

Dark Energy Survey Year 1 Results: Measurement of the Baryon Acoustic Oscillation scale in the distribution of galaxies to redshift 1

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ABSTRACT

We present angular diameter distance measurements obtained by locating the BAO scale in the distribution of galaxies selected from the first year of Dark Energy Survey data. We consider a sample of over 1.3 million galaxies distributed over a footprint of 1318 deg² with $0.6 < z_{\text{photo}} < 1$ and a typical redshift uncertainty of $0.03(1+z)$. This sample was selected, as fully described in a companion paper, using a color/magnitude selection that optimizes trade-offs between number density and redshift uncertainty. We investigate the BAO signal in the projected clustering using three conventions, the angular separation, the co-moving transverse separation, and spherical harmonics. Further, we compare results obtained from template based and machine learning photometric redshift determinations. We use 1800 simulations that approximate our sample in order to produce covariance matrices and allow us to validate our distance scale measurement methodology. We measure the angular diameter distance, D_A , at the effective redshift of our sample divided by the true physical scale of the BAO feature, r_d . We obtain close to a 4 per cent distance measurement of $D_A(z_{\text{eff}} = 0.81)/r_d = 10.75 \pm 0.43$. These results are consistent with the flat Λ CDM concordance cosmological model supported by numerous other recent experimental results.

Key words: cosmology: observations - (cosmology:) large-scale structure of Universe

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1 INTRODUCTION

The signature of Baryon Acoustic Oscillations (BAO) can be observed in the distribution of tracers of the matter density field and used to measure the expansion history of the Universe. BAO data alone prefer dark energy at greater than 6σ and are consistent with a flat Λ CDM cosmology with $\Omega_{\text{matter}} = 0.3$ (Ata et al. 2017). A large number of spectroscopic surveys have measured BAO in the distributions of galaxies, quasars, and the Lyman- α forest, including the Sloan Digital Sky Survey (SDSS) I, II, III, and IV Eisenstein et al. 2005; Gaztañaga et al. 2009; Percival et al. 2010; Ross et al. 2015a; Alam et al. 2016; Ata et al. 2017; Delubac et al. 2015; Bautista et al. 2017, the 2-degree Field Galaxy Redshift

Survey (2dFGRS) (Percival et al. 2001; Cole et al. 2005), WiggleZ (Blake et al. 2011), and the 6-degree Field Galaxy Survey (6dFGS) (Beutler et al. 2011).

BAO have also been measured using purely photometric data, though at less significance. Radial distance measurements are severely hampered, but some information about the angular diameter distance D_A is still accessible. Analysis of this signal is presented in Seo & Eisenstein (2003); Blake & Bridle (2005); Zhan et al. (2009). Recently, Ross et al. (2017b) (hereafter DES-BAO- s_{\perp} -METHOD) studied the signal expected to be present for data similar to DES Y1 and recommended the use of the projected two point correlation function, $\xi(s_{\perp})$, as a clustering estimator ideal for extracting the BAO signal. Measurements of the signal have been presented in Padmanabhan et al. 2007; Estrada et al. 2009; Hütsi 2010; Sánchez et al. 2011; Crocce et al. 2011; Seo et al. 2012; Carnero et al. 2012.

We use imaging data from the first year (Y1) of Dark Energy Survey (DES) observations to measure the angular diameter distance to red galaxies with photometric redshifts $0.6 < z_{\text{photo}} < 1.0$. DES is a five year program to image a 5,000 deg² footprint of the Southern hemisphere using five passbands, *grizY*. It will measure the properties of over 300 million galaxies. Here, we use 1.3 million galaxies over 1318 deg² color and magnitude selected to balance trade-offs in BAO measurement between the redshift precision and the number density. We use these data, supported by 1800 mock realizations of our sample, to allow us to make the first BAO measurement using galaxies centered at $z > 0.8$.

The measurement we present is supported by a series of companion papers. Crocce et al. (2017) presents the selection of our DES Y1 sample, optimized for $z > 0.6$ BAO measurements, and tests of its basic properties; we denote it DES-BAO-SAMPLE hereafter. Avila et al. (2017) describes how 1800 realizations approximating the spatial properties of the DES Y1 data sample were produced and validated; we denote it DES-BAO-MOCKS. Using these mock Y1 realizations, Chan et al. (in prep.) validates and optimizes the methodology for measuring BAO from the angular two point correlation function, $w(\theta)$; we denote it DES-BAO- θ -METHOD. Works on the angular power spectrum C_{ℓ} (Camacho et al. in prep.; DES-BAO- ℓ -METHOD) and a presentation of the photometric redshift validation (Gaztanaga et al. in prep.; DES-BAO-PHOTOZ) are in preparation.

In this paper, we collate the results of the above papers. With this basic framework, we identify the BAO signature in the DES Y1 data, and use it to place constraints on the comoving angular diameter distance to the effective redshift of our sample, $z_{\text{eff}} = 0.81$. The cosmological implications of this measurement are then discussed. Section 2 summarizes the data we use, including all of its basic properties and details on the mock realizations of the data (mocks). Section 3 presents the basic techniques we apply to measure the clustering of galaxies, estimate covariance matrices in order to extract parameter likelihoods, and extract the BAO scale distance from the measurements. Section 4 summarizes tests performed on the 1800 mock Y1 realizations, which help set our fiducial analysis choices. Section 5 presents the clustering measurements and the BAO scale we extract from them. Section 6 compares our measurement to predictions of the flat Λ CDM model and other BAO scale distance measurements. We conclude in Section 7 with a discussion of future prospects.

The fiducial cosmology we use for this work is a flat Λ CDM with $\Omega_{\text{matter}} = 0.25$ with $h = 0.7$. Such a low matter density is ruled out by current observational constraints (see, e.g., Planck Collaboration et al. 2016). However, the cosmology we use is matched

to that of the MICE (Crocce et al. 2015; Fosalba et al. 2015a,b; Carretero et al. 2015) N -Body simulation, which was used to calibrate the mock galaxy samples we employ to test and validate our methodology. We will demonstrate that our results are not sensitive to this choice.

We note that the determination of the color and magnitude cuts, as well as the overall redshift range and the observational systematics treatment, was completed prior to any actual clustering measurement and based on considerations of photo- z performance, area and number density. Therefore, our sample selection was blind to any potential BAO detection in the data.

2 DATA

2.1 DES Year 1 Data

“DES Year 1” (Y1) data were obtained in the period of time between August 31, 2013 and February 9, 2014 using the 570-megapixel Dark Energy Camera (DECam; Flaugher et al. 2015). Y1 contains images occupying a total footprint of more than 1800 deg² in *grizY* photometric passbands (Diehl et al. 2014). The DES Data Management (DESDM) system (Mohr et al. 2008; Sevilla et al. 2011; Desai et al. 2012) detrended, calibrated, and coadded these DES images in order to catalog astrophysical objects. From these results the Y1 ‘Gold’ catalog was produced, which provided photometry and ‘clean’ galaxy samples, as described in Drlica-Wagner et al. (2017). The observed footprint is defined by a HEALPIX (Gorski et al. 2005) map at resolution $N_{\text{side}} = 4096$ and includes only area with a minimum total exposure time of at least 90 seconds in each of the *griz* bands and a valid calibration solution (see Drlica-Wagner et al. 2017 for details). A series of veto masks, covering regions of poor quality or foregrounds for the galaxy sample, reduce the area to 1318 deg² suitable for LSS study. We describe the additional masks we apply to the data in Section 2.4.

2.2 BAO Sample Selection

We use a sample selected from the DES Y1 Gold catalog to provide the best BAO constraints. The sample balances number density and photometric redshift uncertainty considerations in order to produce an optimal sample. The sample definition is fully described in Crocce et al. (2017) (DES-BAO-SAMPLE). We repeat vital information here.

We select our sample based on color, magnitude, and redshift cuts. The primary redshift, colour, and magnitude cuts are

$$17.5 < i_{\text{auto}} < 19.0 + 3.0z_{\text{BPZ-AUTO}} \quad (1)$$

$$(i_{\text{auto}} - z_{\text{auto}}) + 2.0(r_{\text{auto}} - i_{\text{auto}}) > 1.7 \quad (2)$$

$$0.6 < z_{\text{photo}} < 1.0. \quad (3)$$

The color and magnitude cuts use `mag_auto` defined in Y1 Gold and $z_{\text{BPZ-AUTO}}$ is the BPZ photometric redshift (Benitez et al. 2000) determined with the `mag_auto` photometry.¹ The quantity z_{photo} is the photometric redshift used for a particular sample, we describe these in Section 2.3.

¹ While we use `mag_auto` photometry for galaxy selection, our redshift estimates rely on a proper multi-object fitting procedure. The use of `mag_auto` for galaxy selection reflects that the latter color measurements only became available after the galaxy selection had already been finalized.

Table 1. Characteristics of the DES Y1 BAO sample, as a function of redshift: number of galaxies, redshift uncertainties and fraction of star contamination. Results are shown for the DNF redshift estimate, with BPZ results in parentheses. We used z to denote the mean redshift of the given estimator (as each galaxy has a redshift likelihood).

z_{photo}	N_{gal}	$\sigma_{68}/(1+z)$	f_{star}
$0.6 < z < 0.7$	386057 (332242)	0.023 (0.027)	0.004 (0.018)
$0.7 < z < 0.8$	353789 (429366)	0.028 (0.031)	0.037 (0.042)
$0.8 < z < 0.9$	330959 (380059)	0.029 (0.034)	0.012 (0.015)
$0.9 < z < 1.0$	229395 (180560)	0.036 (0.039)	0.015 (0.006)

Stars are removed via the cut

$$\text{spread_model}_i + (5.0/3.0)\text{spreaderr_model}_i > 0.007 \quad (4)$$

and we also remove outliers in colour space via

$$-1 < g_{\text{auto}} - r_{\text{auto}} < 3 \quad (5)$$

$$-1 < r_{\text{auto}} - i_{\text{auto}} < 2.5 \quad (6)$$

$$-1 < i_{\text{auto}} - z_{\text{auto}} < 2. \quad (7)$$

2.3 Redshifts

We define two samples based on two different photometric redshift algorithms, BPZ and DNF (De Vicente et al. 2016). For both samples, our point estimates of the redshift, z_{photo} , use photo z s determined using the ‘MOF’ photometry defined in Y1 Gold. However, for each sample, we use the BPZ value calculated using `mag_auto` photometry with the sample selection cut defined in Eq. 1; this is the only time that photo z s estimated using `mag_auto` photometry are used. We use the DNF method as our fiducial redshift estimator as it performed better, in terms of both precision and accuracy, on validation tests (see DES-BAO-SAMPLE and DES-BAO-PHOTOZ for more details). As a robustness check, we also compare our results to those derived using BPZ redshifts, as determined using MOF photometry. In Table 1 we present the statistics of each sample (after masking, see Section 2.4) divided into redshift bins of width $\Delta z = 0.1$. We define σ_{68} as the half width of the interval containing the median 68% of values in the distribution of $(z_{\text{photo}} - z_{\text{true}})/(1 + z_{\text{true}})$. This is estimated based on the redshift validation described in DES-BAO-SAMPLE and DES-BAO-PHOTOZ.

The redshift estimate for each individual galaxy has substantial uncertainty, typically with non-Gaussian likelihood distributions for z_{true} . We use individual point estimates of the redshift both for binning in redshift and for calculating transverse separation in h^{-1} Mpc. In order to do so, we use the mean redshift produced by the given redshift estimator. In what follows, we will refer to this estimate of the redshift by z (dropping the photo sub-script).

We determine an effective redshift for our sample of $z_{\text{eff}} = 0.81$. This is determined from the mean redshift obtained when applying all weights, including those defined in Eq. 9, which account for the expected signal to noise as a function of redshift. See DES-BAO-SAMPLE and DES-BAO-PHOTOZ for further details on the redshifts used for the DES Y1 BAO sample and their validation.

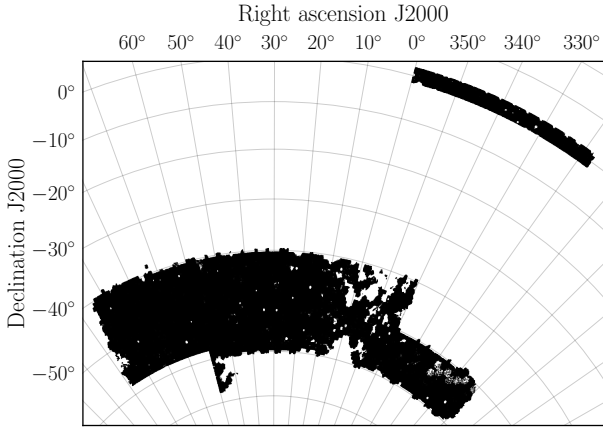


Figure 1. The black shaded region represents the area on the sky to which we restrict our DES Y1 BAO analysis. See Section 2.4.

2.4 Mask

The most basic requirement is that DES Y1 observations exist in *griz*, since our selection requires each of the four bands. We use the Y1 Gold coverage maps, at HEALPIX resolution $N_{\text{side}} = 4096$, to enforce this condition. We require that any pixel be at least 80 per cent covered in the four bands simultaneously. The minimum coverage across all four bands is then used as a weight for the pixel. We also require that the depth limit in each band is at the level required of our colour/magnitude selection. The Y1 Gold catalog includes 10σ MAG_AUTO depth maps for each band, again at HEALPIX resolution $N_{\text{side}} = 4096$. This is an angular size of 0.014 degrees and less than one tenth of the resolution of any clustering statistics we employ. We consider only areas with *i* band depth greater than 22 and depth in the other bands great enough to reliably measure the colour defined by Eq. 2. This involved removing regions of the footprint that did not fulfill the condition $(2r_{\text{maglim}} - z_{\text{maglim}}) < 23.7$. We further cut out ‘bad regions’ identified in Y1GOLD (removing everything with flag bit > 2 in their table 5), and areas with *z*-band seeing greater than 3.7 pixels. We also remove a patch with area 18 deg^2 , where the airmass quantity was corrupted. The resulting footprint occupies 1318 deg^2 and is shown in Fig. 1.

2.5 Observational Systematics

As detailed in DES-BAO-SAMPLE, we have found significant dependencies between the number density of galaxies in our sample and three observational quantities: the local stellar density, the PSF FWHM (‘seeing’), and the detection limit (depth). The dependency with stellar density is understood as stellar contamination: some fraction of our ‘galaxies’ are in fact stars. The inferred stellar contamination, f_{star} , is listed in Table 1. The dependencies with seeing and depth are similar to what was found for a separate DES Y1 sample by Elvin-Poole et al. (2017). We correct for the systematic dependencies via weights that we assign to the catalog, which when applied remove the trend with the quantity in question. The total weight, w_{sys} , is the product of all three individual weights. We apply w_{sys} to all counting and clustering statistics presented in this paper, except where we omit it as a test of robustness. See DES-BAO-SAMPLE for full details on the construction of the weights. We find that the weights have a minimal impact on our analysis.

2.6 Mocks

We simulate our sample using 1800 mock DES Y1 catalogs. These are fully described in Avila et al. (2017) (DES-BAO-MOCKS) and we only repeat the basic details here. Each mock matches the footprint, clustering, and redshift accuracy/distribution of our DES sample. Halo catalogs are generated using the HALOGEN technique (Avila et al. 2015), based on a 2LPT density field with an exponential bias. The method is tuned to reproduce the halo clustering as a function of mass and redshift of a reference N -Body simulation (MICE; Fosalba et al. 2015a). We use a box size of $L_{\text{box}} = 3072h^{-1}\text{Mpc}$ with a halo mass resolution of $M_h = 2.5 \times 10^{12}h^{-1}M_{\odot}$. Haloes are then arranged in a light-cone by superposition of 11 snapshots. We tile 8 replicas of the box together using the periodic conditions to construct a full sky mock from $z = 0$ to $z = 1.42$, from which we draw eight mock catalogues.

We take care to properly reproduce the redshift properties of our DES Y1 sample. For each mock galaxy, we have the true redshift z_{true} . We thus require an estimate of the joint distribution $P(z_{\text{phot}}|z_{\text{true}})$ in order to assign z_{phot} to each mock galaxy. As detailed in DES-BAO-MOCKS, we find that the sum of a normal and a normal-skewed distribution works well to reproduce our estimates of $P(z_{\text{phot}}|z_{\text{true}})$ for the DES Y1 data. This method allows us to accurately model the correspondence between the observed redshift z_{phot} and the true redshift z_{true} , and its effect on the observed clustering. However, small differences remain between the normalized (to integrate to 1) redshift distribution, $\phi(z)$, for the mocks in each redshift bin and that we estimate for the data. Thus, we will use the $\phi(z)$ specific to the mocks for their BAO template.

Galaxies are added to the mocks using a hybrid Halo Occupation Distribution/Halo Abundance Matching model with three parameters. These are each allowed to evolve with redshift in order to account for bias evolution and selection effects. The amplitude of the clustering in the DES Y1 data is reproduced within approximately $1\text{-}\sigma$ in eight z_{photo} bins with $\Delta z_{\text{photo}} = 0.05$ in the range $0.6 < z_{\text{photo}} < 1.0$.

Details of the modelling and validation of the mocks can be found in DES-BAO-MOCKS. Here we use these mock samples to validate our methodology and estimate our covariance matrix, as described in the following section. Having such a large number of mock samples reduces the noise in the derived covariance matrices and is crucial for identifying the proper procedures for dealing with the particularities of the DES Y1 results.

3 ANALYSIS

3.1 Measuring Clustering

We perform clustering analysis using both the angular correlation function, $w(\theta)$, and the angular power spectrum measured in spherical harmonics, C_{ℓ} . We also measure the projected comoving separation correlation function, $\xi(s_{\perp}, s_{\parallel})$, where s_{\perp} and s_{\parallel} are the apparent transverse and radial separations. Flat sky approximations are never used for the determination of angular separations.

3.1.1 Angular Clustering

In order to calculate $w(\theta)$, we create a uniform random sample within the mask defined in Section 2.2 with size 40 times that of our data sample. We down-sample these randoms given the fractional coverage of the pixel (always > 0.8 given our mask threshold) to

produce the final random sample. Given the random sample, we use the [Landy & Szalay \(1993\)](#) estimator

$$w(\theta) = \frac{DD(\theta) - 2DR(\theta) + RR(\theta)}{RR(\theta)}, \quad (8)$$

where, e.g., $DD(\theta)$ is the normalized number of pairs of galaxies with angular separation $\theta \pm \Delta\theta$, with $\Delta\theta$ being half the bin size, and all pair-counts are normalized based on the total size of each sample. We bin paircounts at a bin size of 0.15 degrees, but will combine these to 0.3 degrees for our fiducial bin size (as we will find this to be a more optimal data compression in Section 4). We will use both binnings as a test of robustness. We will use $0.5 < \theta < 5$ degrees for our fiducial scale cuts, yielding 15 θ bins per redshift bin and thus use 60 total $w(\theta)$ measurement bins.

The details of the C_ℓ calculation are presented in DES-BAO- ℓ -METHOD. They are measured from the decomposition into spherical harmonics of the projected 2-dimensional galaxy overdensity δ_{gal} in a given redshift bin. To do so, we use the ANAFIX code contained in HEALPIX ([Gorski et al. 2005](#)). We then use the pseudo- C_ℓ method given by ([Hivon et al. 2002](#)) in order to correct for the effect of the masked sky. In our measurements we use bins of $\Delta\ell = 15$ in the range $30 < \ell < 330$. This ℓ_{max} corresponds to a minimum angular scale of $\theta_{\text{min}} \approx 0.5^\circ$. We thus use 20 ℓ bins per redshift bin and 80 total C_ℓ measurement bins.

3.1.2 Projected Physical Separation Correlation Function

We convert our galaxy sample into a three dimensional map in ‘photometric redshift space’ by converting angles and redshifts to physical distances. In this way, we are treating the redshift from the photometric redshift estimate like redshifts are used for calculating clustering statistics for a spectroscopic survey. For the corresponding random sample, we use the same angular coordinates of the randoms in the $w(\theta)$ measurements and assign redshifts to the randoms by randomly selecting redshifts from individual galaxies in our galaxy catalog. We apply a redshift dependent weight, $w_{\text{FKP}}(z)$, based on the number density, galaxy bias (determined by interpolating the results in DES-BAO-MOCKS), and redshift uncertainty as a function of redshift, based on the form derived in DES-BAO- s_\perp -METHOD

$$w_{\text{FKP}}(z) = \frac{b(z)D(z)}{1 + n_{\text{eff}}(z)P_{\text{lin}}(k_{\text{eff}}, z=0)b^2(z)D^2(z)}, \quad (9)$$

where $n_{\text{eff}}(z)$ is the effective number density accounting for the redshift uncertainty (using the equations and methodology described in DES-BAO- s_\perp -METHOD), and k_{eff} is the k scale given the greatest weight in Fisher matrix forecasts of the BAO signal, accounting for all of the relevant sample properties. We calculated normalized paircounts of galaxies and randoms in bins of $1 h^{-1}\text{Mpc}$ along s_\perp and s_\parallel . Calculating the paircounts with this narrow bin size provides the flexibility to test many different binning schemes. Here, we will combine the paircounts into a fiducial bin size of $12 h^{-1}\text{Mpc}$ for our fiducial measurements, but also present tests with many other bin sizes. Additionally, our final results will combine results across shifts in the center of the bin. This procedure mirrors that used in recent BAO studies ([Anderson et al. 2014](#); [Ata et al. 2017](#)). Again, we use a version of the [Landy & Szalay \(1993\)](#) estimator,

$$\xi_{\text{phot}}(s_\perp, s_\parallel) = \frac{DD(s_\perp, s_\parallel) - 2DR(s_\perp, s_\parallel) + RR(s_\perp, s_\parallel)}{RR(s_\perp, s_\parallel)}, \quad (10)$$

where D represents the galaxy sample and R represents the uniform random sample that simulates the selection function of the galaxies. $DD(s_\perp, s_\parallel)$ thus represents the normalized number of pairs of galaxies with separation s_\perp and s_\parallel . See DES-BAO- s_\perp -METHOD for further details.

The statistic used for ξ measurements is

$$\xi(s_\perp) = \int_0^1 d\mu_{\text{obs}} W(\mu_{\text{obs}}) \xi_{\text{phot}}(s_\perp, s_\parallel), \quad (11)$$

where the window function $W(\mu_{\text{obs}})$ is normalized such that $\int_0^1 d\mu_{\text{obs}} W(\mu_{\text{obs}}) = 1$. $\mu_{\text{obs}} = s_\parallel / \sqrt{s_\perp^2 + s_\parallel^2}$ is the observed cosine of the angle to the line of sight. We have simply used the data with $\mu_{\text{obs}} < 0.8$ and adjusted the normalization to compensate, i.e., our $W(\mu)$ is a step function that is 1 for $\mu < 0.8$ and 0 for $\mu > 0.8$. Once more, this matches the approach advocated in DES-BAO- s_\perp -METHOD, where it was found that the BAO signal to noise and the ability to model it degrades considerably for $\mu > 0.8$.

3.2 Covariance and Parameter Inference

In order to estimate the covariance matrix for our clustering estimates, we use a large number of mock samples, described in Section 2.6. We have 1800 realizations, so the correlation between data vector, X , elements i and j is

$$C_{i,j} = \frac{1}{1799} \sum_{k=1}^{k=1800} (X_i^k - \langle X_i \rangle)(X_j^k - \langle X_j \rangle). \quad (12)$$

For the angular clustering measurements, the full data vector includes multiple redshift bins and the covariance matrix thus includes terms for the covariance of the clustering between different redshift bins.

When using mocks to estimate covariance matrices, we must account for the noise imparted due to the fact we use a finite set of realizations. This noise introduces biases into the inverse covariance matrix. Thus, corrections must be applied to the χ^2 values, the width of the likelihood distribution, and the standard deviation of any parameter determined from the same set of mocks used to define the covariance matrix. These factors are defined in [Hartlap et al. \(2007\)](#); [Dodelson & Schneider \(2013\)](#); [Percival et al. \(2014\)](#). Given that we use 1800 mocks, these factors are at most 3.6 per cent.

We use the standard χ^2 analysis to quantify the level of agreement between between data and model vectors and to determine the likelihood of parameter values. Given a covariance matrix, C , representing covariance of the elements of a data vector, and the difference D between a data vector and model data vector, the χ^2 is given by

$$\chi^2 = DC^{-1}D^T. \quad (13)$$

The likelihood, \mathcal{L} , of a given parameter, p , is then

$$\mathcal{L}(p) \propto e^{-\chi^2(p)/2}. \quad (14)$$

3.3 Determining the BAO Scale

In order to extract the BAO scale from each clustering statistic, we use a template-based method. This approach was used in [Seo et al. \(2012\)](#); [Xu et al. \(2012\)](#); [Anderson et al. \(2014\)](#); [Ross et al. \(2017a\)](#). The template is derived from a linear power spectrum, $P_{\text{lin}}(k)$, with ‘damped’ BAO modeled using a parameter Σ_{nl} (defined below) that

accounts for the smearing of the BAO feature due to non-linear structure growth. We first obtain $P_{\text{lin}}(k)$ from CAMB² (Lewis et al. 2000) and fit for the smooth ‘no-wiggle’³ $P_{\text{nw}}(k)$ via the Eisenstein & Hu (1998) fitting formulae with a running spectral index. We account for redshift-space distortions (RSD) and non-linear effects via

$$P(k, \mu) = (1 + \mu^2 \beta)^2 \left((P_{\text{lin}} - P_{\text{nw}}) e^{-k^2 \Sigma_{\text{nl}}^2} + P_{\text{nw}} \right), \quad (15)$$

where $\mu = \cos(\theta_{\text{LOS}}) = k_{\parallel}/k$, and $\beta \equiv f/b$. This factor is set based on the galaxy bias, b , and effective redshift of the sample we are modeling, with f defined as the logarithmic derivative of the growth factor with respect to the scale factor. The factor $(1 + \beta \mu^2)^2$ is the ‘Kaiser boost’ (Kaiser 1987), which accounts for linear-theory RSD. The BAO ‘damping’ factor is

$$\Sigma_{\text{nl}}^2 = (1 - \mu^2) \Sigma_{\perp}^2 / 2 + \mu^2 \Sigma_{\parallel}^2 / 2. \quad (16)$$

Given that we have little sensitivity to the line of sight, we will only test varying Σ_{nl} (as opposed to its transverse and line of sight components separately).

Each of $\xi(s_{\perp})$, $w(\theta)$, and C_{ℓ} require one or both of the combination of Fourier transforming and projecting Eq. 15 over redshift distributions or uncertainties, in order to obtain the BAO template, $T_{\text{BAO}}(x)$, as a function of scale, x .⁴ For both of the configuration space templates, the anisotropic redshift-space correlation function, $\xi_s(s, \mu)$ is obtained from the Fourier transform of $P(k, \mu)$ defined above. For the angular statistics, we project over the redshift distribution, $\phi(z)$, normalized to integrate to 1. For $w(\theta)$, we have

$$w_{\text{BAO}}(\theta) = \int dz_1 \int dz_2 \phi(z_1) \phi(z_2) \xi_s(s[z_1, z_2, \theta], \mu[z_1, z_2, \theta]). \quad (17)$$

Further details can be found in DES-BAO- θ -METHOD. Similar equations for C_{ℓ} (projecting over $P[k]$) are presented in DES-BAO- ℓ -METHOD.

When modeling the projected correlation function $\xi(s_{\perp})$ we follow the formalism of Ross et al. (2017b), which strictly speaking is only appropriate for Gaussian photometric redshift errors. Our model for $\xi(s_{\perp})$ is as follows

$$\xi(s_{\perp}, \mu) = \int dz G(z) \xi(s_{\text{true}}[s_{\perp}, \mu, z], \mu_{\text{true}}[s_{\perp}, \mu, z]), \quad (18)$$

where $G(z)$ is a normal distribution of width $\sqrt{2}\sigma_z$ and we used the weighted average of the σ_{68} quantities listed in Table 1. The s_{\perp} and μ quantities are those we observe in DES, in the presence of redshift uncertainties, thus requiring the distinction between them and the ‘true’ quantities involved in the projection. See DES-BAO- s_{\perp} -METHOD for more details.

Note that unlike our treatment of $\xi(s_{\perp})$, our treatment of the angular correlation function does not assume that the photometric redshift are Gaussian, and is in fact completely general. This is a primary reason that we adopt our measurement of the angular correlation function as our fiducial analysis. We still explore whether an analysis of the projected correlation function produces consistent results, while possibly reducing the statistical error budget. The impact of the Gaussian photo z assumption for $\xi(s_{\perp})$ is further discussed in the following sections.

For the configuration space T_{BAO} , the BAO scale is obtained

through⁵

$$M(x) = B T_{\text{BAO}}(x\alpha) + A(x), \quad (19)$$

where the parameter α rescales the separation to allow a match between the BAO feature in the theory and observation. It therefore parameterizes the BAO measurement (how different the BAO position is in the measurement versus assumed by the template). The parameter B allows the amplitude to change (e.g., due to galaxy bias), and $A(x)$ is a free polynomial meant to account for any differences in between the broadband shape in the data and template. These differences can be due to, e.g., differences between the fiducial and true cosmology or observational systematic effects. Therefore, including the polynomial helps both to isolate BAO scale information and make the measurements robust. Generally, a three term polynomial is used, e.g., for $\xi(s_{\perp})$, $A(s_{\perp}) = a_1 + a_2/s_{\perp} + a_3/s_{\perp}^2$. Similar expressions hold for $A(\theta)$ and $A(\ell)$. Details can be found in DES-BAO- θ -METHOD and DES-BAO- ℓ -METHOD.

For $w(\theta)$ we determine Σ_{nl} by fitting to the mean $w(\theta)$ of the mocks. We have fitted to each redshift bin individually. We find that a constant damping scale of $5.2 h^{-1}$ Mpc offers a good fit to all four redshift bins. Based on the modeling described in DES-BAO- θ -METHOD, we expect to find a value consistent with the transverse damping scale for spectroscopic redshift space. Indeed, our recovered value is close to the value of $5.6 h^{-1}$ Mpc one obtains when extrapolating the discussion preceding equation 3 of Seo & Eisenstein (2007) to $z = 0.8$ and $\sigma_8 = 0.8$. See DES-BAO- θ -METHOD for more details. Thus, we will use this damping scale when fitting to the $w(\theta)$ mocks and data, though we will demonstrate our results are robust against this choice.

We repeat the procedure in order to find a best-fit Σ_{nl} for $\xi(s_{\perp})$. In principle, we should find the same result as found for $w(\theta)$. However, our modeling DES-BAO- s_{\perp} -METHOD assumes Gaussian redshift uncertainties, while the true distributions have significant non-Gaussian tails DES-BAO-MOCKS. Given that the size of the BAO feature depends strongly on the redshift uncertainty, we might expect that our inaccuracies in the treatment of the redshift uncertainty translates to finding a best-fit Σ_{nl} that is greater than the theoretical expectation. Indeed, we find $\Sigma_{\text{nl}} = 8 h^{-1}$ Mpc; just over 50 per cent larger than both the value found for $w(\theta)$ and the theoretical expectation. We thus set $\Sigma_{\text{nl}} = 8 h^{-1}$ Mpc for our fiducial $\xi(s_{\perp})$ model, to also account for the known inaccuracies with respect to modeling the redshift uncertainties. We will explore the sensitivity of the results obtained from the DES Y1 mocks and the data to this choice. We will improve the modeling in future analyses.

Each method allows us to obtain the likelihood $L(\alpha)$, which represents our BAO measurement. This can be converted to a likelihood for the angular diameter distance D_A at the effective redshift of our sample, z_{eff} , via

$$\alpha = \frac{D_A(z_{\text{eff}}) r_{\text{d}}^{\text{fid}}}{D_A^{\text{fid}}(z_{\text{eff}}) r_{\text{d}}}, \quad (20)$$

where r_{d} is the sound horizon at the drag epoch (and thus represents the expected location of the BAO feature in co-moving distance units, due to the physics of the early Universe). The superscript ^{fid} denotes that the fiducial cosmology was used to determine the value. In this work, $r_{\text{d}}^{\text{fid}} = 153.44$ Mpc. One can see that Eq. 20

² camb.info

³ Models using only this component will be labeled ‘noBAO’ in plots.

⁴ Here x represents either r_{\perp} , θ , or ℓ depending on the statistic in question.

⁵ For C_{ℓ} , the argument is ℓ/α .

can be re-arranged to obtain

$$\frac{D_A(z_{\text{eff}})}{r_d} = \alpha \frac{D_A^{\text{fid}}(z_{\text{eff}})}{r_d^{\text{fid}}}. \quad (21)$$

The likelihood we obtain for $\alpha \frac{D_A(z_{\text{eff}})}{r_d}$ can directly be used to constrain cosmological models. In a flat geometry, D_A , D_A is given by

$$D_A(z) = \frac{c}{H_0(1+z)} \int_0^z dz' \frac{H_0}{H(z')}. \quad (22)$$

In our fiducial cosmology, $D_A(0.81) = 1597.2$ Mpc. The fiducial $D_A(0.81)/r_d$ is thus 10.41.

Our DES Y1 sample is in a regime with an expected signal to noise, in terms of detection ability, of close to 2. In such a regime, we do not expect Gaussian likelihoods. In general for low signal to noise BAO measurements, the tails of the distribution extend to both large and small values of α . See, e.g., [Ross et al. \(2015a\)](#); [Ata et al. \(2017\)](#) for recent similar signal to noise BAO measurement and DES-BAO- θ -METHOD for a detailed investigation of what we expect for DES Y1 $w(\theta)$ measurements. Indeed, we find such tails in our DES Y1 analysis and one consequence is that when using our 1800 mock catalogs, we find that 8 per cent of the realizations lead do no clear detection of the BAO feature. An important consequence of these facts is that it is critically important for any cosmological application of our results to consider the full likelihood. We restrict our analysis to $0.8 < \alpha < 1.2$, equivalent to obtaining the posterior likelihood assuming a flat prior on α in this range. This posterior likelihood will be released as a $\chi^2(\alpha)$ lookup table after this work has been accepted for publication.

In the interest of reporting a meaningful summary statistic, we restricted ourselves to the fraction of mock realizations in which the BAO feature was detected (92 per cent), and calculated the error in α by demanding $\Delta\chi^2 = 1$ relative to the maximum likelihood point. This is the error that we report throughout. Our approach matches that of [Ross et al. \(2015a\)](#) and [Ata et al. \(2017\)](#), who faced similar issues. When restricting ourselves to mock galaxy catalogs with a BAO detection, we found that this error corresponds to a 68 per cent confidence region (see DES-BAO- θ -METHOD for details, where alternative approaches are also explored and where the approach we adopt is determined to be the best option). Thus, while this quantity is not formally a 68 per cent confidence region for our posterior likelihood, we have opted for utilizing this quantity as a summary statistic. In practice, all cosmological inferences from our results will utilize our full posterior likelihood.

4 TESTS ON MOCKS

In this section, we report the results of testing our BAO fitting methodology on the 1800 mock realizations. We test fits to both the mean of these mocks and each mock individually. These tests inform how we obtain our final consensus Y1 BAO measurement and how we decide fiducial settings such as bin size and the range of scales considered. We report the results of tests for each clustering statistic we present BAO measurements for. Additional tests for $\xi(s_\perp)$ and $w(\theta)$ measurements can be found in DES-BAO- s_\perp -METHOD and DES-BAO- θ -METHOD, with implications beyond the DES Y1 sample. The motivation for fiducial choices for the $w(\theta)$ analysis are described in DES-BAO- θ -METHOD. We divide the section into tests done on the mean of the mocks (giving us one data vector with the signal to noise for 1800 DES Y1) and tests

Table 2. The expected uncertainty for DES Y1 data, assuming a Gaussian likelihood applied to the mean $\xi(s_\perp)$ obtained from 1800 mock realizations, as a function of the s_\perp binning that is used. See text for details.

binning	σ_G
0.6 < z < 1.0:	
$\Delta s_\perp = 5h^{-1}\text{Mpc}$	0.054
$\Delta s_\perp = 8h^{-1}\text{Mpc}$	0.053
$\Delta s_\perp = 10h^{-1}\text{Mpc}$	0.052
$\Delta s_\perp = 12h^{-1}\text{Mpc}$	0.051
$\Delta s_\perp = 15h^{-1}\text{Mpc}$	0.052
$\Delta s_\perp = 20h^{-1}\text{Mpc}$	0.059

done on each individual mock (providing distributions for the signal to noise we should expect to recover).

4.1 Test on mean statistics

The total number of mock realizations has high signal to noise. In principle, we should divide our covariance matrix by 1800 in order to fit the mean of the mocks. However, we are primarily interested in the uncertainty we should expect for DES Y1, and thus we will quote results obtained either from the nominal covariance matrix for DES Y1 or with the appropriate scaling.

First, we determine the fiducial bin size for the $\xi(s_\perp)$ analysis by fitting to the mean $\xi(s_\perp)$ of the 1800 mock realizations. If not for noise from the covariance matrix, using the smallest bin size possible would always maximize the signal to noise. However, the noise in the covariance matrix increases with its number of elements and thus the optimal bin size will be somewhat greater than the size where significant information starts to be lost. The signal to noise for one realization is such that the likelihoods are typically non-Gaussian. As the signal to noise of BAO measurements increases, the likelihoods typically become well-approximated by Gaussians (e.g., compare [Ross et al. 2015a](#) to [Anderson et al. 2014](#)). To take advantage of this, we divide the DES Y1 covariance matrix obtained from the mocks by 10 and obtain the likelihood. We then obtain α and σ as usual but define a ‘Gaussian’ uncertainty $\sigma_G = \sqrt{10}\sigma$. The results are unchanged if we use a factor of 20 rather than our factor of 10. The results are presented in Table 2. We find that the optimal results are expected for a bin size of $12h^{-1}\text{Mpc}$. This is significantly greater than the optimal bin size typically found for spectroscopic surveys; a potential explanation is that the redshift uncertainty has significantly smeared the BAO, making a narrow bin size less important for recovering the total signal (see figure 1 of [Ross et al. 2017b](#)).

Table 3 displays results for fits to the mean of the 1800 mocks, using the DES Y1 covariance matrix. For our fiducial analysis choices, we expect an uncertainty of just greater than 5 per cent. We also see that choosing $s_{\perp,\text{min}} = 30h^{-1}\text{Mpc}$ opposed to $50h^{-1}\text{Mpc}$ improves the results both in terms of the bias in α and the recovered uncertainty. For $w(\theta)$ using a larger bin size of 0.3 degrees improves the results compared to 0.15 degrees. This is due to the fact that the number of elements in the covariance matrix is reduced from 120^2 to 60^2 , significantly reducing the required correction factors. DES-BAO- θ -METHOD reports further tests of the bin size, suggesting no significant improvement is to be achieved compared to the fiducial 0.3 degree bin size. We further see that we expect to recover slightly smaller uncertainties from ξ compared to

Table 3. BAO fits to the mean Y1 mocks. The α values suggest how biased our fitting methods are and the σ represents something akin to a Fisher matrix prediction for the precision we should achieve on the data. The fiducial analysis choices for $\xi(s_{\perp})$ are $30 \leq s_{\perp} < 200h^{-1}\text{Mpc}$ and $\Delta s_{\perp} = 12h^{-1}\text{Mpc}$. For $w(\theta)$, they are $0.5 < \theta < 5$ degrees and $\Delta\theta = 0.3$ degrees.

case	α
$0.6 < z < 1.0$:	
$w(\theta)$	1.003 ± 0.055
$w(\theta), \theta_{\min} = 1$ deg	1.003 ± 0.055
$w(\theta), \Delta\theta = 0.15$ deg	1.004 ± 0.057
C_{ℓ}	1.009 ± 0.056
ξ	1.007 ± 0.052
$\xi, s_{\perp, \min} = 50h^{-1}\text{Mpc}$	1.008 ± 0.052
$\xi, \Sigma_{\text{nl}} = 4h^{-1}\text{Mpc}$	1.005 ± 0.045
$\xi, \Sigma_{\text{nl}} = 12h^{-1}\text{Mpc}$	1.009 ± 0.065

$w(\theta)$ or C_{ℓ} , but this is at most a 5 per cent difference. Further tests of the C_{ℓ} are detailed in [Camacho et al. \(in prep.\)](#).

The α obtained from the mean of the mocks is biased high for all three methods we have tested. For the uncertainty expected from a single Y1 realization, it is a 0.06σ (0.003) bias for $w(\theta)$, 0.13σ (0.007) for ξ , and 0.16σ (0.009) for C_{ℓ} . This is small enough to not be a significant concern for the Y1 signal to noise. However, given that this is the mean of 1800 mocks, the significance of the detection of a bias is 6.8σ for C_{ℓ} , 5.6σ for ξ , and only 2.3σ for $w(\theta)$. This suggests it is a true bias that will need to be addressed as the signal to noise increases for future data samples. We will use the $w(\theta)$ results for our DES Y1 measurement, where the bias is only of marginal significance. As detailed in, e.g., both [Crocce & Scoccimarro \(2008\)](#) and [Padmanabhan & White \(2009\)](#), a small positive bias is expected from non-linear structure growth, which could explain ~ 0.003 worth of the bias and thus fully account for the $w(\theta)$ results.

4.2 Tests on individual mocks

Results obtained from fitting each individual mock realization are shown in Table 4. We denote the mean and standard deviation of any measured quantity x across realizations using $\langle x \rangle$ and S_x . Results are shown for cases where there is a $\Delta\chi^2 = 1$ region within $0.8 < \alpha < 1.2$; these are referred to as ‘detections’ (and those mocks where this is not the case are ‘non-detections’). For $\xi(s_{\perp})$ just over 91 per cent of the mocks yield a detection while for $w(\theta)$ it is just less than 90 per cent. The results are generally consistent with the tests on the mean of the mocks. We learn that the standard deviation and mean uncertainties are matched to within 4 per cent. The mean uncertainties are generally slightly smaller than the standard deviations, reflecting the fact that the likelihoods have non-Gaussian tails and we are using $\Delta\chi^2 = 1$ to quote the uncertainty.

For all three methods, the biases in α have decreased slightly, though this is likely due to our detection criteria within $0.8 < \alpha < 1.2$ (since it is symmetric around $\alpha = 1$ instead of $\alpha \sim 1.005$). The uncertainties for $w(\theta)$ are only 5 per cent greater than for ξ , and the C_{ℓ} results are somewhat less precise than the $w(\theta)$ results. In configuration space, varying the bin size or minimum scale does not reveal any large changes in the results. Further tests are performed on the C_{ℓ} measurements in [Camacho et al. \(in prep.\)](#), while comparisons between them and $w(\theta)$ measurements are presented

Table 4. Statistics for BAO fits on mocks. $\langle \alpha \rangle$ is either the BAO dilation-scale measured from the correlation function averaged over all of the mocks (denoted ‘mean’), or the mean of the set of dilation-scales recovered from mocks with $> 1\sigma$ BAO detections. $\langle \sigma \rangle$ is the same for the uncertainty obtained from $\Delta\chi^2 = 1$ region. S is the standard deviation of the α recovered from the mock realizations with $> 1\sigma$ BAO detections and $f(N_{\text{det}})$ is the fraction of realizations satisfying the given condition.

case	$\langle \alpha \rangle$	$\langle \sigma \rangle$	S_{α}	$f(N_{\text{det}})$
$0.6 < z < 1.0$:				
$\xi + w$	1.004	0.050	0.050	0.917
$w(\theta)$	1.001	0.051	0.054	0.898
$w(\theta), \Delta\theta = 0.15$ deg	1.001	0.054	0.055	0.907
$w(\theta), \theta_{\min} = 1$ deg	1.002	0.051	0.053	0.898
C_{ℓ}	1.007	0.058	0.053	0.864
ξ (bins combined)	1.004	0.048	0.050	0.916
$\xi, +0h^{-1}$ Mpc	1.004	0.048	0.050	0.916
$\xi, +3h^{-1}$ Mpc	1.004	0.048	0.051	0.916
$\xi, +6h^{-1}$ Mpc	1.005	0.048	0.050	0.916
$\xi, +9h^{-1}$ Mpc	1.005	0.048	0.050	0.921
$\xi, s_{\perp, \min} = 50h^{-1}$ Mpc	1.005	0.049	0.050	0.913
$\xi, \Delta s_{\perp} = 5h^{-1}$ Mpc	1.005	0.050	0.051	0.918
$\xi, \Delta s_{\perp} = 10h^{-1}$ Mpc	1.005	0.049	0.050	0.916
$\xi, \Delta s_{\perp} = 15h^{-1}$ Mpc	1.004	0.048	0.051	0.911

in Appendix B. In this work, the C_{ℓ} are presented primarily for comparison, rather than for use as the primary DES Y1 measurement, but based on these results we expect to use C_{ℓ} results more extensively in future analyses.

For $\xi(s_{\perp})$, we also vary the center of the bin, in steps of $3h^{-1}\text{Mpc}$, and combine the results by taking the mean of the resulting four likelihoods. This process is similar to that of [Ross et al. \(2015a\)](#) and [Ata et al. \(2017\)](#), where it was found such a procedure provides small improvements in the accuracy of both the recovered α and its uncertainty. We find that this process has a small effect on the results. The standard deviation is not improved at the level reported in Table 4, but comparing the combined result to the $+0h^{-1}\text{Mpc}$ result, there is a one per cent improvement in the standard deviation for the combined results. The biggest change from combining the likelihoods is that there is somewhat less dispersion in the uncertainty recovered from the likelihood. In the $+0h^{-1}\text{Mpc}$ case, the standard deviation of the uncertainties is 0.018, while after combining it is reduced to 0.017. We also determine the standard deviation of the scatter, per mock, for the results in each of the four bin centers. We find 0.004 (so this is the level of difference we expect to find when repeating these tests on the DES Y1 data).

Fig. 2 compares the results of BAO fits to the mocks for ξ and $w(\theta)$ using white circles. The results are shown only for realizations that have a detection for both statistics, which is 1565 realizations (87 per cent). Stars represent the results for the DES Y1 data and are discussed in Section 5. The bottom panel displays the results for the value of α . As expected, the two results are correlated, though there is significant scatter. The correlation factor is 0.81, while for these realizations the standard deviation in the ξ results is 0.048 and it is 0.051 for $w(\theta)$. Taking their mean, the standard deviation is reduced to 0.047; this suggests some small gain is possible from combining the measurements. The top panel displays the results for the recovered uncertainty. ξ recovers a lower uncertainty on average, but there is a large amount of scatter. We test our results when taking the mean of the $\xi(s_{\perp})$ and $w(\theta)$ likelihoods, labeled ‘ $\xi + w$ ’ in Table 4. We find mean uncertainty matching the

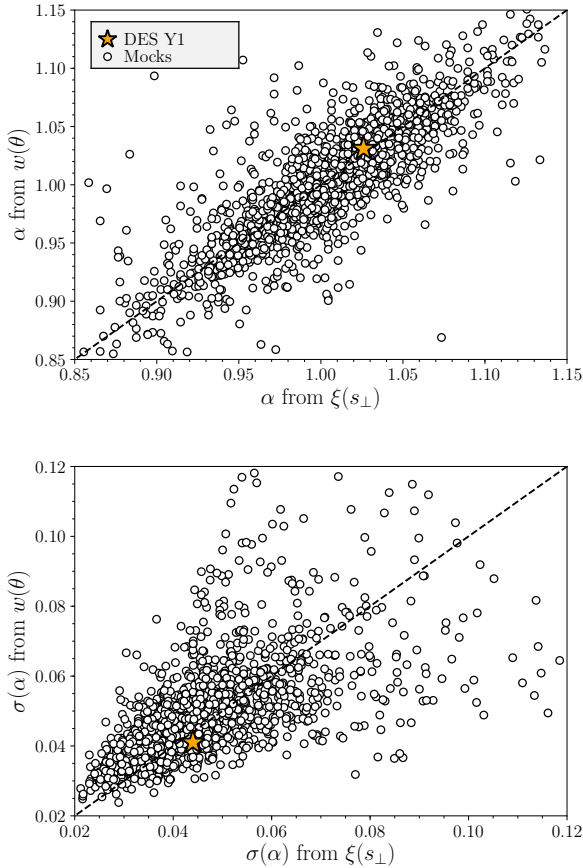


Figure 2. A comparison of $w(\theta)$ and $\xi(s_{\perp})$ BAO fit parameter α and its uncertainty performed on mock realizations (white circles) and the DES Y1 data (stars). The mock realizations are for $0.6 < z < 1.0$. The uncertainty, σ , is obtained from the $\Delta\chi^2 = 1$ definition (see text).

standard deviation at 0.050 and the highest fraction of ‘detections’. However, the gain in the precision from the combination is similar to the shift in α (away from the unbiased value of 1), suggesting the gain from combining the results is not worthwhile for the cases where $w(\theta)$ has sufficient signal to noise on its own for a robust measurement.

The strength of the BAO feature, and thus its signal to noise, in any particular realization of the data can vary. This is clear from the wide range of uncertainties shown in Fig. 2, and is consistent with previous BAO analyses (see, e.g., figure 10 of Ata et al. 2017). We can use the mocks to determine the extent to which the scatter in the uncertainties recovered from the likelihood are truly representative of the variance in the ability to estimate the BAO parameter α . We do so by dividing the mock samples into bins based on the recovered uncertainty and comparing to the standard deviation of α values in each bin, using the mean of the $\xi + w$ likelihoods. Dividing into bins with approximately the same number of mocks in each (to within 30 mocks), the mean uncertainty and standard deviations are $\langle\sigma\rangle, S_{\alpha} = (0.035, 0.039), (0.043, 0.049), (0.052, 0.054), (0.073, 0.055)$. For the mock realizations with the highest uncertainty, the scatter in α values is significantly smaller. This is likely due to the fact that the α values must lie within $(0.8+\sigma, 1.2-\sigma)$ in order to be counted as a detection and this therefore decreases their standard deviation.

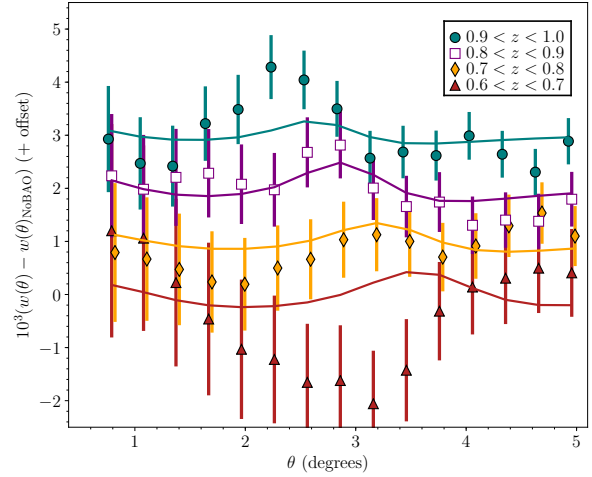


Figure 3. The BAO signal in DES Y1 clustering, observed in the angular auto-correlation, $w(\theta)$ and isolated by subtracting the no BAO component of the best-fit model. The result has been multiplied by 10^3 and we add vertical offsets of 0, 1, 2, and 3 sequentially with redshift. The θ values have been shifted by 0.03 for the $0.7 < z < 0.8$ and by -0.03 for the $0.9 < z < 1.0$ redshift bins. The BAO feature moves to lower θ at higher redshift, as it has the same co-moving physical scale. The signal from these redshift bins is combined, accounting for the covariance between them, in order to provide a 4 per cent angular diameter distance measurement at the effective redshift of the full sample. Neighboring data points are strongly correlated. The total χ^2/dof (including all cross-covariance between redshift bins) is 53/43 and other studies show that, despite its appearance, the $0.6 < z < 0.7$ bin has a $\chi^2/\text{dof} \sim 1$.

At lower values of uncertainty, there is a clear correlation between the mean recovered uncertainty and the scatter in best-fit α . The standard deviations are found to be somewhat larger than the mean uncertainties, likely due to the fact that the likelihoods are non-Gaussian. These results suggest that, generally, we can trust the individual likelihoods (more so than, e.g., taking the mean shape and width of the likelihood of the mocks), especially in the cases with the best apparent signal to noise.

5 RESULTS

Here we focus only on the BAO signal. The validation of the full shape of the clustering signal of the DES Y1 BAO sample is presented in DES-BAO-MOCKS and DES-BAO-SAMPLE. DES-BAO-MOCKS shows that both the angular and $\xi(s_{\perp})$ clustering measurements agree well with the clustering in the mock samples. DES-BAO-SAMPLE shows that the clustering is well-matched to expectations of linear theory in all of our redshift bins and that the galaxy bias evolves from approximately 1.8 to 2.0 within our $0.6 < z < 1.0$ redshift range. DES-BAO-SAMPLE also shows that the impact from observational systematics, determined by comparing the clustering with and without the systematics weights, is small. Harmonic space measurements and interpretation are presented in DES-BAO- ℓ -METHOD. We present the configuration space DES Y1 BAO signal, determined by subtracting the ‘no wiggle’ component (see Eq. 15 and surrounding discussion) of the best-fit model (labeled as ‘noBAO’ in figures). We present the DES Y1 measurements of the angular diameter distance to $z = 0.81$ in the following subsection and describe the series of robustness tests we apply to the data in Section 5.2.

Table 5. Results for BAO fits to the Y1 data. The top line quotes our consensus DES Y1 result from $w(\theta)$ in terms of the physical distance ratio $D_A(z = 0.81)/r_d$. The other lines report measurements of α , which represent the measured shift in $D_A(z = 0.81)/r_d$ relative to our fiducial MICE cosmology; e.g., the value expected for Planck Λ CDM is $\alpha = 1.042$. All results assume a flat prior $0.8 < \alpha < 1.2$. Robustness tests against our fiducial analysis settings are reported. These settings include: We use the full $0.6 < z < 1.0$ data set; the binning in $w(\theta)$ is 0.3 degrees and its range is $0.5 < \theta < 5$ degrees; the binning in ξ is $\Delta s_\perp = 12h^{-1}\text{Mpc}$, the range of included bin centres is $30 < s_\perp < 200h^{-1}\text{Mpc}$, and the first included bin centre allows pairs with $27 < s_\perp < 39h^{-1}\text{Mpc}$. The ‘bins combined’ ξ result is derived from the mean likelihood of the fiducial result and three additional bin centres, shifted in steps of $3h^{-1}\text{Mpc}$ (and each individual result is denoted below by +/-x). ‘BPZ’ denotes that the BPZ photozs were used, as opposed to the fiducial DNF and ‘z uncal’ refers to the case where we use the redshift distribution reported by DNF without any additional calibration for determining the theoretical template. For cases where we alter the assumed Σ_{nI} in the template, the units of the quoted values are $h^{-1}\text{Mpc}$; the fiducial values are $8h^{-1}\text{Mpc}$ for ξ and $5.2h^{-1}\text{Mpc}$ for $w(\theta)$. ‘Planck’ denotes the case where a cosmology consistent with Planck Λ CDM has been used to calculate paircounts and the BAO template.

Y1 Measurement	D_A/r_d	
$z_{\text{eff}} = 0.81$	10.75 ± 0.43	
case	α	χ^2/dof
$w(\theta)$ [consensus]	1.033 ± 0.041	53/43
ξ (bins combined)	1.026 ± 0.044	9/9
Robustness tests:		
C_ℓ	1.023 ± 0.047	94/63
$w(\theta)$ fiducial	1.033 ± 0.041	53/43
$w(\theta) \Delta\theta = 0.15$	1.033 ± 0.045	159/103
$w(\theta) \theta_{\text{min}} = 1$	1.038 ± 0.038	50/39
$w(\theta)$ Planck $\times 1.042$	1.034 ± 0.041	52/43
$w(\theta)$ BPZ	1.018 ± 0.043	56/43
$w(\theta)$ z uncal	1.023 ± 0.040	52/43
$w(\theta)$ no w_{sys}	1.028 ± 0.039	51/43
$w(\theta) \Sigma_{\text{nI}} = 2.6$	1.028 ± 0.035	51/43
$w(\theta) \Sigma_{\text{nI}} = 7.8$	1.033 ± 0.056	55/43
$w(\theta)$ free Σ_{nI}	1.028 ± 0.033	51/42
$w(\theta) 0.7 < z < 1.0$	1.053 ± 0.040	37/32
ξ fiducial binning	1.031 ± 0.040	9/9
$\xi -3$	1.031 ± 0.045	12/9
$\xi +3$	1.017 ± 0.041	8/9
$\xi +6$	1.025 ± 0.050	7/8
$\xi \Delta s_\perp = 5$	1.021 ± 0.041	45/29
$\xi \Delta s_\perp = 8$	1.029 ± 0.046	31/16
$\xi \Delta s_\perp = 10$	1.022 ± 0.037	16/12
$\xi \Delta s_\perp = 15$	1.012 ± 0.039	7.5/6
$\xi s_{\perp, \text{min}} = 50$	1.032 ± 0.046	8/7
ξ Planck $\times 1.042$	1.018 ± 0.041	7/9
ξ BPZ	1.012 ± 0.040	12/9
ξ no w_{sys}	1.029 ± 0.040	10/9
$\xi \Sigma_{\text{nI}} = 4$	1.023 ± 0.038	9/9
$\xi \Sigma_{\text{nI}} = 12$	1.043 ± 0.052	11/9
$\xi \Sigma_{\text{nI}}$ free	1.024 ± 0.039	9/9
$\xi 0.7 < z < 1.0$	1.052 ± 0.031	17/9

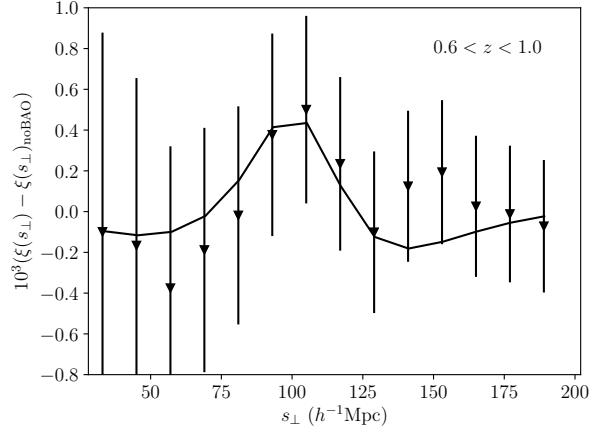


Figure 4. The BAO signal in DES Y1 clustering, observed in the auto-correlation binned in projected physical separation, $\xi(s_\perp)$, and isolated by subtracting the no BAO component of the best-fit model. Neighboring data points are strongly correlated.

5.1 BAO Measurements

Here, we present the best-fit BAO results and likelihoods. Table 5 lists our BAO measurements for the DES Y1 data and robustness tests on these data. We find similar results for $w(\theta)$ and $\xi(s_\perp)$, both in terms of α and its uncertainty. Fig. 2 displays these results for our DES Y1 data using orange stars for $0.6 < z < 1.0$ and yellow stars for $0.7 < z < 1.0$. Clearly, our results are consistent within the expected scatter.

Fig. 3 displays the BAO signal we measure in $w(\theta)$. To make this plot, we have subtracted the model obtained when using the same best-fit parameters but using the smooth $w(\theta)_{\text{noBAO}}$ template (obtained from P_{nw}). In order to plot each redshift bin clearly, we have added significant vertical offsets (and some small horizontal ones). One can see that the BAO feature in the model moves to lower values of θ as the redshift increases, as the co-moving location of the BAO feature is constant. Such a pattern is observed in the data for $z > 0.7$. The combination of these four $w(\theta)$ measurements, accounting for the covariance between the redshift bins, yields a measurement of $\alpha = 1.031 \pm 0.041$, i.e., approximately a 3 per cent greater angular diameter distance than predicted by our fiducial cosmology, but with 4 per cent uncertainty. The overall fit to the DES Y1 data is acceptable, as a $\chi^2 = 53$ for 43 degrees of freedom has a p -value of 0.14. Despite its appearance, the $0.6 < z < 0.7$ does not have a substantial affect on the goodness of fit; as the best-fit has a $\chi^2/\text{dof} = 37/32$ when these data are removed.

Fig. 4 displays the DES Y1 BAO signal in $\xi(s_\perp)$ using $0.6 < z < 1.0$, again by subtracting the no BAO component of the best-fit model. This represents the result listed as ‘fiducial’ in Table 5. The $\chi^2 = 9$ for 9 dof. This result is chosen as the fiducial result ξ (from among four choices of bin center) as it has very similar signal to noise and best fit value as the $w(\theta)$ result, which we will use for our DES Y1 measurement, and thus represents a highly compressed illustration of the DES Y1 BAO signal. The ξ result we quote as ‘combined’ in Table 5 is obtained from the mean likelihood of four ξ results, each using a bin size of $12h^{-1}\text{Mpc}$ with the bin size shifted in increments of $3h^{-1}\text{Mpc}$; this procedure of taking the mean across the bin centers was demonstrated to slightly improve the results for mock data in Section 4. This result is similar to the $w(\theta)$ result, with a slightly greater uncertainty. Comparing the orange stars to the white circles in Fig 2 indicates that the differences we find in the $w(\theta)$ and $\xi(s_\perp)$ results are typical.

We recover, for both $w(\theta)$ and $\xi(s_\perp)$, a smaller uncertainty when we ignore the $0.6 < z < 0.7$ data; i.e., the signal to noise appears greater in the $0.7 < z < 1.0$ sample than for the $0.6 < z < 1.0$ data. This is, of course, unexpected. In Appendix A, we compare results obtained from mock realizations using both redshift ranges. We find that eight per cent of the realizations obtain an uncertainty that is improved by a greater factor than we find for DES Y1 when ignoring the $0.6 < z < 0.7$ data (and 30 per cent satisfy the condition that the $0.7 < z < 1.0$ uncertainty is less than the $0.6 < z < 1.0$ uncertainty). This eight per cent becomes more significant when one considers that to truly consider how likely the result is, we would have to test removing all independent equal sized volumes, not just those with $0.6 < z < 0.7$. These eight per cent of cases are thus not particularly unusual. Studying them further, we find that the $0.6 < z < 1.0$ results are more trust-worthy, but the uncertainty on α is likely over-estimated. Thus, we use the full $0.6 < z < 1.0$ data set for our DES Y1 result as this is the more conservative choice. A final decision to be made is how to treat the $w(\theta)$ and $\xi(s_\perp)$ results. Given that the $w(\theta)$ results are

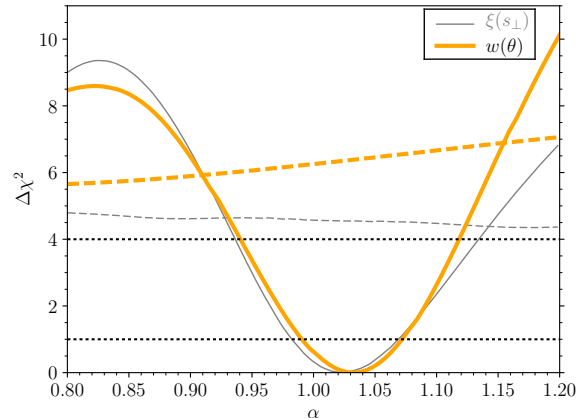


Figure 5. The BAO likelihood for DES Y1 data, for $w(\theta)$ and $\xi(s_\perp)$. The dashed line shows the result for a model with no BAO, indicating that the data prefers a BAO feature at greater than 2σ significance. The dotted black lines denote 1 and 2σ , based on $x\sigma = \sqrt{\Delta\chi^2}$.

more precise in the $0.6 < z < 1.0$ redshift range, are less biased when tested on the mock samples, and are less dependent on the choice of damping scale (see next subsection), we use the $w(\theta)$ results as our consensus DES Y1 measurement.

Fig. 5 displays the $\Delta\chi^2$ likelihood for α using $w(\theta)$ and $\xi(s_\perp)$. The dashed line is for the no BAO model (derived from P_{nw}). We find a preference for BAO that is greater than 2σ for both $w(\theta)$ and $\xi(s_\perp)$. The $w(\theta)$ and $\xi(s_\perp)$ likelihoods are close near the maximum likelihood, but diverge at high α values. Thus, our $\Delta\chi^2 = 1$ definition for α and its uncertainty recovers results that agree quite well. A summary of the differences is that ξ rejects low α with slightly greater significance and $w(\theta)$ rejects high α with greater significance. We use the full $w(\theta)$ likelihood for any cosmological tests, as the Gaussian approximation is clearly poor outside of the $\sim 1\sigma$ region.

5.2 Robustness Tests

We vary our methodology in a variety of ways in order to test the robustness of our results. We have already shown that ξ and $w(\theta)$ obtain consistent results and that the change in results when eliminating $0.6 < z < 0.7$ data are consistent with expectations based on tests on mock realizations. Here, we consider how the results change with different modeling assumptions, changes in the range of scales used, the bin size, the use of the systematic weights, the choice of photometric redshifts, and if a harmonic-space estimator is used instead of the configuration space ones. The results are tabulated in the bottom rows of Table 5.

In harmonic space (labeled ‘ C_ℓ ’ in Table 5), we find a shift in α of approximately 0.5σ compared to the $w(\theta)$ measurement and slightly greater uncertainty for C_ℓ . These are preliminary results based on the methodology to be finalized in Camacho et al. (in prep.). As shown in Appendix B, such differences are typical for the mock results. In general, its level of shift matches the 1σ expectation for Gaussian-distributed results with a correlation of 0.9. The correlation between the mock $w(\theta)$ and C_ℓ results is 0.77. We are therefore satisfied with the agreement between configuration and harmonic space results. The $\chi^2/\text{dof} = 94/63$ we obtain for the

C_ℓ fit is slightly high. The formal p -value is 0.007, suggesting that the result is unlikely. For DES Y1, the C_ℓ methodology continues to mature as we end this study and we therefore choose to use the current preliminary results only as a robustness test. However, we expect to incorporate C_ℓ results into future DES consensus results.

One significant concern in our work is the use of photometric redshifts. Throughout, we have assumed the fiducial $\phi(z_{\text{true}})$ results obtained from the redshift validation performed in DES-BAO-PHOTOZ and described in DES-BAO-SAMPLE are correct. However, the impact of this validation on our recovered results is relatively small. The output of DNF provides an initial estimate of the redshift distribution, which we also used to produce $w(\theta)$ BAO templates. Using these BAO templates, labeled ‘z uncal’ in Table 5, our measurement by only 0.25σ towards a smaller α value. DES-BAO-PHOTOZ produces more accurate determinations of the redshift distributions and estimate that the uncertainties in the mean redshift obtained from the redshift validation are less than 0.8 per cent at all redshifts, i.e., $\sigma(\bar{z})/\bar{z} < 0.008$. Converting this to a systematic uncertainty on our α measurement recovers 0.006. This is 15 per cent of our statistical uncertainty and thus negligible for this DES Y1 analysis. More detailed tests are shown in DES-BAO-METHOD.

An additional test of the robustness to redshift uncertainties is to use a different method, BPZ, to estimate the photometric redshifts and reproduce the sample and measurements. For this test, we still use the covariance obtained from the fiducial 1800 mock realizations with redshift distributions matched to our fiducial DNF photometric redshifts. However, the BAO templates for the measurements are produced using the BPZ redshift distributions estimated by DES-BAO-PHOTOZ. As for DNF, we find similar results for $w(\theta)$ and ξ , as each shifts to a slightly smaller value of α . This is a 0.32σ shift for ξ and 0.37σ for $w(\theta)$. For $w(\theta)$, this is the level of shift expected if the two samples have a correlation, c , of 0.93 (calculated via $\sigma = \sqrt{2 - 2 * c}$). Given that only 88 per cent of the galaxies used are the same (it is less than 100 per cent because galaxies scatter across the redshift boundaries) and the number of matches per $\Delta z = 0.1$ redshift bin is at most 56 per cent, we are confident the expected correlation in BAO results obtained from the two redshift estimates is less than 0.93. We therefore conclude the differences in the results between the two redshift estimates are not statistically significant.

The damping scale that we assume in our BAO template affects our results, mostly in terms of the recovered uncertainty for $w(\theta)$ (which we use for our Y1 measurement). For both $w(\theta)$ and ξ , we test both halving our fiducial scale and making it 50 per cent greater. For $w(\theta)$, using the low damping scale shifts α lower by 0.005 (0.12σ) and decreases the uncertainty by 15 per cent. Using the greater damping scale does not shift α but increases the uncertainty by 37 per cent. The data slightly prefer the lower damping scale, as $\Delta\chi^2 = 2$ compared to the fiducial case. Allowing the damping to be free has a best-fit at low Σ_{nI} values and thus significantly reduces the uncertainty but shifts α (lower) by only 0.12σ . Thus, the distance obtained from our $w(\theta)$ results used for our DES Y1 measurement is robust to the choice of damping scale. The uncertainty on the measurement depends fairly strongly on how the damping scale is treated, and we thus choose to use the damping scale that is best-fit to our mock samples, $\Sigma_{\text{nI}} = 5.2h^{-1}\text{Mpc}$, which is close to theoretical expectations.

For $\xi(s_\perp)$, we find a similar effect on the uncertainty and greater shifts in the recovered α . The α values shift by $\sim \pm 0.25\sigma$. Allowing Σ_{nI} to be a free parameter yields a result that is close to the result for $\Sigma_{\text{nI}} = 4h^{-1}\text{Mpc}$, as, similar to $w(\theta)$, the DES Y1

data slightly prefers the smaller damping scale. Thus, marginalizing over Σ_{nI} results in a smaller estimated uncertainty. Therefore, as with $w(\theta)$, we choose to use the results with the fixed damping scale as our measurement. However, for the DES Y1 data set the $\xi(s_\perp)$ results are not as robust to the choice of damping value as $w(\theta)$, which is one of the reasons we use the $w(\theta)$ results as our consensus DES Y1 measurement.

When ignoring the systematic weights, we find almost no change in the recovered BAO measurements. The change is greatest for $w(\theta)$, but only 0.13σ . This is consistent with results from spectroscopic surveys (Ross et al. 2017a; Ata et al. 2017), which have consistently demonstrated that BAO measurements are robust to observational systematic effects. Additionally, no large deviations are found when the bin size or range of scale fit are changed.

As a final test, we obtain results when we assume a cosmology consistent with Planck ΛCDM (Planck Collaboration et al. 2016) for calculating both the pair counts and BAO template. For this, we use the same fiducial cosmology recently assumed in Alam et al. (2016), which is flat ΛCDM with $\Omega_{\text{matter}} = 0.31$, $h = 0.676$, and $\Omega_{\text{baryon}}h^2 = 0.022$. When using this cosmology, we expect to obtain an α value that is lower by 1.042, thus in Table 5 we have multiplied the Planck results by 1.042. For ξ , the shift is 0.008 in α (0.18σ) away from the combined result using the MICE cosmology. For ξ , we expect a difference similar to what was found for the bin center tests, as the pair-counts were re-calculated assuming the Planck cosmology; our result is only slightly greater than the variance associated with alternative binnings. For $w(\theta)$, the results using the Planck template are nearly identical to those using the default MICE template as all differences are within 0.001. Thus, we conclude the choice of fiducial cosmology has a negligible effect on our results.

6 COSMOLOGICAL CONTEXT

Our DES Y1 BAO measurement can be used to constrain cosmological models, given the likelihood for α (shown in Fig. 5), our fiducial cosmology, and the effective redshift of our measurement. This requires multiplying the α measurements by $\frac{D_A^{\text{fid}}(z_{\text{eff}})}{r_d} = 10.41$ and testing this against the $\frac{D_A(z_0, s_\perp)}{r_d}$ predicted by any given cosmological model⁶. In the top row of Table 5, we have thus multiplied the $w(\theta)$ results by 10.41 in order to quote our Y1 measurement of $\frac{D_A(z_0, s_\perp)}{r_d} = 10.75 \pm 0.043$.

Fig. 6 displays our measurement, compared to other BAO angular diameter distance measurements and the Planck ΛCDM prediction (with fixed minimal neutrino mass). We include measurements from Beutler et al. (2011) (6dFGS), Ross et al. (2015a) (SDSS MGS), Alam et al. (2016) (BOSS), Kazin et al. (2014) (WiggleZ), Ata et al. (2017) (eBOSS quasars) and the combination of Bautista et al. (2017) and du Mas des Bourboux et al. (2017) (BOSS Ly α). These make up the most up to date, and largely independent, BAO distance ladder. Many of the BAO measurements were made in terms of the spherically averaged distance quantity, which is a combination of the angular diameter distance and $H(z)$. Assuming spherical symmetry, the $D_A(z)$ constraints are 50 per cent less precise (Ross et al. 2015b) and we have thus multiplied the error-bars by 1.5 while fixing the relative $(D_A/r_d)/(D_A/r_d)_{\text{Planck}\Lambda\text{CDM}}$ value to be the same as for spherically averaged measurement.

⁶ We will make our likelihood publicly available after this work has been accepted for publication by the journal.

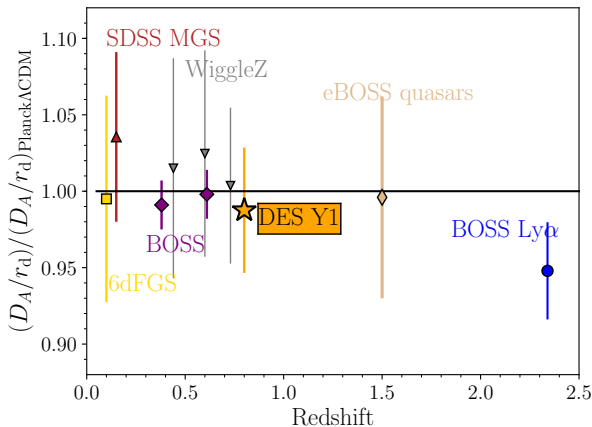


Figure 6. Measurement of the angular diameter distance measured from BAO, compared to the Planck Λ CDM prediction. The DES Y1 measurement is shown using a gold star. The additional measurements are described in the text, but we note that for experiments that measured spherically averaged distances, we have multiplied the uncertainty by 1.5.

The DES Y1 measurement is consistent with expectations from Planck Λ CDM and previous BAO measurements. While the new measurement is not nearly as precise as BOSS measurements, it is the most precise D_A measurement in the range $0.6 < z < 2$. The DES Y1 and the 6dFGS (yellow square) are the only measurements displayed that do not rely on imaging from SDSS. The DES measurement is the only one that does not rely on spectroscopic redshifts. The precision of our measurement is similar to that obtained previously at $z \sim 0.55$ by the combination of Crocce et al. (2011) and Carnero et al. (2012) and independently Seo et al. (2012) using SDSS imaging data and photometric redshifts (not plotted).

We can also compare with the recent DES Y1 results obtained in DES Collaboration et al. 2017a (hereafter ‘DES 3x2pt’). Converting the results from the DES 3x2pt Λ CDM Monte-Carlo Markov Chains to a posterior likelihood for $D_A(0.81)/r_d$, we obtain 10.59 ± 0.44 . Thus, our DES Y1 BAO measurement is in agreement with the results of DES 3x2pt assuming the Λ CDM model.

7 CONCLUSIONS

The results of this study can be summarized as follows:

- We have used a sample of 1.3 million DES Y1 galaxies spread over 1318 deg^2 with $0.6 < z_{\text{photo}} < 1.0$, defined in Crocce et al. (2017) (DES-BAO-SAMPLE), in order to obtain a four per cent measurement of the ratio of the angular diameter distance to $z = 0.81$ to the size of the BAO standard ruler set by early Universe recombination physics: $D_A(z_{\text{eff}} = 0.81)/r_d = 10.75 \pm 0.43$.
- In order to construct covariance matrices and set analysis choices, we have used 1800 mock realizations of the DES Y1 sample, constructed as described in Avila et al. (2017) (DES-BAO-MOCKS). Our DES Y1 results are typical given the distribution of recovered from the 1800 mock realizations.
- We have used two separate projected clustering statistics, one defined in terms of the angular separation ($w(\theta)$), with methodology described in Chan et al. in prep.; DES-BAO- θ -METHOD) and the other defined in terms of the projected physical separation

($\xi(s_{\perp})$), with methodology described in Ross et al. 2017b; DES-BAO- s_{\perp} -METHOD). Each statistic returns consistent results (the difference is 0.17σ in the best-fit value and the uncertainties differ by less than 10 per cent). These differences are consistent with differences found in the mock realizations. The preference for a BAO feature in the data is greater than 2σ for both clustering statistics. We use the $w(\theta)$ result as our consensus DES Y1 measurement.

- We obtain results using two photometric redshift estimates, one machine learning based (DNF) and the other template based (BPZ), and obtain results that are matched to within 0.37σ . The DES Y1 results are based on the DNF results, which are the most precise and accurate as determined by Gaztanaga et al. (in prep.) (DES-BAO-PHOTOZ). The validation provided by DES-BAO-PHOTOZ (and described in DES-BAO-SAMPLE) suggests that uncertainties in the accuracy of the DNF redshifts contribute a negligibly small systematic uncertainty to our DES Y1 BAO measurements.

- We find no significant changes in the $w(\theta)$ BAO measurements when varying the methodology, including omitting corrections for observational systematics and using a different fiducial cosmology.

In short, we find our DES Y1 BAO measurement is robust to a number of stress tests and is consistent with our simulations of the DES Y1 dataset. These results are the first BAO measurement obtained from DES. DES year three (Y3) data has already been observed and occupies the full 5000 deg^2 with greater average coverage in the number of exposures than Y1 over our 1318 deg^2 . With these data, we expect to obtain results with approximately a factor of two smaller statistical uncertainty in the near future. Even so, based on our results, we expect no systematic uncertainties close to the future level of statistical precision. We expect our work can be used as a guide for future imaging surveys such as the Large Synoptic Survey Telescope (LSST; LSST Science Collaboration. 2009).

BAO measurements had previously been proven to be a robust and precise method for measuring cosmological distances when using spectroscopic redshifts (Alam et al. 2016 and references therein). We have obtained a similar level of robustness using a purely photometric data set. Based on this work, we expect DES Y3 data to provide the most precise BAO angular diameter distance measurement, excluding BOSS galaxy results. Further, the increased photometric depth of the Y3 and then final DES data will allow extensions to higher redshifts than probed here. Thus, together with emission line galaxy data from the extended Baryon Oscillation Spectroscopic Survey (eBOSS; Dawson et al. 2016; comparable precision is expected), these data will be the first to use galaxies beyond redshift 1 to measure BAO. These measurements will thus pave the way for those obtained by the Dark Energy Spectroscopic Instrument (DESI; DESI Collaboration et al. 2016a,b) and Euclid (Laureijs et al. 2011; Amendola et al. 2013).

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APPENDIX A: COMPARISON BETWEEN $0.6 < Z < 0.7$ AND $0.7 < Z < 1.0$ RESULTS

As described in Section 5, we obtain more precise BAO measurements when excluding data with $0.6 < z < 0.7$. In this appendix, we use the mock realizations in order to assess how unusual this is and how best to treat the results in such a case. We compare the results of fitting to 1800 mock realizations without using the $0.6 < z < 0.7$ data compared to the full range. This is shown in Fig. A1. 1538 mock realizations (85 per cent) have a detection in both redshift ranges. As to be expected the results are strongly correlated. We see that the recovered uncertainty is usually greater when omitting the $0.6 < z < 0.7$, but this is not always the case. We find 130 (8 per cent) of the mock realizations recover an un-

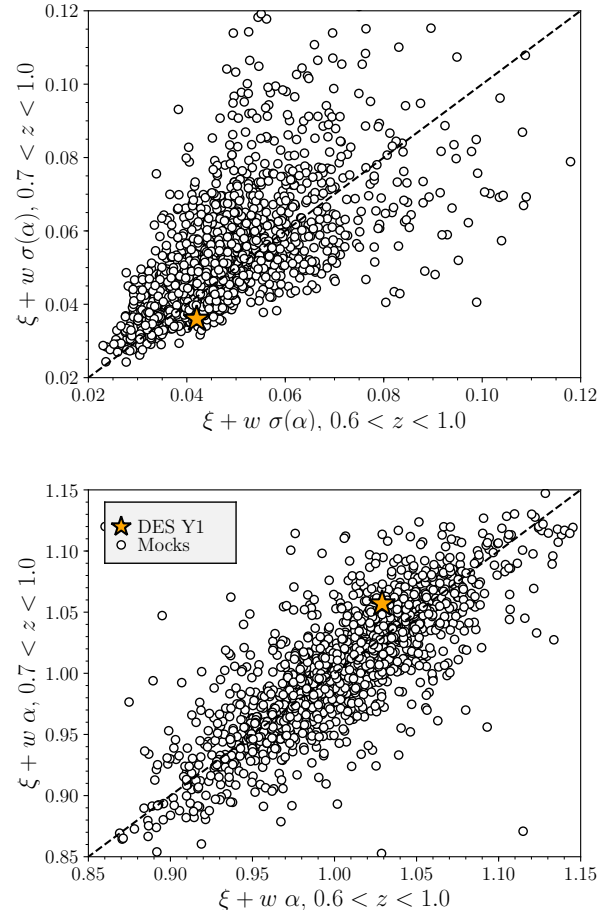


Figure A1. A comparison of $\xi + w$ BAO fit results when using the full $0.6 < z < 1.0$ redshift range and one restricted to $0.7 < z < 1.0$.

certainty $\sigma_1/\sigma_2 > 0.043/0.036$. The values $\sigma = 0.43$ and 0.36 represent the mean of the $w(\theta)$ and $\xi(s_{\perp})$ uncertainties recovered from the DES Y1 data for the respective redshift ranges. Thus, our data measurement is not particularly unlikely in terms of this statistic, even without folding in the look-elsewhere effect, which would further decrease the significance because we are only considering a single anomalous statistic.

As can be seen based on the position of the orange star in the bottom panel of Fig. A1, the value of α shifts when removing the $0.6 < z < 0.7$ data, but remains within the locus of mock realization results. In order to quantify the shift, we consider $|\alpha_1 - \alpha_2|/\sigma_1$ (using 1 to denote $0.6 < z < 1.0$ and 2 to denote $0.7 < z < 1.0$) for each mock realization. We find the quantity is greater than that of the DES Y1 data in 443 (29 per cent) of the mock realizations. Thus, the difference in α is not unusual.

At the end of Section 4, we found a correlation between the mean uncertainty and the scatter in α that suggested the obtained BAO likelihoods can generally be trusted. If this were to be true in all cases, it would suggest we should use only the $0.7 < z < 1.0$ data for our DES Y1 measurement. To test this, we further consider the 8 per cent of mock realizations that exhibit more extreme behavior in the ratio of uncertainties with and without removing the $0.6 < z < 0.7$ data. These realizations have been selected in order to have significantly greater uncertainty for the

$0.6 < z < 1.0$ realizations and we indeed obtain $\langle\sigma_1\rangle = 0.073$ compared to $\langle\sigma_2\rangle = 0.054$. However, the standard deviations are flipped, $S_1 = 0.054$ compared to $S_2 = 0.061$. This suggests that in these cases the uncertainty is significantly over-(under-) estimated for the $0.6 < z < 1.0$ ($0.7 < z < 1.0$) and that the underestimated $0.7 < z < 1.0$ uncertainty is actually a better match to the uncertainty of the $0.6 < z < 1.0$ results. In order to consider cases that are even more similar to our DES Y1 case, we take only the mocks out of this eight per cent that have an uncertainty less than 0.05 for $0.6 < z < 1.0$. This yields only 22 mocks. Their mean uncertainties are $\langle\sigma_1\rangle = 0.046$ and $\langle\sigma_2\rangle = 0.037$, to be compared to standard deviations of $S_1 = 0.047$ and $S_2 = 0.046$. While this is a limited number of mocks, the results are consistent with the conclusion that the uncertainty is under-estimated in the cases where $0.7 < z < 1.0$ yields a lessor uncertainty than the $0.6 < z < 1.0$ data.

The findings can be summarized as

- Eight per cent of the mock realizations are more extreme in terms of the comparison between the recovered $0.6 < z < 1.0$ and $0.7 < z < 1.0$ uncertainties.
- These realizations have been chosen to have worse uncertainties for $0.6 < z < 1.0$; we find $\langle\sigma_\alpha\rangle = 0.073$ for $0.6 < z < 1.0$ and $\langle\sigma_\alpha\rangle = 0.054$ for $0.7 < z < 1.0$.
- For these eight per cent of realizations, we find the standard deviations for the scatter in the recovered α values are 0.054 for $0.6 < z < 1.0$ and 0.061 for $0.7 < z < 1.0$.
- Changing our criteria to be only cases where the $0.6 < z < 1.0$ uncertainty is less than 0.05 (and thus similar to our DES Y1 result) or simply $\sigma_2/\sigma_1 > 1$ (which is true for 30 per cent of the mock cases) yields consistent results.

Thus, for these cases, the uncertainties are generally underestimated for $0.7 < z < 1.0$ and we consider the $0.6 < z < 1.0$ result more trustworthy.

APPENDIX B: COMPARISON BETWEEN ANGULAR POWER SPECTRUM AND CORRELATION FUNCTION RESULTS

Here, we directly compare the BAO results from $w(\theta)$ and C_ℓ measurements, using both the mocks and the DES Y1 data. Fig. B1 compares the recovered uncertainties (top panel) and α values (bottom panel) for each statistic, for the 1502 (83 per cent of) mock realizations that have a $\Delta\chi^2 = 1$ bound within $0.8 < z < 1.2$ for both statistics. As expected, the results are strongly correlated in α , with a correlation factor of 0.80. The orange star represents the α values recovered for the DES Y1 data; the fact that it lies within the locus of points representing the mock realizations suggests the differences we found in α are typical. The same is true for the recovered uncertainty, where there is a fairly large dispersion but the uncertainty recovered from the C_ℓ measurements is greater on average. Correspondingly, for this selection of mock realizations the standard deviation in α is slightly greater for the C_ℓ : 0.052 compared to 0.051. We conclude that the results in configuration and harmonic space are consistent with each other and we expect to incorporate C_ℓ results into our consensus BAO measurements in future DES data analyses.

Fig. B2 reinforces the fact that the $w(\theta)$ and C_ℓ BAO measurements are similar for the Y1 data. The maximum likelihood value is shifted by ~ 0.01 in α , with a similar overall shape. The $w(\theta)$ method recovers a slightly more narrow likelihood, while the

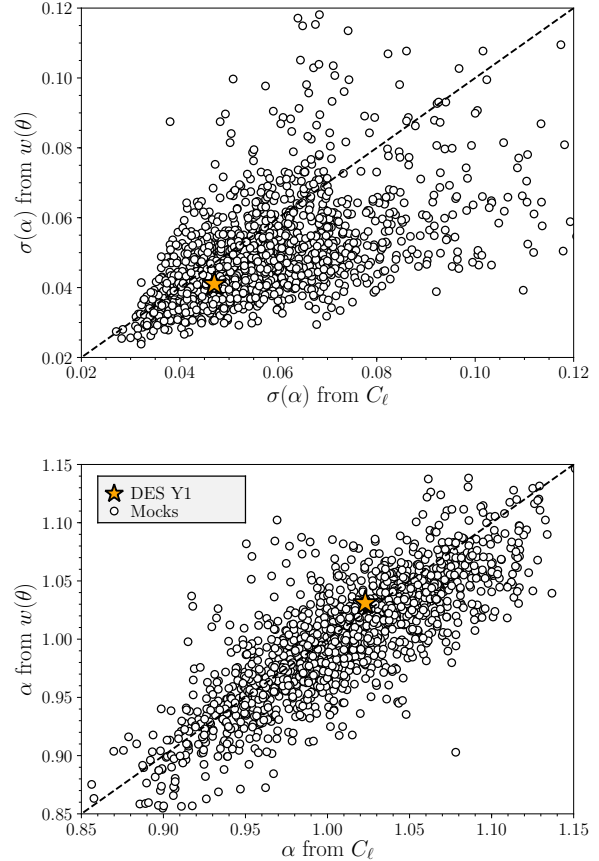


Figure B1. A comparison of BAO results for $w(\theta)$ and C_ℓ , for both the mock realizations (white circles) and the DES Y1 data (orange stars).

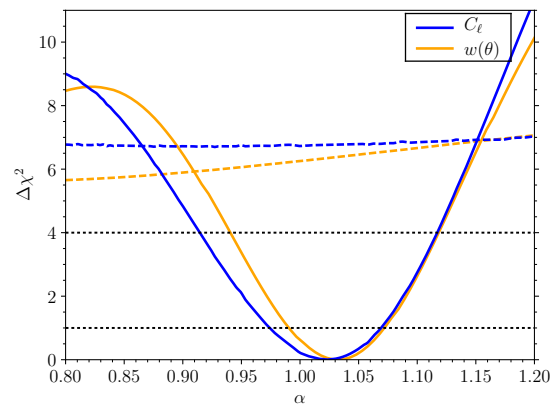


Figure B2. The $\Delta\chi^2$ likelihood for the BAO parameter α , as obtained for DES Y1 data from the configuration space $w(\theta)$ measurements (orange) and from the angular power spectra in spherical harmonics (C_ℓ ; blue). As expected, we recover similar results for each method.

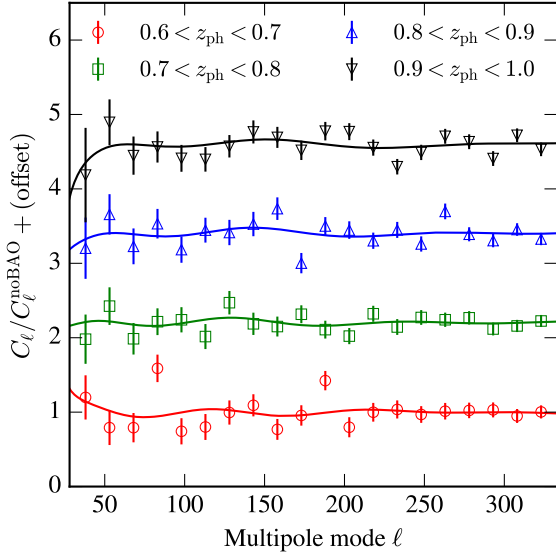


Figure B3. The measured Y1 BAO feature, isolated in spherical harmonic space. From top to bottom, one can see that the BAO feature moves to the left, towards lower ℓ , reflecting the redshift evolution of a feature of constant co-moving size.

C_ℓ measurement more strongly rejects the model without any BAO (shown by the dashed curves).

Finally, Fig. B3 displays the Y1 BAO feature, isolated in harmonic space and compared to the best-fit model. This figure is analogous to 3 for $w(\theta)$. Here, we see that the BAO feature in the model moves towards higher ℓ as the redshift increases and that this behavior is traced by the data points.