Directly measuring the tensor structure of the scalar coupling to gauge bosons

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Directly Measuring the Tensor Structure of the Scalar Coupling to Gauge Bosons

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Kinematic distributions in the decays of the newly discovered resonance to four leptons can provide a direct measurement of the tensor structure of the particle's couplings to gauge bosons. Even if the particle is shown to be a parity even scalar, measuring this tensor structure is a necessary step in determining if this particle is responsible for giving mass to the Z. We consider a Standard Model like coupling as well as coupling via a dimension five operator to either ZZ or $Z\gamma$. We show that using full kinematic information from each event allows discrimination between renormalizable and higher dimensional coupling to ZZ at the 95% confidence level with $\mathcal{O}(50)$ signal events, and coupling to $Z\gamma$ can be distinguished with as few as 20 signal events. This shows that these measurements can be useful possibly even with this year's LHC data.

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I. INTRODUCTION

The discovery of a new particle at the LHC [1] is a great triumph for particle physics, but it also leads to a host of new questions about the nature of the new state. The question of whether this particle gives mass to the W and Z is of paramount importance. Since the discovery, the theoretical community has begun to weigh in on this question with many different analyses [2, 3]. These analyses show that the new state is broadly consistent with the Standard Model (SM) Higgs, but all of these analyses use only the information obtained from cross sections and branching ratios. While this form of analysis is very useful, it is ultimately a model dependent test of the properties of the new state.

Here we attempt to delve into the signal events themselves and see what information can be learned about the new particle from the kinematic distributions of the final state particles. Specifically, the channel where the new particle decays to four leptons via intermediate gauge bosons [4] contains a tremendous amount of information about the new resonance. It has been shown that this channel can be used to distinguish the parity and spin [5–8] of a new resonance, and that kinematic methods can be used to distinguish signal from background [9]. Previous analyses, however, mostly considered Higgs masses above $2m_Z$, and it has yet to be shown these methods can work for a resonance with a mass as low as the observed value.

Here we take the hypothesis that the new particle is a parity even scalar and try to see if this channel can be used to directly measure the tensor structure of the coupling of this particle to the four lepton final state. If we denote the new scalar by ϕ, it can have the following couplings to ZZ

$$\frac{1}{v}\left(a_h\, m_Z^2\, \phi\, Z_\mu Z^\mu + a_s\, \phi\, Z^{\mu\nu} Z_{\mu\nu} + ...\right) \tag{1}$$

where Z_μ is the Z field while $Z_{\mu\nu} = \partial_\mu Z_\nu - \partial_\nu Z_\mu$. Here $v = 246$ GeV is the SM Higgs vev chosen as normalization, and the ... is for operators of dimension higher than five. If ϕ is the Standard Model Higgs, then $a_h = i$, and the other coupling is loop induced and small.

If the new particle is not the SM Higgs and does not give mass to the Z, then its linear coupling to gauge bosons can proceed via the field strength tensor, $Z_{\mu\nu}$ as in the operator a_s in Eq. (1). There are many such models in the literature, see for example [7, 10] and references therein. The a_s operator is generically loop induced and its coefficient is model dependent. We see this sort of operator even in the SM Higgs' coupling to $\gamma\gamma$ and $Z\gamma$:

$$\frac{1}{v}\Big(a_\gamma\, \phi\, F^{\mu\nu} F_{\mu\nu} + a_{Z\gamma}\, \phi\, Z^{\mu\nu} F_{\mu\nu} + ...\Big) \tag{2}$$

where $F_{\mu\nu}$ is the field strength of the photon. In the SM, a_γ and $a_{Z\gamma}$ are induced by loops. If ϕ is not the Higgs, then a plausible alternative is that it decays to four leptons via a_s or $a_{Z\gamma}$. Generically, a_s, $a_{Z\gamma}$ and a_γ are all present and of comparable size, and all three operators can mediate four lepton final states. The experimental searches [4] require that the invariant mass of the one of the lepton pairs is near the Z pole, so the contribution of a_γ is small, but both a_s and $a_{Z\gamma}$ need to be considered.

If ϕ couples dominantly via a_h, that would be evidence that it is a Higgs. It could still be something more exotic such as a dilation [11] or a radion [12], but the crucial point is that if we are going determine if ϕ gives mass to the Z boson, we must show that its coupling to ZZ^* is dominantly through a_h. As we will show in this paper, the kinematic distributions of the four lepton events can discriminate a_h from a_s and $a_{Z\gamma}$.

This question was briefly considered in [13]; here we do a more thorough analysis including more kinematic variables and studying off-shell Z's. In [7], they use kinematic methods to distinguish two different kinds of parity even scalars, but both give mass to the Z.

The analysis of [2] uses the $\gamma\gamma$, ZZ^*, and WW^* rates, as well as the absence of a large anomaly in continuum $Z\gamma$, to show that the scenario of four lepton decays being due to a_s is strongly disfavored. While this statement has few assumptions, it is still model dependent, and we seek to confirm this exclusion by a direct measurement.

II. FOUR LEPTON EVENTS

The kinematics of four lepton events are described in detail in many places in the literature, see for example [7, 9]. Here we describe only the variables relevant to our analysis. Because we are trying to distinguish different scalar scenarios, information from the production vertex is lost. Therefore, all the kinematic information from the Higgs decay can be parameterized in terms of three types of kinematic variables: (1) Φ – the angle between the decay planes of the two vector bosons in the rest frame of the scalar, (2) θ_i – the angle between the fermion coming from the decay of Z_i and the other Z's momentum in the Z_i rest frame, and (3) M_i – the reconstructed invariant mass of the two vector bosons. We take the convention $M_1 > M_2$, and in most events $M_1 \sim M_Z$. These variables are all independent subject to the constraint $(M_1+M_2) \leq \sqrt{s}$ where s is the invariant mass squared of the four lepton system.

We compute tree level analytic expressions for the full differential decay width. These expressions, at least for the Higgs, can be found in many places in the literature including [9]. NLO and finite mass corrections have been computed in the case of the Higgs [14] and have been shown to be a few per cent. In Fig. 1 we plot representative distributions taking $m_\phi = 125$ GeV here and throughout. We consider the operators a_h, a_s and $a_{Z\gamma}$ turning on one operator at a time with others set to zero.

In general, all three operators, a_h, a_s, and $a_{Z\gamma}$ will be non-zero. In the case of a Higgs-like state which gives mass to the Z, a_s and $a_{Z\gamma}$ are loop suppressed and a_h will dominate. If the new state does not contribute to electroweak symmetry breaking, then a_h will often be negligible. If $a_s \sim a_{Z\gamma}$, which is typically the case if the two operators are generated by loops of electroweak charged matter, then the effects of $a_{Z\gamma}$ will dominate due to the off-shell propoatagor and the Z's suppressed coupling to leptons. Therefore, we can consider turning on just $a_{Z\gamma}$ as a reasonable approximation. On the other hand, one could imagine a model where $a_{Z\gamma}$ is very small, possibly due to tuning, and we therefore consider turning on only a_s as a stand in for this possibility. While this analysis would ideally be able to distinguish general linear combinations of the three operators, we see that in most of the parameter space, one operator will dominate over the other two, which is why we consider scenarios where only one operator is turned on at a time.

Fig. 1 shows some example kinematic distributions, demonstrating the discriminating power of this analysis. The M_2 distribution is a particularly good discriminator because it is different for all three scenarios, especially at small values of M_2. This can be seen from a simple analysis of the derivative structure of the three operators, and this figure shows that the experiments could get enhanced discriminatory power by extending their reach to lower values of M_2.

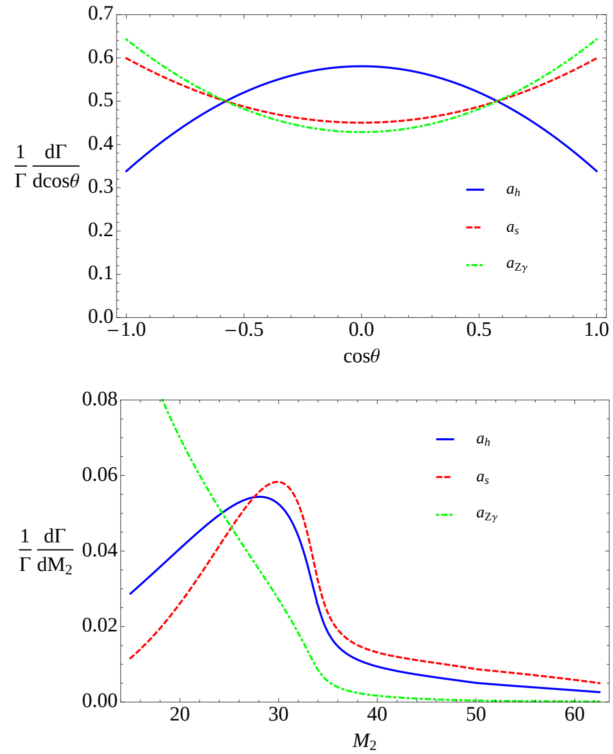

FIG. 1: Normalized distributions for $\cos\theta$ (top) and M_2 (bottom). Each plot shows our three different scenarios with a_h blue (solid), a_s red (dashed), and $a_{Z\gamma}$ green (dot-dashed).

If the four lepton events are dominated by $a_{Z\gamma}$, then there should also be decays to on-shell photons, a powerful channel [15]. While there is as yet no direct limit in this channel, [2] uses the measurement of the $Z\gamma$ cross section to place a limit on the ratio of $Z\gamma$ to four lepton decays to be about 40. Given this, we take the $Z\gamma$ mode to be an unlikely possibility, but we still believe in checking the data to see if it can be directly excluded.

In order to compare to experiment, we generate Monte Carlo (MC) events using the Johns Hopkins MC [6] and Madgraph 5 [16]. We generate $\phi \to 4\ell$ where $\ell = e, \mu$. We require the leptons to have

- $p_T > 10$ GeV
- $|\eta| < 2.5$
- $50\,\text{GeV} < M_1 < 110\,\text{GeV}$
- $M_2 > 15$ GeV,

which roughly mimics the experimental selection criteria in [4]. An example comparison of simulated data to

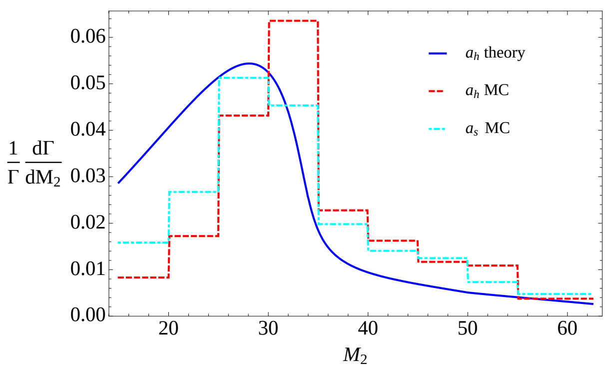

FIG. 2: Normalized M_2 distributions. The blue (solid) curve is the theory prediction in the a_h scenario, while the light blue (dot-dashed) histogram is 1000 Monte Carlo events also in the a_h scenario. The red (dashed) histogram is 1000 events in the a_s scenario.

theory is shown in Fig. 2. Because the experimental resolution for energy and direction of leptons is so precise, we do not apply any smearing to the events.

Comparing the solid curve to the dot-dashed histogram in Fig. 2, we see that the experimental cuts reduce the event rate for small M_2. Even after these cuts, however, the histograms for a_h and a_s still differ, so the experimental cuts do not wash out the discriminating power. We note that the experiments could gain significance if they were able to push down their reach in M_2.

III. DISTINGUISHING OPERATORS

To estimate the ability of the LHC to distinguish a Higgs-like scenario from others, we employ a likelihood analysis. We consider only signal events because this channel has good signal to background ratio in the signal region around 125 GeV. Of course, ideally one would include the background as well in the discriminator since separating the signal from the background is a logically prior question to hypothesis testing. Since the background is dominantly $Z\gamma^*$ at 125 GeV it may be more difficult to obtain a clean signal sample if the new scalar couples dominantly through $a_{Z\gamma}$. More detailed background calculations have been preformed in [17]. Here we assume a clean sample has been achieved through an appropriate method such as the ${}_s\mathit{Plots}$ technique [18] employed in [7].

We follow the statistical analysis described in [6]. We use the computed normalized differential cross section as a probability distribution $P(\Phi, \theta_i, M_i|a_i)$ for each operator a_h, a_s, and $a_{Z\gamma}$. The normalization is computed with the M_i cuts described above because they are independent of Lorentz frame. The computation of P uses the full matrix element taking into account correlations in different kinematic variables.

Given a sample of N events, we construct a likelihood

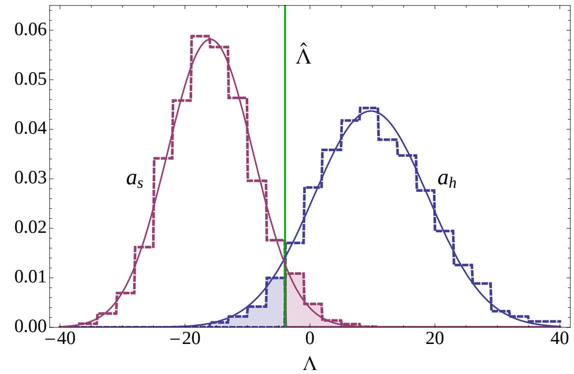

FIG. 3: Normalized distribution of our test statistic Λ when a_h is true on the right (blue), and when a_s is true on the left (pink). Each histogram is the result of 5000 pseudo-experiments with 50 events each. The vertical (green) line is $\hat{\Lambda}$ defined in Eq. (3) such that the area to the right of $\hat{\Lambda}$ under the a_s histogram is equal to the area to the left of $\hat{\Lambda}$ under the a_h histogram. We also draw a Gaussian over each histogram with the same median and standard deviation.

$\mathcal{L}(a_i) = \prod_{j=1}^{N} P_j(a_i)$. With this likelihood we can then compare two different scenarios, a_1 and a_2 by constructing a hypothesis test with test statistic [19] defined by $\Lambda = 2\log[\mathcal{L}(a_1)/\mathcal{L}(a_2)]$. To estimate the expected significance of discriminating between two different hypotheses, we take one hypothesis as true, say a_1 and generate a set of N a_1 events. We then construct Λ for a large number of pseudo-experiments each containing N events in order to obtain a distribution for Λ. We repeat this exercise taking a_2 to be true and obtain a different distribution for Λ. These two distributions are shown in Fig. 3 comparing a_h and a_s.

With the two distributions for Λ in hand we can compute an approximate significance by denoting the distribution with negative mean as f and the distribution with positive mean as g and finding a value $\hat{\Lambda}$ such that

$$\int_{\hat{\Lambda}}^{\infty} f dx = \int_{-\infty}^{\hat{\Lambda}} g dx. \quad (3)$$

We then interpret this probability as a one sided Gaussian p-value, which can be used to compute the number of σ. For a simple hypothesis test, this Gaussian approximation is often sufficient [19].

This procedure is repeated many times for a range of numbers of events N to obtain a significance as a function of N for each hypothesis. We show this for a_h and a_s in Fig. 4. We see that with $\mathcal{O}(50)$ events, we can distinguish a_h from a_s at 95% confidence, and with $\mathcal{O}(100)$ events we can get a 99% exclusion Based on the number of events observed in the signal region presented by the CMS collaboration in [4], we estimate that 50 events can be collected with roughy 60 fb^{-1} of integrated luminosity with $\sqrt{s} = 7$ or 8 TeV, showing that with the combined dataset of CMS and ATLAS, a discrimination may be possible in 2012. The operator $a_{Z\gamma}$ can be distinguished

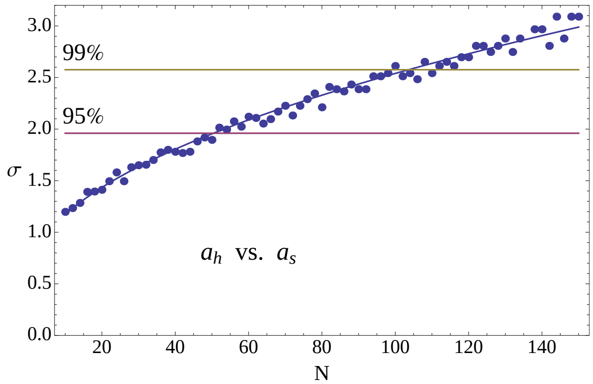

FIG. 4: Expected significance as a function of number of events in the case of a_h vs a_s. We also fit with a function proportional to $\sqrt{N}$, which is the expected scaling. We mark the σ value of 95% and 99% confidence level exclusion.

from a_h at 95% confidence with as few as 20 events, and the same discrimination can be made between a_s and $a_{Z\gamma}$ with just 10 events.

IV. CONCLUSIONS AND OUTLOOK

Testing the properties of the newly discovered resonance is of utmost importance. While the rate and branching ratio data are consistent with the new particle being the SM Higgs, direct tests of its properties are still essential. In this paper we have examined the discriminating power of events where the new particle decays to four leptons. These events can be used to measure the Lorentz transformation properties of this particle, but even if it is confirmed to be a parity even scalar, it still need not be the Higgs.

In this work we have focused on four lepton final states, but it would be interesting to look at kinematic variables in other final states such as WW^*. A search for decay to $Z\gamma$ where the photon is on-shell would give a direct measurement of the $a_{Z\gamma}$ coupling. If this mode is in fact observed, kinematic analysis of final states in that channel could further uncover the nature of the new particle.

Here, we have analyzed how well kinematic distributions in four lepton events can distinguish between different tensor structures of the coupling to gauge bosons. In particular, we looked at coupling directly to $Z_\mu Z^\mu$, as well as couplings to a pair of field strength tensors of the Z, and a coupling to the field strength of the Z and the photon. All three scenarios will produce one lepton pair near the Z pole, while the other pair will have much lower invariant mass. We find that with $\mathcal{O}(50)$ signal events, a Higgs-like state can be discriminated from ZZ field strength tensor couplings with 95% confidence, while only 20 events are needed to make the same determination for field strength coupling to $Z\gamma$. Even fewer events are needed to distinguish the two field strength scenarios from one another. This shows that the 2012 LHC run has excellent prospects to constrain the tensor structure of the new state's coupling to gauge bosons.

Note Added: While completing this paper, we received Refs. [20, 21] which discuss similar ideas.

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