Upsilon \gamma} \) (pink) or *vice versa* as a function of the number of four lepton signal events for the operators defined in Eq. 2 and Eq. 3. We see that \( \varphi \rightarrow \Upsilon \ell^+ \ell^- \rightarrow 4\ell \) decays should be able to discriminate at \( \sim 95\% \) confidence between the \( A_1^{\Upsilon \Upsilon} \) operator and the other possibilities with as few as 10 events in the case of \( A_3^{\Upsilon \gamma} \) while \( \sim 150 \) signal events will be needed to distinguish it from \( A_3^{\Upsilon \Upsilon} \) which has the same \( CP \) and pole structure. Since there is not a clear prediction for the production cross section, it is difficult to give robust results in terms of luminosity. However, assuming a 4b tetraquark and a gluon initiated process, the results from [10] estimate a \( \varphi \rightarrow 4\ell \) production cross section of \( O(1) \) fb\(^{-1} \) at a 13 TeV LHC. In this case our results indicate that \( O(10–150) \) fb\(^{-1} \) of luminosity would be needed to probe its bottom tetraquark nature which may be achievable perhaps not long after a discovery.

**Sensitivity around the di-\( \Upsilon \)-threshold**

We also examine how the ability to distinguish between the operators in Eq. 2 and Eq. 3 depends on how close to the di-\( \Upsilon \)-threshold the resonance mass is. For this we again perform hypothesis tests for a range of resonance masses around the di-\( \Upsilon \)-threshold. In Fig. 5 we show the number of four lepton signal events needed to distinguish the \( A_1^{\Upsilon \Upsilon} \) operator from \( A_2^{\Upsilon \Upsilon} \) (black), \( A_3^{\Upsilon \Upsilon} \) (blue), \( A_1^{\Upsilon Z} \) (red), \( A_2^{\Upsilon Z} \) (turquoise), \( A_3^{\Upsilon Z} \) (forest green), \( A_3^{\Upsilon \gamma} \) (dark green), \( A_3^{\Upsilon \gamma} \) (pink) or *vice versa* with 95\% confidence *versus* the four lepton resonance mass. The points correspond to the values for the resonance mass of \( m_\varphi = 18.4, 18.8, 18.9, 18.92 \) (threshold), 18.94, 19.0, 19.3 GeV. In this case we have neglected backgrounds and assumed 5 signal events for the \( 2e2\mu \) channel and 5 events for \( 4e+4\mu \) channel before combining into one likelihood [32, 33] formed out of the \( \varphi \rightarrow 4\ell \) fully differential decay width.

We see the ability to distinguish between the different operators in Eq. 2 and Eq. 3 depends quite strongly on the exact resonance mass. In general we see that the operator most difficult to distinguish from \( A_1^{\Upsilon \Upsilon} \), is \( A_2^{\Upsilon \Upsilon} \) which has the same \( CP \) and pole structure. Furthermore, we see that the nearer to threshold the more difficult it is to distinguish these two operators. Interestingly, we see that distinguishing between \( A_1^{\Upsilon \Upsilon} \) and the \( CP \) odd \( A_2^{\Upsilon \Upsilon} \) operator is much easier and becomes more so the closer to the di-\( \Upsilon \)-threshold we get. This is due to a combination of the \( \Phi \) distribution (see Fig. 3) as well as the di-lepton invariant mass distribution (\( M_{\ell\ell} \)), which in general is not peaked at the same mass and has a different slope than the \( M_{\ell\ell} \) distribution in \( A_1^{\Upsilon \Upsilon} \) and \( A_2^{\Upsilon \Upsilon} \). In other words, the \( M_{\ell\ell} \) distribution also contains information about the \( CP \) properties of the \( \varphi \Upsilon \) distribution (see Fig. 2) which of course has also been noted in SM-like Higgs boson decays to four leptons [39]. In general we see that, depending on the nature and mass of a putative resonance around the di-\( \Upsilon \)-threshold, just a few handful of signal events may be sufficient for deciphering its \( CP \) and tensor properties in the four lepton channel.

The strong dependence on the exact resonance implies that detector resolution effects may play an important role and need to be included for a precise quantification of the sensitivity. While we have not done so for this preliminary study, including these detector effects can be done with the framework developed in [16, 18] which we leave to future work should a four lepton resonance be discovered near the di-\( \Upsilon \)-threshold.
FIG. 5. The probability (in $p$-values) of mistaking the $A_1^{TT}$ operator (as defined in Eq. (2) and Eq. (3)) for $A_2^{TT}$ (black), $A_3^{TT}$ (blue), $A_4^{ZZ}$ (red), $A_5^{ZZ}$ (turquoise), $A_6^{\gamma\gamma}$ (forest green), $A_7^{ZZ}$ (dark green), $A_8^{\gamma\gamma}$ (pink) or vice versa versus four lepton resonance mass. The points correspond to four lepton resonance masses of $m_{\varphi} = 18.4, 18.8, 18.9, 18.92$ (di-$\Upsilon$ threshold), 18.94, 19.0, 19.3 GeV. We have neglected backgrounds and assumed 5 signal events for the $2e2\mu$ channel and 5 events for $4e + 4\mu$ channel before combining into one likelihood $32, 33$ for the $\varphi \to 4\ell$ signal.

Opportunities for parameter extraction

One of our primary assumptions in this analysis is that only one operator from Eq. (2) and Eq. (3) dominates at a time. We have also neglected any momentum dependence in the form factors as well as parton showering and jets. These assumptions of course may not be true in reality and therefore an analysis which can extract multiple form factors simultaneously with possible momentum dependence is also important. Furthermore, as Fig. 1 shows, even if one operator dominates, interference effects may be relevant which would allow us to probe a multitude of effects. As more four lepton events are collected, utilizing multi-parameter fitting methods $15, 16$ to extract the various form factors may become possible and also opens the possibility of probing $CP$ violating effects. However, this requires a more careful examination of backgrounds and detector resolution effects so we leave this to interesting possibilities which can be explored should a four lepton resonance around $\sim 18 - 19$ GeV be observed.

SUMMARY AND CONCLUSIONS

Motivated by recent studies $11, 12$ which indicate that a QCD state composed of four bottom quarks may be present around around the di-$\Upsilon$ threshold in the range $\sim 18 - 19$ GeV and potentially observable in its decays to four leptons, we have explored the possibility of using the normalized fully differential decay width to four leptons to probe its underlying nature and in particular its $CP$ and tensor properties. Further motivated by the exciting possibility of a tetraquark bound state explored in some of these studies $13, 19$, we emphasize in our analysis a spin-0 resonance $\sim 500$ MeV below the di-$\Upsilon$ threshold, but also examine resonance masses just below, at, and above the di-$\Upsilon$ threshold.

Assuming the putative resonance is a spin-0 boson, we have performed a simplified matrix element method analysis based on hypothesis testing and assuming its decays are dominated by one effective operator at a time. We find excellent prospects at the LHC once $\mathcal{O}(10 - 100)$ signal events are collected indicating that perhaps its underlying nature, including $CP$ properties, can be directly probed. This may in principle be possible not long after discovery depending on (unknown) production cross sections and the exact resonance mass. We have also briefly discussed various potential $CP$ violating effects which might be present in these decays, but we leave a study of this as well as spin-1 and spin-2 resonances to ongoing $20$ and future work.

While this study is motivated by possible four bottom quark QCD states near the di-$\Upsilon$ threshold, our analysis methods easily generalize to any potential light scalar, including other multi-quark states, which can decay to four lepton final states at the LHC or other colliders.

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[1] A. V. Berezhnoy, A. V. Luchinsky, and A. A. Novoselov, Phys. Rev. D86, 034004 (2012), 1111.1867.
[2] M.-L. Du, W. Chen, X.-L. Chen, and S.-L. Zhu, Phys. Rev. D87, 014003 (2013), 1209.5134.
[3] H.-X. Chen, W. Chen, X. Liu, T. G. Steele, and S.-L. Zhu, Phys. Rev. Lett. 115, 172001 (2015), 1507.03717.
[4] M. Karliner, S. Nussinov, and J. L. Rosner, Phys. Rev. D95, 034011 (2017), 1611.00348.
[5] W. Chen, H.-X. Chen, X. Liu, T. G. Steele, and S.-L. Zhu, Phys. Rev. B773, 247 (2017), 1605.01647.
[6] Y. Bai, S. Lu, and J. Osborne (2016), 1612.00012.
[7] J. Wu, Y.-R. Liu, K. Chen, X. Liu, and S.-L. Zhu (2016), 1605.01134.
[8] J.-M. Richard, A. Valcarce, and J. Vijande, Phys. Rev. D95, 054019 (2017), 1703.00783.
[9] Z.-G. Wang, Eur. Phys. J. C77, 432 (2017), 1701.04285.
[10] E. Eichten and Z. Liu (2017), 1709.09605.
[11] S. Durgut (2018), Search for Exotic Mesons at CMS: http://meetings.aps.org/Meeting/APR18/Session/U09.6.
[12] C. Hughes, E. Eichten, and C. T. H. Davies, Phys. Rev. D97, 054505 (2018), 1710.03236.
[13] M. N. Anwar, J. Ferretti, F.-K. Guo, E. Santopinto, and B.-S. Zou (2017), 1710.02540.
[14] Y. Chen, N. Tran, and R. Vega-Morales, JHEP 1301, 182 (2013), 1211.1959.
[15] Y. Chen and R. Vega-Morales, JHEP 1404, 057 (2014), 1310.2893.
[16] Y. Chen, E. Di Marco, J. Lykken, M. Spiropulu, R. Vega-Morales, et al., JHEP 1501, 125 (2015), 1401.2077.
[17] Y. Chen, R. Harnik, and R. Vega-Morales, Phys.Rev.Lett. 113, 191801 (2014), 1404.1336.
[18] Y. Chen, E. Di Marco, J. Lykken, M. Spiropulu, R. Vega-Morales, et al. (2014), 1410.4817.
[19] A. Falkowski and R. Vega-Morales, JHEP 12, 037 (2014), 1405.1095.
[20] Y. Chen, R. Harnik, and R. Vega-Morales, JHEP 09, 185 (2015), 1503.05855.
[21] M. Karliner, J. L. Rosner, and T. Skwarnicki (2017), 1711.10626.
[22] V. Khachatryan et al. (CMS), JHEP (2016), 1610.07095.
[23] C. Patrignani et al. (Particle Data Group), Chin. Phys. C40, 10001 (2016).
[24] D. Aloni, A. Efrati, Y. Grossman, and Y. Nir (2017), 1702.07356.
[25] R. Van Royen and V. F. Weisskopf, Nuovo Cim. A50, 617 (1967), [Erratum: Nuovo Cim.A51,583(1967)].
[26] V. Khachatryan et al. (CMS), Phys. Rev. D92, 012004 (2015), 1411.3441.
[27] Y. Chen, A. Falkowski, I. Low, and R. Vega-Morales, Phys.Rev. D90, 113006 (2014), 1405.6723.
[28] G. Li, H.-R. Wang, and S.-h. Zhu (2015), 1506.06453.
[29] X. Chen, G. Li, and X. Wan (2017), 1705.01254.
[30] Q.-H. Cao, C. Jackson, W.-Y. Keung, I. Low, and J. Shu, Phys.Rev. D81, 015010 (2010), 0911.3398.
[31] D. Stolarski and R. Vega-Morales, Phys.Rev. D86, 117504 (2012), 1208.4840.
[32] Y. Chen, D. Stolarski, and R. Vega-Morales, Phys. Rev. D92, 053003 (2015), 1505.01168.
[33] Y. Chen, J. Lykken, M. Spiropulu, D. Stolarski, and R. Vega-Morales, Phys. Rev. Lett. (2016), [Phys. Rev. Lett.117,241801(2016)], 1608.02159.
[34] J. Albwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H. S. Shao, T. Stelzer, P. Torrielli, and M. Zaro, JHEP 07, 079 (2014), 1405.0301.
[35] N. D. Christensen and C. Duhr, Comput. Phys. Commun. 180, 1614 (2009), 0806.4194.
[36] R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, R. Pittau, and P. Torrielli, JHEP 02, 099 (2012), 1110.4738.
[37] B. Biedermann, A. Denner, S. Dittmaier, L. Hofer, and B. Jager, JHEP 01, 033 (2017), 1611.05338.
[38] A. De Rujula, J. Lykken, M. Pierini, C. Rognan, and M. Spiropulu, Phys. Rev. D82, 013003 (2010), 1001.5300.
[39] R. Boughezal, T. J. LeCompte, and F. Petriello (2012), 1208.4311.
[40] Y. Chen, R. Vega-Morales, et al. (2017), Work in progress.