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Angular characterization of the $ZZ \to 4\ell$ background continuum to improve sensitivity of new physics searches

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ABSTRACT

The process $q\bar{q} \to ZZ \to 4\ell$, dominant background for new physics signals in the four-lepton channel, is characterized by a fully transverse polarization of the two Z bosons with respect to the q and $\bar{q}$ directions. We show that the Z decay angular distributions can be described by a simple, analytical function of the event kinematics, not depending on parton distributions. Using the search for a heavy Higgs boson as an example, we show that the angular discrimination improves the sensitivity to rare signals and is especially beneficial when the background contribution is large.

The direct production of pairs of real Z bosons is the dominant Standard Model background for $ZZ \to 4\ell$ signals with masses larger than 200 GeV/c^2. The angular distribution of this process represents a strong topological signature and can be used as a background discriminant. Comprehensive studies on the characterization of hypothetical signals were presented in Refs. [1,2], adopting a Monte Carlo template modelling of the background. A per-event description of the background angular distribution is possible [3,4], but is, in general, computationally more complex than for the signal distributions. In particular, it usually requires the knowledge of parton distribution functions and depends on collision type and energy. In this Letter we show, using basic principles and minimal assumptions, that the $ZZ \to 4\ell$ background distribution can be modelled in a simple, fully analytical and yet universal way, through optimal choices of the quantization axes. We then evaluate the role of this description in setting limits on heavy Higgs boson production.

The $q\bar{q} \to ZZ \to 4\ell$ process is described by five angular degrees of freedom: the Z emission angle in the ZZ rest frame and the two dilepton decay angles in the Z rest frame, for each of the two Z bosons (here denoted by Z_1 and Z_2). Because of helicity conservation (assuming massless fermions), Z bosons produced in the t- or u-channel $q\bar{q} \to ZZ$ processes have always angular momentum projection $J_z = \pm 1$ (full transverse polarization) along the direction of either one or the other of the incoming quarks. The dilepton decay distribution of each Z_i ($i = 1, 2$) can thus be calculated as the superposition of the two distributions $1 + \cos^2 \vartheta^i_q$ and $1 + \cos^2 \vartheta^i_{\bar{q}}$, where ϑ^i_q and $\vartheta^i_{\bar{q}}$ are the angles between the momentum of one lepton and the two quark directions in the Z_i rest frame. We take the average of these two directions as the polarization axis ($\hat{z}_i$) and the plane they form as the reference for the azimuthal coordinate (Collins–Soper frame, CS [5]). In terms of the momenta of the two proton beams, A and B, in the Z_i rest frame, $\vec{P}^i_A$ and $\vec{P}^i_B$, we define the axis vectors as

$$\hat{z}_i = \vec{P}^i_A/\left|\vec{P}^i_A\right| - \vec{P}^i_B/\left|\vec{P}^i_B\right|,$$
$$\hat{y}_i = \vec{P}^i_A \times \vec{P}^i_B/\left|\vec{P}^i_A \times \vec{P}^i_B\right|, \qquad (1)$$

with $\hat{x}_i = \hat{y}_i \times \hat{z}_i$. The quark directions form angles δ_i and $\pi - \delta_i$ with respect to the chosen $\hat{z}_i$ axis, where $\sin^2 \delta_i = p^{i2}_{\mathrm{T}}/(m^2 + p^{i2}_{\mathrm{T}})$, p^i_{T} is the Z_i transverse momentum and m the Z mass. We assume that Z_1 and Z_2 are experimentally distinguished according to criteria not involving rapidity ordering, so that both their rapidity distributions are symmetrical with respect to zero. With these ingredients we obtain the following expression for the observable decay distribution:

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$$w(\cos\vartheta_i, \varphi_i) = \frac{3/(4\pi)}{3+\lambda_\vartheta^i}\left(1 + \lambda_\vartheta^i \cos^2\vartheta_i + \lambda_\varphi^i \sin^2\vartheta_i \cos 2\varphi_i\right), \tag{2}$$

with

$$\lambda_\vartheta^i = \frac{1-\zeta_i}{1+3\zeta_i}, \qquad \lambda_\varphi^i = \frac{\zeta^i}{1+3\zeta_i}, \tag{3}$$

where ϑ_i, φ_i are the polar and azimuthal angles of the lepton emission and $\zeta_i = p_T^{i2}/(2m^2)$. The Z polarization is transverse at low p_T ($\lambda_\vartheta^i = +1$) and changes to partially longitudinal at high p_T ($\lambda_\vartheta^i = -1/3$, with $\lambda_\varphi^i = +1/3$, in the CS frame, corresponding to a transverse polarization along the Z direction itself, in agreement with the distributions shown in Ref. [4]).

We note that no parity-violating terms appear in Eq. (2), because the specific axis choices of Eq. (1) cancel *exactly* any parity-violating effects. In proton–proton collisions such effects would be measurable (with different axes definitions) only at high-rapidity, where the directions of the quark and antiquark can be statistically inferred. Their interpretation, however, would crucially rely on the parton distribution functions.

In obtaining this result we have implicitly assumed a factorization of the dependencies on the angular degrees of freedom of the two dilepton systems and on the Z emission angle. This simplifying assumption is motivated by our choice of the Z polarization axis, defined so as to be directly coupled to the "natural" quantization direction represented by the fermion line, along which helicity is conserved. This definition minimizes possible correlations. Previous studies, using the standard choice of the Z polarization axis in the direction of the ZZ momentum [3], have found, anyhow, rather small correlations [6,4]. The factorized form comes closer to the conditions of experimental analyses of complex angular distributions, where the acceptance as a function of several angular variables is conveniently determined in factorized form.

The advantage of our description with respect to previous calculations is that it is fully contained in a plain analytical formula, explicitly accounting for the kinematic dependence of the dilepton distributions and not depending on type and energy of the colliding hadrons. We must mention that Eq. (2) describes the difermion decay of any vector boson produced in $(t+u)$-channel processes by direct coupling to quarks. For example, the formula reproduces exactly the calculation, for W boson production in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV, presented in Fig. 2a of Ref. [7].

We, therefore, model the complete angular distribution of the process as

$$\mathcal{W}_{q\bar{q}\to ZZ\to 4\ell}(\cos\Theta, \cos\vartheta_1, \varphi_1, \cos\vartheta_2, \varphi_2) = W(\cos\Theta)\, w(\cos\vartheta_1, \varphi_1)\, w(\cos\vartheta_2, \varphi_2), \tag{4}$$

where Θ is the Z emission angle, measured with respect to the direction of $\vec{P}'_A/|\vec{P}'_A| - \vec{P}'_B/|\vec{P}'_B|$, being $\vec{P}'_A$ and $\vec{P}'_B$ the momenta of the beams A and B in the ZZ rest frame. The $\cos\Theta$ distribution reflects the typical $(t+u)$-channel topology, strongly favouring small scattering angles [8]:

$$W(\cos\Theta) \propto \frac{t}{u} + \frac{u}{t} + \frac{4M^2m^2}{ut} - m^4\left(\frac{1}{t^2} + \frac{1}{u^2}\right),$$
$$t, u = -\frac{M^2}{2} + m^2 \pm \frac{M^2}{2}\sqrt{1 - 4\frac{m^2}{M^2}}\cos\Theta, \tag{5}$$

being M the ZZ invariant mass. At $M = 700$ GeV/c^2, for example, half of the continuum Z pairs are emitted with $|\cos\Theta| > 0.97$.

To illustrate the efficacy of our description of the angular distribution, we consider the example of the search for a heavy Higgs boson (H) in pp collisions at $\sqrt{s} = 14$ GeV. We use a simulation based on resummed calculations for the kinematics of the ZZ continuum [9] and of the Higgs boson produced in gg fusion [10], also including the modification of the p_T distribution due to vector-boson-fusion (VBF) contribution [11]. Production cross-sections for ZZ continuum, gg and VBF Higgs production, Higgs boson widths and branching ratios are taken from Refs. [12,13]. We consider the rapidity and mass ranges $|y(ZZ)| < 2.5$ and $[M_H - \sigma_H, M_H + \sigma_H]$, being M_H and σ_H the Higgs pole mass and natural width (e.g., $\sigma_H \simeq 200$ GeV/c^2 for $M_H = 700$ GeV/c^2). The experimental acceptance and efficiency are simulated by imposing selection criteria on transverse momentum ($p_T > 15$ GeV/c) and pseudorapidity ($|\eta| < 2.5$) for each of the four leptons. If M_H is large enough, the Z bosons coming from H decay are pure $J_z = 0$ states [14] and, therefore, the two dilepton distributions are uncorrelated. The Z emission in the H rest frame is isotropic. The full angular distribution of the "signal" events is thus

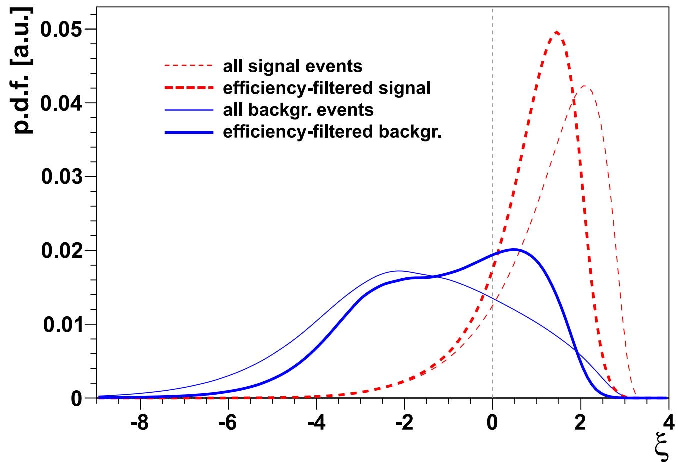

Fig. 1. Distributions of the angular discriminant ξ for ZZ continuum and $H \to ZZ$ events with and without experimental selection criteria applied, for $M_H = 700$ GeV/c^2 and $500 < M(ZZ) < 900$ GeV/c^2.

$$\mathcal{W}_{H\to ZZ\to 4\ell}(\cos\Theta, \cos\theta_1, \phi_1, \cos\theta_2, \phi_2) = \frac{9}{128\pi^2}\left(1 - \cos^2\theta_1\right)\left(1 - \cos^2\theta_2\right), \tag{6}$$

where θ_i, ϕ_i $(i = 1, 2)$ are lepton emission angles defined taking the Z polarization axis in the direction of the ZZ momentum. For $M_H > 500$ GeV/c^2 the corrections to this formula due to $J_z = \pm 1$ Z components are smaller than 1%.

The full information of the signal and background angular distributions and their kinematic dependences can be condensed into one per-event shape discriminant:

$$\xi = \ln \frac{\mathcal{W}_{H\to ZZ\to 4\ell}(\mathcal{A}\epsilon)_{H\to ZZ\to 4\ell}/\mathcal{N}_{H\to ZZ\to 4\ell}}{\mathcal{W}_{q\bar{q}\to ZZ\to 4\ell}(\mathcal{A}\epsilon)_{q\bar{q}\to ZZ\to 4\ell}/\mathcal{N}_{q\bar{q}\to ZZ\to 4\ell}}, \tag{7}$$

where the theoretical distribution, $\mathcal{W}$, and the experimental acceptance and efficiency, $\mathcal{A}\epsilon$, are calculated using the full kinematic information of the event, in the two hypotheses that the event is, respectively, signal, in the numerator of the fraction, or background, in the denominator. Each of the two normalization factors $\mathcal{N}$ is calculated by integrating the corresponding product $\mathcal{W}\mathcal{A}\epsilon$ over the phase space of, respectively, the signal or the background events. Fig. 1 shows the resulting ξ distribution in the case $M_H = 700$ GeV/c^2, for simulated signal and background events separately. The effect of the applied experimental selection criteria is an attenuation of the difference between the two distributions. In fact, the restricted lepton pseudorapidity coverage of the detector tends to smooth the strong $\cos\Theta$ modulation of the background and, more importantly, the limited sensitivity to low-p_T leptons reduces the effectiveness of the Z polarization discriminant. However, the results that follow are not substantially affected, for example, by a variation of the minimum lepton p_T in the range 10–20 GeV/c.

We have not explicitly included the polarization description of ZZ production via gluon–gluon fusion, a contribution of $\lesssim 20\%$ in the pp cross-section at 14 TeV in the mass ranges considered in our study. The Z kinematics (and thus the $\cos\Theta$ distribution) are very similar, especially at high ZZ mass, in the gg and $q\bar{q}$ cases [15] and the intrinsic Z polarization remains fully transverse also in the gg case, due to helicity conservation in the Z coupling to the internal quark lines of the involved box loops. We expect, therefore, a minimal smearing of the picture here presented because of gg contributions. More generally, the *definition* of the shape discriminant ξ can obviously be used even in the presence of deviations from the analytical formulas used to define it, provided that the template background and signal distributions are produced with an accurate simulation. With this procedure, higher-order contributions or correlation effects neglected in the analytical description can lead to a slight reduction of the significance of the discrimination, not to its artificial increase.

We should mention that the sensitivity to new particles can be further improved by exploiting the different production kinematics of signal and background. For example, the p_T distribution of heavy Higgs bosons is peaked at ~25 GeV/c for $gg \to H$ and at ~80 GeV/c in VBF production (a contribution of ~10–30% for $m_H = 500$–800 GeV/c^2), while direct ZZ production is maximum at ~10 GeV/c. The ZZ p_T distributions can be straightforwardly included in the definition of the shape discriminant ξ (Eq. (7)), without increasing the complexity of the following procedure.

To calculate the size of the ZZ event sample necessary to set limits on the discovery or exclusion of a Higgs signal, we define the following likelihood function enclosing the angular shape constraints:

$$\mathcal{L}_{\text{ang}}(\beta) = \prod_{i=1}^{N_{ZZ}} \bigl\{\bigl[1 - f_S(\beta)\bigr]\mathcal{T}_B(\xi_i) + f_S(\beta)\mathcal{T}_S(\xi_i)\bigr\}, \tag{8}$$

where N_{ZZ} is the number of observed ZZ events, $\mathcal{T}_B$ and $\mathcal{T}_S$ the normalized Monte Carlo template ξ distributions for background and signal events (as shown in Fig. 1), $f_S(\beta) = \frac{\beta\mu_S}{\mu_B+\beta\mu_S}$ the fraction of signal events, parametrized as a function of the average expected numbers μ_B and μ_S of background and signal events for a given integrated luminosity. The parameter of interest, β, represents the scale factor relating the estimated number of signal events to the expected one. For comparison purposes, we also construct the likelihood function corresponding to the "counting" method adopted in conventional searches, where the signal is defined as the excess with respect to the expected background yield:

$$\mathcal{L}_{\text{count}}(\beta) \propto e^{\mu_B+\beta\mu_S}(\mu_B + \beta\mu_S)^{N_{ZZ}}/N_{ZZ}!, \tag{9}$$

with $\mathcal{L}_{\text{count}} = 0$ for $\beta < -\mu_B/\mu_S$. Furthermore, we consider the combination of the two methods, $\mathcal{L}_{\text{comb}} = \mathcal{L}_{\text{ang}} \times \mathcal{L}_{\text{count}}$. The confidence levels obtained in a given experiment for the discovery and exclusion of a Higgs signal are defined, respectively, as $\int_{\beta>0} \mathcal{L}(\beta)\,d\beta$ and $\int_{\beta<1} \mathcal{L}(\beta)\,d\beta$. We note that the limits set by the angular constraints are independent of μ_B and of global normalization factors: in fact, f_S itself could be chosen as significance parameter. On the contrary, the counting method, using μ_B as constraint, relies crucially on the knowledge of the absolute background yield (cross-section, luminosity and efficiency determinations). In what follows we conservatively estimate the advantage

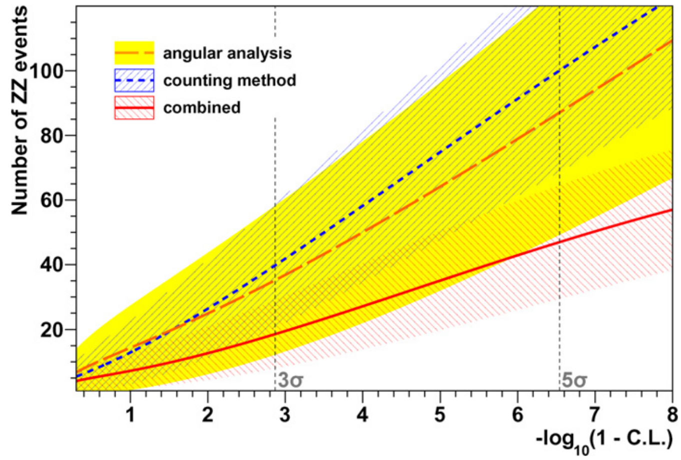

Fig. 2. Number of reconstructed ZZ events in the range $500 < M(ZZ) < 900$ GeV/c^2 as a function of the required confidence level (C.L.) for the observation of a Higgs boson signal with $M_H = 700$ GeV/c^2. Lines and bands represent average and ±1 rms range.

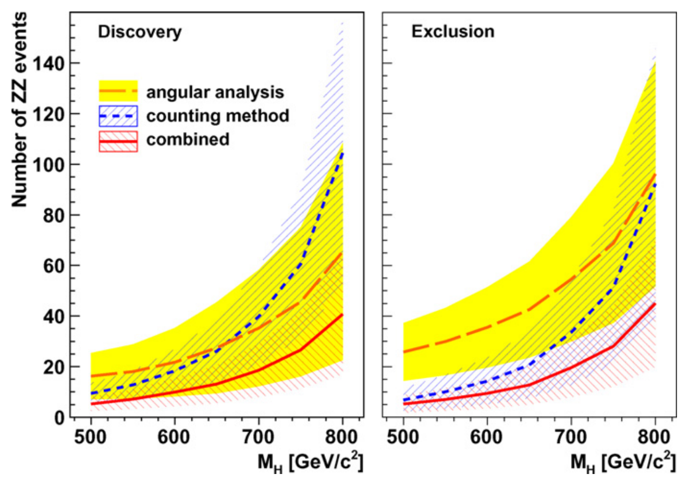

Fig. 3. Number of reconstructed ZZ events necessary for the observation or exclusion of a Higgs boson signal at the "three sigma" level, as a function of the Higgs mass. The events belong to the ZZ invariant mass range $[M_H - \sigma_H, M_H + \sigma_H]$. Lines and bands represent average and ±1 rms range.

of the angular method by neglecting normalization uncertainties (as well as look-elsewhere effects in the considered ZZ invariant mass window), which would reduce the significance levels obtained with $\mathcal{L}_{\text{count}}$.

We perform thousands of toy experiments with varying integrated luminosity. The number of generated events for each experiment is randomly extracted from a Poisson distribution centred at the value expected according to the assumed signal and background cross-sections. Pseudo-data containing signal and background events generated according to the expected mixture (or background-only events) are used to determine the discovery (or exclusion) confidence levels. For each experiment we record the number of events observed after the experimental filter and the obtained discovery or exclusion confidence level. Fig. 2 shows the distribution of the number of observed events as a function of the confidence level for the discovery of a 700 GeV/c^2 Higgs boson, comparing the results obtained with the angular and counting methods and with their combination. The number of events necessary for discovery and exclusion at the "three sigma" significance level are shown in Fig. 3 as a function of the Higgs boson mass.

By using the combined likelihood, a given confidence level for discovery can be reached with, on average, one third to one half of the reconstructed events necessary when using the event-yield constraint alone, and a given exclusion limit with half to three thirds of the events. The relative efficacy of the angular analysis increases with M_H, essentially because of the increasing background yield (from 30% of the total events for $M_H = 500$ GeV/c^2 to 70% for $M_H = 800$ GeV/c^2), being $\mathcal{L}_{\text{ang}}$ exempt from the explicit dependence on μ_{B} characterizing $\mathcal{L}_{\text{count}}$. Keeping this into account, these results represent a smooth continuation of those obtained for lower M_H values in Ref. [4], where the inclusion of the angular constraints is seen to reduce by about one third the luminosity necessary to reach a certain discovery limit for $M_H = 300$ GeV/c^2.

In summary, we have shown that the angular distribution of the $ZZ \to 4\ell$ background continuum can be effectively modelled with a simple analytical formula, removing any dependence on collision system and energy and on parton distribution functions. Using this formula, we have shown that the search of new signals in the ZZ mass spectrum can significantly benefit from the angular characterization of the background. This strategy is conceptually very different from the simple event-counting procedure: instead of identifying the signal with an excess of events of whatever physical origin, it uses a shape discriminant based on a given hypothesis for the signal angular distribution, therefore focussing on the search for a particle of specific spin and coupling properties. The two methods are essentially uncorrelated from a statistical point of view, in that they exploit independent degrees of freedom of the measurement. The angular approach is not affected by normalization uncertainties related to efficiency and luminosity determinations. Given their complementarity, the two kinds of searches can provide mutual confirmation and can be combined to increase the signal sensitivity. As an illustration, we have considered the search for a scalar particle decaying into longitudinally polarized Z pairs. In particular, we have simulated the signal as a hypothetical Higgs boson of mass between 500 and 800 GeV/c^2 in 14 TeV pp collisions. The constraint imposed by the measured shape of the angular distribution competes in effectiveness with that imposed by the number of observed events. By combining the two methods, a given observation or exclusion limit can be established on the basis of a considerably smaller ZZ event sample. The improvement is larger for larger ZZ masses, because of the larger background contribution. The same background description can be applied in the search of new massive neutral spin-0, 1, or 2 bosons (extended Higgs sectors, Z', graviton, etc.). Moreover, our analytical formula for the dilepton decay distribution is equally suitable to model the Z decay in the continuum $Z\gamma$ production (only the distribution of the Z emission angle being different [3]), dominant background in searches for neutral bosons in the $Z\gamma$ channel and for manifestations of anomalous three-vector-boson couplings.

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