



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

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Abstract

We present an analysis based on models of the intrinsic transverse momentum 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, from the Tevatron, and from the LHC, our investigation spans three orders of magnitude in center-of-mass energy and two orders of magnitude in dilepton invariant mass. The results show an energy-scaling behavior of the intrinsic transverse momentum parameters, independent of the dilepton invariant mass at a given center-of-mass energy.

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The description of high-energy hadron-hadron collisions relies on the modeling of the non-perturbative 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-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 PYTHIA 8 [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 Letter.

The region of Drell–Yan (DY) production where the lepton-pair system is produced with low transverse momentum around a few GeV is especially suited for the study of the intrinsic k_T models as 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, 26].

For the results presented in this Letter, 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, 27]. Their models of the underlying event (UE), 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 [28–30]. The measurements of the differential cross section of DY processes as a function of the dilepton transverse momentum ($p_T(\ell^+\ell^-)$) are summarized in Table 1, 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 [31].

Predictions of the DY cross section are produced at next-to-leading order (NLO) using MADGRAPH5_aMC@NLO v3.4.1 [32] and the matrix-element computation is matched to the PYTHIA 8 or HERWIG 7 generator for parton shower and UE activity modeling. The intrinsic k_T parameter is tuned without changing any other parameters. We observe that the UE parameters have a small impact on the DY $p_T(\ell^+\ell^-)$ distribution, and that the intrinsic k_T parameter has little effect on the UE observables, as shown in Appendix A. The UE tunes used in this analysis are based on various PDFs, partonic emission orderings, and settings in MPI and BR modeling, as listed below:

- PYTHIA 8 tunes: The PYTHIA 8.243 generator is used for the p_T -ordered parton shower and hadronization, and the UE model is parameterized by the CP3, CP4, or CP5 tune [29]. 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.
- HERWIG 7 tunes: The HERWIG 7.1.4 generator is used for the angular-ordered parton

Table 1: Measurements of the Drell–Yan 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	$m(Z)$

shower and hadronization, and the CH2 and CH3 tunes [30] 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 used measurements at \sqrt{s} from 0.9 to 13 TeV by the CDF and CMS experiments, modelling 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 `BEAMREMNANTS:PRIMORDIALKTHARD` $\simeq q_s/\sqrt{2}$, whereas in HERWIG, it is given by the parameter `SHOWERHANDLER:INTRINSICPTGAUSSIAN` $= q_s$. Either of these parameters is referred to as tunable intrinsic k_T parameter q in the following.

In each scenario of \sqrt{s} given in Table 1, 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 PROFESSOR 2 software [34] 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 defined as

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

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 GOF.

The uncertainties in the tuned parameter originate from the variations of the GOF. 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 $[0 \text{ GeV}, \max(p_T)]$ 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.

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 1. The results show an energy-scaling behavior of the intrinsic k_T parameter for both generators and all setups, as indicated in Fig. 1. 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 χ_{lin}^2 of all linear fits divided by the total number of degrees of freedom (NDF), $\chi_{\text{lin}}^2/\text{NDF} = 1.27$, under this assumption and the corresponding p -value [35] 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.

Besides 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, controlled by the regularization parameter `SPACEFLOWER:PT0REF` in PYTHIA and `SUDAKOVCOMMON:PTMIN` in HERWIG. The tuning process and determination of the uncertainty follows the same strategy used in the results shown in Fig. 1 in the PYTHIA CP5 or HERWIG CH3 setups. The `SPACEFLOWER: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 contribu-

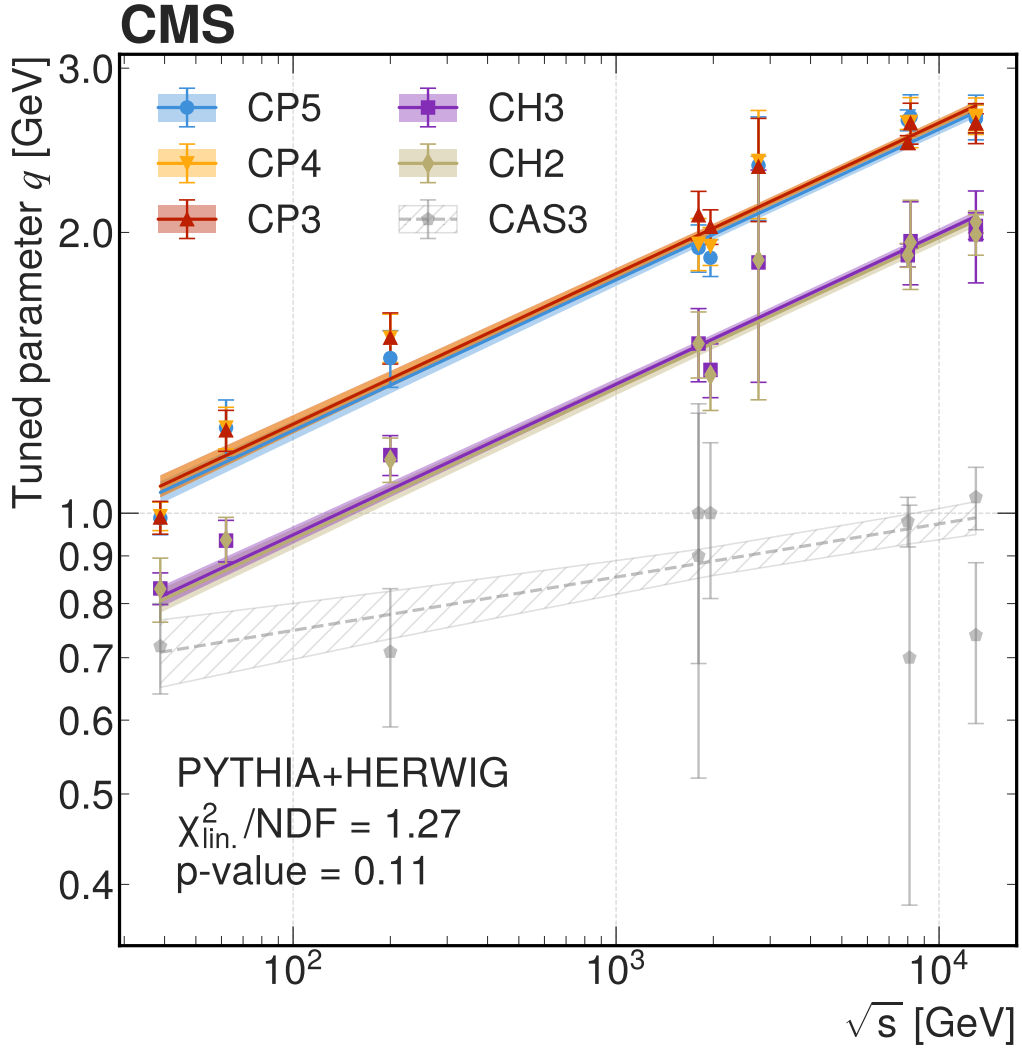


Figure 1: Tuned parameter q values for DY measurements at different center-of-mass energies (points) for various PYTHIA and HERWIG setups (colors). The error bars on the points represent the tuning uncertainties. The tuned values are given in Appendix B. For each generator setup, the function $b\sqrt{s}^a$ is fitted to the points and shown as a line, assuming the same slope a for all the settings. The $\chi^2_{\text{lin.}}/\text{NDF}$ 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.

tions to the low- $p_T(\ell^+\ell^-)$ DY distribution.

Figure 2 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 $\chi_{\text{lin}}^2/\text{NDF}$ 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 16 degrees of freedom from 20 tuned 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 the 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 the linear fit, as shown in the fits in Figs. 1 and 2. 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. 1. 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 Drell–Yan 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 [27] (“CAS3” in Fig. 1), 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. 1. 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.

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, and 8, 8.16, and 13 TeV, in which measurements in multiple $m(\ell^+\ell^-)$ ranges are available. As shown in Fig. 3, 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 3 shows the results of a constant fit to the tuned parameter val-

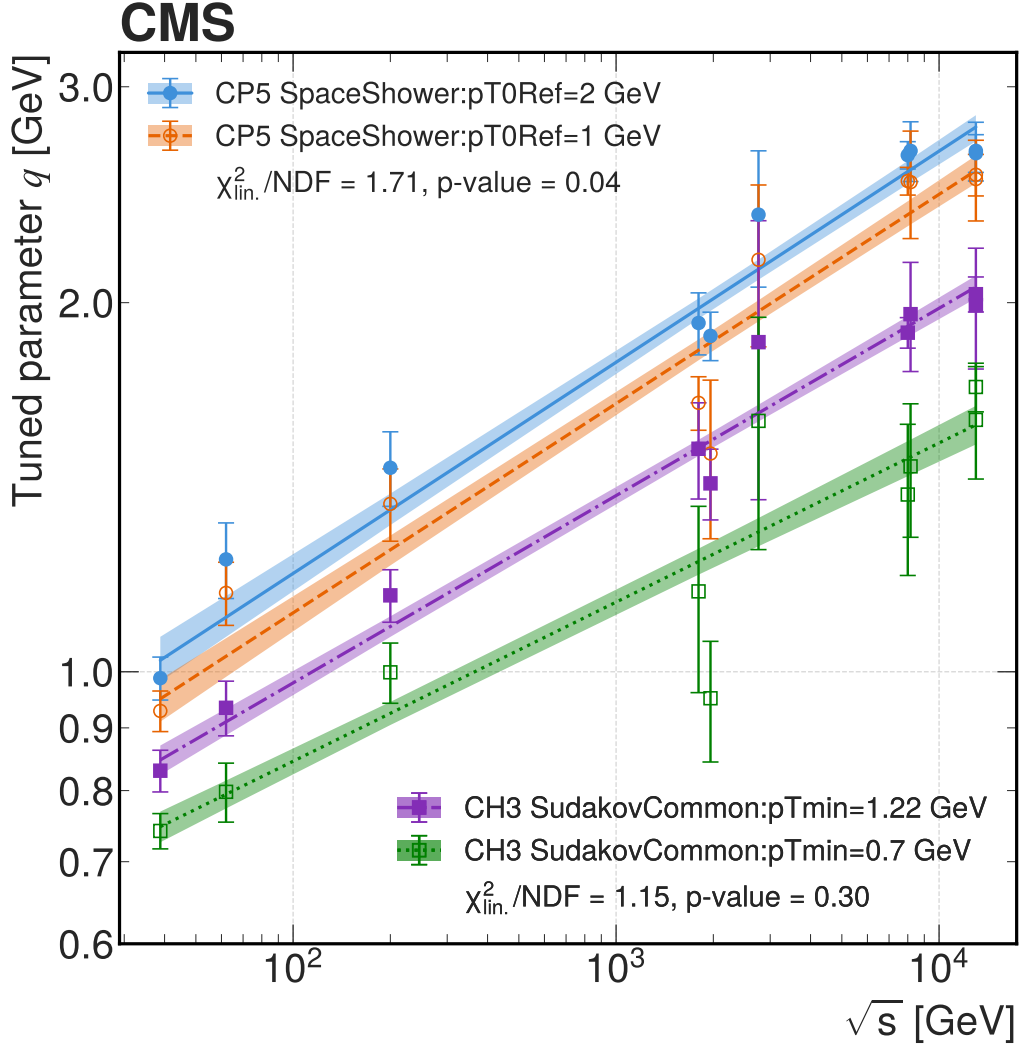


Figure 2: Tuned parameter q values for DY measurements at different center-of-mass energies (points) for various generator settings (lines and bands). The error bars on the points represent the tuning uncertainties. The tuned values are given in Appendix B. For the PYTHIA CP5 setup, the parameter `SPACE SHOWER: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.

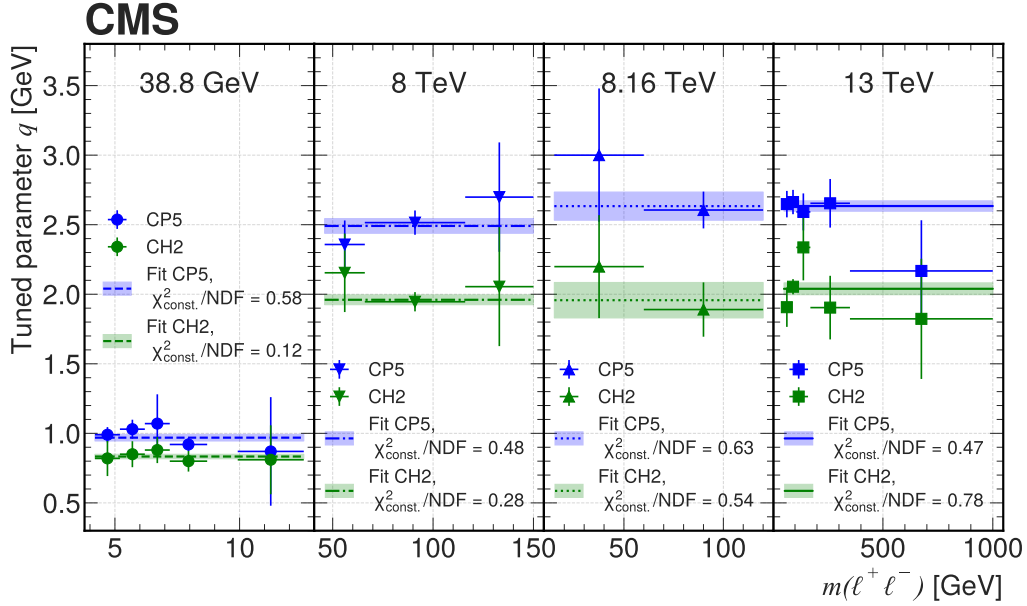


Figure 3: Tuned parameter values (points) for DY measurements at four different center-of-mass energies (panels) for the PYTHIA CP5 (blue) and HERWIG CH3 (green) setups. The error bars on the points represent the tuning uncertainties. The tuned values are given in Appendix B. For each generator setup, 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.

ues based on this hypothesis, which is compatible with the tuned values as indicated by the value of $\chi_{\text{const.}}^2/\text{NDF}$ 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. [36].

Defining the fractions of the hadron momentum carried by the incoming pair of quarks in the DY process to be x_1 and x_2 , $m(\ell^+\ell^-)$ is given by $m(\ell^+\ell^-) = x_1x_2\sqrt{s}$ at leading order. Since the tuned values are stable versus $x_1x_2\sqrt{s}$ for given values of \sqrt{s} , the intrinsic k_T parameter is independent of x_1x_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. 1), 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.

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 setups in the generators PYTHIA and HERWIG using the Drell–Yan cross section differential in 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 setups, 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 generator setup, and related to nonperturbative-QCD effects such as nonresolvable low-energy gluon emissions in parton showers. The tunes were also performed using measurements in various regions of dilepton invariant mass and demonstrated the independence of the intrinsic k_T parameter with respect to the dilepton mass

at each \sqrt{s} . This indicates the independence of the intrinsic k_T on the longitudinal momentum fractions of the quarks in colliding hadrons in Drell–Yan processes.

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A Decoupling the underlying-event and Drell–Yan dilepton transverse momentum descriptions

The analysis in this chapter shows the mutual influence of the intrinsic k_T tune on the underlying-event (UE) description, and vice versa. The results of approximate decoupling of the two parts rationalize the studies in the main text of tuning the intrinsic k_T using fixed UE tunes. Our baseline is the PYTHIA CP5 UE tune [29], recently developed by the CMS Collaboration, for which five parameters controlling multiple-parton interactions and color reconnection were varied. This tune was obtained using UE data measured by CDF and CMS at center-of-mass energies of 1.96, 7 and 13 TeV.

To assess the impact of the UE parameterization on the Drell–Yan (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. A.1 (left), which are much smaller than the uncertainty from the intrinsic k_T variations shown as violet bands.

Similarly, we studied 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. With the UE parameters fixed to the CP5 tune, we generated minimum-bias events with the tuned intrinsic k_T parameter, shown as violet markers in Fig. A.1 (right). The intrinsic k_T tune uncertainty was estimated from the difference between the tune-up and -down variations, represented as the violet band in Fig. A.1 (right). 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. A.1 imply that the parameter space for UE and intrinsic k_T can be factorized.

Besides the intrinsic k_T model, also the lower cutoff scale of initial state radiation (ISR) (SPACESHOWER:PT0REF in PYTHIA) affects the DY $p_T(\ell^+\ell^-)$ distribution, as indicated in the main text and shown in Fig. 2. 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, which is shown as the blue markers in Fig. A.1 (right). 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. 1 and 3.

In summary, the study assesses the mutual impacts of the variation of the intrinsic k_T tune on the UE, and that of the UE tune on the DY transverse momentum, and concludes that the impacts are negligible, which supports our approach of tuning the intrinsic k_T parameters with fixed UE parameters.

B Tuning results

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

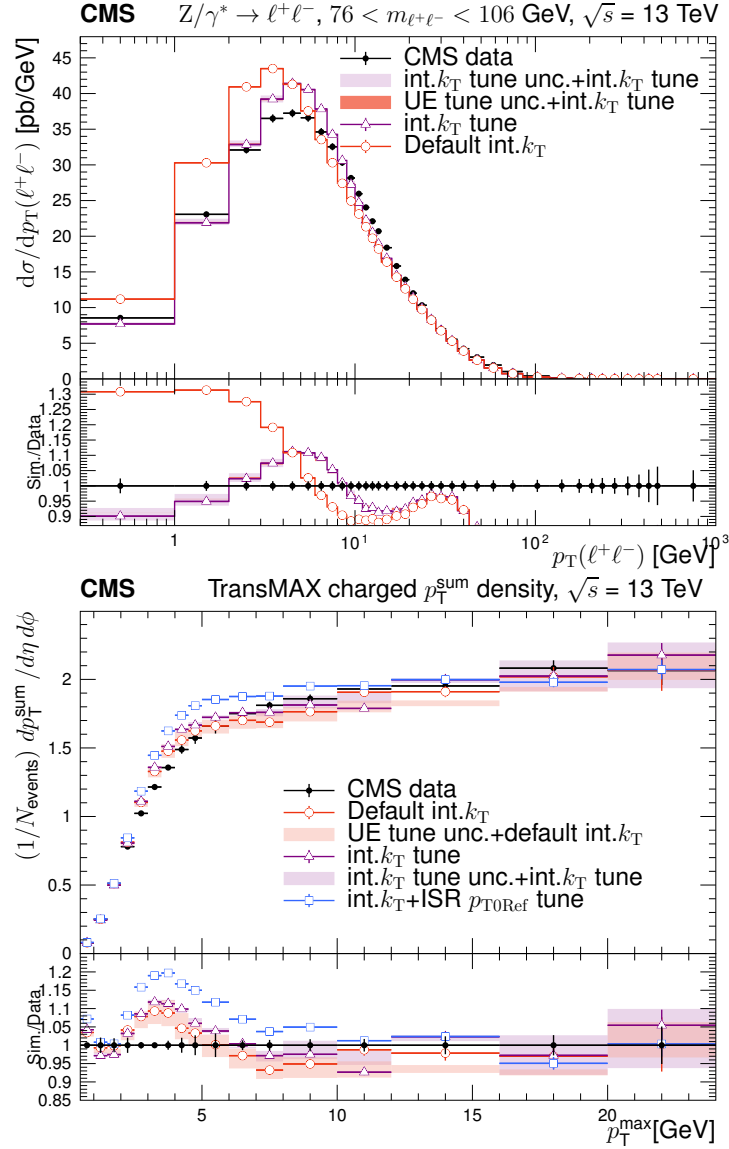


Figure A.1: Effects of the variation of the UE parameters on the DY $p_T(\ell^+\ell^-)$ spectrum (upper), and of the variation of the intrinsic k_T parameter on the density of the scalar sum of the charged-particle transverse momenta (p_T^{sum}) on the rapidity (η) - azimuthal angle (ϕ) space as a function of the transverse momentum of the leading charged particle (p_T^{max}) in the transMAX region averaged over N_{events} generated events [28] in the minimum bias (MB) process (lower), which is one of the observables used for UE tuning. 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 $60^\circ < |\phi - \phi_1| < 120^\circ$ define the two transverse regions, in which transMAX is the one with a higher activity. 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 area is 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 ”), while 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 upper 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 $p_{T0\text{Ref}}$ tune”).

Table B.1: Tune results for the BEAMREMNANTS:PRIMORDIALKTHARD parameter in PYTHIA 8 and the SHOWERHANDLER:INTRINSICPTGAUSSIAN parameter in HERWIG 7, taking into account the uncertainty from tune ranges (range) and the functions for interpolation (int.).

\sqrt{s}	Generator setup	Tune result \pm MC stat. \pm data unc. \pm range \pm 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 B.2: Tune results for the BEAMREMNANTS:PRIMORDIALKTHARD parameter in PYTHIA 8 with the CP5 tune setup. The parameter SPACESHOWER:PT0REF was set to 1 GeV.

\sqrt{s}	Tune result \pm MC stat. \pm data unc. \pm range \pm 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 B.3: 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.


\sqrt{s}	Tune result \pm MC stat. \pm data unc. \pm range \pm 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 B.4: 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.


















\sqrt{s}	$m(\ell^+\ell^-)$ range	Tune result \pm MC stat. and data unc. \pm range \pm 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	$2.17 \pm 0.4 \pm 0.018 \pm 0.017$	$1.8 \pm 0.4 \pm 0.13 \pm 0.03$

C The CMS Collaboration

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







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


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
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




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



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















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A. Benecke , A. Bethani , G. Bruno , C. Caputo , J. De Favereau De Jeneret , C. Delaere , I.S. Donertas , A. Giammanco , A.O. Guzel , Sa. Jain , V. Lemaitre, J. Lidrych , P. Mastrapasqua , T.T. Tran , S. Wertz 










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










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













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











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





















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
















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






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




























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
























































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




































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C. Dziwok , G. Flügge , T. Kress , A. Nowack , O. Pooth , A. Stahl , T. Ziemons , A. Zotz 










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H. Aarup Petersen , M. Aldaya Martin , J. Alimena , S. Amoroso, Y. An , J. Bach , S. Baxter , M. Bayatmakou , H. Becerril Gonzalez , O. Behnke , A. Belvedere , F. Blekman²⁴ , K. Borras²⁵ , A. Campbell , A. Cardini , C. Cheng, F. Colombina , G. Eckerlin, D. Eckstein , L.I. Estevez Banos , O. Filatov , E. Gallo²⁴ , A. Geiser , V. Guglielmi , M. Guthoff , A. Hinzmann , L. Jeppe , B. Kaech , M. Kasemann , C. Kleinwort , R. Kogler , M. Komm , D. Krücker , W. Lange, D. Leyva Pernia , K. Lipka²⁶ , W. Lohmann²⁷ , F. Lorkowski , R. Mankel , I.-A. Melzer-Pellmann , M. Mendizabal Morentin , A.B. Meyer , G. Milella , K. Moral Figueroa , A. Mussgiller , L.P. Nair , J. Niedziela , A. Nürnberg , Y. Otari, J. Park , E. Ranken , A. Raspereza , D. Rastorguev , J. Rübenach, L. Rygaard, A. Saggio , M. Scham^{28,25} , S. Schnake²⁵ , P. Schütze , C. Schwanenberger²⁴ , D. Selivanova , K. Sharko , M. Shchedrolosiev , D. Stafford, S. Taheri Monfared, F. Vazzoler , A. Ventura Barroso , R. Walsh , D. Wang , Q. Wang , Y. Wen , K. Wichmann, L. Wiens²⁵ , C. Wissing , Y. Yang , A. Zimmermann Castro Santos 

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


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


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B. Ujvari , G. Zilizi 










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

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H. Bakhshiansohi⁴¹ , A. Jafari⁴² , M. Zeinali⁴³ 































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
























University College Dublin, Dublin, Ireland

M. Felcini , M. Grunewald 





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















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


















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






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




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






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A.O.M. Iorio^{a,b} , L. Lista^{a,b,50} , P. Paolucci^{a,29} , B. Rossi^a 









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A.T. Meneguzzo^{a,b} , M. Migliorini^{a,b} , J. Pazzini^{a,b} , P. Ronchese^{a,b} , R. Rossin^{a,b} ,
F. Simonetto^{a,b} , M. Tosi^{a,b} , A. Triossi^{a,b} , S. Ventura^a , M. Zanetti^{a,b} , P. Zotto^{a,b} ,
A. Zucchetta^{a,b} , G. Zumerle^{a,b}









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P. Salvini^a , I. Vai^{a,b} , P. Vitulo^{a,b}









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





























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











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





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




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















































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G.B. Marozzo, T. Niknejad , A. Petrilli , M. Pisano , J. Seixas , J. Varela , J.W. Wulff



































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











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







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












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



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






















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








































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

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



















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















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























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









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





























































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












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








Fermi National Accelerator Laboratory, Batavia, Illinois, USA

M. Albrow , M. Alyari , O. Amram , G. Apollinari , A. Apresyan , L.A.T. Bauerdick , D. Berry , J. Berryhill , P.C. Bhat , K. Burkett , J.N. Butler , A. Canepa , G.B. Cerati , H.W.K. Cheung , F. Chlebana , G. Cummings , J. Dickinson , I. Dutta , V.D. Elvira , Y. Feng , J. Freeman , A. Gandrakota , Z. Gecse , L. Gray , D. Green, A. Grummer , S. Grünendahl , D. Guerrero , O. Gutsche , R.M. Harris , R. Heller , T.C. Herwig , J. Hirschauer , B. Jayatilaka , S. Jindariani , M. Johnson , U. Joshi , T. Klijsma , B. Klima , K.H.M. Kwok , S. Lammel , C. Lee , D. Lincoln , R. Lipton , T. Liu , C. Madrid , K. Maeshima , C. Mantilla , D. Mason , P. McBride , P. Merkel , S. Mrenna , S. Nahn , J. Ngadiuba , D. Noonan , S. Norberg, V. Papadimitriou , N. Pastika , K. Pedro , C. Pena⁸⁴ , F. Ravera , A. Reinsvold Hall⁸⁵ , L. Ristori , M. Safdari , E. Sexton-Kennedy , N. Smith , A. Soha , L. Spiegel , S. Stoynev , J. Strait , L. Taylor , S. Tkaczyk , N.V. Tran , L. Uplegger , E.W. Vaandering , I. Zoi 






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C. Aruta , P. Avery , D. Bourilkov , P. Chang , V. Cherepanov , R.D. Field, C. Huh , E. Koenig , M. Kolosova , J. Konigsberg , A. Korytov , K. Matchev , N. Menendez , G. Mitselmakher , K. Mohrman , A. Muthirakalayil Madhu , N. Rawal , S. Rosenzweig , Y. Takahashi , J. Wang 
























Florida State University, Tallahassee, Florida, USA

T. Adams , A. Al Kadhim , A. Askew , S. Bower , V. Hagopian , R. Hashmi , R.S. Kim , S. Kim , T. Kolberg , G. Martinez, H. Prosper , P.R. Prova, M. Wulansatiti , R. Yohay , J. Zhang











Florida Institute of Technology, Melbourne, Florida, USA

B. Alsufyani, M.M. Baarmand , S. Butalla , S. Das , T. Elkafrawy¹⁹ , M. Hohlmann , E. Yanes












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M.R. Adams , A. Baty , C. Bennett, R. Cavanaugh , R. Escobar Franco , O. Evdokimov , C.E. Gerber , M. Hawksworth, A. Hingrajiya, D.J. Hofman , J.h. Lee , D. S. Lemos , A.H. Merrit , C. Mills , S. Nanda , G. Oh , B. Ozek , D. Pilipovic , R. Pradhan , E. Prifti, T. Roy , S. Rudrabhatla , N. Singh, M.B. Tonjes , N. Varelas , M.A. Wadud , Z. Ye , J. Yoo 
























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M. Alhusseini , D. Blend, K. Dilsiz⁸⁶ , L. Emediato , G. Karaman , O.K. Köseyan , J.-P. Merlo, A. Mestvirishvili⁸⁷ , O. Neogi, H. Ogul⁸⁸ , Y. Onel , A. Penzo , C. Snyder, E. Tiras⁸⁹ 









Johns Hopkins University, Baltimore, Maryland, USA

B. Blumenfeld , L. Corcodilos , J. Davis , A.V. Gritsan , L. Kang , S. Kyriacou , P. Maksimovic , M. Roguljic , J. Roskes , S. Sekhar , M. Swartz 


















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A. Abreu , L.F. Alcerro Alcerro , J. Anguiano , S. Arteaga Escatel , P. Baringer , A. Bean , Z. Flowers , D. Grove , J. King , G. Krintiras , M. Lazarovits , C. Le Mahieu , J. Marquez , M. Murray , M. Nickel , M. Pitt , S. Popescu⁹⁰ , C. Rogan , C. Royon , R. Salvatico , S. Sanders , C. Smith , G. Wilson 
























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B. Allmond , R. Gujju Gurunadha , A. Ivanov , K. Kaadze , Y. Maravin , J. Natoli , D. Roy , G. Sorrentino 








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A. Baden , A. Belloni , J. Bistany-riebman, Y.M. Chen , S.C. Eno , N.J. Hadley , S. Jabeen , R.G. Kellogg , T. Koeth , B. Kronheim, Y. Lai , S. Lascio , A.C. Mignerey , S. Nabili , C. Palmer , C. Papageorgakis , M.M. Paranjpe, E. Popova⁹¹ , A. Shevelev , L. Wang 













Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

J. Bendavid , I.A. Cali , P.c. Chou , M. D'Alfonso , J. Eysermans , C. Freer , G. Gomez-Ceballos , M. Goncharov, G. Grosso, P. Harris, D. Hoang, D. Kovalskiy , J. Krupa , L. Lavezzo , Y.-J. Lee , K. Long , C. McGinn, A. Novak , M.I. Park , C. Paus , C. Reissel , C. Roland , G. Roland , S. Rothman , G.S.F. Stephans , Z. Wang , B. Wyslouch , T. J. Yang 












University of Minnesota, Minneapolis, Minnesota, USA

B. Crossman , B.M. Joshi , C. Kapsiak , M. Krohn , D. Mahon , J. Mans ,
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













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K. Bloom , D.R. Claes , G. Haza , J. Hossain , C. Joo , I. Kravchenko , J.E. Siado ,
W. Tabb , A. Vagnerini , A. Wightman , F. Yan , D. Yu 

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H. Bandyopadhyay , L. Hay , H.w. Hsia, I. Iashvili , A. Kalogeropoulos ,
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
























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G. Alverson , E. Barberis , J. Bonilla , B. Bylsma, M. Campana , J. Dervan, Y. Haddad ,
Y. Han , I. Israr , A. Krishna , J. Li , M. Lu , G. Madigan , R. Mccarthy ,
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



Northwestern University, Evanston, Illinois, USA

J. Bueghly, S. Dittmer , K.A. Hahn , Y. Liu , M. Mcginnis , Y. Miao , D.G. Monk ,
M.H. Schmitt , A. Taliercio , M. Velasco

















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G. Agarwal , R. Band , R. Bucci, S. Castells , A. Das , R. Goldouzian , M. Hildreth ,
K.W. Ho , K. Hurtado Anampa , T. Ivanov , C. Jessop , K. Lannon , J. Lawrence ,
N. Loukas , L. Lutton , J. Mariano, N. Marinelli, I. Mcalister, T. McCauley , C. Mcgrady ,
C. Moore , Y. Musienko¹⁶ , H. Nelson , M. Osherson , A. Piccinelli , R. Ruchti ,
A. Townsend , Y. Wan, M. Wayne , H. Yockey, M. Zarucki , L. Zygala 

The Ohio State University, Columbus, Ohio, USA

A. Basnet , M. Carrigan , L.S. Durkin , C. Hill , M. Joyce , M. Nunez Ornelas , K. Wei,
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












Princeton University, Princeton, New Jersey, USA

H. Bouchamaoui , K. Coldham, P. Das , G. Dezoort , P. Elmer , A. Frankenthal ,
B. Greenberg , N. Haubrich , K. Kennedy, G. Kopp , S. Kwan , D. Lange ,
A. Loeliger , D. Marlow , I. Ojalvo , J. Olsen , D. Stickland , C. Tully 




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A.S. Bakshi , S. Chandra , R. Chawla , A. Gu , L. Gutay, M. Jones , A.W. Jung ,
A.M. Koshy, M. Liu , G. Negro , N. Neumeister , G. Paspalaki , S. Piperov ,
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A. Wildridge , W. Xie , Y. Yao 










Purdue University Northwest, Hammond, Indiana, USA

J. Dolen , N. Parashar , A. Pathak 





















Rice University, Houston, Texas, USA

D. Acosta , T. Carnahan , K.M. Ecklund , P.J. Fernández Manteca , S. Freed, P. Gardner,
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




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A. Bodek , P. de Barbaro , R. Demina , J.L. Dulemba , A. Garcia-Bellido , O. Hindrichs , A. Khukhunaishvili , N. Parmar, P. Parygin⁹¹ , R. Taus 
















Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA

B. Chiarito, J.P. Chou , S.V. Clark , D. Gadkari , Y. Gershtein , E. Halkiadakis , M. Heindl , C. Houghton , D. Jaroslowski , S. Konstantinou , I. Laflotte , A. Lath , R. Montalvo, K. Nash, J. Reichert , H. Routray , P. Saha , S. Salur , S. Schnetzer, S. Somalwar , R. Stone , S.A. Thayil , S. Thomas, J. Vora , H. Wang 

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D. Ally , A.G. Delannoy , S. Fiorendi , S. Higginbotham , T. Holmes , A.R. Kanuganti , N. Karunarathna , L. Lee , E. Nibigira , S. Spanier 












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














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