Energy-scaling behavior of intrinsic transverse-momentum parameters in Drell-Yan simulation

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An analysis is presented based on models of the intrinsic transverse momentum (intrinsic k_T) of partons in nucleons by studying the dilepton transverse momentum in Drell-Yan events. Using parameter tuning in event generators and existing data from fixed-target experiments and from hadron colliders, our investigation spans 3 orders of magnitude in center-of-mass energy and 2 orders of magnitude in dilepton invariant mass. The results show an energy-scaling behavior of the intrinsic k_T parameters, independent of the dilepton invariant mass at a given center-of-mass energy.

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I. INTRODUCTION

The description of high-energy hadron-hadron collisions relies on the modeling of the nonperturbative regime of quantum chromodynamics (QCD). In particular, the modeling of the intrinsic transverse momenta of partons inside the colliding protons (intrinsic k_T) represents a challenge both experimentally and theoretically. Several approaches exist to describe the intrinsic k_T, including those with transverse-momentum (p_T)-dependent parton distribution functions (PDFs) [1–3], and those based on first-principle approaches such as lattice QCD [4–6]. The most widely used frameworks for the description of collision events at the LHC are general-purpose Monte Carlo (MC) event generators that include parton shower descriptions, such as PYTHIA8 [7,8], HERWIG 7 [9], and SHERPA [10]. They are based on collinear PDFs and usually model the intrinsic k_T as a random variable with a Gaussian distribution, whose width is a tunable parameter. However, the extracted intrinsic k_T parameter does not necessarily correspond to a simple model of nonperturbative physics, but also compensates for deficiencies in the parton shower model. These considerations motivate the study presented in this paper.

The region of Drell-Yan (DY) production where the lepton-pair system is produced with low p_T, around a few GeV, is especially suited for the study of the intrinsic k_T models because it provides a clean, high-resolution final state and has been studied widely in collider experiments [11–23]. Previous studies illustrate the sensitivity of this region to high-order QCD contributions [24] and include their own treatments of nonperturbative physics effects [25–36].

In this paper, we investigate the intrinsic k_T models in PYTHIA and HERWIG by parameter tuning to DY measurements and their implications for the perturbative and nonperturbative-QCD effects in the DY initial-state kinematics. The use of CMS data in this investigation extends the probed energy scale of the hard scattering to 1 TeV. The experimental data and simulations are described in Sec. II. The strategy for generator tuning and uncertainty estimation is discussed in Sec. III. Section IV investigates the interdependence between the underlying-event (UE) and the DY lepton-pair transverse-momentum ($p_T(\ell^+\ell^-)$) descriptions. The impacts of the hadron-collision energies and the DY hard-scattering energy scales on the intrinsic k_T tunes are discussed in Secs. V and VI, respectively. Finally, the results are summarized in Sec. VII.

II. DATA AND SIMULATION

We use DY data measured from various types of hadron collisions at different center-of-mass energies and the corresponding simulations to extract nonperturbative-QCD information and to study the interplay between the intrinsic k_T parameter and the perturbative evolution including the initial-state radiation (ISR). The analysis is performed with the PYTHIA 8 and HERWIG 7 event generators, which provide different options of ordering variables and energy thresholds for partonic emissions, and the results are compared with those of the previous studies with CASCADE [2,3,37]. The UE models of the two generators, which consist of multiple-parton interactions (MPI) and beam remnants (BR), as well as hadronization, ISR, and final-state radiation (FSR), have been extensively studied

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TABLE I. Measurements of the DY differential cross section as a function of $p_T(\ell^+\ell^-)$ at various center-of-mass energies $\sqrt{s}$ from different hadron-collision processes used as inputs for the intrinsic k_T tunes. The $\sqrt{s}$ in pPb collisions represents the nucleon-nucleon center-of-mass energy. The variable Q represents the energy scale of the hard scattering, approximated by the dilepton invariant mass. The Z boson mass is denoted as $m(Z)$.

Experiment	Collision type	$\sqrt{s}$ (GeV)	Q (GeV)
E866/NuSea [11,12]	pp/pd, fixed target	38.8	4–12.85
R209 [13]	pp	62	5–8
PHENIX [14]	pp	200	4.8–8.2
D0/CDF [15,16]	$p\bar{p}$	1800	$m(Z)$
D0/CDF [17,18]	$p\bar{p}$	1960	$m(Z)$
CMS [19]	pp	2760	$m(Z)$
ATLAS [20]	pp	8000	46–150
CMS [21]	pPb	8160	15–120
CMS [22]	pp	13000	50–1000
LHCb [23]	pp	13000	$m(Z)$

[38–40]. The measurements of the differential cross section of DY processes as a function of the $p_T(\ell^+\ell^-)$ are summarized in Table I, in which the proton-lead (pPb) measurement data were converted for comparison with pp collisions by correcting for the number of nucleons, and corresponding simulations are used to tune the intrinsic k_T parameter. Tabulated results are provided in the HEPData record for this analysis [41].

Predictions of the DY cross section are produced at next-to-leading order (NLO) using MADGRAPH5_AMC@NLOv3.4.1 [42], and the matrix-element computation is matched to the PYTHIA 8 or HERWIG 7 generator in the CMS software interface for parton shower and UE activity modeling. The UE tunes used in this analysis are based on various PDFs, partonic emission orderings, and settings in MPI and BR modelings, as listed below:

(i) PYTHIA 8 tunes: The PYTHIA 8.243 generator is used for the p_T-ordered parton shower and hadronization, and the UE model is parametrized by the CP3, CP4, or CP5 tune [39]. The three tunes have the strong coupling $\alpha_S(m_Z)$ set to 0.118, use NLO strong-coupling evolution, and employ NLO or next-to-NLO (NNLO) PDFs in the hard scattering, parton showering, ISR, FSR, MPI, and BR modelings.

(ii) HERWIG 7 tunes: The HERWIG 7.1.4 generator is used for the angular-ordered parton shower and hadronization, and the CH2 and CH3 tunes [40] are used for the UE modeling. Both tunes use $\alpha_S(m_Z) = 0.118$ with NNLO strong-coupling evolution and the NNLO NNPDF3.1 PDFs for the parton shower, but different α_S and PDF sets in the MPI and BR modelings.

These UE tunes from the CMS Collaboration used measurements at $\sqrt{s}$ from 0.9 to 13 TeV by the CDF and CMS experiments, modeling the behavior of UE-sensitive variables across all these energies, as well as the kinematics of high p_T jet, $t\bar{t}$, and DY production at the CMS.

The intrinsic k_T is modeled similarly in PYTHIA and HERWIG by a Gaussian distribution with tunable parameters. In PYTHIA, the width q_s of the Gaussian distribution is related to the parameter $\text{BeamRemnants:primordialkThard} \simeq q_s/\sqrt{2}$, whereas in HERWIG, it is given by the parameter $\text{ShowerHandler:IntrinsicPtGaussian} = q_s$. Either of these parameters is referred to as tunable intrinsic k_T parameter q in the following.

III. GENERATOR TUNING STRATEGY

In each scenario of $\sqrt{s}$ given in Table I, we assume that the DY differential cross section versus $p_T(\ell^+\ell^-)$ depends on q. Simulated samples of events are generated with different choices of the parameter q sampled from the tuning range, resulting in varied predictions of the DY differential cross section. The dependence of the cross section on q predicted for each bin in $p_T(\ell^+\ell^-)$ is extracted by interpolating the simulated values, as well as their uncertainty, with polynomial functions $f_i(q)$ and $u_{f_i(q)}$, respectively, in each bin i of $p_T(\ell^+\ell^-)$. The PROFESSOR2 software [43] is employed to perform the interpolation and compute a goodness of fit (GOF), based on the χ^2 distribution, for quantifying the agreement between the interpolated simulated values and those measured in the data. The GOF is measured by the χ^2 as a function of q

$$\chi^2(q) = \sum_i \frac{(f_i(q) - d_i)^2}{u_{d_i}^2 + u_{f_i(q)}^2}, \tag{1}$$

where d_i and u_{d_i} are the cross section and its uncertainty measured in data in bin i, respectively. For measurements performed at $\sqrt{s} > 1$ TeV, the value of χ^2 is obtained by summing over the bins i that correspond to the low-$p_T(\ell^+\ell^-)$ range 0–10 GeV because of its high sensitivity to the intrinsic k_T model. For measurements at $\sqrt{s} < 1$ TeV, the whole range of $p_T(\ell^+\ell^-)$ available in the data, which is below 10 GeV, is considered for computing the value of χ^2. For each measurement at a given $\sqrt{s}$, the final tuned parameter q is taken to be the one that minimizes the respective χ^2.

The uncertainties in the tuned parameter originate from the variations of the χ^2. The uncertainty due to the choice of $p_T(\ell^+\ell^-)$ range is estimated as the difference between the resulting tuned parameter when considering the $p_T(\ell^+\ell^-)$ ranges [0, 10] and [0, 15] GeV for $\sqrt{s} > 1$ TeV, because the transition from the nonperturbative to perturbative contributions takes place approximately between 10–20 GeV. With regard to the $\sqrt{s} < 1$ TeV cases, this uncertainty is estimated as the difference between the parameter tuned using the range [0 GeV, max(p_T)] and [0, 2] GeV (for $\sqrt{s} = 38.8$ GeV) or [0, 4] GeV (for $\sqrt{s} = 62$ and 200 GeV). The uncertainty due to the choice of the functional form used for the interpolation is taken to be the difference between the parameter tuned using order-5 polynomials as the central value and that using order-3 polynomials as the systematic deviation. The uncertainty from the limited statistical precision in the simulation is estimated by substituting the denominator of Eq. (1) with ${u_{f_i(q)}}^2$ and determining the parameter values that result in a value of χ^2 increased by 1 compared to the minimum. The contribution from the uncertainty of the measured data is estimated by repeating the tuning for varied values of the differential DY cross section. These varied values are obtained by sampling from Gaussian distributions centered at the nominal values of measured cross sections and with standard deviations equal to their uncertainties. The covariance between the uncertainties contributed by the measured data for different generator setups is estimated from the covariance between the corresponding tunes obtained from the varied measurements. The other uncertainty sources are approximately uncorrelated among the tunes. The uncertainty from the measurement is dominant in most of the tunes, ranging from 2 to 20%, depending on the measurement precision.

IV. UNDERLYING-EVENT TUNES AND DY $p_T(\ell^+\ell^-)$

Our baseline UE description is given by the PYTHIA CP5 tune [39], for which five parameters controlling MPI and color reconnection were varied. To assess the impact of the UE parametrization on the DY dilepton transverse momentum ($p_T(\ell^+\ell^-)$) spectrum, we generated DY samples and their $p_T(\ell^+\ell^-)$ distributions with the intrinsic k_T parameter fixed to the tuned result and the UE parameters set to either the CP5 tune-up or tune-down variation. The difference between the two predictions reflects the effects of the UE-tune uncertainty on the DY $p_T(\ell^+\ell^-)$ spectrum, shown as red bands in Fig. 1 (upper), which are much smaller than the uncertainty from the intrinsic k_T variations shown as violet bands.

Similarly, we study the impact of the intrinsic k_T variation on observables that are sensitive to the UE models and have been used to obtain the CP5 tune. An observable used for the UE tuning is the density of the scalar p_T sum of the charged particles ($p_T^{\rm sum}$) in the pseudorapidity (η)–azimuthal angle (ϕ) space as a function of the p_T of the leading charged particle ($p_T^{\rm max}$) in the transMAX region averaged over $N_{\rm events}$ generated events [38] in the minimum bias (MB) process. This observable is shown in Fig. 1 (lower). For each event, the transMAX region is defined by the direction of the leading charged particle in the space transverse to the proton beams. Assuming ϕ as the azimuthal angle of the leading charged particle, the ranges of ϕ_1 satisfying $60° < |\phi - \phi_1| < 120°$ define the two transverse regions, in which transMAX is the one with a

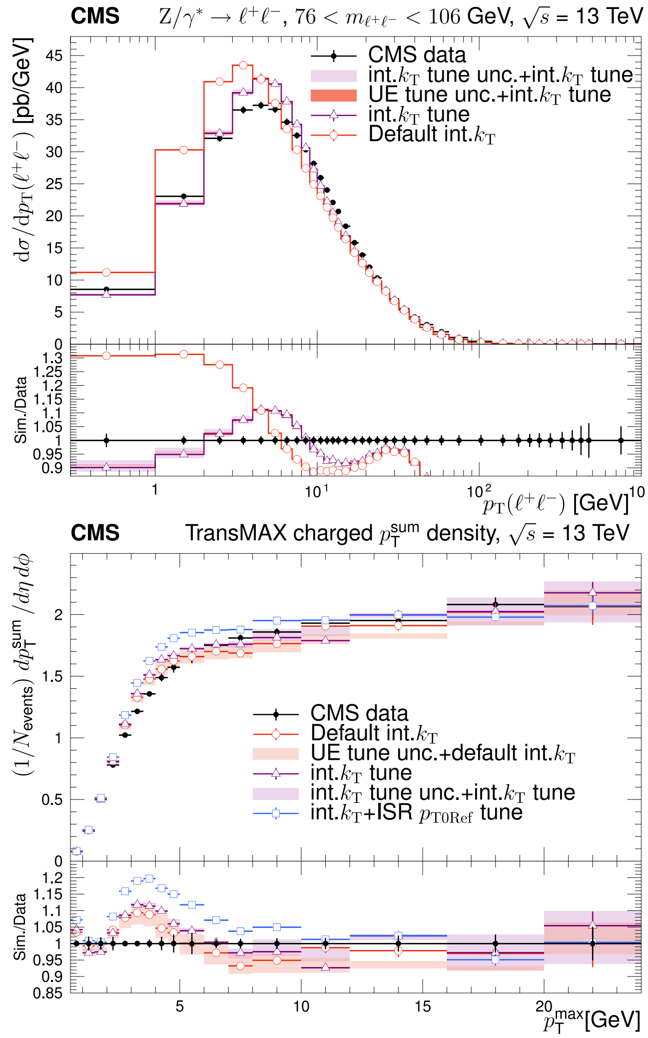

FIG. 1. Effect of the variation of the UE parameters on the DY $p_T(\ell^+\ell^-)$ spectrum (upper) and of the variation of the intrinsic k_T parameter on the charged $p_T^{\rm sum}$ density as a function of $p_T^{\rm max}$ in the transMAX region of the MB process (lower). The red and violet shaded areas represent the predictions from the up and down variations of the UE tune and the intrinsic k_T tune, respectively. In the upper distribution, both shaded areas are based on the prediction of tuned intrinsic k_T parameter on top of PYTHIA CP5 ("int.k_T tune"). In the lower distribution, the red shaded areas are based on the prediction of the intrinsic k_T parameter set to the default 1.8 and the UE tune set to PYTHIA CP5 ("Default int.k_T"), and the violet shaded area is based on the "int.k_T tune" prediction. The error bars represent the statistical uncertainty in the simulated events. The lower distribution also includes the UE prediction of the combined tune of the intrinsic k_T and the ISR cutoff scale to the DY $p_T(\ell^+\ell^-)$ distribution ("int.k_T + ISR $p_{\rm T0Ref}$ tune"). The data are from the CMS measurements on the DY process [22] and the MB process [38] at 13 TeV.

higher activity. With the UE parameters fixed to the CP5 tune, we generated MB events with the tuned intrinsic k_T parameter, shown as violet markers in Fig. 1 (lower). The intrinsic k_T tune uncertainty was estimated from the difference between the tune-up and -down variations, represented by the violet band in Fig. 1 (lower). Compared with the UE tune uncertainty represented by the red band, the impact of the intrinsic k_T variations on UE-sensitive observables is small. The results shown in Fig. 1 imply that the parameter space for UE and intrinsic k_T can be factorized. Therefore, in the results presented in the following sections, the intrinsic k_T parameters are tuned without changing the UE tune parameters.

Besides the intrinsic k_T model, the lower cutoff scale of ISR also affects the DY $p_T(\ell^+\ell^-)$ distribution, which is discussed in Sec. V. However, the UE observables are sensitive to the ISR cutoff scale. The combined tune of the intrinsic k_T parameter and the cutoff scale of ISR to the DY $p_T(\ell^+\ell^-)$ distribution alters the UE observable as shown in Fig. 1 (lower, blue markers). For the purpose of decoupling the intrinsic k_T study from the UE modeling when investigating its scaling behavior with the collision energy and hard-scattering scale, the parameter for the ISR cutoff is fixed to its default value in the studies shown in Figs. 2 and 4.

V. IMPACT OF THE COLLISION ENERGY ON THE INTRINSIC k_T TUNES

The impact of the center-of-mass energy on the intrinsic k_T parameter is investigated by tuning the generators to the $p_T(\ell^+\ell^-)$ measurements for each experimental setup in Table I. The results show an energy-scaling behavior of the intrinsic k_T parameter for both generators and all setups, as indicated in Fig. 2. The function $q(\sqrt{s}) = b\sqrt{s}^a$ is fitted to the points, with fit parameters a and $\log_{10}(b)$ describing the slope and intercept of the function, respectively. The same slope a is assumed for all generator setups based on observation, which is supported by the combined value of $\chi^2_{\text{lin.}}$ of all linear fits divided by the total number of degrees of freedom (NDF), $\chi^2_{\text{lin.}}/\text{NDF} = 1.27$, under this assumption and the corresponding p value [44] of 0.11. The slope of the fitted function is $a = 0.162 \pm 0.005$. When fitted with free-floating slopes, the resulting slopes are 0.163 ± 0.006, 0.164 ± 0.006, 0.170 ± 0.008, 0.160 ± 0.008, and 0.155 ± 0.007 for the CP3, CP4, CP5, CH2 and CH3 tunes, respectively, which are compatible with each other. The generators can be improved by implementing the energy scaling of the intrinsic k_T parameters provided by this analysis.

In addition to the intrinsic k_T model, the DY $p_T(\ell^+\ell^-)$ distribution also receives contributions from ISR. Therefore, the intrinsic k_T parameters in the generators practically compensate the ISR contribution below the cutoff scale in the tunes to DY measured data. To investigate the effect of the ISR cutoff scale on the intrinsic k_T parameter, we perform an energy-dependent intrinsic k_T tune with a different ISR cutoff scale, by varying the regularization parameter SPACESHOWER:PT0REF in PYTHIA and SUDAKOVCOMMON:PTMIN in HERWIG. The tuning

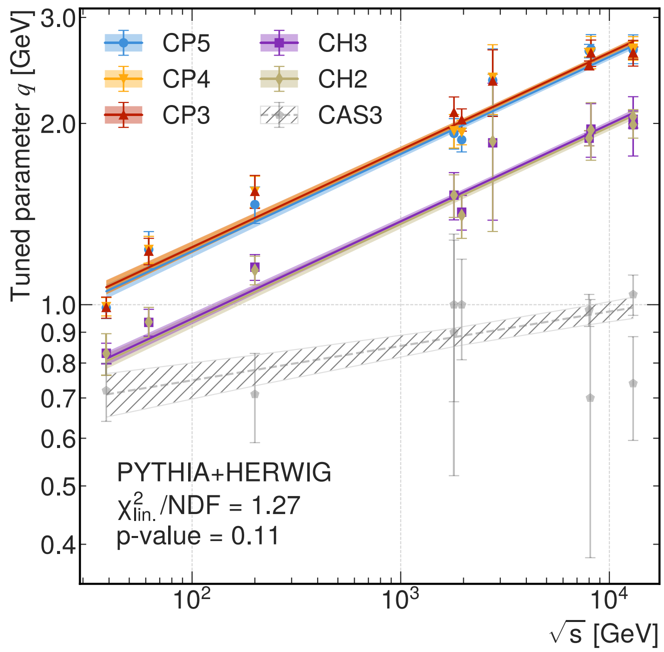

FIG. 2. Tuned parameter q values for DY measurements at different center-of-mass energies (points) for various PYTHIA and HERWIG setups (colors). The error bars on the points represent the tuning uncertainties. The tuned values are given in Appendix. For each generator setup, the function $b\sqrt{s}^a$ is fitted to the points and shown as a line, assuming the same slope a for all the settings. The $\chi^2_{\text{lin.}}$/NDF and p value of the combined linear fit is given in the plot. The uncertainty in each fit is shown as a colored band and corresponds to the up and down variations of the fit parameters, propagated from the tune uncertainties. The CASCADE predictions (CAS3) [2,3] are also fitted separately with the function $b\sqrt{s}^a$ for comparison with PYTHIA and HERWIG.

process and determination of the uncertainty follows the same strategy used in the results shown in Fig. 2 in the PYTHIA CP5 or HERWIG CH3 setups. The SPACESHOWER: PT0REF parameter is changed to 1 GeV from the default value of 2 GeV for PYTHIA, and the SUDAKOVCOMMON: PTMIN parameter is changed to 0.7 GeV from the default value of 1.22 GeV for HERWIG, such that the simulation can still reasonably describe the observed DY $p_T(\ell^+\ell^-)$ distribution after the intrinsic k_T tunes. Lowering the cutoff scale induces more low-energy ISR contributions to the low-$p_T(\ell^+\ell^-)$ DY distribution.

Figure 3 shows the results of the combined fit for the tuned parameter in the PYTHIA CP5 setup with SPACESHOWER:PT0REF set to 1 GeV and the default case and those for the tuned parameter in the HERWIG CH3 setup with SUDAKOVCOMMON:PTMIN set to 0.7 GeV and the default case. For each generator setting, the function $b\sqrt{s}^a$ is fitted to the points and shown as a line, allowing various slopes a and offsets $\log_{10}(b)$. The $\chi^2_{\text{lin.}}$/NDF and p value of the fit are 1.71 and 0.04 for PYTHIA (1.15 and 0.30 for HERWIG), respectively. The reported p values are the significance of the χ^2 test with NDF = 16 from 20 tuned

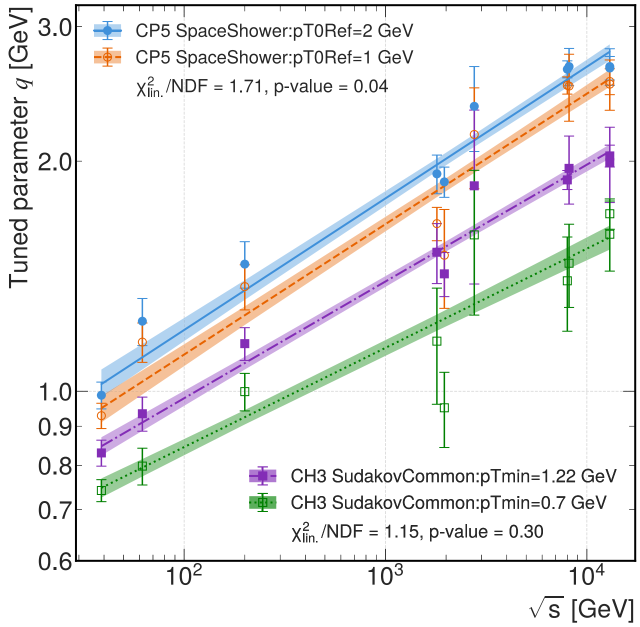

FIG. 3. Tuned parameter q values for DY measurements at different center-of-mass energies (points) for various generator settings (lines and bands). The error bars on the points represent the tuning uncertainties. The tuned values are given in Appendix. For the PYTHIA CP5 setup, the parameter SPACESHOWER:PT0REF is set to 1 GeV (orange dashed) or its default value of 2 GeV (blue solid). For the HERWIG CH3 setup, the parameter SUDAKOVCOMMON:PTMIN is set to 0.7 GeV (green dotted) or its default value of 1.22 GeV (purple dash dotted). The function $b\sqrt{s}^a$ is fitted to the points of each generator setting and shown as a line, allowing free-floating slopes a and offsets $\log_{10}(b)$. The uncertainty in each fit is shown as a colored band and corresponds to the up and down variations of the fit parameters, propagated from the tune uncertainties.

results and four parameters to fit, including two slope parameters and two offset parameters. The slope parameters for the PYTHIA setups are 0.172 ± 0.009 (default) and 0.170 ± 0.009 (lower ISR cutoff), and the slopes for the HERWIG setups are 0.153 ± 0.007 (default) and 0.130 ± 0.009 (lower ISR cutoff). This result shows that the variation of the ISR threshold in the simulation does not change the energy-scaling behavior of intrinsic k_T tunes and causes a mild change of the slope only for very low values of the threshold.

The energy-scaling behavior of the intrinsic k_T tunes can lead to deeper insights about the nonperturbative-QCD contributions in the low-$p_T(\ell^+\ell^-)$ region of the DY process after extracting and comparing the effects of perturbative QCD in the tunes. On one hand, the tunes are affected by perturbative-QCD models varying among the generator setups because both ISR and intrinsic k_T play a role in describing the $p_T(\ell^+\ell^-)$ in the DY process. These effects are demonstrated by the variations of the intercepts of linear fit, as shown in the fits in Figs. 2 and 3. Additionally, the PYTHIA and HERWIG generators use different showering models, PYTHIA using p_T-ordered showering and HERWIG using angular-ordered showering, which leads to more low-energy ISR in the HERWIG generation of DY events and less compensation from the nonperturbative part to model $p_T(\ell^+\ell^-)$. Therefore, the intercepts in the HERWIG fit are smaller than those for the PYTHIA fit in Fig. 2. On the other hand, the slopes of the linear fits are similar for the various PYTHIA and HERWIG tunes in combination with the DY matrix element computed at NLO, despite their differences in the PDF, the order in the parton shower, and the cutoff scale of showering. Stable under variations of perturbative-QCD modeling and hard-scattering scales, this energy-scaling behavior potentially originates from nonperturbative-QCD effects, pointing to the need for further theoretical investigation. The adjustment of intrinsic k_T under higher-order or resummed DY matrix elements and their corresponding energy-scaling behaviors presents a compelling avenue for future research, as nonperturbative-QCD effects are increasingly incorporated into these matrix elements.

A different approach to modeling the intrinsic k_T is implemented in the CASCADE generator [37] ("CAS3" in Fig. 2), which accounts for the effect of low-energy gluons with a nonperturbative Sudakov form factor [26], using the parton branching method [1,2]. The CASCADE generator predicts an intrinsic k_T [2,3] that, compared with PYTHIA and HERWIG, is less dependent on the collider energy as shown in Fig. 2. The energy scaling of the intrinsic k_T parameters in the PYTHIA and HERWIG models may be necessary to account for nonperturbative and low-energy gluon emissions not included in the parton showers.

VI. IMPACT OF THE HARD-SCATTERING SCALES ON THE INTRINSIC k_T TUNES

To explore the dependence of intrinsic k_T parameters on the DY hard-scattering scale Q, tunings are performed using the DY differential cross section versus $p_T(\ell^+\ell^-)$ in exclusive ranges of dilepton invariant mass $m(\ell^+\ell^-)$ for $\sqrt{s} = 38.8$ GeV [11,12], and 8 [20], 8.16 [21], and 13 TeV [22], in which measurements in multiple $m(\ell^+\ell^-)$ ranges are available. As shown in Fig. 4, the intrinsic k_T tunes of either PYTHIA (CP5) or HERWIG (CH2) are similar for various $m(\ell^+\ell^-)$ ranges at the same $\sqrt{s}$, which leads to the hypothesis that the intrinsic k_T parameter is identical for all the $m(\ell^+\ell^-)$ ranges at a fixed $\sqrt{s}$. Figure 4 shows the results of a constant fit to the tuned parameter values based on this hypothesis, which is compatible with the tuned values as indicated by the value of $\chi^2{}_{\text{const}}$/NDF being close to 1. This investigation of the Q dependence of the intrinsic k_T tunes under fixed $\sqrt{s}$ complements previous studies on the $\sqrt{s}$ dependence of the resummed nonperturbative Sudakov factor under fixed Q, as summarized in Ref. [45].

Defining the fractions of the hadron momentum carried by the incoming pair of quarks in the DY process to be x_1

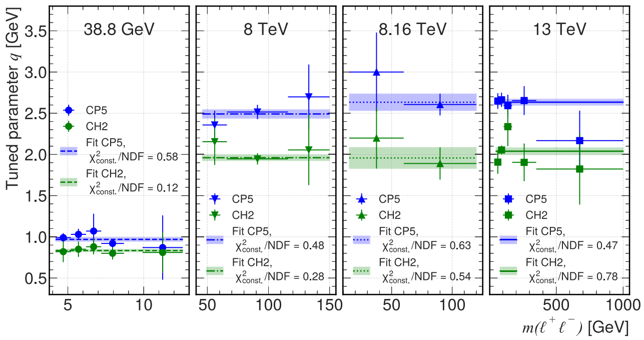

FIG. 4. Tuned parameter values (points) for DY measurements at four different center-of-mass energies $\sqrt{s} = 38.8$ GeV [11,12], and 8 [20], 8.16 [21], and 13 TeV [22], for the PYTHIA CP5 (blue dark) and HERWIG CH2 (green light) setups. The error bars on the points represent the tuning uncertainties. The tuned values are given in Appendix. For each generator setup, a constant is fitted to the points and shown as a line. The uncertainty in each fit, propagated from the tune uncertainties, is shown as a colored band.

and x_2, $m(\ell^+\ell^-)$ is given by $m(\ell^+\ell^-) = x_1 x_2 \sqrt{s}$ at leading order. Since the tuned values are stable versus $x_1 x_2 \sqrt{s}$ for given values of $\sqrt{s}$, the intrinsic k_T parameter is independent of $x_1 x_2$ within the present precision. Furthermore, the impact of x_1/x_2 on the intrinsic k_T tunes is demonstrated by the tunes using the CMS and LHCb measurements at $\sqrt{s} = 13$ TeV because of the different rapidity regions used for the measurements by the two experiments. The tunes to the two measurements agree within the uncertainties (shown in Fig. 2), which indicates the intrinsic k_T tune to be stable under x_1/x_2 variations and suggests its independence of the momentum fractions x_1 and x_2 individually.

VII. SUMMARY

In summary, generator tunes of the intrinsic transverse momentum k_T were used to explore model-independent features of nonperturbative quantum chromodynamics (QCD). The tunes were performed for various underlying-event (UE) setups in the generators PYTHIA and HERWIG using the Drell-Yan differential cross section as a function of the dilepton transverse momentum measured in multiple types of hadron collision experiments with $\sqrt{s}$ ranging from 38.8 GeV to 13 TeV. The results show a linear relation between the logarithm of the intrinsic k_T parameter and $\log_{10}(\sqrt{s})$ for all generator tunes, with the intercepts altered by generator-dependent perturbative-QCD models such as choices of parton distribution functions or parton shower parameters. The slope is 0.162 ± 0.005, independent of the UE tune or generator, and related to nonperturbative-QCD effects such as nonresolvable low-energy gluon emissions in parton showers. The tunes were also performed using experiments that probe different regions of dilepton invariant mass and rapidity and demonstrate the independence of the intrinsic k_T parameter with respect to these variables at each $\sqrt{s}$. This indicates the independence of the intrinsic k_T on the longitudinal momentum fractions of the quarks within colliding hadrons in Drell-Yan processes.

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DATA AVAILABILITY

Release and preservation of data used by the CMS Collaboration as the basis for publications is guided by the CMS data preservation, re-use, and open access policy [46].

APPENDIX: TUNING RESULTS

Table II gives the tuning results shown in Fig. 2. Tables III and IV give the tuning results corresponding to the entries “CP5 SpaceShower:pT0Ref = 1 GeV” and “CH3 SudakovCommon:pTmin = 0.7 GeV” in Fig. 3, respectively. Table V gives the tuning results shown in Fig. 4.

TABLE II. Tune results for the BEAMREMNANTS:PRIMORDIALKTHARD parameter in PYTHIA 8 and the SHOWERHANDLER:INTRINSICPTGAUSSIAN parameter in HERWIG 7, taking into account the statistical uncertainty of simulations (MC stat.), the measurement uncertainty in data (data unc.), the uncertainty from choices of tune ranges (range), and the uncertainty from choices of the functions for interpolation (int.).

$\sqrt{s}$	Generator setup	Tune result ±MC stat. ± data unc. ± range ± int.
38.8 GeV	PYTHIA 8 CP5	$0.988 \pm 0.0008 \pm 0.029 \pm 0.022 \pm 0.015$
	PYTHIA 8 CP4	$0.993 \pm 0.0008 \pm 0.029 \pm 0.017 \pm 0.009$
	PYTHIA 8 CP3	$0.990 \pm 0.004 \pm 0.03 \pm 0.017 \pm 0.020$
	HERWIG 7 CH2	$0.829 \pm 0.0005 \pm 0.017 \pm 0.010 \pm 0.06$
	HERWIG 7 CH3	$0.830 \pm 0.0005 \pm 0.017 \pm 0.010 \pm 0.026$
62 GeV	PYTHIA 8 CP5	$1.24 \pm 0.0008 \pm 0.07 \pm 0.0015 \pm 0.06$
	PYTHIA 8 CP4	$1.24 \pm 4 \times 10^{-8} \pm 0.06 \pm 0.0012 \pm 0.006$
	PYTHIA 8 CP3	$1.23 \pm 0.0009 \pm 0.06 \pm 0.0010 \pm 0.012$
	HERWIG 7 CH2	$0.94 \pm 0.0006 \pm 0.05 \pm 0.0012 \pm 0.024$
	HERWIG 7 CH3	$0.93 \pm 0.0006 \pm 0.04 \pm 0.0014 \pm 0.019$
200 GeV	PYTHIA 8 CP5	$1.47 \pm 0.0022 \pm 0.08 \pm 0.005 \pm 0.06$
	PYTHIA 8 CP4	$1.54 \pm 0.0024 \pm 0.09 \pm 0.003 \pm 0.004$
	PYTHIA 8 CP3	$1.54 \pm 0.0024 \pm 0.09 \pm 0.003 \pm 0.022$
	HERWIG 7 CH2	$1.14 \pm 0.0014 \pm 0.06 \pm 0.003 \pm 0.018$
	HERWIG 7 CH3	$1.15 \pm 0.0015 \pm 0.06 \pm 0.005 \pm 0.004$
1.8 TeV	PYTHIA 8 CP5	$1.93 \pm 0.012 \pm 0.11 \pm 0.02 \pm 0.015$
	PYTHIA 8 CP4	$1.94 \pm 0.013 \pm 0.12 \pm 0.04 \pm 0.0005$
	PYTHIA 8 CP3	$2.09 \pm 0.013 \pm 0.12 \pm 0.03 \pm 0.007$
	HERWIG 7 CH2	$1.52 \pm 0.014 \pm 0.12 \pm 0.03 \pm 0.0024$
	HERWIG 7 CH3	$1.52 \pm 0.014 \pm 0.13 \pm 0.03 \pm 0.010$
1.96 TeV	PYTHIA 8 CP5	$1.88 \pm 0.017 \pm 0.08 \pm 0.10 \pm 0.009$
	PYTHIA 8 CP4	$1.93 \pm 0.018 \pm 0.08 \pm 0.03 \pm 0.009$
	PYTHIA 8 CP3	$2.03 \pm 0.019 \pm 0.08 \pm 0.03 \pm 0.008$
	HERWIG 7 CH2	$1.41 \pm 0.023 \pm 0.10 \pm 0.08 \pm 0.0019$
	HERWIG 7 CH3	$1.42 \pm 0.021 \pm 0.09 \pm 0.024 \pm 0.021$
2.76 TeV	PYTHIA 8 CP5	$2.36 \pm 0.022 \pm 0.3 \pm 0.005 \pm 0.005$
	PYTHIA 8 CP4	$2.39 \pm 0.020 \pm 0.3 \pm 0.024 \pm 0.013$
	PYTHIA 8 CP3	$2.35 \pm 0.023 \pm 0.3 \pm 0.004 \pm 0.007$
	HERWIG 7 CH2	$1.87 \pm 0.03 \pm 0.5 \pm 0.06 \pm 0.003$
	HERWIG 7 CH3	$1.9 \pm 0.03 \pm 0.4 \pm 0.18 \pm 0.018$
8 TeV	PYTHIA 8 CP5	$2.64 \pm 0.006 \pm 0.0251 \pm 0.06 \pm 0.0016$
	PYTHIA 8 CP4	$2.62 \pm 0.008 \pm 0.022 \pm 0.04 \pm 0.006$
	PYTHIA 8 CP3	$2.50 \pm 0.008 \pm 0.012 \pm 0.03 \pm 0.026$
	HERWIG 7 CH2	$1.89 \pm 0.008 \pm 0.015 \pm 0.05 \pm 0.007$
	HERWIG 7 CH3	$1.89 \pm 0.007 \pm 0.009 \pm 0.05 \pm 0.007$
8.16 TeV	PYTHIA 8 CP5	$2.66 \pm 0.029 \pm 0.14 \pm 0.02 \pm 0.015$
	PYTHIA 8 CP4	$2.63 \pm 0.029 \pm 0.16 \pm 0.023 \pm 0.013$
	PYTHIA 8 CP3	$2.62 \pm 0.029 \pm 0.13 \pm 0.015 \pm 0.007$
	HERWIG 7 CH2	$1.96 \pm 0.03 \pm 0.19 \pm 0.06 \pm 0.027$
	HERWIG 7 CH3	$1.96 \pm 0.03 \pm 0.17 \pm 0.09 \pm 0.02$
13 TeV (CMS)	PYTHIA 8 CP5	$2.648 \pm 0.006 \pm 0.027 \pm 0.028 \pm 0.04$
	PYTHIA 8 CP4	$2.654 \pm 0.006 \pm 0.027 \pm 0.08 \pm 0.004$
	PYTHIA 8 CP3	$2.619 \pm 0.006 \pm 0.028 \pm 0.05 \pm 0.009$
	HERWIG 7 CH2	$2.05 \pm 0.03 \pm 0.04 \pm 0.03 \pm 0.035$
	HERWIG 7 CH3	$2.03 \pm 0.03 \pm 0.04 \pm 0.021 \pm 0.010$
13 TeV (LHCb)	PYTHIA 8 CP5	$2.66 \pm 0.009 \pm 0.06 \pm 0.13 \pm 0.0007$
	PYTHIA 8 CP4	$2.67 \pm 0.009 \pm 0.06 \pm 0.10 \pm 0.003$
	PYTHIA 8 CP3	$2.62 \pm 0.009 \pm 0.06 \pm 0.11 \pm 0.00007$
	HERWIG 7 CH2	$1.99 \pm 0.04 \pm 0.06 \pm 0.05 \pm 0.04$
	HERWIG 7 CH3	$1.99 \pm 0.06 \pm 0.14 \pm 0.16 \pm 0.06$

TABLE III. Tune results for the BEAMREMNANTS:PRIMORDIALKTHARD parameter in PYTHIA 8 with the CP5 tune setup. The parameter SPACESHOWER:PT0REF was set to 1 GeV, taking into account the statistical uncertainty of simulations (MC stat.), the measurement uncertainty in data (data unc.), the uncertainty from choices of tune ranges (range), and the uncertainty from choices of the functions for interpolation (int.).

$\sqrt{s}$	Tune result ±MC stat. ± data unc. ± range ± int.
38.8 GeV	$0.929 \pm 0.001 \pm 0.03 \pm 0.015 \pm 0.0005$
62 GeV	$1.16 \pm 1.8 \times 10^{-10} \pm 0.07 \pm 0.0014 \pm 0.00018$
200 GeV	$1.37 \pm 0.003 \pm 0.09 \pm 0.006 \pm 0.003$
1.8 TeV	$1.66 \pm 0.013 \pm 0.08 \pm 0.007 \pm 0.016$
1.96 TeV	$1.51 \pm 0.016 \pm 0.11 \pm 0.18 \pm 0.08$
2.76 TeV	$2.2 \pm 0.026 \pm 0.3 \pm 0.006 \pm 0.025$
8 TeV	$2.51 \pm 0.04 \pm 0.03 \pm 0.008 \pm 0.04$
8.16 TeV	$2.51 \pm 0.05 \pm 0.20 \pm 0.021 \pm 0.14$
13 TeV (CMS)	$2.54 \pm 0.008 \pm 0.04 \pm 0.09 \pm 0.0024$
13 TeV (LHCb)	$2.52 \pm 0.014 \pm 0.09 \pm 0.17 \pm 0.0021$

TABLE IV. Tune results for the SHOWERHANDLER:INTRINSICPTGAUSSIAN parameter in HERWIG 7 with the CH3 tune setup. The parameter SUDAKOVCOMMON:PTMIN was set to 0.7 GeV, taking into account the statistical uncertainty of simulations (MC stat.), the measurement uncertainty in data (data unc.), the uncertainty from choices of tune ranges (range), and the uncertainty from choices of the functions for interpolation (int.).

$\sqrt{s}$	Tune result ±MC stat. ± data unc. ± range ± int.
38.8 GeV	$0.742 \pm 0.0010 \pm 0.024 \pm 0.0010 \pm 0.004$
62 GeV	$0.80 \pm 0.00021 \pm 0.04 \pm 0.0020 \pm 0.00024$
200 GeV	$1.00 \pm 0.0018 \pm 0.06 \pm 0.004 \pm 0.0023$
1.8 TeV	$1.16 \pm 0.024 \pm 0.18 \pm 0.06 \pm 0.07$
1.96 TeV	$0.95 \pm 0.025 \pm 0.10 \pm 0.012 \pm 0.005$
2.76 TeV	$1.60 \pm 0.018 \pm 0.23 \pm 0.10 \pm 0.24$
8 TeV	$1.395 \pm 0.07 \pm 0.17 \pm 0.14 \pm 0.08$
8.16 TeV	$1.47 \pm 0.028 \pm 0.17 \pm 0.03 \pm 0.04$
13 TeV (CMS)	$1.71 \pm 0.025 \pm 0.016 \pm 0.00017 \pm 0.07$
13 TeV (LHCb)	$1.60 \pm 0.06 \pm 0.08 \pm 0.13 \pm 0.05$

TABLE V. Results of the tune to various ranges of the $m(\ell^+\ell^-)$ for values of $\sqrt{s}$ of 38.8 GeV and 8, 8.16, and 13 TeV, taking into account the statistical uncertainty of simulations (MC stat.), the measurement uncertainty in data (data unc.), the uncertainty from choices of tune ranges (range), and the uncertainty from choices of the functions for interpolation (int.).

$\sqrt{s}$	$m(\ell^+\ell^-)$ range	Tune result ±MC stat. and data unc. ± range ± int.	
		PYTHIA CP5	HERWIG CH2
38.8 GeV	4.2–5.2 GeV	$0.99 \pm 0.05 \pm 0.020 \pm 0.010$	$0.82 \pm 0.03 \pm 0.011 \pm 0.05$
	5.2–6.2 GeV	$1.03 \pm 0.06 \pm 0.020 \pm 0.025$	$0.85 \pm 0.03 \pm 0.010 \pm 0.09$
	6.2–7.2 GeV	$1.07 \pm 0.08 \pm 0.010 \pm 0.20$	$0.88 \pm 0.05 \pm 0.010 \pm 0.11$
	7.2–8.7 GeV	$0.92 \pm 0.04 \pm 0.025 \pm 0.005$	$0.80 \pm 0.03 \pm 0.016 \pm 0.05$
	10.2–12.85 GeV	$0.87 \pm 0.31 \pm 0.18 \pm 0.16$	$0.81 \pm 0.23 \pm 0.09 \pm 0.06$
8 TeV	46–66 GeV	$2.36 \pm 0.17 \pm 0.0016 \pm 0.05$	$2.15 \pm 0.27 \pm 0.03 \pm 0.07$
	66–116 GeV	$2.51 \pm 0.07 \pm 0.017 \pm 0.05$	$1.95 \pm 0.05 \pm 0.04 \pm 0.011$
	116–150 GeV	$2.70 \pm 0.33 \pm 0.13 \pm 0.17$	$2.1 \pm 0.4 \pm 0.0005 \pm 0.006$
8.16 TeV	15–60 GeV	$3.0 \pm 0.4 \pm 0.19 \pm 0.10$	$2.2 \pm 0.3 \pm 0.10 \pm 0.11$
	60–120 GeV	$2.61 \pm 0.13 \pm 0.033 \pm 0.009$	$1.89 \pm 0.18 \pm 0.08 \pm 0.003$
13 TeV	50–76 GeV	$2.65 \pm 0.07 \pm 0.06 \pm 0.017$	$1.91 \pm 0.14 \pm 0.02 \pm 0.007$
	76–106 GeV	$2.66 \pm 0.03 \pm 0.08 \pm 0.003$	$2.05 \pm 0.05 \pm 0.02 \pm 0.01$
	106–170 GeV	$2.59 \pm 0.07 \pm 0.11 \pm 0.03$	$2.34 \pm 0.23 \pm 0.07 \pm 0.16$
	170–350 GeV	$2.65 \pm 0.16 \pm 0.07 \pm 0.007$	$1.90 \pm 0.16 \pm 0.16 \pm 0.02$
	350–1000 GeV	$2.17 \pm 0.4 \pm 0.018 \pm 0.017$	$1.8 \pm 0.4 \pm 0.13 \pm 0.03$

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