

Cosmology and source redshift constraints from galaxy clustering and tomographic weak lensing with HSC Y3 and SDSS using the point-mass correction model

Tianqing Zhang^{1,2,*}, Xiangchong Li^{2,3}, Sunao Sugiyama⁴, Rachel Mandelbaum⁵, Surhud More^{5,6}, Roohi Dalal⁷, Arun Kannawadi⁸, Hironao Miyatake^{6,9,10}, Atsushi J. Nishizawa^{9,11}, Takahiro Nishimichi^{6,12,13}, Masamune Oguri^{6,14,15}, Ken Osato^{6,14,15}, Markus M. Rau^{16,17}, Masato Shirasaki^{18,19}, Tomomi Sunayama^{6,9,20} and Masahiro Takada^{6,21}

¹*Department of Physics and Astronomy and PITT PACC, University of Pittsburgh, Pittsburgh, Pennsylvania 15260, USA*

²*McWilliams Center for Cosmology and Astrophysics, Department of Physics, Carnegie Mellon University, 5000 Forbes Avenue, Pittsburgh, Pennsylvania 15213, USA*

³*Brookhaven National Laboratory, Building 510, Upton, New York 11973, USA*

⁴*Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA*

⁵*The Inter-University Centre for Astronomy and Astrophysics, Post bag 4, Ganeshkhind, Pune 411007, India*

⁶*Kavli Institute for the Physics and Mathematics of the Universe (WPI), The University of Tokyo Institutes for Advanced Study (UTIAS), The University of Tokyo, Chiba 277-8583, Japan*

⁷*American Astronomical Society, 1667 K Street NW 800, Washington, DC 20006, USA*

⁸*Department of Physics, Duke University, Durham, North Carolina 27708, USA*

⁹*Kobayashi-Maskawa Institute for the Origin of Particles and the Universe (KMI), Nagoya University, Nagoya, 464-8602, Japan*

¹⁰*Institute for Advanced Research, Nagoya University, Nagoya 464-8601, Japan*

¹¹*Gifu Shotoku Gakuen University, 1-1 Takakuwanishi, Yanaizu, Gifu, 501-6194, Japan*

¹²*Center for Gravitational Physics, Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606-8502, Japan*

¹³*Department of Astrophysics and Atmospheric Sciences, Faculty of Science, Kyoto Sangyo University, Motoyama, Kamigamo, Kita-ku, Kyoto 603-8555, Japan*

¹⁴*Center for Frontier Science, Chiba University, Chiba 263-8522, Japan*

¹⁵*Department of Physics, Graduate School of Science, Chiba University, Chiba 263-8522, Japan*

¹⁶*School of Mathematics, Statistics and Physics, Newcastle University, Newcastle upon Tyne, NE17RU, United Kingdom*

¹⁷*High Energy Physics Division, Argonne National Laboratory, Lemont, Illinois 60439, USA*

¹⁸*National Astronomical Observatory of Japan, National Institutes of Natural Sciences, Mitaka, Tokyo 181-8588, Japan*

¹⁹*The Institute of Statistical Mathematics, Tachikawa, Tokyo 190-8562, Japan*

²⁰*Academia Sinica Institute of Astronomy and Astrophysics (ASIAA), No. 1, Sec. 4, Roosevelt Road, Taipei 106319, Taiwan, Republic of China*

²¹*Center for Data-Driven Discovery (CD3), Kavli IPMU (WPI), UTIAS, The University of Tokyo, Kashiwa, Chiba 277-8583, Japan*



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The combination of galaxy clustering and weak lensing is a powerful probe of the cosmology model. We present a joint analysis of galaxy clustering and weak lensing cosmology using Sloan Digital Sky Survey (SDSS) data as the tracer of dark matter (lens sample) and the Hyper Suprime-Cam year-3 (HSC Y3) dataset as source galaxies. The analysis divides HSC Y3 galaxies into four tomographic bins for both galaxy-galaxy lensing and cosmic shear measurements and employs a point-mass correction model to utilize galaxy-galaxy lensing signals down to $2 h^{-1}$ Mpc, extending up to $70 h^{-1}$ Mpc. These strategies enhance the signal-to-noise ratio of the galaxy-galaxy lensing data vector. Using a flat Λ CDM model, we

*Contact author: tq.zhang@pitt.edu

find $S_8 = 0.780^{+0.029}_{-0.030}$, and using a w CDM model, we obtain $S_8 = 0.756^{+0.038}_{-0.036}$ with $w = -1.176^{+0.310}_{-0.346}$. We apply uninformative priors on the redshift mean-shift parameters for the third and fourth tomographic bins. Leveraging the self-calibration power of tomographic weak lensing, we measure $\Delta z_3 = -0.112^{+0.046}_{-0.049}$ and $\Delta z_4 = -0.185^{+0.071}_{-0.081}$, in agreement with previous HSC Y3 results. This demonstrates that weak lensing self-calibration can achieve redshift constraints comparable to other methods such as photometric and clustering redshift calibration.

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I. INTRODUCTION

The standard cosmological model describes a Universe composed of regular (baryonic) matter, dark matter, and dark energy. Together, regular and dark matter account for approximately 30% of the total energy density, while dark energy makes up the remaining 70% [1–3]. Dark matter and baryons drive the growth of the large-scale structure (LSS), forming gravitationally bound dark matter halos in which galaxies form and evolve. In contrast, dark energy causes the accelerated expansion of the Universe [4,5], which pushes galaxies and the LSS apart over cosmic time.

Such a cosmological model can be described using fewer than a dozen parameters, several of which are tightly constrained by measurements of galaxy clustering and weak gravitational lensing [6,7], due to their sensitivity to the matter distribution across different epochs. Galaxy clustering assumes that galaxies trace the underlying dark matter distribution with a bias, making the galaxy power spectrum a probe of the LSS. Weak gravitational lensing, on the other hand, leverages the deflection of light from background (source) galaxies to measure the projected matter distribution along the line of sight to foreground structures [8,9].

By correlating the shapes of galaxy pairs at large scale, one measures the integrated two-point lensing effect caused by LSS in the foreground, or cosmic shear [10–14]. Correlation of the shapes of source galaxies with the positions of foreground (lens) galaxies—known as galaxy-galaxy lensing—probes the average projected matter density around those lens galaxies [15,16]. Galaxy clustering can be measured as the position-position two-point correlation function of the lens galaxies. Galaxy clustering, galaxy-galaxy lensing, and cosmic shear each depend differently on galaxy bias. Therefore, a joint analysis of these three two-point correlation functions helps break the degeneracy between galaxy bias and the amplitude of the matter power spectrum. This combined approach is commonly referred to as the “three-by-two-point” (3×2 pt) analysis [2,17–20].

As previously mentioned, matter drives the formation of LSS through gravitational attraction, while dark energy causes the accelerated expansion of space-time. As a result, the matter power spectrum evolves over cosmic time. To observe this evolution, both galaxy tracers and source

galaxies must be divided into redshift “slices” or tomographic bins [6]. Specifically, galaxy clustering in a given tomographic bin probes the matter power spectrum within that redshift range; galaxy-galaxy lensing measures the projected matter profile around lens galaxies at those redshifts; and cosmic shear captures the cumulative lensing effect from all the LSS in front of the source galaxies [7].

Using tomographic source bins in galaxy-galaxy lensing provides additional self-calibration power on the mean redshift of the source galaxies [21]. Since previous analysis based on Hyper Suprime-Cam year-3 (HSC Y3) shear catalog found inconsistent redshift parameter from the cosmological analysis to the photo- z redshift distribution [12,13,17,18], we utilize this self-calibration power to provide redshift parameter constraints for the third and fourth HSC bins. Furthermore, employing multiple source bins improves the signal-to-noise ratio of the galaxy-galaxy lensing measurement by increasing the number of tomographic lens-source bin pairs available.

In this work, a sample of Sloan Digital Sky Survey (SDSS) DR11 galaxies is used as tracers of LSS in the redshift range $0.15 < z_l < 0.7$. These galaxies also serve as the lens sample in the galaxy-galaxy lensing measurement and are divided into three tomographic bins. The HSC Y3 source galaxies, covering an area of 419 deg^2 , are divided into four tomographic bins spanning $0.3 < z_s < 1.5$. The binning scheme of the source galaxies here is identical to that used in the HSC Y3 cosmic shear analysis [12,13].

The clustering measurements of the SDSS galaxies are taken from [22], and the tomographic galaxy-galaxy lensing measurements are adapted from [23], which also established the 2×2 pt analysis framework combining galaxy clustering and galaxy-galaxy lensing. The cosmic shear measurements are consistent with those in [12], although a different multiplicative factor is applied for blinding purposes. Details of the 3×2 pt data vector and its covariance matrix are provided in Sec. II.

The theoretical forward model generates predicted 3×2 pt data vectors to constrain cosmological and nuisance parameters via Markov chain Monte Carlo sampling. Most of the theoretical modeling used in this work follows [17,23]. We compute the nonlinear matter power spectrum with a single parameter controlling the strength of baryonic feedback. A single galaxy bias parameter is used to model the galaxy clustering signal w_p , and an additional

point-mass correction parameter is introduced to account for small-scale modeling uncertainties in $\Delta\Sigma(R_p)$. For intrinsic alignment, we adopt the tidal alignment and tidal torquing model. Each tomographic bin of the source galaxies is assigned one nuisance parameter for residual multiplicative shear bias, redshift bias, and point-spread function (PSF) systematics. We perform likelihood analyses on the full data vector as well as on its subsets to test internal consistency. Details of the theoretical modeling are provided in Sec. III.

We present the cosmological constraints from our fiducial data vector, along with results obtained from various subsets of the data vector and alternative analysis choices. These tests help assess the robustness of the fiducial results. We also compare our fiducial cosmological constraints with results from other surveys. The main results are presented in Sec. IV, and the implications and conclusions are summarized in Sec. V. We summarize our findings in Sec. V.

II. DATASETS AND DATA VECTORS

In this section, we describe the datasets and the 3×2 pt data vector used in our analysis. The 3×2 pt data vector is constructed by combining previously published measurements and our companion 2×2 pt paper [23]. The galaxy clustering measurement is identical to that presented in [22], the galaxy-galaxy lensing measurement of $\Delta\Sigma(R_p)$ follows [23], and the cosmic shear measurement is redone consistently with [12], except for a global multiplicative factor applied for blinding purposes. We briefly summarize the measurement procedures and underlying datasets here and refer the reader to the respective works for further details.

A. Datasets

1. SDSS DR11

We use the SDSS DR11 LSS catalog to measure the galaxy clustering signal [24,25] and to define the lens galaxy sample for the galaxy-galaxy lensing measurements. The SDSS catalog covers an area of approximately 11000 deg^2 and is divided into three redshift tomographic bins: $0.15 < z_l < 0.35$ for LOWZ, $0.43 < z_l < 0.55$ for CMASS1, and $0.55 < z_l < 0.7$ for CMASS2. To make the sample approximately volume limited, we apply absolute magnitude cuts of $M_q - 5 \log h < -21.5$, -21.9 , and -22.2 for the LOWZ, CMASS1, and CMASS2 bins, respectively. The comoving number densities of galaxies in these bins are 1.8, 0.74, and $0.45 \times 10^{-4} (h^{-1} \text{ Mpc})^{-3}$, respectively.

In Fig. 1, we demonstrate the drastically different angular and redshift space coverage of the lens and source galaxies used in our 3×2 pt analysis, plotted in (Dec, z) coordinates. The SDSS lens galaxies span a larger sky area

and occupy a lower redshift range compared to the HSC source galaxies. The SDSS galaxy sample used in this work is identical to that used in the 2×2 pt paper [23] and the previous HSC Y3 3×2 pt analyses [17,18,22]. For further details on the SDSS catalog used in this analysis, we refer readers to [22,23].

2. HSC Y3

We use the HSC year-3 shear catalog as the source sample for measuring the galaxy-galaxy lensing and cosmic shear signal. The catalog¹ [28] is based on the S19A internal data release, which uses data between the second and third public releases of the HSC-Subaru Strategic Program survey [27,29]. It contains 35.7 million galaxies over a footprint of 433 deg^2 , with an effective source galaxy number density of 19.9 arcmin^{-2} . The HSC Y3 footprint is divided into six fields: GAMA09H, GAMA15H, WIDE12H, XMM, VVDS, and HECTOMAP.

Galaxy shapes in the catalog are measured using the re-Gaussianization method [30,31], and the shear response is calibrated using image simulations [28,32], implemented with GalSim [33]. The multiplicative shear bias is calibrated to the 1% level, and various systematics and null tests confirm that the catalog is free of significant additive shear bias [28,34]. For further details on the shear catalog selection function and image simulation-based calibration, we refer readers to [28]. For PSF-related systematics and null tests, we refer to [34].

The redshift information in the HSC Y3 shape catalog is estimated using three photometric redshift (photo- z) algorithms [35]. Mizuki is a template-fitting-based method, while DNNz and DEmPz are machine-learning-based approaches. All three methods provide a redshift probability density function (PDF), $P(z_s)$, for each galaxy. These PDFs are used both to assign optimal weights in the galaxy-galaxy lensing measurement and to define priors on the redshift distributions of the tomographic source bins.

The optimal weights, which are expressed in Eq. (14) in [23], are constructed to (a) weight the lens-source pairs based on lensing efficiency [36]; (b) weight lens sample based on observing condition [31,37]; and (c) weight source sample based on shear SNR [30]. The optimal weights effectively suppress the intrinsic alignment (IA) contamination to galaxy-galaxy lensing (GGL) data vector and increase the overall SNR for GGL.

For the tomographic cosmological analysis, the HSC Y3 source galaxies are divided into four tomographic bins based on the DNNz photo- z estimator's z_{best} values [38]. The bin edges are defined as $[0.3, 0.6]$, $[0.6, 0.9]$, $[0.9, 1.2]$, and $[1.2, 1.5]$. To reduce contamination from galaxies with poorly constrained redshifts, we exclude galaxies with double-peaked PDFs in either Mizuki or DNNz, which

¹The shape catalog is publicly available [26] as a catalog of the Public Data Release 3 [27].

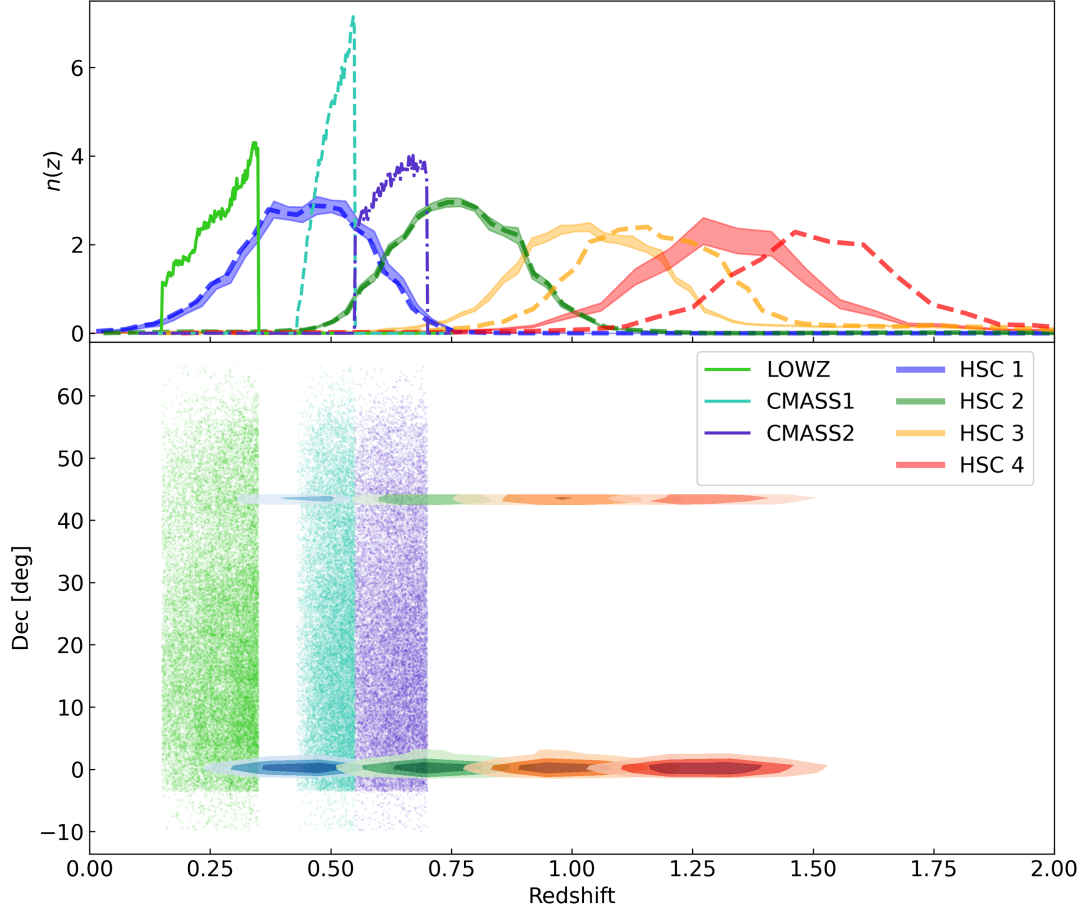


FIG. 1. Top: redshift distributions $n(z)$ for the three SDSS lens galaxy bins and the four HSC source bins used in this work. The dashed lines are $n(z)$ shifted by the mode of the fiducial 3×2 pt analysis. Bottom: declination-redshift distribution of galaxies. SDSS lens galaxies are shown as individual points, color coded by lens bin, highlighting their broad angular coverage. HSC source galaxies are overlaid by the contour plots, which covers a larger redshift range. The HSC redshift of the galaxies are sampled by the corresponding $n(z)$. This figure demonstrates the complementary characteristic of the SDSS and HSC datasets.

removes 31% of galaxies in bin 1 and 8% in bin 2. The percentage of galaxies with double-peaked photo- z PDF in bins 3 and 4 is insignificant.

The redshift distribution $n_i(z)$ for each tomographic bin is inferred by combining stacked photo- z PDFs (used as priors) with clustering redshift measurements between the photometric galaxies and CAMIRA luminous red galaxies (CAMIRA LRGs) [39,40], which serve as the likelihood term. The inference is performed using a logistic Gaussian process. It is important to note that the CAMIRA-LRG sample spans the redshift range $0.1 < z < 1.1$, so redshift information for $z > 1.1$ relies solely on photometric estimates. This limitation may explain the tension observed between Λ CDM-preferred and photometric-redshift-preferred redshift mean for the third and fourth redshift bins (see Sec. III C 1 for further discussion). In the upper panel of Fig. 1, we show the fiducial 67% confidence interval of the $n_i(z)$ of the four HSC tomographic bins.

We note that the source catalog used in this work was jointly blinded with [23] to mitigate confirmation bias.

The three blinded catalogs differ by $\sim 5\%$ offsets in their applied multiplicative shear bias. All internal consistency tests were performed independently on each of the three blinded catalogs, and we verified that the best-fitting models lie within the empirical χ^2 distributions computed from mock realizations of the data vector. After all internal consistency and validation tests were passed, we unblinded and identified `blind_id = 0` as the true catalog. For further details on the blinding procedure, we refer the reader to [23].

3. Mock catalog

Mock catalogs generated from high-fidelity simulations play a critical role in HSC cosmological analyses [41]. In this work, we utilize mock catalogs to compute the covariance matrix of the 3×2 pt data vector.

We use the same suite of mock catalogs as those employed in the HSC Y3 analysis. For details of the underlying simulations, we refer the reader to [41] and for

their application in tomographic 2×2 pt and 3×2 pt analyses to [12,13,17,23]. Briefly, the simulation suite consists of 108 full-sky gravitational lensing realizations, each divided into 13 nonoverlapping HSC Y3-like fields, yielding a total of 1404 independent mock realizations. For each mock realization, we compute the full 3×2 pt data vector using the same measurement pipeline applied to the real data. These mock data vectors are then used to estimate the covariance matrix (see Sec. II C).

B. Data vector

The full 3×2 pt data vector is presented in Fig. 2, organized into three components: the galaxy clustering signal $w_p(R_p)$, the galaxy-galaxy lensing signal $\Delta\Sigma(R_p)$, and the cosmic shear correlation functions $\xi_{\pm}$. The measured two-point functions are shown as blue points with error bars. The solid black lines represent the theoretical predictions from the best-fit model, defined as the parameter set that minimizes the χ^2 . The red shaded bands denote the 68% and 95% confidence intervals of the model predictions, derived from the posterior distribution of the fiducial analysis in Sec. IV A.

1. Galaxy clustering

The galaxy clustering data vector is measured using the volume-limited sample of BOSS galaxies from SDSS DR11 [42]. As the measurement procedure is identical to that described in [22], we only provide a brief summary here and refer readers to that work for full details.

The first step in measuring the clustering signal involves computing the three-dimensional correlation function using the Landy-Szalay estimator [43], evaluated as a function of projected separation R_p and line-of-sight separation π :

$$\xi(R_p, \pi) = \frac{DD - 2DR + RR}{RR}, \quad (1)$$

where DD , DR , and RR represent the number of data-data, data-random, and random-random galaxy pairs in a given (R_p, π) bin, respectively. Here R_p is the projected radius. To suppress shot noise in the estimator, the random catalog contains 50 times more points than the galaxy sample.

We further compress the measurement by projecting three-dimensional correlation function along the line of sight to obtain the projected correlation function:

$$w_p(R_p) = 2 \int_0^{\pi_{\max}} \xi(R_p, \pi) d\pi, \quad (2)$$

where $\pi_{\max} = 100h^{-1}$ Mpc. The $w_p(R_p)$ measurement is binned into 30 logarithmically spaced bins from $0.5h^{-1}$ Mpc to $80h^{-1}$ Mpc, resulting in a total of 90 data points across the three SDSS tomographic bins. However, for cosmological inference, we restrict the analysis to large scales ($R_p > 8h^{-1}$ Mpc) to avoid modeling uncertainties at

small scales. This scale cut yields an effective clustering data vector length of 42. The measurements, along with the best-fit theoretical prediction and the 68% and 95% confidence intervals, are shown in the top three panels of Fig. 2.

2. Galaxy-galaxy lensing

Galaxy-galaxy lensing measures the gravitational lensing effect caused by the mass distribution around foreground (lens) galaxies, using the shapes of background (source) galaxies. In this work, we use the same galaxies as in the clustering measurement (Sec. II B 1) as the lens sample and the same galaxies as in the cosmic shear measurement (Sec. II B 3) as the source sample. Using a consistent lens sample with the clustering analysis helps break the degeneracy between the matter power spectrum and galaxy bias. Similarly, using the same source sample as the cosmic shear measurement allows the galaxy-galaxy lensing to provide self-calibration power on the source redshift distribution.

The galaxy-galaxy lensing measurement used in this work is identical to that of [23]; therefore, we provide only a brief description here and refer the reader to [23] for further details.

The galaxy-galaxy lensing measurement in this work adopts the formalism of the excess surface mass density, $\Delta\Sigma(R_p)$ [36], which is computed for a given lens-source pair at redshifts z_l and z_s as

$$\Delta\Sigma(R_p) = \gamma_t(R_p) \Sigma_{\text{cr}}(z_l, z_s). \quad (3)$$

Here, R_p is the projected comoving separation between the lens and source, γ_t [37,44] is the tangential shear, approximated by the tangential component of the galaxy shape e_t with respect to the lens galaxies, defined as

$$e_t = -e_1 \cos(2\phi) - e_2 \sin(2\phi), \quad (4)$$

where $e_1 + ie_2$ is the complex ellipticity measured for the source galaxies, and ϕ is the position angle between the source and the lens. The critical surface density Σ_{cr} is given by

$$\Sigma_{\text{cr}}(z_l, z_s) = \frac{c^2}{4\pi G} \frac{D_A(z_s)}{D_A(z_l) D_A(z_l, z_s) (1 + z_l)^2}, \quad (5)$$

where $D_A(z_l, z_s)$ denotes the angular diameter distance between redshifts z_l and z_s .

Our full estimator computes the galaxy-galaxy lensing signal $\widehat{\Delta\Sigma}(R_p)$ for the q th lens bin and i th source bin as

$$\widehat{\Delta\Sigma}(R_p) = \frac{1}{1 + \hat{m}_i} \left(\frac{\sum_{l \in q, s \in i} w_{ls} e_{t, ls} \langle \Sigma_{\text{cr}}^{-1} \rangle_{ls}^{-1}}{2\mathcal{R} \sum_{l \in q, s \in i} w_{ls}} \right), \quad (6)$$

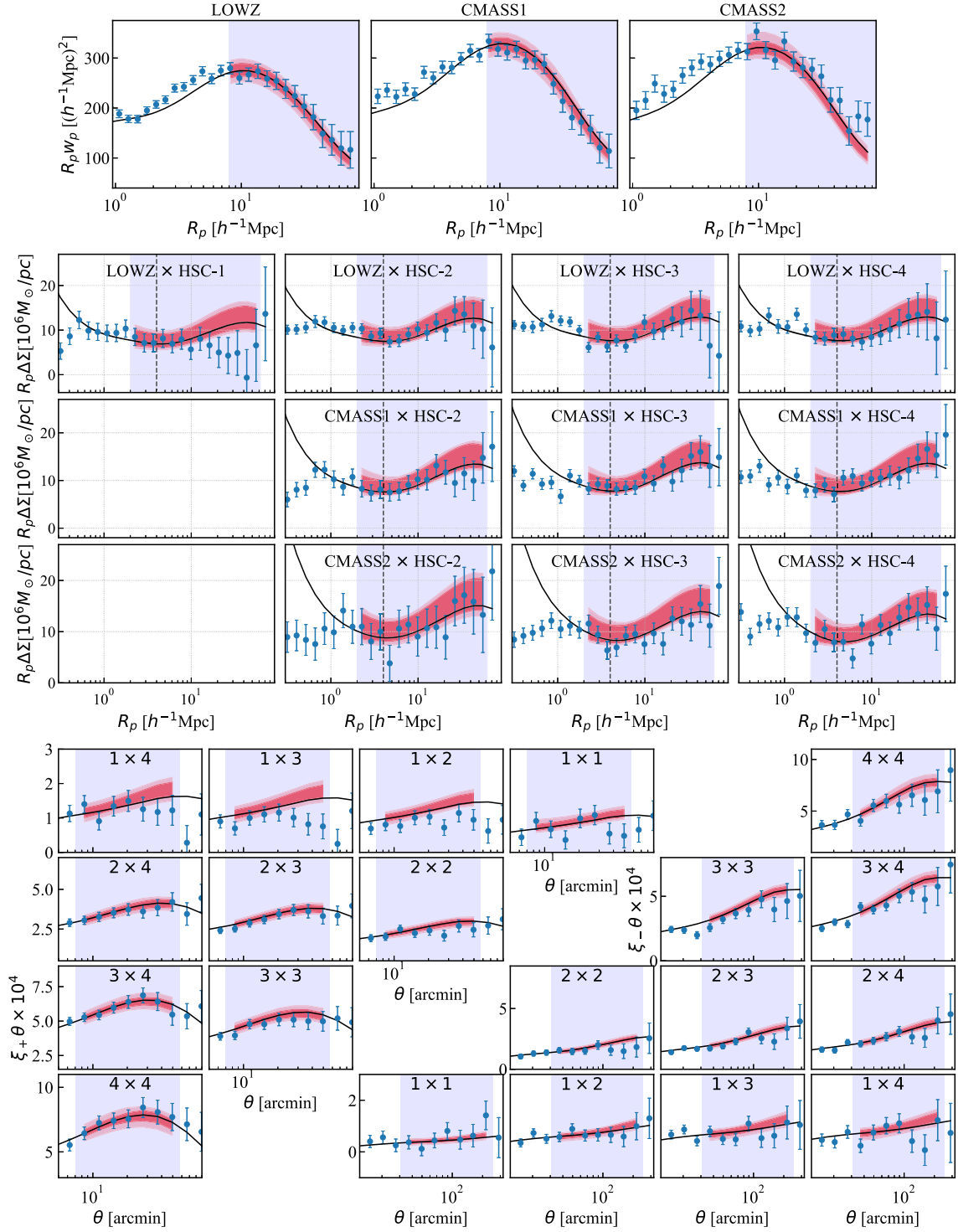


FIG. 2. Measurements (blue points), best-fit theoretical predictions (black lines), and the 68% and 95% confidence intervals of the model (red shaded regions) for the three components of the 3×2 pt data vector: the projected galaxy clustering signal $w_p(R_p)$ (top), the galaxy-galaxy lensing signal $\Delta\Sigma(R_p)$ (middle), and the cosmic shear correlation functions ξ_+ and ξ_- (bottom). The blue shaded regions indicate the radial scales used in the cosmological inference. In the $\Delta\Sigma$ panels, the dashed lines denote $R_0 = 4h^{-1} \text{ Mpc}$, as discussed in Sec. III B 2.

where $\langle \Sigma_{\text{cr}}^{-1} \rangle_{\text{ls}}$ is the expectation value of the inverse critical surface density. This is computed by integrating over the source redshift probability distribution to account for photometric redshift uncertainty. The lensing weight for each lens-source pair is defined as $w_{\text{ls}} = w_l w_s \langle \Sigma_{\text{cr}}^{-1} \rangle_{\text{ls}}$, which assigns zero weight to pairs with $z_s \leq z_l$ and higher weights to pairs with larger $z_s - z_l$. The sums $\sum_{l \in q, s \in i}$ run over all lens-source pairs where the lens is in the q th lens bin and the source is in the i th source bin.

The $\Delta\Sigma(R_p)$ signal is measured for all SDSS-HSC lens-source bin pairs, although we exclude the LOWZ-HSC1 and CMASS1-HSC1 pairs due to significant overlap in redshift space. To examine potential field dependence, we perform the $\Delta\Sigma(R_p)$ measurement separately in each of the six HSC fields. The measurements are binned into 30 logarithmically spaced bins between $0.05h^{-1}\text{Mpc}$ and $80h^{-1}\text{Mpc}$. The full data vector has a length of 360. For the cosmological analysis, we apply a scale cut of $2h^{-1}\text{Mpc} < R < 70h^{-1}\text{Mpc}$, resulting in an effective data vector length of 140. The lower limit of the scale cuts are motivated by the sensitivity to the off-centering of the lens samples (see Sec. VIC 2 of [23]). The measurements, best-fit model predictions, and the 68% and 95% confidence intervals for the $\Delta\Sigma(R_p)$ signal in the SDSS-HSC bin pairs included in the analysis are shown in the second to fourth row panels of Fig. 2.

3. Cosmic shear

The cosmic shear measurement in this work follows the methodology of [12]. However, because the source catalog is blinded independently from other analyses, we remeasure the shear two-point functions using both the real and mock catalogs. The cosmic shear correlation functions $\xi_{\pm}^{ij}(\theta)$ [8] are computed for galaxy pairs in tomographic bins i and j as follows:

$$\xi_{\pm}^{ij}(\theta) = \frac{\sum_x w(x) \gamma_+^i(x) w(x+\theta) \gamma_+^j(x+\theta)}{\sum_x w(x) w(x+\theta)} \pm \frac{\sum_x w(x) \gamma_{\times}^i(x) w(x+\theta) \gamma_{\times}^j(x+\theta)}{\sum_x w(x) w(x+\theta)}. \quad (7)$$

Here, the summation runs over all galaxy pairs with angular separation θ between tomographic bins i and j . The quantities γ_+ and $\gamma_{\times}$ represent the tangential and cross shear components, respectively, defined with respect to the vector connecting each galaxy pair.

We use the open-source software `TreeCorr` to measure the shear-shear correlation functions. Following [12], we apply angular scale cuts of $7.1 < \theta/\text{arcmin} < 56.6$ for ξ_+ and $31.2 < \theta/\text{arcmin} < 248$ for ξ_- . The small-scale cuts are chosen to minimize modeling error of baryonic feedback with a mock data vector emulating overwhelmingly large simulations (OWLS)-AGN level feedback [45]. The large-

scale cuts are determined by ensuring the B mode of the cosmic shear 2pt are statistically consistent with zero. For all tomographic bin pairs, we adopt logarithmic angular binning with an interval of $\Delta \log(\theta) = 0.29$, resulting in seven bins for both ξ_+ and ξ_- . In total, the cosmic shear data vector consists of 140 data points. The measurements, best-fit theoretical model, and the 68% and 95% confidence regions for the auto- and cross-correlations $\xi_{\pm}^{ij}(\theta)$ are shown in the bottom four rows of Fig. 2.

C. Covariance matrix

The covariance matrix used for the 3×2 pt analysis is estimated from 108 realizations of full-sky gravitational lensing simulations [41,46,47]. Each realization is populated with SDSS-like galaxies and subdivided into 13 nonoverlapping regions to emulate the HSC-like footprint, yielding a total of 1404 mock realizations (108×13). Given that the overlap between the SDSS DR11 and HSC-Y3 footprints is only about 5% (i.e., $416 \text{ deg}^2 / 8300 \text{ deg}^2$), we neglect the correlation between galaxy clustering (w_p) and weak lensing observables. However, since the HSC source catalog contributes to both galaxy-galaxy lensing ($\Delta\Sigma$) and cosmic shear ($\xi_{\pm}$), we expect a positive correlation between these two lensing signals. The correlation and covariance matrix of the full data vector is shown in Fig. 3. The mock measurements of w_p and $\Delta\Sigma$ are described in [23], and the mock cosmic shear measurements $\xi_{\pm}$ follow the methodology described in [12].

From Fig. 3, we observe strong correlation between GGL data points that share the same lens bins. This suggest that using multiple source bins will not significantly increase the GGL signal-to-noise ratio. We also observe strong correlation between the GGL and cosmic shear, highlighting the importance of measuring the mock data vector jointly.

III. MODELING AND INFERENCE

In this section, we describe the forward model used to compute the 3×2 pt data vector, which is parametrized by cosmological and nuisance parameters. This includes the theoretical modeling of galaxy clustering w_p , galaxy-galaxy lensing $\Delta\Sigma$ and cosmic shear $\xi_{\pm}$, treatments for systematic errors, the framework for Bayesian inference, and the validation and internal consistency tests performed to ensure the robustness of the results. The modeling of the cosmic shear correlation functions $\xi_{\pm}$ follows the methodology in [12]. Therefore, we only briefly here and refer the readers to [12].

We use the open-source software package `CosmoSIS` [48] for forward modeling and Bayesian inference. All modules employed in this work are publicly available through the `CosmoSIS` Standard Library [49].

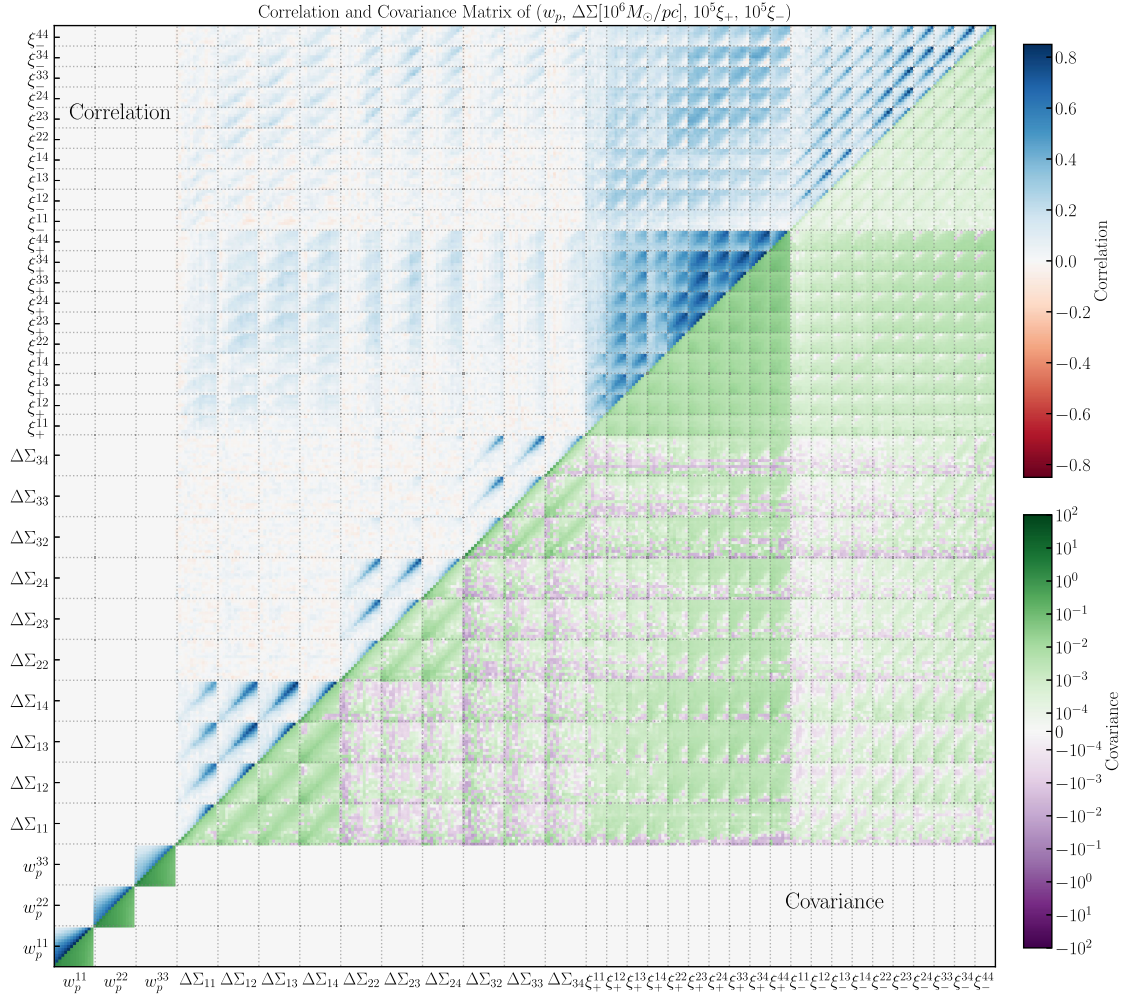


FIG. 3. The correlation and covariance matrix of the data vector used in the fiducial 3×2 pt cosmological analysis, computed from measurements on 1404 mock SDSS and HSC realizations. $\xi_{\pm}^{ij}$ are multiplied by 10^5 to match the order of magnitude of the 2×2 pt data vector. The covariance matrix is shown in the lower triangular and the diagonal elements, while the correlation matrix is shown as an upper triangular matrix. We assume no correlation between the galaxy clustering signal w_p and the weak lensing observables. Significant correlations are observed among $\Delta\Sigma$ measurements that share the same lens tomographic bin, as well as among the shear-shear correlation functions $\xi_{\pm}^{ij}$. Additionally, we detect notable correlations between the galaxy-galaxy lensing and cosmic shear signals, which arise from their shared sensitivity to the same underlying LSS.

A. Cosmological and astrophysical modeling

1. Matter power spectrum

We compute the matter power spectrum as the first step in the forward modeling process. The linear matter power spectrum $P_{\text{mm}}(k; z_l)$ is calculated using the CAMB interface [50] within CosmoSIS. The shape and amplitude of the linear power spectrum are governed by the logarithmic amplitude of the primordial curvature perturbations, $\log(10^{10}A_s)$, and the spectral index n_s , as well as the physical densities of baryons and cold dark matter, $\Omega_b h^2$ and $\Omega_c h^2$, respectively, where h is the dimensionless Hubble parameter. Throughout this work, we fix the total neutrino mass to $\sum m_\nu = 0.06$ eV. Throughout the

survey, we assume a spatially flat geometry for the Universe, i.e., $\Omega_k = 0$.

At small scales, the power spectrum is not well described by linear perturbation theory. Therefore, we need to compute the nonlinear power spectrum. We use HMCode [51] 2016 to compute the nonlinear power spectrum through a customized interface in CosmoSIS.

The clustering signal $w_p(R_p)$ and galaxy-galaxy lensing signal $\Delta\Sigma(R_p)$ are directly derived from the nonlinear matter power spectrum $P_{\text{nl}}(k; z)$ (see Secs. III B 1 and III B 2). In contrast, the cosmic shear two-point correlation functions $\xi_{\pm}^{ij}(\theta)$ are related to the angular power spectrum $C_{\text{GG}}^{ij}(\ell)$ [52], which, under the assumption of a flat universe and the Limber approximation, can be written as

$$C_{\text{GG}}^{ij}(\ell) = \int_0^{\chi_H} d\chi \frac{q_i(\chi)q_j(\chi)}{\chi^2} P_m\left(k = \frac{\ell + 1/2}{\chi}, \chi\right), \quad (8)$$

where χ is the comoving radial distance, χ_H is the comoving distance to the horizon, and $q_i(\chi)$ is the lensing efficiency kernel for the i th tomographic bin, defined as

$$q_i(\chi) = \frac{3}{2} \Omega_m \left(\frac{H_0}{c}\right)^2 \frac{\chi}{a(\chi)} \int_{\chi}^{\chi_H} d\chi' n_i(\chi') \frac{\chi' - \chi}{\chi'}, \quad (9)$$

where $n_i(\chi')$ is the comoving redshift distribution of the i th tomographic bin and $H_0 = 100 \text{ h km s}^{-1} \text{ Mpc}^{-1}$. For a single source galaxy at comoving distance χ , the lensing efficiency peaks near $\chi/2$.

2. Baryonic feedback

Baryonic effects such as feedback from supernovae and active galactic nuclei (AGN) are known to suppress the matter power spectrum at small scales [53,54]. To account for these effects, we follow [55] and adopt HMCODE 2016 to model baryonic suppression. HMCODE 2016 parametrizes baryonic feedback using the halo mass-concentration amplitude A_b and a halo bloating parameter η_b , which depends on A_b according to [56]:

$$\eta_b = 0.98 - 0.12 A_b. \quad (10)$$

We place a uniform prior on A_b over the range $U[1.5, 3.13]$, where $A_b = 3.13$ corresponds to the dark-matter-only scenario with no baryonic feedback. The parameter A_b is marginalized over in our Bayesian inference. The lower bound $A_b = 1.5$ is chosen to avoid bias in case of a strong feedback models, e.g., OWLS-like [45] or COSMO-OWLS-like [57] presented in the validation test. We do not use the more recent HMCODE 2020 model due to computational efficiency. The improvements in HMCODE 2020 primarily affect models with large neutrino masses ($\sum m_\nu > 0.5 \text{ eV}$), which are not relevant to this analysis. In Appendix A, we validate that our fiducial model is robust against baryonic physics.

3. Intrinsic alignment

IA refers to the correlation between the shapes of galaxies due to physical effects unrelated to gravitational lensing. IA contaminates cosmic shear through two main mechanisms: (a) the intrinsic shapes of two galaxies can be correlated because they are physically associated and experience the same tidal field—this is known as the II (intrinsic-intrinsic) term; (b) the intrinsic shape of one galaxy is aligned with the local tidal field, while the other galaxy, located farther away, is gravitationally lensed by the same LSS that generated the tidal field—this is known as the GI (gravitational-intrinsic) term [58].

Under the Limber approximation [59], the angular power spectra for the II and GI terms between the i th and j th tomographic bins are given by

$$C_{\text{II}}^{ij}(\ell) = \int_0^{\chi(z_{\text{max}})} d\chi \frac{n_i(\chi)n_j(\chi)}{\chi^2} P_{\text{II}}\left(k = \frac{\ell + 1/2}{\chi}; \chi\right), \quad (11)$$

$$C_{\text{GI}}^{ij}(\ell) = \int_0^{\chi(z_{\text{max}})} d\chi \frac{q_i(\chi)n_j(\chi)}{\chi^2} P_{\text{GI}}\left(k = \frac{\ell + 1/2}{\chi}; \chi\right), \quad (12)$$

where $q_i(\chi)$ is the lensing efficiency of the i th bin and $n_i(\chi)$ is the comoving number density. P_{II} and P_{GI} are the intrinsic alignment power spectra. z_{max} is set to 6 across the analysis.

In this work, we follow [12] and adopt the tidal alignment and tidal torque (TATT) model [60] to model IA contamination to the cosmic shear correlation functions $\xi_{\pm}$. The TATT model expresses the IA power spectra in terms of the following components:

$$P_{\text{GI}}^E(k) = c_1 P_{\delta}(k) + b_{\text{TA}} c_1 P_{0|0E}(k) + c_2 P_{0|E2}(k), \quad (13)$$

$$\begin{aligned} P_{\text{II}}^E(k) = & c_1^2 P_{\delta}(k) + 2b_{\text{TA}} c_1^2 P_{0|0E}(k) + b_{\text{TA}}^2 c_1^2 P_{0E|0E}(k) \\ & + c_2^2 P_{E2|E2}(k) + 2c_1 c_2 P_{0|E2}(k) \\ & + 2b_{\text{TA}} c_1 c_2 P_{0E|E2}(k), \end{aligned} \quad (14)$$

$$\begin{aligned} P_{\text{II}}^B(k) = & b_{\text{TA}}^2 c_1^2 P_{0B|0B}(k) + c_2^2 P_{B2|B2}(k) \\ & + 2b_{\text{TA}} c_1 c_2 P_{0B|B2}(k). \end{aligned} \quad (15)$$

The terms on the right-hand side represent various one-loop contributions to the IA power spectrum. For details of the notation and derivation, we refer readers to [60]. These spectra are computed using FAST-PT v2.1 [61,62], which we interface through a CosmoSIS module.

The coefficients c_1 and c_2 are redshift dependent and parametrized as

$$c_1(z) = -A_{\text{IA},1} \frac{\bar{C} \rho_c \Omega_m}{D(z)} \left(\frac{1+z}{1+z_0} \right)^{\eta_{\text{IA},1}}, \quad (16)$$

$$c_2(z) = 5A_{\text{IA},2} \frac{\bar{C} \rho_c \Omega_m}{D^2(z)} \left(\frac{1+z}{1+z_0} \right)^{\eta_{\text{IA},2}}. \quad (17)$$

Here, $A_{\text{IA},1}$ and $A_{\text{IA},2}$ are the amplitudes of the tidal alignment and tidal torque components, $\eta_{\text{IA},1}$ and $\eta_{\text{IA},2}$ control their redshift evolution, $D(z)$ is the linear growth factor, ρ_c is the critical density today, and $\bar{C} = 5 \times 10^{-14} h^{-2} M_{\odot}^{-1} \text{ Mpc}^3$ is a normalization constant.

In this work, we parametrize the TATT model using five free parameters: $A_{\text{IA},1}$, $A_{\text{IA},2}$, $\eta_{\text{IA},1}$, $\eta_{\text{IA},2}$, and b_{TA} . We adopt

wide, uninformative priors in the range $[-6, 6]$ for all five parameters due to the lack of reliable prior constraints. The pivot redshift is fixed at $z_0 = 0.62$ for all IA terms, and the normalization constant is set to $\bar{C} = 5 \times 10^{-14} h^{-2} M_{\odot}^{-1} \text{Mpc}^3$. We note that the commonly used nonlinear alignment model [63,64] is a special case of the TATT model obtained by setting $A_{\text{IA},2} = 0$ and $b_{\text{TA}} = 0$.

Intrinsic alignment can also affect the GGL signal if the source galaxies are physically associated with the lens galaxies. However, our GGL measurements employ optimal weighting, which downweights or eliminates lens-source pairs at the same redshift. As a result, the impact of IA on the GGL signal is expected to be negligible. We confirm this expectation through validation tests in which we artificially inject significant IA contamination into the mock GGL data vector. These tests show that the key cosmological constraints from the 3×2 pt analysis remain unaffected. Details of these validation tests are provided in Appendix A.

B. Correlation functions

1. Projected correlation function $w_p(R_p)$

The modeling of the projected correlation function $w_p(R_p)$ follows the formalism presented in Sugiyama *et al.* [17], which adopts the “minimal bias” model. This model describes the galaxy number density field as a linear tracer of the underlying matter density field. Sugiyama *et al.* [65] demonstrated that the minimal bias model provides an accurate description of w_p and allows unbiased inference of the cosmological parameters when applied to scales $R_p > 8h^{-1} \text{Mpc}$. In this work, we use the implementation of the minimal bias model provided in the CosmoSIS framework to compute $w_p(R_p)$.

In the forward modeling, we first compute the 3D galaxy correlation function:

$$\xi_{gg}(r; z_l) = b_l(z_l)^2 \int_0^\infty \frac{k^2 dk}{2\pi^2} P_{\text{mm}}^{\text{NL}}(k; z_l) j_0(kr), \quad (18)$$

where $P_{\text{mm}}^{\text{NL}}(k; z_l)$ is the nonlinear matter power spectrum described in Secs. III A 1 and III A 2, including baryonic feedback. The function $j_0(x)$ is the zeroth-order spherical Bessel function. The Hankel transform is performed using FFTLog [66]. We introduce one linear galaxy bias parameter $b_l(z_l)$ for each lens redshift bin.

The projected correlation function w_p is derived by integrating $\xi_{gg}(r; z_l)$ over the line-of-sight direction of z_l :

$$w_p(R_p; z_l) = 2f_{\text{corr}}^{\text{RSD}}(R_p; z_l) \int_0^{\Pi_{\text{max}}} d\Pi \xi_{gg}(\sqrt{R_p^2 + \Pi^2}; z_l). \quad (19)$$

Here Π is the line-of-sight distance. Following [17,67], the maximum line-of-sight distance Π_{max} is set to $100h^{-1} \text{Mpc}$, and f^{RSD} is the correction factor for the Kaiser redshift space distortion effect (RSD) [68].

In this work, we evaluate the clustering signal at the weighted average redshifts of each tomographic bin: $z_l = 0.26, 0.51$, and 0.63 for the LOWZ, CMASS1, and CMASS2 bins, respectively.

2. Projected surface density $\Delta\Sigma(R_p)$

The modeling of the projected surface mass density profile $\Delta\Sigma(R_p)$ from the nonlinear power spectrum follows the point-mass correction model described in the companion 2×2 pt paper [23].

The galaxy-galaxy lensing signal is quantified by the excess surface density $\Delta\Sigma(R_p)$ at projected radius R_p . To model this signal across a wide range of scales ($2h^{-1} \text{Mpc}$ to $80h^{-1} \text{Mpc}$), we combine the minimal bias model with a point-mass correction. The latter assumes that the additional mass within a small radius R_0 to what the minimal bias model predicts is concentrated at the center of the halo and can be approximated as a power-law contribution at larger radii. The model includes three components:

$$\Delta\Sigma(R_p) = \Delta\Sigma_{gG}(R_p) + \Delta\Sigma_{\text{PM}}(R_p) + \Delta\Sigma_{\text{mag}}(R_p), \quad (20)$$

where $\Delta\Sigma_{gG}(R_p)$ is the predicted excess surface density from the minimal bias model assuming a single linear galaxy bias b_l for all lens galaxies in a given tomographic bin:

$$\Delta\Sigma_{gG}(R_p) = b_l(z_l) \bar{\rho}_{m_0} \int_0^\infty \frac{k dk}{2\pi} P_{\text{mm}}^{\text{NL}}(k; z_l) J_2(kR_p), \quad (21)$$

where $\bar{\rho}_{m_0}$ is the present-day mean matter density and $J_2(x)$ is the second-order Bessel function. Here, $b_l(z_l)$ denotes the galaxy bias in the l th lens bin evaluated at redshift z_l . The Hankel transform is computed using FFTLog [66]. This analysis uses the CosmoSIS modules for the minimal bias model, the point-mass (Upsilon) correction, and the magnification bias to compute the three terms in Eq. (20).

The second term, $\Delta\Sigma_{\text{PM}}(R_p)$, represents a point-mass correction to account for the small-scale behavior of the galaxy-matter correlation. It assumes that the mass profile within a radius R_0 can be approximated as a point mass located at the center of the halo, leading to a R^{-2} dependence due to the inverse-square law. The reduced observable, originally introduced as the annular differential surface density, is expressed using the $\Upsilon(R_p)$ statistic [36,69]:

$$\Upsilon(R_p) = \Delta\Sigma_{gG}(R_p) - \Delta\Sigma_{gG}(R_0) \left(\frac{R_p}{R_0}\right)^{-2}. \quad (22)$$

In the point-mass correction model, we account for the missing one-halo contribution, denoted $\Delta\Sigma_{\text{PM}}(R_0)$, which is not captured by the `HaloFit` prediction. This leads to a modified model for $\Delta\Sigma(R_p)$:

$$\Delta\Sigma'(R_p) = \Upsilon(R_p) + \Delta\Sigma_{\text{PM}}(R_0) \left(\frac{R_p}{R_0}\right)^{-2} \quad (23)$$

$$= \Delta\Sigma_{gG}(R_p) + [\Delta\Sigma_{\text{PM}}(R_0) - \Delta\Sigma_{gG}(R_0)] \left(\frac{R_0}{R_p}\right)^2. \quad (24)$$

Here, $\Delta\Sigma_{gG}(R_p)$ is the prediction from the minimal bias model, and $\Delta\Sigma_{\text{PM}}(R_0)$ is a free parameter in our analysis, defined per lens bin. We fix the inner scale radius to $R_0 = 4h^{-1}$ Mpc and set the minimum scale used in the cosmological inference to $R_{p,\text{min}} = 2h^{-1}$ Mpc.

The third term, $\Delta\Sigma_{\text{mag}}(R_p)$, accounts for the magnification bias in the lensing signal. This effect arises because gravitational lensing increases the apparent brightness of background (source) galaxies, making more of them detectable in flux-limited samples when being lensed. We refer the reader to Sugiyama *et al.* [17] and Ref. [23] for a detailed description of the formalism used to calculate the contribution of the magnification bias.

3. Shear-shear correlation function $\xi_{\pm}(\theta)$

The calculation of the shear-shear correlation function between the i th and j th tomographic bins, $\xi_{\pm}^{ij}(\theta)$, largely follows Li *et al.* [12]. Under the flat-sky approximation, the shear-shear two-point correlation function can be expressed as

$$\xi_{\pm}^{ij}(\theta) = \frac{1}{2\pi} \int d\ell \ell J_{0/4}(\theta\ell) (C^{E:ij}(\ell) \pm C^{B:ij}(\ell)), \quad (25)$$

where $J_{0/4}(\theta\ell)$ is the zeroth- or fourth-order Bessel function. The Hankel transform is performed using `FFTLg` [66] as implemented in `CosmoSIS`.

$C^{E/B:ij}(\ell)$ denotes the total E - and B -mode angular power spectra of the shear-shear correlation, which are determined by both gravitational lensing of the LSS (Sec. III A 1) and intrinsic alignments (Sec. III A 3). Specifically,

$$C^{E:ij}(\ell) = C_{GG}^{E:ij}(\ell) + C_{II}^{E:ij}(\ell) + C_{GI}^{E:ij}(\ell) + C_{GI}^{E:ji}(\ell), \quad (26)$$

$$C^{B:ij}(\ell) = C_{II}^{B:ij}(\ell). \quad (27)$$

The E -mode spectrum includes contributions from lensing-lensing autospectra ($C_{GG}^{E:ij}$), intrinsic-intrinsic alignments ($C_{II}^{E:ij}$), and the galaxy-lensing cross terms ($C_{GI}^{E:ij}$ and $C_{GI}^{E:ji}$).

The B -mode spectrum is assumed to arise solely from intrinsic-intrinsic correlations, as the B -mode contribution from lensing is neglected in this work [70]. The B -mode signal in the HSC Y3 shear catalog is not statistically significant and is therefore set to zero throughout the analysis.

C. Observational systematics

The systematics of the shear catalog need to be meticulously modeled to shield our results from systematic bias [9,71].

In this section, we describe the parameters used to model observational systematics present in the HSC Y3 shear catalog, including uncertainties in the redshift distribution, multiplicative shear bias, and PSF-related systematics.

1. Source redshift distribution

The fiducial redshift distribution of the HSC Y3 shear catalog is shown as the shaded region in the upper panel of Fig. 1. For the fiducial analysis, the HSC Y3 shear catalog is divided into four tomographic bins using the `dNNz` z_{best} estimates. The redshift distribution of each tomographic bin is modeled as a joint probability distribution on a redshift grid spanning $z = 0$ to 4, with a step size of 0.025. Each distribution is inferred using a logistic Gaussian process [38], constrained by

- (1) the `dNNz` photo- z estimates, with prior information that accounts for the cosmic variance of the photo- z training set; and
- (2) the clustering redshift between the photometric sample and the CAMIRA LRG reference sample [39,40,72], available in the range $z = 0.1$ – 1.1 .

As discovered in the HSC Y3 cosmic shear analysis [12,13], the mean redshifts of the third and fourth tomographic bins preferred by the Λ CDM model are inconsistent with those inferred from the fiducial redshift distributions based on photometric and clustering redshift calibrations. This discrepancy may arise because the clustering redshift calibration is limited to $z < 1.1$, which excludes part of bin 3 and all of bin 4. Independent 3×2 pt analyses—though using only a single source bin—also suggest deviations from the fiducial mean redshifts for the source sample [17,18]. As highlighted in [12], the inconsistency between the fiducial redshift distribution and the value preferred by cosmic shear is unlikely to be caused by statistical fluctuations, with statistical significance exceeding 95%.

We use a shift parameter Δz_i for each source redshift distribution [73], which modifies the mean redshift of the i th tomographic bin as

$$n_i(z) \longrightarrow n_i(z + \Delta z_i). \quad (28)$$

This shift affects both the cosmic shear and galaxy-galaxy lensing components of the data vector. In the case of cosmic

shear, modifying $n_i(z)$ alters the lensing efficiency $q_i(\chi)$ defined in Eq. (8). A redshift distribution shifted to higher redshift corresponds to (a) larger volume of foreground matter field and (b) higher lensing efficiency and therefore tends to prefer a lower amplitude of the matter power spectrum, parametrized by $S_8 = \sigma_8 \sqrt{\Omega_m/0.3}$.

For galaxy-galaxy lensing, the redshift distribution $n_i(z)$ of the source galaxies does not directly affect the theoretical value of $\Delta\Sigma(R_p)$ for a given lens bin q , since the model assumes fixed lens redshifts. However, the observed galaxy-galaxy lensing signal $\Delta\Sigma_{qi}$ between the q th lens bin and the i th source bin must be corrected for changes in the source redshift distribution $n_i(z)$.

We define the correction factor based on the ratio of average inverse critical surface densities, weighted by the lens and source weights w_l and w_s , over all galaxies in the q th lens bin and i th source bin:

$$f_{\Delta\Sigma}^{qi}(\Delta z_i) = \frac{\sum_{l \in q, s \in i} w_l w_s \langle \Sigma_{\text{crit}/ls}^{-1} \rangle^{\text{est}}(\Delta z_i)}{\sum_{l \in q, s \in i} w_l w_s \langle \Sigma_{\text{crit}/ls}^{-1} \rangle^{\text{fid}}}. \quad (29)$$

Here, $\langle \Sigma_{\text{crit}/ls}^{-1} \rangle^{\text{est}}(\Delta z_i)$ denotes the estimated average inverse critical surface density using the shifted source redshift distribution $n_i(z + \Delta z_i)$, while $\langle \Sigma_{\text{crit}/ls}^{-1} \rangle^{\text{fid}}$ uses the fiducial $n_i(z)$. The lens and source weights w_l and w_s follow the definitions in Sec. III B of [23]. Notice that $\langle \Sigma_{\text{crit}/ls}^{-1} \rangle^{\text{fid}}$ is computed by a cosmology with $\Omega_m = 0.279$ and $w_0 = -1$, while $\langle \Sigma_{\text{crit}/ls}^{-1} \rangle^{\text{est}}(\Delta z_i)$ is computed by the sampled Ω_m and w_0 . Therefore, $f_{\Delta\Sigma, qi}(\Delta z_i)$ also correct for the difference in comoving distance by the cosmology. It is shown that the impact of the assumed cosmology when measuring $\Delta\Sigma$ does not cause significant bias on the GGL inference if it is accounted for [74].

The corrected galaxy-galaxy lensing measurement is then

$$\Delta\Sigma_{\text{corr}}^{qi}(R_p, \Delta z_i) = f_{\Delta\Sigma}^{qi}(\Delta z_i) \Delta\Sigma^{qi}(R_p). \quad (30)$$

Note that the mean lens redshift z_q is assumed to be fixed, as the redshifts of the lens galaxies are spectroscopic and thus do not carry significant uncertainty. This correction factor applies to the entire theoretical prediction $\Delta\Sigma(R_p|z_q)$, including the main galaxy-galaxy lensing signal $\Delta\Sigma_{gG}(R_p)$, the magnification bias term $\Delta\Sigma_{\text{mag}}(R_p)$, and the one-halo correction term $\Delta\Sigma_{\text{PM}}(R_p)$.

As a result of the redshift discrepancies identified in previous HSC Y3 cosmology analyses, we adopt informative priors for Δz_1 and Δz_2 based on the estimates from [38] and use flat priors in the range $[-1, 1]$ for Δz_3 and Δz_4 . The full set of priors on Δz_i is listed in Table I. We expect that the implicit lensing ratio encoded in the tomographic galaxy-galaxy lensing and cosmic shear data vectors can self-constrain the redshift parameters Δz_3 and Δz_4 and yield competitive cosmological constraints. We leave the

TABLE I. The prior distributions used in the fiducial Bayesian analysis. The first section lists the cosmological parameters: five parameters are varied in the fiducial Λ CDM analysis, and the dark energy equation-of-state parameter w is additionally varied in the w CDM model; other cosmological parameters are fixed. The second section includes astrophysical parameters: one for baryonic feedback and five for the TATT intrinsic alignment model. The third section contains lens-related nuisance parameters, including linear galaxy biases, point-mass correction terms, and magnification bias parameters for each tomographic lens bin. The final section presents source-related nuisance parameters, which include one multiplicative shear bias and photometric redshift shift parameter per tomographic source bin, and four PSF systematics parameters.

Parameter	Prior
Cosmological parameters (Sec. III A 1)	
$\log(A_s \times 10^{10})$	$U[1.0, 5.0]$
$\Omega_b h^2$	$U[0.1, 0.025]$
n_s	$U[0.94, 1.0]$
$\Omega_c h^2$	$U[0.0998, 0.1398]$
Ω_m	$U[0.0906, 0.5406]$
$\sum m_\nu$ [eV]	0.06
w	$-1.0/(U[-2, -0.33] \text{ wCDM})$
w_a	0.0
Ω_k	0.0
Baryonic feedback (Sec. III A)	
A_b	$U[1.5, 3.13]$
Intrinsic alignment (Sec. III B 3)	
$A_{\text{IA},1}$	$U[-6, 6]$
$A_{\text{IA},2}$	$U[-6, 6]$
$\alpha_{\text{IA},1}$	$U[-6, 6]$
$\alpha_{\text{IA},2}$	$U[-6, 6]$
b_{TA}	$U[0, 2]$
Linear galaxy bias (Secs. III B 1 and III B 2)	
b_1	$U[0.1, 5.0]$
b_2	$U[0.1, 5.0]$
b_3	$U[0.1, 5.0]$
Point-mass correction (Sec. III B 2)	
$\Delta\Sigma_{\text{PM},1}$ (4 Mpc/h)	$U[0.0, 10.0]$
$\Delta\Sigma_{\text{PM},2}$ (4 Mpc/h)	$U[0.0, 10.0]$
$\Delta\Sigma_{\text{PM},3}$ (4 Mpc/h)	$U[0.0, 10.0]$
Magnification biases (Sec. III B 2)	
$\alpha_{\text{mag},1}$	$\mathcal{N}(2.258, 0.5)$
$\alpha_{\text{mag},2}$	$\mathcal{N}(3.563, 0.5)$
$\alpha_{\text{mag},3}$	$\mathcal{N}(3.729, 0.5)$
Multiplicative shear biases (Sec. III C 2)	
m_1	$\mathcal{N}(0.0, 0.01)$
m_2	$\mathcal{N}(0.0, 0.01)$
m_3	$\mathcal{N}(0.0, 0.01)$
m_4	$\mathcal{N}(0.0, 0.01)$

(Table continued)

TABLE I. (*Continued*)

Parameter	Prior
Photo- z systematics (Sec. III C 1)	
Δz_1	$\mathcal{N}(0, 0.024)$
Δz_2	$\mathcal{N}(0, 0.022)$
Δz_3	$U[-1, 1]$
Δz_4	$U[-1, 1]$
PSF systematics (Sec. III C 3)	
$\alpha'^{(2)}$	$\mathcal{N}(0, 1)$
$\beta'^{(2)}$	$\mathcal{N}(0, 1)$
$\alpha'^{(4)}$	$\mathcal{N}(0, 1)$
$\beta'^{(4)}$	$\mathcal{N}(0, 1)$

calibration of the high-redshift source redshift distribution for future work, through methods such as clustering redshift inference [75] or direct calibration [76], leveraging emerging high-redshift spectroscopic datasets overlapping the HSC footprint, including the DESI DR1 LSS sample [77].

2. Multiplicative calibration bias

The shear multiplicative bias of the HSC Y3 shear catalog is calibrated using image simulations, as described in [28]. These simulations account for galaxy model bias, noise bias, selection bias, and detection bias, using realistic galaxy samples derived from HST F814W-band images.

In this work, we model the residual multiplicative shear bias with one nuisance parameter per source tomographic bin, denoted m_i . For the cosmic shear data vector, the correction is applied as

$$\xi_{\pm}^{ij}(\theta) \longrightarrow (1 + m_i)(1 + m_j)\xi_{\pm}^{ij}(\theta). \quad (31)$$

For galaxy-galaxy lensing, as shown in Eq. (3), the $\Delta\Sigma$ signal is modified as

$$\Delta\Sigma_{qi}(R_p) \longrightarrow (1 + m_i)\Delta\Sigma_{qi}(R_p). \quad (32)$$

The image simulations confirm that the multiplicative bias m is controlled to within 1% across the redshift range of the source sample. In our analysis, the priors on m_i are Gaussian distributions centered at zero with a standard deviation of 0.01.

3. PSF additive bias

The correlation between PSF modeling residuals and PSF shapes can contaminate the shear-shear correlation function [78, 79]. Following [34], the HSC Y3 shear catalog is impacted by PSF leakage and modeling residuals

associated with the spin-2 components of the second moments e_{PSF} and the fourth moments $M_{\text{PSF}}^{(4)}$. The observed shear can be modeled as

$$\begin{aligned} \gamma_{\text{obs}} &= \frac{1}{2\mathcal{R}} e_{\text{obs}} \\ &= \frac{1}{2\mathcal{R}} (e_{\text{gal}} + \alpha^{(2)} e_{\text{psf}}^{(2)} + \beta^{(2)} \Delta e_{\text{psf}}^{(2)} \\ &\quad + \alpha^{(4)} M_{\text{psf}}^{(4)} + \beta^{(4)} \Delta M_{\text{psf}}^{(4)}), \end{aligned} \quad (33)$$

where the second through fifth terms represent, respectively, second-moment leakage, second-moment modeling residuals, fourth-moment leakage, and fourth-moment modeling residuals. Reference [34] finds significant additive bias in ξ_+ , while the contamination to ξ_- is negligible.

The additive PSF bias on ξ_+ is modeled as

$$\xi_+(\theta) \longrightarrow \xi_+(\theta) + \sum_{k=1}^4 \sum_{q=1}^4 p_k p_q \langle S_k S_q \rangle, \quad (34)$$

where $\mathbf{p} = [\alpha^{(2)}, \beta^{(2)}, \alpha^{(4)}, \beta^{(4)}]$ is the parameter vector and $\mathbf{S} = [e_{\text{psf}}^{(2)}, \Delta e_{\text{psf}}^{(2)}, M_{\text{psf}}^{(4)}, \Delta M_{\text{psf}}^{(4)}]$ is the vector of PSF moments. The parameters $\mathbf{p}$ are constrained by the shear-PSF and PSF-PSF correlation functions; we refer the reader to [34] for a detailed description.

To account for correlations between the components of $\mathbf{p}$, we reparametrize the PSF additive bias using $\mathbf{p}' = [\alpha'^{(2)}, \beta'^{(2)}, \alpha'^{(4)}, \beta'^{(4)}]$. The parameters $\mathbf{p}$ are related to $\mathbf{p}'$ via an invertible linear transformation:

$$\mathbf{p} = \mathbf{T} \cdot \mathbf{p}' + \bar{\mathbf{p}}, \quad (35)$$

where $\mathbf{T}$ is constructed so that the components of $\mathbf{p}'$ are uncorrelated and follow standard normal distributions (mean 0 and standard deviation 1). The transformation matrix $\mathbf{T}$ is given by

$$\mathbf{T} = \mathbf{V}^{1/2} \mathbf{U}, \quad (36)$$

where $\mathbf{V}$ is the diagonal matrix of eigenvalues of the covariance matrix of $\mathbf{p} - \bar{\mathbf{p}}$ and the columns of $\mathbf{U}$ are the corresponding eigenvectors. The Bayesian inference samples from the $\mathbf{p}'$ space with Gaussian priors centered at zero and standard deviation of one.

We do not model the PSF systematics in the galaxy-galaxy lensing signal, since the PSF condition does not correlate with lens selection in this work and, thus, does not affect the two-point statistics between lens and shape.

D. Summary of the theoretical template

We use both public and custom modules within CosmoSIS to construct the theoretical model for the 3×2 pt data vector. The linear matter power spectrum is computed using

CAMB, with the parameters $\log(10^{10}A_s)$, n_s , $\Omega_b h^2$, $\Omega_c h^2$, and Ω_ϵ as free parameters for the Λ CDM model. For the w CDM model, we additionally free the dark energy equation-of-state parameter w_0 . We assign flat prior on $\log(10^{10}A_s)$ following [1].

Nonlinear evolution and baryonic effects are modeled using HMCODE 2016, parametrized by a single baryonic feedback parameter A_b . Intrinsic alignments are modeled using the TATT model, with five free parameters: $A_{IA,1}$, $A_{IA,2}$, $\eta_{IA,1}$, $\eta_{IA,2}$, and b_{TA} .

The clustering signal w_p and galaxy-galaxy lensing signal $\Delta\Sigma$ are computed using the minimal bias model and are modulated by the linear galaxy bias parameters b_1 , b_2 , and b_3 for each lens bin. Magnification bias is modeled with one parameter $\alpha_{\text{mag},q}$ per lens bin, with informative priors derived from the slope of the SDSS galaxy number counts near the luminosity cut.

We implement a customized module in CosmoSIS for the point-mass correction term, with one free parameter $\Delta\Sigma_{\text{PM},q}(4h^{-1}\text{Mpc})$ per lens bin and uninformative priors. For the shear-shear correlation function $\xi_\pm$, we compute the angular power spectra including both lensing and intrinsic alignment terms and transform them into configuration space via Hankel transforms.

The shear observables are modified with one multiplicative shear bias parameter m_i per source bin, calibrated using image simulations. We adopt Gaussian priors centered at zero with standard deviation $\sigma = 0.01$. For the source redshift distribution uncertainties, we use informative priors on Δz_1 and Δz_2 from photometric and clustering redshift calibration and adopt flat uninformative priors $\Delta z_{3,4} \sim \mathcal{U}[-1, 1]$ due to empirical evidence for a non-negligible bias in $\Delta z_{3,4}$.

We model the PSF additive bias with four parameters $\alpha^{(2)}$, $\beta^{(2)}$, $\alpha^{(4)}$, and $\beta^{(4)}$, using informative priors constrained by PSF-shape cross-correlations.

In total, the fiducial Bayesian inference involves 32 (or 33) free parameters depending on whether the w CDM model is used. We collectively denote the full parameter vector as $\mathbf{p}$.

For the 3×2 pt data vector $\mathbf{d}$, we arrange the probes in the following order:

$$\mathbf{d} = \{\mathbf{w}_p, \Delta\Sigma, \xi_+, \xi_-\}. \quad (37)$$

Throughout this work, the elements of the data vector $d^{ij}(R_k)$ are ordered lexicographically in ijk .

For the galaxy clustering, we define $\mathbf{w}_p = w_{qq}(R_k)$, where $q = 0, 1, 2$ corresponds to the LOWZ, CMASS1, and CMASS2 tomographic bins, respectively. We use the projected clustering signal in the range $R_p = [8, 80]h^{-1}\text{Mpc}$, sampled at 14 logarithmically spaced points per tomographic bin. The lower limit of the scale cut is set by the validity range of the minimal bias model [17, 80], while the upper limit is chosen to avoid the baryon acoustic

oscillation feature. In total, the clustering data vector $\mathbf{w}_p$ consists of 42 data points.

For galaxy-galaxy lensing, we define $\Delta\Sigma = \Delta\Sigma_{qi}(R_k)$, where q indexes the lens bins and i indexes the source bins. We include all four HSC source bins for the LOWZ lens bin and use the second through fourth HSC bins for CMASS1 and CMASS2, in order to avoid significant redshift overlap between the lens and source populations. For each lens-source bin pair, we use the $\Delta\Sigma(R_p)$ signal in the range $R_p = [2, 70]h^{-1}\text{Mpc}$ for Bayesian inference. The lower scale cut is chosen based on the off-centering effect in the lens sample, as characterized in mock validation tests [23], while the upper scale cut is determined from the null test of the cross-component $\Delta\Sigma_\times$. Each lens-source pair contributes 14 logarithmically spaced data points, resulting in a total of 140 data points for the galaxy-galaxy lensing data vector.

For cosmic shear, we define $\xi_\pm = \xi_\pm^{ij}(\theta_k)$, where i and j label the tomographic bins. We use the angular range $\theta \in [7.1, 56.6]$ arcmin for all ξ_+ bin pairs and $\theta \in [31.2, 248]$ arcmin for all ξ_- bin pairs. The small-scale cuts are imposed to avoid the modeling uncertainties due to baryonic feedback, while the large-scale cuts are set based on the B-mode null test of the observed data.

E. Bayesian inference

We conduct Bayesian inference to estimate cosmological parameter constraints using the data vector measured from the HSC and SDSS datasets. We define the terminology relevant to the inference, as well as the parameter space and data vector used in the analysis.

We denote the parameter vector as $\mathbf{p}$, the observed data vector as $\mathbf{d}^{\text{obs}}$, the theoretical data vector as $\mathbf{d}^{\text{theory}}(\mathbf{p})$, and the covariance matrix of $\mathbf{d}^{\text{obs}}$ as $\mathbf{C}$. For each analysis, we sample $\mathbf{p}$ and compute the log-likelihood function as

$$\log \mathcal{L}(\mathbf{d}|\mathbf{p}) = -\frac{1}{2}[\mathbf{d}^{\text{obs}} - \mathbf{d}^{\text{theory}}(\mathbf{p})]^T \mathbf{C}^{-1} [\mathbf{d}^{\text{obs}} - \mathbf{d}^{\text{theory}}(\mathbf{p})]. \quad (38)$$

Since our covariance matrix is estimated by finite realizations of the mock catalogs, we multiply the log likelihood by the Hartlap factor [81] $\mathcal{P}$, defined by

$$\mathcal{P} = \frac{N_{\text{mock}} - n_{\text{DV}} - 2}{N_{\text{mock}} - 1}. \quad (39)$$

For our fiducial analysis, $N_{\text{mock}} = 1404$, and $n_{\text{DV}} = 322$, so $\mathcal{P}_{\text{fid}} = 0.77$. The Hartlap factor inflates our constraining power by ~ 10 percent.

The priors for all parameters are summarized in Table I. We sample the posterior using the nested sampling algorithm MultiNest, implemented within the CosmoSIS framework [48]. For the fiducial analysis, we set the number of live points to 500, the efficiency parameter to 0.3, and the

tolerance parameter to 1.0. We additionally run a MultiNest analysis with the tolerance parameter reduced to 0.05 and find no significant differences in the results (see Appendix B).

We note that physically $\Delta\Sigma_{\text{PM},q}(4 \text{ Mpc}/h)$ and b_q should be correlated due to their dependence on halo mass. Due to software constraints, we model the priors as independent parameters and leave the study with correlated priors to future studies.

For the fiducial analysis, we report the results of the Bayesian inference using the 1σ and 2σ confidence contours, along with summary statistics in the format

$$\text{mode}_{-34\% \text{ lower}}^{+34\% \text{ upper}}(\text{MAP}, \text{mean}), \quad (40)$$

where the mode refers to the peak of the one-dimensional marginalized posterior distribution of the parameter. We also compute the maximum *a posteriori* (MAP) estimate

for the fiducial analysis by performing optimization from 100 random starting points in the parameter space. However, we do not compute the MAP for the validation tests or internal consistency analyses.

IV. RESULTS AND COMPARISON

A. Key results

We present the key findings of this work. The fiducial analysis, defined in Sec. III, is a Bayesian inference of 32 free parameters using a $3 \times 2\text{pt}$ data vector that includes galaxy clustering, galaxy-galaxy lensing, and cosmic shear measurements. After successfully passing all null tests, internal consistency checks, and validation tests across the three blinded catalogs, we unblinded the results and identified the $\text{blind_id} = 0$ catalog as the true dataset. Importantly, no modifications were made to the fiducial analysis after unblinding.

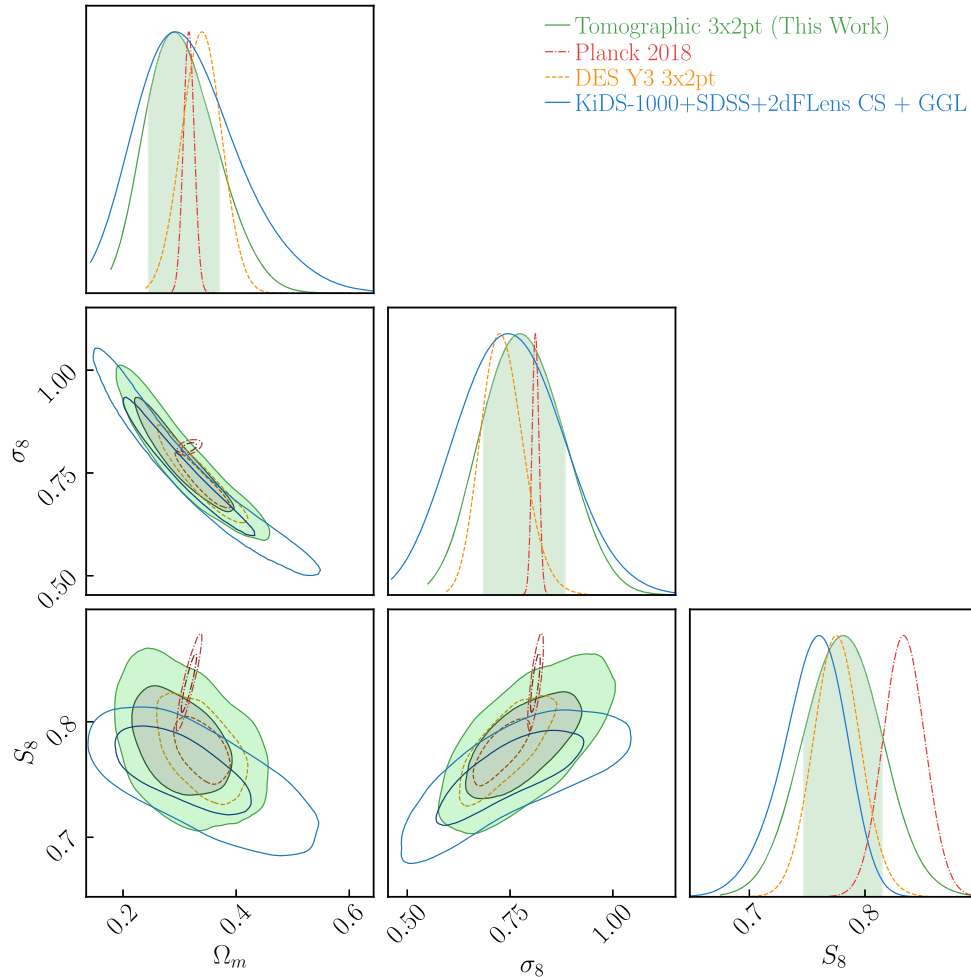


FIG. 4. Comparison of the fiducial cosmological constraints from this work (green contours) with external datasets. Shown for reference are the Planck 2018 TTTEEE + lowE CMB results (red contours; [1]), the Dark Energy Survey (DES) year-3 $3 \times 2\text{pt}$ analysis (orange contours; [2]), and the Kilo-Degree Survey (KiDS)-1000 joint cosmic shear and galaxy-galaxy lensing analysis (blue contours; [82]). Our $3 \times 2\text{pt}$ constraints from HSC Y3 are consistent with those from other clustering and weak lensing surveys while providing improved redshift calibration through self-consistent tomographic lensing.

The fiducial analysis under the Λ CDM model yields the following constraints on key cosmological and redshift parameters:

$$S_8 = \sigma_8 \left(\frac{\Omega_m}{0.3} \right)^{0.5} = 0.780^{+0.029}_{-0.030} (0.782, 0.781), \quad (41)$$

$$\Delta z_3 = -0.112^{+0.046}_{-0.049} (-0.128, -0.129), \quad (42)$$

$$\Delta z_4 = -0.185^{+0.071}_{-0.081} (-0.192, -0.206), \quad (43)$$

where the values are presented in the format $\text{mode}^{+34\%}_{-34\%} (\text{MAP}, \text{mean})$. When optimizing along the principal degeneracy between Ω_m and σ_8 , the fiducial analysis yields

$$\tilde{S}_8 = \sigma_8 \left(\frac{\Omega_m}{0.3} \right)^{0.6} = 0.781^{+0.027}_{-0.027} (0.783, 0.781). \quad (44)$$

We also obtain constraints on parameters that derive S_8 :

$$\Omega_m = 0.284^{+0.061}_{-0.050} (0.300, 0.306), \quad (45)$$

$$\sigma_8 = 0.774^{+0.093}_{-0.086} (0.782, 0.783). \quad (46)$$

The $\tilde{S}_8$ constraint achieves a precision of 3.5%, representing the most precise S_8 measurement obtained to date from HSC cosmological analyses. In Fig. 4, we compare the fiducial results on Ω_m , σ_8 , and S_8 with external datasets, including the Planck TTTEEE + lowE cosmic microwave background (CMB) results [1], the DES Y3 3×2 pt analysis [2], and the KiDS – 1000 + SDSS + 2dFLenS cosmic shear and galaxy-galaxy lensing analysis [82]. The HSC Y3 tomographic 3×2 pt analysis shows consistency with other clustering and weak lensing analyses.

We do not find significant tension between our 3×2 pt results and the Planck 2018 constraints. To quantify this comparison, we compute the eigentension metric

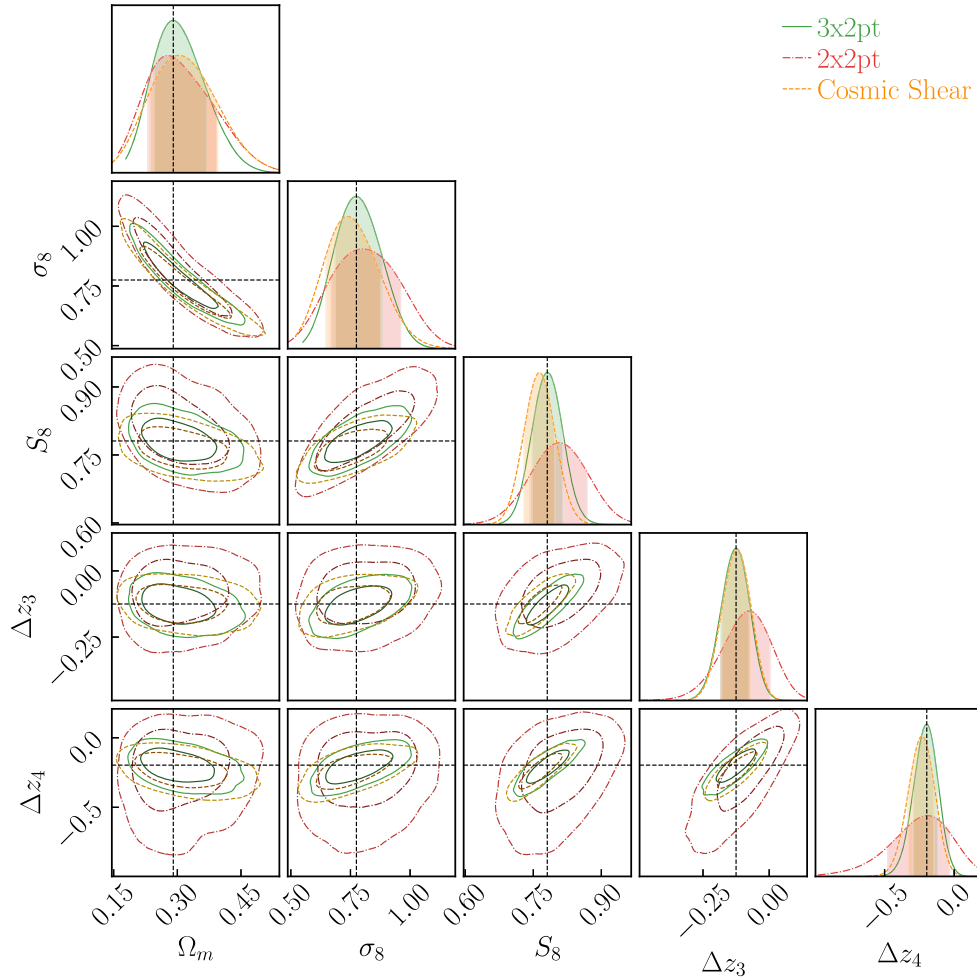


FIG. 5. Marginalized constraints on Ω_m , σ_8 , S_8 , Δz_3 , and Δz_4 from the 3×2 pt (clustering + galaxy – galaxy lensing + cosmic shear), 2×2 pt (clustering + galaxy-galaxy lensing), and cosmic shear analyses presented in this work. The constraints on Ω_m and σ_8 are jointly informed by the 2×2 pt and cosmic shear measurements, while the constraints on S_8 , Δz_3 , and Δz_4 are primarily driven by the cosmic shear component. The 2×2 pt analysis yields results consistent with the 3×2 pt constraints across all parameters.

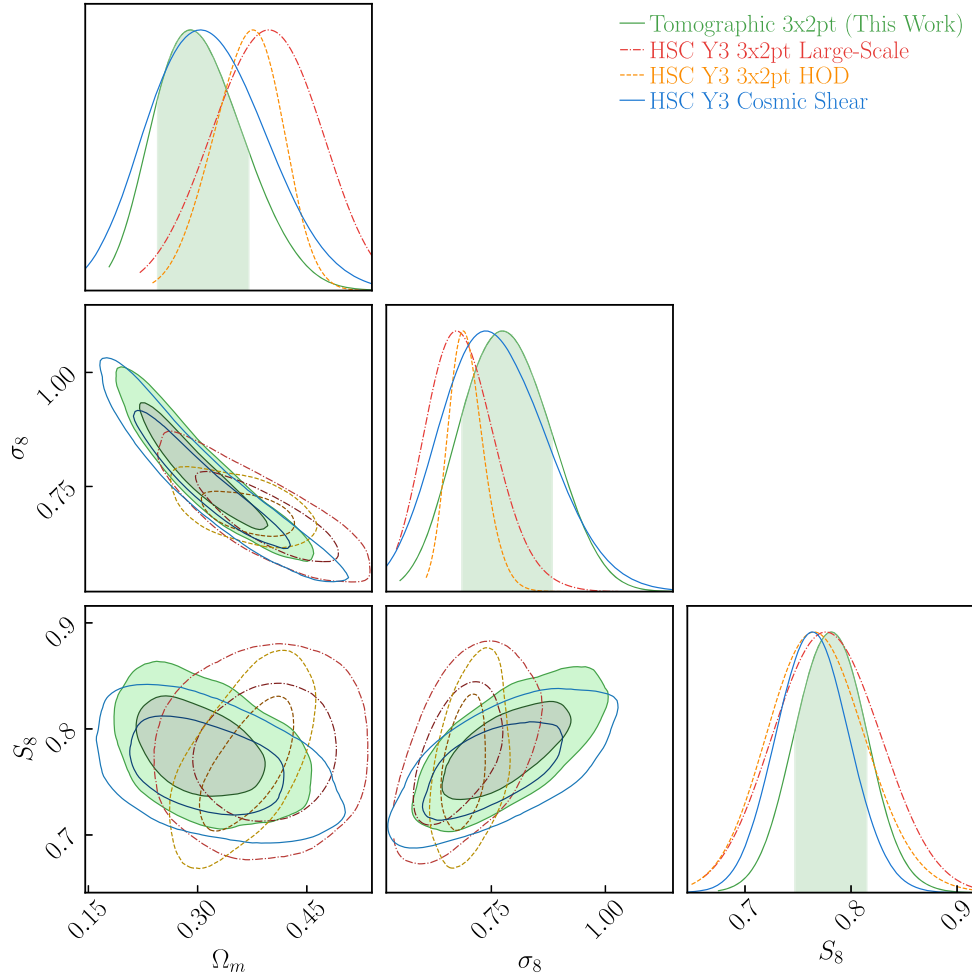


FIG. 6. Comparison of the 3×2 pt analysis results from this work (black contours) to previous HSC Y3 results: the 3×2 pt analysis using a single source bin at large scales (red contours; [17]), the 3×2 pt analysis using a single source bin including small scales (orange contours; [18]), and the cosmic shear analysis (blue contours; [12]). Relative to previous 3×2 pt results, our analysis yields slightly lower Ω_m and higher σ_8 values, while the S_8 constraints remain statistically consistent across all analyses.

introduced by [83]. Specifically, we diagonalize the posterior covariance matrix of our fiducial analysis and identify the two principal eigenvectors:

$$\mathbf{e}_1 = \sigma_8 \Omega_m^{0.6}, \quad (47)$$

$$\mathbf{e}_2 = \Omega_m \sigma_8^{-0.6}. \quad (48)$$

The first eigenmode $\mathbf{e}_1$ corresponds to the most constrained direction in the 3×2 pt data vector—closely aligned with S_8 —while $\mathbf{e}_2$ is approximately orthogonal and reflects the degeneracy direction. We find that the probability that our fiducial 3×2 pt posterior and the Planck 2018 posterior are statistically inconsistent in the $(\mathbf{e}_1, \mathbf{e}_2)$ space is 80.1%, corresponding to a 1.31σ tension.

Figure 5 shows the 1D marginalized constraints on Ω_m , σ_8 , S_8 , Δz_3 , and Δz_4 from our 3×2 pt, 2×2 pt, and cosmic shear analyses. We observe that the constraints on S_8 , Δz_3 ,

and Δz_4 are primarily driven by cosmic shear, while the constraints on Ω_m and σ_8 are jointly informed by both 2×2 pt and cosmic shear probes.

The S_8 result from our analysis is statistically consistent with previous HSC Y3 3×2 pt analyses presented in [17,18], as well as with cosmic shear results in [12,13]. In Fig. 6, we compare our constraints with those from the HSC Y3 3×2 pt large-scale analysis [17], the 3×2 pt small-scale halo-based analysis [18], and the HSC Y3 cosmic shear analysis [12]. Our analysis provides the most precise constraint on S_8 among the HSC Y3 cosmology results to date. In terms of $\Omega_m - \sigma_8$ 2D figure of merit, the halo occupation distribution 3×2 pt remains to be the most constraining.

We also find that the redshift distribution parameters Δz_3 and Δz_4 are constrained by the 3×2 pt analysis and are statistically consistent with the results from the cosmic shear analysis [12,13]. By computing the covariance matrix of the joint posterior of $(\Delta z_3, \Delta z_4)$, we determine that the

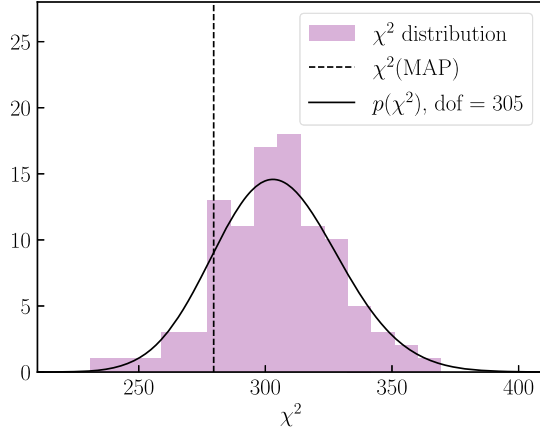


FIG. 7. The empirical χ^2 distribution (purple) of the 3×2 pt data vector, estimated from the minimum χ^2 values of the MAP parameters fitted to 100 noisy mock data vectors. The χ^2 value corresponding to the MAP fit of the real data vector is shown as the black dotted line. The resulting p value for the goodness of fit of our fiducial analysis is 0.91, indicating good agreement between the model and the data.

probability of inconsistency with the fiducial value (0,0) is 98.3%, corresponding to a 2.4σ tension between the Λ CDM-preferred redshift distributions and those inferred from photometric redshifts. This emphasizes the importance of accurately calibrating the redshift distributions of high-redshift source bins for HSC, and, in the future, for Rubin Observatory and Roman, using external spectroscopic datasets such as DESI DR1 [77].

In Fig. 7, we show the empirical χ^2 distribution of the 3×2 pt data vector (purple histogram), compared to the χ^2 value of the best-fit parameters from the real data (black dotted line). The empirical distribution is estimated from 100 synthetic data vectors generated by sampling from the fiducial covariance matrix, which has been corrected by the Hartlap factor [81] to account for the noise due to the limited number of simulations used in its estimation. For each synthetic data vector, we compute the χ^2 of the best-fit parameter set, defined as the MAP solution obtained by running the optimizer from ten different starting points to mitigate the risk of converging to local maxima in the likelihood surface. The resulting χ^2 distribution corresponds to a model with 305 effective degrees of freedom. Given the minimum χ^2 value of 279.6 from the real data, we find a p value of 0.91, indicating that the fiducial theoretical model provides an excellent fit to the data vector.

B. w CDM analysis

In addition to the Λ CDM results, we perform a w CDM analysis in which the dark energy equation of state parameter w_0 is treated as a free parameter with a uniform prior $U[-2, -0.33]$, while the time variation parameter w_a

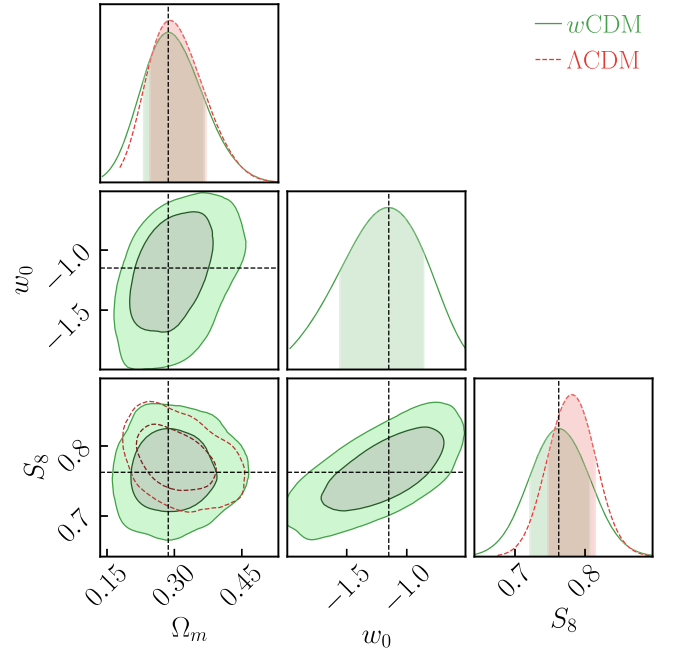


FIG. 8. Comparison of the 68% and 95% confidence contours between the Λ CDM (red) and w CDM (green) analyses in the (w_0, Ω_m, S_8) parameter space. The w CDM model allows for a free dark energy equation of state w_0 , while w_a is fixed to zero. The two models yield consistent results, with w CDM exhibiting slightly broader contours and a marginally lower mode value of S_8 . The dotted lines indicate the mode of the marginalized 1D posterior distributions in the w CDM model.

is fixed to zero. In Fig. 8, we show the 68% and 95% confidence contours for the w CDM and Λ CDM analyses in the $\Omega_m - w_0 - S_8$ parameter space. Under the w CDM model, we recover the following parameter constraints:

$$S_8 = s_8 \left(\frac{\Omega_m}{0.3} \right)^{0.5} = 0.756^{+0.038}_{-0.036} \quad (0.773, 0.764), \quad (49)$$

$$w_0 = -1.17^{+0.31}_{-0.35} \quad (-1.15, -1.21), \quad (50)$$

$$\Delta z_3 = -0.120^{+0.048}_{-0.051} \quad (-0.121, -0.124), \quad (51)$$

$$\Delta z_4 = -0.199^{+0.077}_{-0.079} \quad (-0.164, -0.201). \quad (52)$$

Compared to the Λ CDM results, we observe a slightly lower S_8 value under the w CDM model. The recovered w_0 value is consistent with the cosmological constant ($w_0 = -1$) within 1σ . Importantly, the constraining power on the source redshift shift parameters Δz_3 and Δz_4 remains robust, indicating that the tomographic lensing ratio information is largely insensitive to the expansion history parametrized by w_0 .

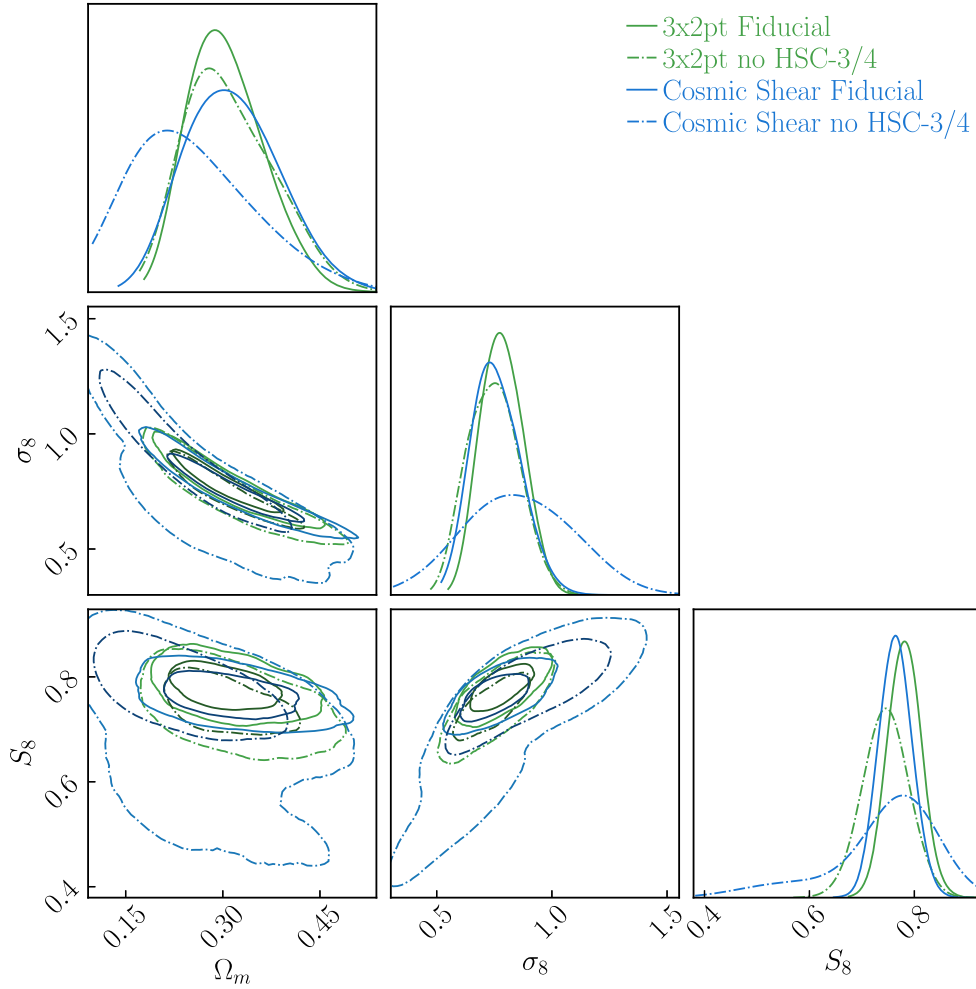


FIG. 9. HSC Y3 3×2 pt and cosmic shear analysis with and without HSC bins 3 and 4. Cosmological constraints degrade significantly for both analyses, especially cosmic shear, showing that the high redshift bins still contain cosmological information without well-calibrated redshift distributions.

C. Analysis without high- z source bins

In this section, we discuss an interesting scenario—the HSC Y3 3×2 pt and cosmic shear analysis without its third and fourth tomographic bins. In Fig. 9, we show cosmological constraints on Ω_m , σ_8 , and S_8 with and without HSC bin 3 and bin 4 for 3×2 pt and cosmic shear analysis. The cosmological constraints significantly degrade without HSC bin 3 and bin 4, especially for cosmic shear. The S_8 1σ went down to 0.051 from 0.030 for cosmic shear and to 0.040 from 0.028 for 3×2 pt analysis. This result shows that, despite not having well-calibrated redshift distributions, the lensing of HSC bins 3 and 4 still contains significant cosmological information.

D. Internal consistency tests

We conduct extended internal consistency tests to ensure that our cosmological results are unbiased. These tests include analyses performed on subsets of the data vector or with slightly different analysis choices. In Fig. 10, we show

the 1D constraints on Ω_m , σ_8 , S_8 , Δz_3 , and Δz_4 from all internal consistency tests and the bias compared to the fiducial analysis.

The first set of tests (“ 2×2 pt” and “cosmic shear”) compares results from individual cosmological probes within the 3×2 pt data vector. As discussed in Sec. IV A, both the 2×2 pt and cosmic shear results are consistent with the fiducial analysis, although the 2×2 pt analysis yields a slightly higher S_8 value than cosmic shear. This trend is also reported in [17,18].

The second set of tests (“no LOWZ,” “no CMASS1,” “no CMASS2,” “no HSC-1,” “no HSC-2,” “no HSC-3,” and “no HSC-4”) assesses the impact of removing individual lens or source tomographic bins. We observe no significant bias in S_8 from the removal of a single tomographic bin, except for the no HSC-4 case. To test whether the -0.8σ bias is statistically significant, we run fiducial and no HSC-4 analyses on 50 noisy data vectors generated for the χ^2 calculation and computed the distribution of $|\Delta S_8|$ with and without the HSC-4 bin, shown in Fig. 11. We find that

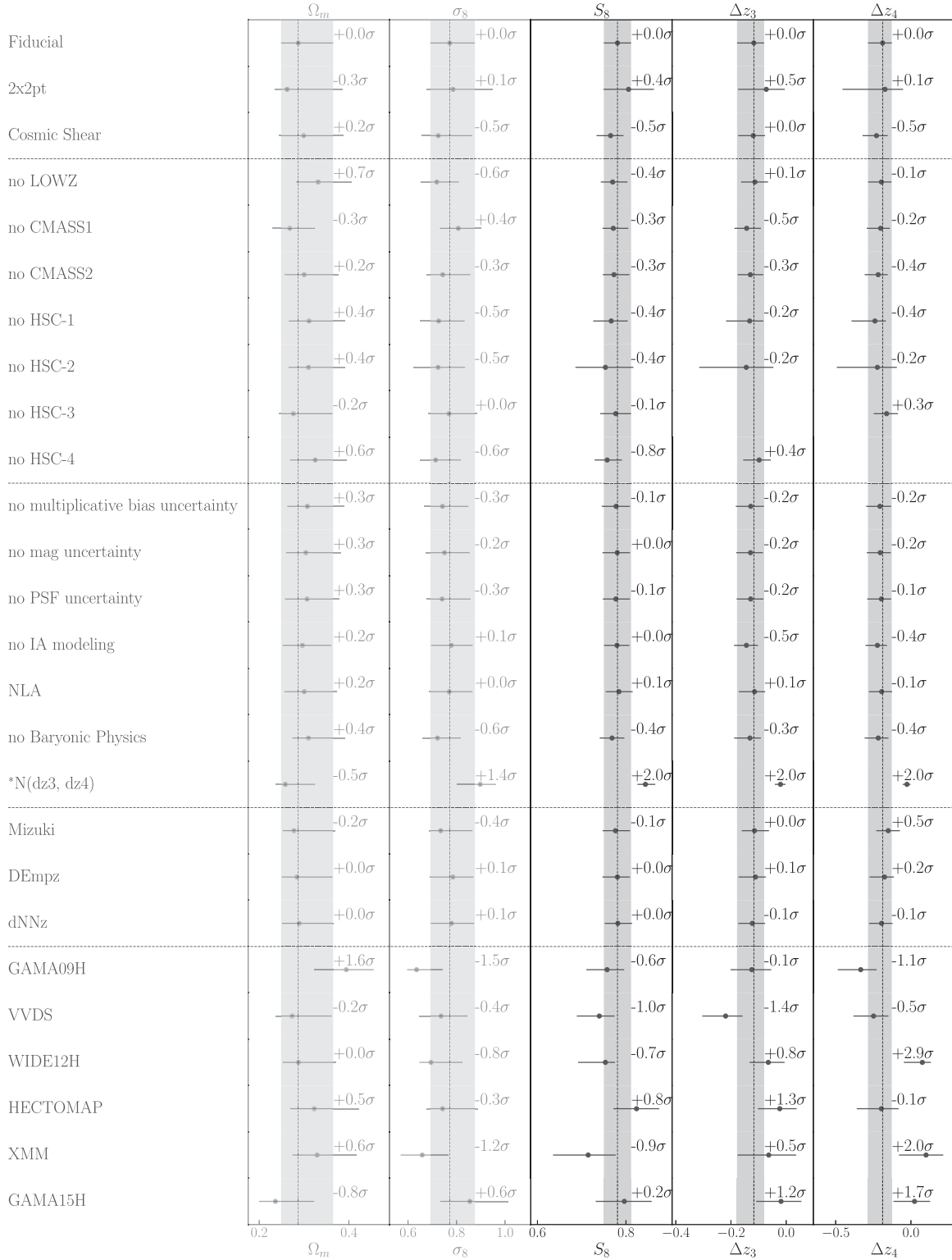


FIG. 10. Summary of internal consistency results for five key parameters. Each point represents the mode of the marginalized 1D posterior distribution from a different test, with error bars denoting the 34% upper and lower confidence intervals. The vertical dashed lines and shaded bands mark the mode and 1σ region of the fiducial analysis for comparison. We find that the inferred parameters are consistent across all subsets of the data vector and insensitive to variations in systematic modeling, except for the case where we apply Gaussian prior to Δz_3 and Δz_4 . For systematics where results show sensitivity (e.g., baryonic feedback and redshift distribution), we adopt conservative modeling choices in the fiducial analysis. The bias of the mode compared to the fiducial analysis is printed onto the figure. The inconsistent row [“N(dz3, dz4)”] is marked “*”, which leads to the prior choices of these parameters.

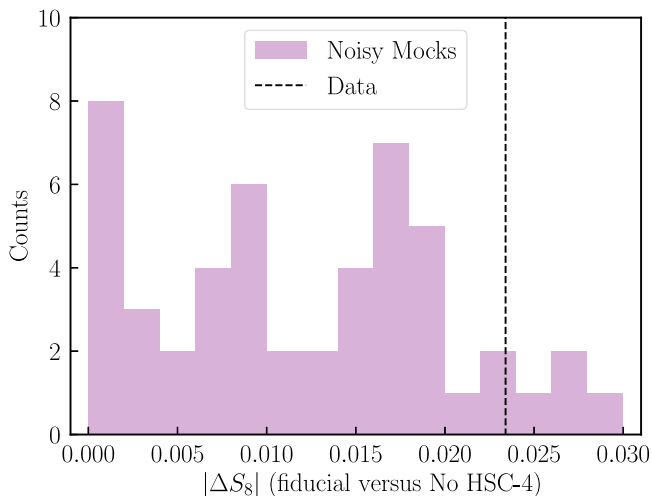


FIG. 11. The distribution of ΔS_8 between the fiducial and “no HSC-4” analyses of 50 noisy data vectors. The dashed line shows the level of bias in Fig. 10, i.e., 0.8σ . The p value that this bias is drawn from the distribution is 0.08, which is not a conclusive evidence that the bias is significant.

the p value that the -0.8σ is drawn from the uncertainty to be 0.08, which is not strong enough evidence to conclude that the bias is significant. However, this is worth further notice in future analyses. We also note the constraints on S_8 and $(\Delta z_3, \Delta z_4)$ rely strongly on the second source bin, which serves as an anchor point for redshift self-calibration. We find that removing the third and fourth HSC bins merely increase the S_8 uncertainties, suggesting that the cosmological parameters, the point-mass correction term, and the galaxy bias are mainly constrained by the first and second HSC bins, due to their degeneracy with the redshift parameters.

The third set of internal consistency tests applies alternative analysis choices, including removing the uncertainty associated with nuisance parameters (“no magnification uncertainty,” “no multiplicative bias uncertainty,” and “no PSF uncertainty”), removing systematic modeling altogether (“no IA modeling” and “no baryonic physics”), and using Gaussian informative priors on the redshift shift parameters [$\mathcal{N}(\Delta z_3), \mathcal{N}(\Delta z_4)$]. We find that removing the uncertainty of nuisance parameters does not significantly alter the results. Similarly, omitting the intrinsic alignment modeling does not induce a significant shift in the constraints. However, turning off baryonic feedback modeling (by setting $A_{\text{bary}} = 3.13$) leads to a lower inferred value of S_8 by 0.4σ .

When adopting the Gaussian informative priors on Δz_3 and Δz_4 inferred from photometric redshift and clustering redshift cross-correlation calibrations [38], we observe significant shifts in the posterior distributions of S_8 , Δz_3 , and Δz_4 . This is consistent with findings from [12,13], which motivated the use of uninformative priors in our fiducial analysis. Notably, this test also demonstrates the

potential constraining power of the HSC 3×2 pt analysis if the redshift distribution were accurately calibrated—yielding a precision of approximately 2% on S_8 .

We also test the robustness of our results against the choice of photometric redshift (photo- z) estimation method (“DNNz”, “DEmPz”, and “Mizuki”). In these tests, we retain the same tomographic bin assignments as in the fiducial analysis but use each specific photo- z method to compute the critical surface density $\Sigma_{\text{cr}}^{-1}(z_l, z_s)$ in the galaxy-galaxy lensing measurement, as well as the redshift distribution $n_i(z)$ used in the theoretical modeling. We find that our cosmological results remain consistent across all photo- z methods tested.

In the final set of internal consistency tests, we measure the 3×2 pt data vector and its covariance matrix independently on each HSC field, while continue using the entire SDSS catalog. We then perform the fiducial analysis on these individual field datasets. The resulting parameter constraints show scatter consistent with their expected uncertainties. Given that the fields are largely independent—except for their shared clustering signal—this level of variation is expected.

We note that the parameter constraints in the internal consistency tests are likely to be correlated to the fiducial analysis. Therefore, the significance of the parameter difference $\theta_1 - \theta_2$ relates to their correlation matrix and should not be judged only based on their own uncertainty. Without the correlation of θ_1 and θ_2 , we would not draw conclusion of whether the parameter difference is statistically significant.

Overall, we do not find significant bias in our cosmological results when using subsets of the data. The only cases where notable shifts occur are when making more aggressive assumptions about baryonic feedback or applying informative redshift priors. As a result, we adopt conservative modeling choices for these components in the fiducial analysis.

V. DISCUSSION AND CONCLUSION

This work presents a cosmological analysis based on the measurement of clustering and weak lensing two-point correlation functions using the HSC Y3 shear catalog and the SDSS DR11 LSS catalog. This work introduces two major improvements over previous cosmological analyses with HSC.

- (1) We employ tomographic binning for the source galaxies in both galaxy-galaxy lensing and cosmic shear measurements. This approach increases the overall signal-to-noise ratio and enables joint constraints on the redshift distribution parameters Δz_3 and Δz_4 , which are critical due to the limited redshift calibration in the third and fourth tomographic bins.
- (2) We extend the modeling of the galaxy-galaxy lensing signal down to $2h^{-1}$ Mpc by adopting a point-mass correction term in addition to the linear

galaxy bias model in the $\Delta\Sigma$ formalism. The point-mass correction accounts for additional lensing from a hypothetical mass concentration at the halo center and is parametrized by one free parameter per lens bin. This allows us to include small-scale information without explicitly modeling higher-order galaxy bias terms.

Our fiducial analysis yields a LSS clustering amplitude of $S_8 = \sigma_8(\Omega_m/0.3)^{0.5} = 0.780^{+0.029}_{-0.030}$, consistent with previous HSC cosmology results [12,13,17,18] as well as the DES Y3 cosmic shear and 3×2 pt analyses [2,10]. The optimized parameter yield $\tilde{S}_8 = \sigma_8(\Omega_m/0.3)^{0.6} = 0.781^{+0.027}_{-0.027}$. Our S_8 result shows a mild 1.3σ tension with the Planck CMB constraint [1], although the discrepancy is not statistically significant. Additionally, we report constraints on $\Omega_m = 0.284^{+0.061}_{-0.050}$ and $\sigma_8 = 0.774^{+0.093}_{-0.086}$. Our measurement of Ω_m is in good agreement with independent cosmological probes, including baryon acoustic oscillation measurements and the Planck CMB results. In the w CDM analysis, we obtain $S_8 = 0.756^{+0.038}_{-0.036}$ and $w_0 = -1.17^{+0.31}_{-0.35}$, consistent with a cosmological constant and slightly lower S_8 than in Λ CDM.

One important feature of our analysis is that we do not fully rely on photometric redshift estimates or external redshift calibration for the third and fourth source bins. Instead, we adopt flat (uninformative) priors on the redshift shift parameters Δz_3 and Δz_4 , allowing the 3×2 pt data vector to self-calibrate these parameters. Our fiducial analysis yields $\Delta z_3 = -0.112^{+0.046}_{-0.049}$ and $\Delta z_4 = -0.185^{+0.071}_{-0.081}$. The joint posterior on $(\Delta z_3, \Delta z_4)$ is in 2.3σ tension with (0,0), highlighting the critical importance of accurate redshift calibration in weak lensing cosmology.

This work motivates future improvements in several directions. As tomographic galaxy-galaxy lensing and cosmic shear measurements extract higher signal-to-noise ratios from the catalog, the corresponding increase in the size of the data vector brings it closer to the number of simulations used to estimate the covariance matrix. As a result, the Hartlap correction becomes significant in the likelihood evaluation, reducing the constraining power of the analysis. To mitigate this issue, one can generate more simulations or consider alternative methods for estimating the covariance matrix, such as analytic covariance modeling. Additionally, data compression techniques may be explored (e.g., [84]) to reduce the dimensionality of the data vector without losing cosmological information.

Looking ahead, this work lays the groundwork for future HSC 3×2 pt analyses that aim to maximize signal-to-noise ratio across a broad range of redshifts and angular scales, particularly in galaxy-galaxy lensing. It also provides a methodological foundation for joint DESI-LSST analyses. Importantly, we demonstrate that 3×2 pt analyses can still deliver competitive cosmological constraints even when

redshift calibration is uncertain, provided that the source catalog is defined consistently for both cosmic shear and galaxy-galaxy lensing. Nonetheless, this work further underscores the critical importance of precise redshift calibration in the current era of weak lensing cosmology.

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DATA AVAILABILITY

The data that support the findings of this article are openly available [86].

APPENDIX A: VALIDATION ANALYSIS

We perform 3×2 pt analyses on a suite of mock catalogs incorporating various features to validate that our analysis pipeline and methodological choices are robust against systematic errors. These mock data vectors are computed by halo-based mock catalogs generated in [16]. In this section, we describe the validation tests and present their results.

Figure 12 displays the mode and 1σ uncertainty of the one-dimensional posterior distributions for Ω_m , σ_8 , S_8 , Δz_3 , and Δz_4 across all validation tests. The true input values of the data vector are indicated by dashed lines. We emphasize that our validation focuses on S_8 , Δz_3 , and Δz_4 , which are the primary parameters constrained in this work. The shaded regions represent the 1σ uncertainty of the fiducial analysis, centered on the true parameter values. While

deviations from the fiducial result quantify the relative impact of a specific systematic effect, the offset from the true values reflects a combination of model imperfections and projection effects [64].

The first three tests—labeled “fiducial,” “ 2×2 pt,” and “cosmic shear”—analyze the 3×2 pt, 2×2 pt, and cosmic shear probes, respectively. We observe no significant biases in S_8 , Δz_3 , or Δz_4 for any of these configurations. However, the 3×2 pt and cosmic shear analyses exhibit notable projection effects in the inferred values of Ω_m and σ_8 , potentially driven by the imposed priors on the parameter space.

In the second set of validation tests, we assess the robustness of the analysis against various astrophysical effects. nonfidNsat, sat-DM, and sat-subhalo represent different methods for populating satellite galaxies. offcenter refers to simulations where central galaxies are displaced from the halo centers. assembly_bias modifies the assembly history relative to the fiducial model. baryon includes the effects of baryonic feedback in the simulations, while incompleteness introduces incompleteness in the galaxy population to emulate observational limitations in SDSS. fof assigns galaxies using halos identified via the friends-of-friends algorithm. We find that none of these astrophysical effects introduces a significant bias in the key parameters.

We introduce a significant IA signal into the galaxy-galaxy lensing measurement based on the overlapping redshift distributions and prediction of nonlinear alignment model, and perform an analysis without modeling this effect (GGL-IA). We find no significant bias in the inferred parameters, as galaxy-galaxy lensing is not the dominant probe for the constraints on S_8 , Δz_3 , or Δz_4 . Furthermore, we do not expect the real IA contamination to our GGL data vector to be severe, because our lens-source pair weights w_{ls} effectively eliminate lens-source pair that are physically associated.

The third set of validation tests focuses on the impact of baryonic effects on the cosmic shear data vector. We apply baryonic feedback consistent with the OWLS [45], BAHAMAS [87], and COSMO-OWLS [57] simulations by setting the baryonic parameters to $A_{\text{bary}} = 1.6$, $\log(T_{\text{agn}}) = 7.7$, and $\log(T_{\text{agn}}) = 8.3$, respectively. We also test a case with $A_{\text{bary}} = 2.2$, which approximately corresponds to the mode value inferred from our fiducial analysis.

We find no significant bias in S_8 for the OWLS-like, BAHAMAS-like, or $A_{\text{bary}} = 2.2$ mock data vectors. However, the COSMO-OWLS-like data vector exhibits a $\sim 1\sigma$ downward bias in S_8 . While this bias is marginal, we note that $\log(T_{\text{agn}}) = 8.3$ corresponds to a relatively extreme AGN feedback scenario and may not reflect realistic astrophysical conditions.

To further explore this trend, we perform MAP estimations on a suite of data vectors constructed with baryonic feedback models spanning $\log(T_{\text{agn}}) = 7.3$ to 8.3.

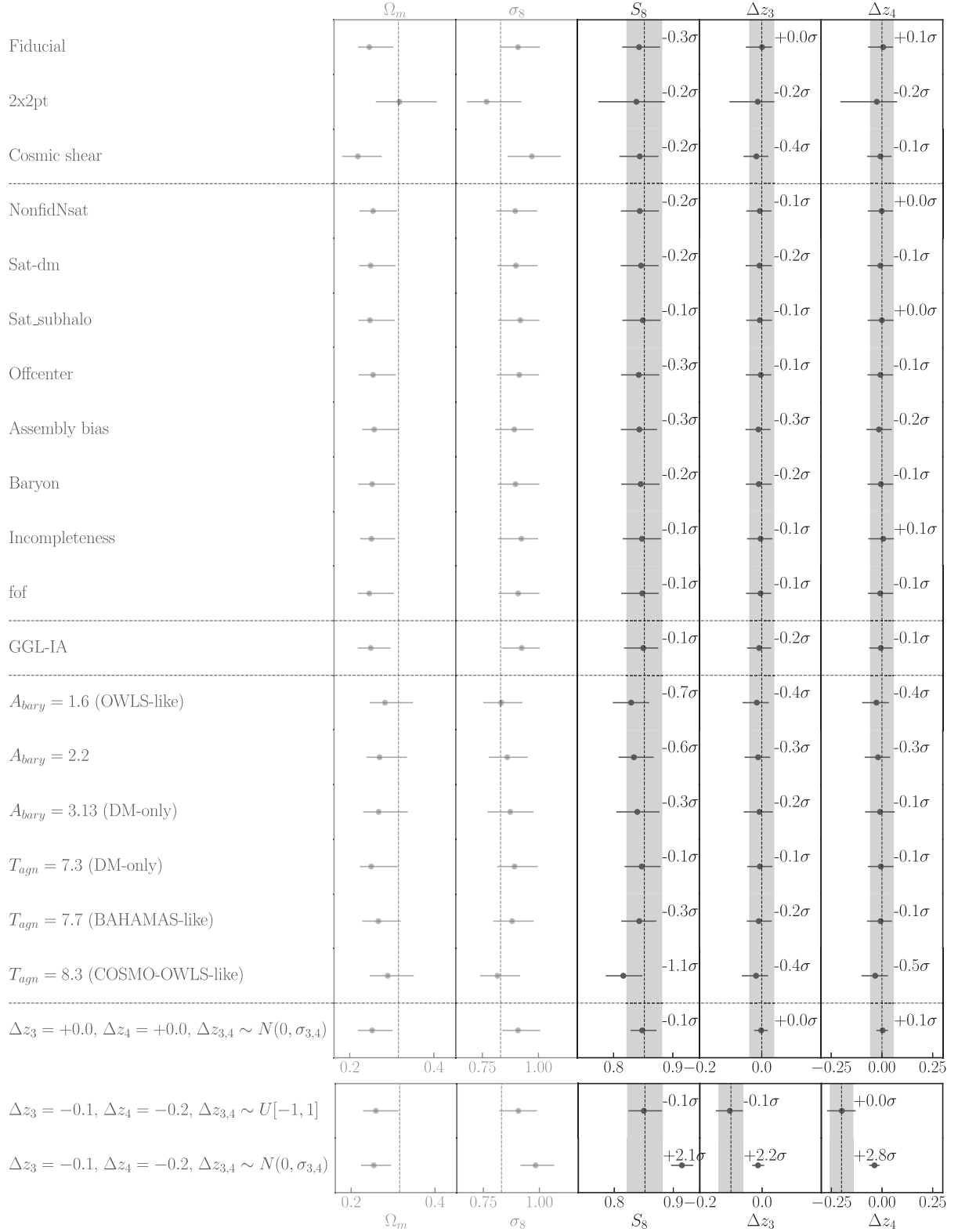


FIG. 12. The validation results are summarized for five key parameters. The points indicate the mode of the marginalized one-dimensional posterior distributions, while the error bars represent the central 68% credible intervals. The dashed lines and shaded gray regions denote the true parameter values and the 68% confidence interval from the fiducial analysis, respectively, for comparison. Overall, we find that our pipeline is robust against a wide range of astrophysical systematics and successfully recovers the true values of S_8 , Δz_3 , and Δz_4 . In particular, we demonstrate that the analysis framework can accurately recover redshift parameter biases when they are present in the data.

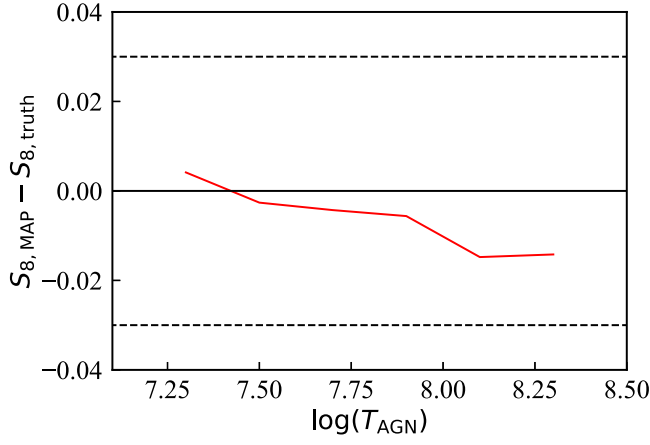


FIG. 13. Bias in the S_8 parameter at the MAP estimate as a function of $\log(T_{\text{agn}})$, used to model varying levels of baryonic feedback. The dashed horizontal line indicates the 1σ uncertainty from the fiducial analysis. Across the full range of $\log(T_{\text{agn}}) = 7.3\text{--}8.3$, the S_8 bias remains well within 1σ . This demonstrates that baryonic effects do not induce significant bias in cosmological parameter inference.

Figure 13 shows the S_8 bias at the MAP relative to the true input value, illustrating that the bias induced by baryonic feedback remains below 1σ across this range. The mild bias in the posterior mode observed in the full Bayesian inference is likely attributable to projection effects in the high-dimensional parameter space.

The final set of validation tests ensures that our pipeline is robust against potential systematics in the

redshift distribution. In the test labeled “ $\Delta z_3 = -0.1$, $\Delta z_4 = -0.2$, $\Delta z_{3,4} \sim U[-1, 1]$,” we use the Gaussian prior centered around zero for $\Delta z_{3,4}$. In the test labeled “ $\Delta z_3 = -0.1$, $\Delta z_4 = -0.2$, $\Delta z_{3,4} \sim U[-1, 1]$,” we introduce redshift biases to the HSC-3 and HSC-4 bins and demonstrate that our inference correctly recovers these input shifts. In the test “ $\Delta z_3 = -0.1$, $\Delta z_4 = -0.2$, $\Delta z_{3,4} \sim \mathcal{N}(0, \sigma_{3,4})$,” we apply the same redshift bias but assume a Gaussian prior on Δz_3 and Δz_4 centered at zero during the analysis. In this case, we observe a significant bias in the inferred value of S_8 , which highlights the importance of accurate prior modeling for redshift uncertainties.

As an additional validation to the point-mass correction model, we compare fitting to best-fit parameter to $\Delta\Sigma(R_p)$ of CMASS2 produced by HMCode [51] and Halofit [88] to the linear bias model in Fig. 14. We observe no significant difference between the HMCode and Halofit, both of which sufficiently trace the $\Delta\Sigma(R_p)$ mock signal within the scale of this analysis.

APPENDIX B: BAYESIAN INFERENCE PARAMETERS

The default tolerance parameter in MultiNest is set to 1.0 in this work. To validate this choice, we perform an additional MultiNest run with the tolerance set to 0.05, which corresponds to the default setting used in previous works such as [12,13]. In Fig. 15, we compare the posterior contours from

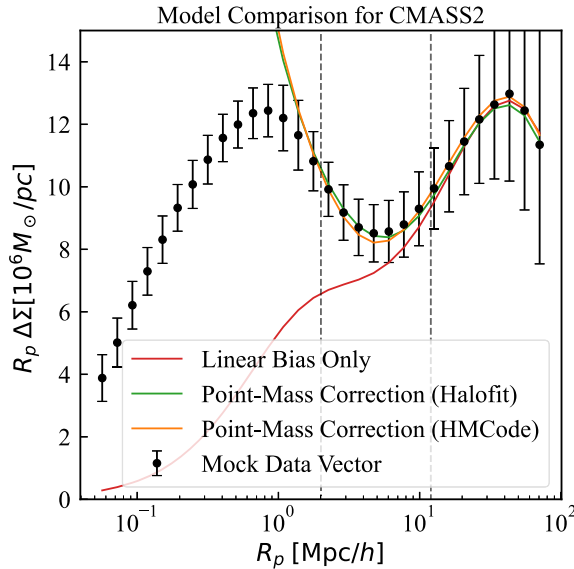


FIG. 14. This figure compares the best-fitting “linear bias only” model versus the “point-mass correction” model on the mock measurement of $R_p \Delta\Sigma$ of CMASS2 generated by HMCode and Halofit. The point-mass correction model can model the small scale $R_p \Delta\Sigma$ better than the linear galaxy bias model.

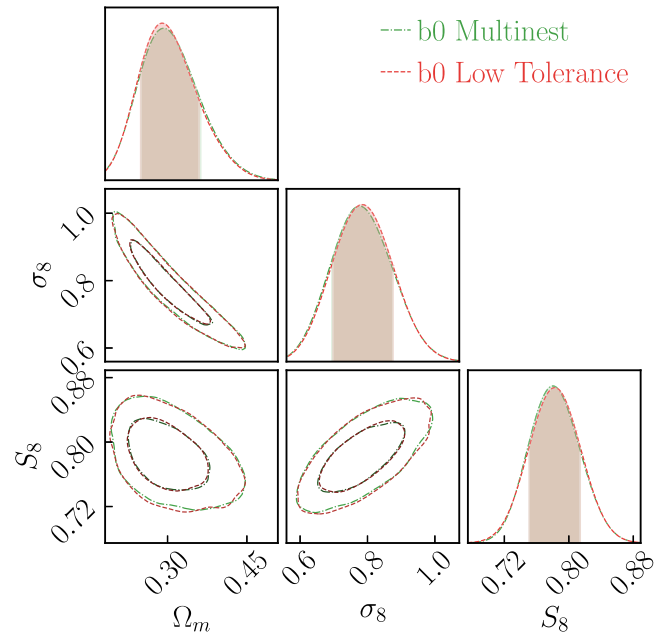


FIG. 15. The 1 and 2σ contour Ω_m , σ_8 , and S_8 constraints of the fiducial analysis (green contours) and of the analysis with low tolerance (red contours). There is no visible difference in the results.

the low-tolerance run to our fiducial results. We find no visible differences between the two, indicating that our parameter constraints are not sensitive to this setting. Given the significantly longer runtime required for convergence at lower tolerance, we adopt 1.0 as the default tolerance value for our analysis.

APPENDIX C: FULL CORNER PLOT

Figure 16 shows the full corner plot of the 32 sampled parameters and two derived parameters σ_8 and S_8 . The parameter constraints are obtained by the fiducial 3×2 pt analysis.

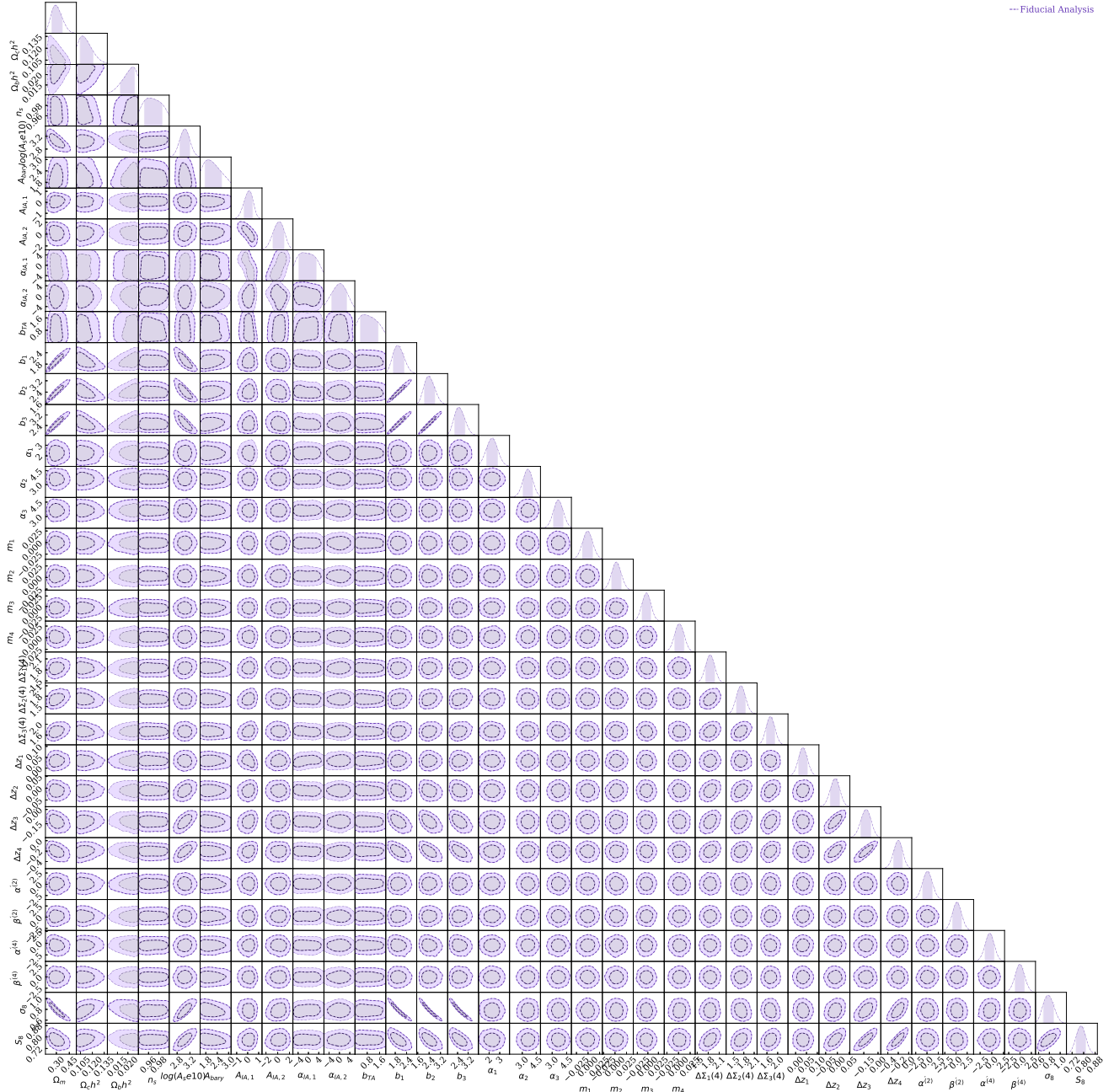


FIG. 16. The posterior distribution of the fiducial 3×2 pt analysis on 32 free parameters and two derived parameters σ_8 and S_8 .

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