

# New Herwig7 underlying event tune: From RHIC to LHC energies

Umar Sohail Qureshi,<sup>1,2,\*</sup> Luke Mozarsky,<sup>3,4,†</sup> Helen Caines,<sup>3</sup> Raghav Kunnawalkam Elayavalli<sup>1b,2</sup> and Isaac Mooney<sup>3,5</sup>

<sup>1</sup>Physics Department, *Stanford University*, Stanford, California, USA

<sup>2</sup>Department of Physics and Astronomy, *Vanderbilt University*, Nashville, Tennessee, USA

<sup>3</sup>Department of Physics, *Yale University*, New Haven, Connecticut, USA

<sup>4</sup>Department of Physics, *Columbia University*, New York, New York, USA

<sup>5</sup>*Brookhaven National Laboratory*, Upton, New York, USA



(Received 5 May 2025; accepted 5 November 2025; published 24 December 2025)

We present parameter sets corresponding to new underlying event tunes for the Herwig7.3 Monte Carlo event generator. The existing Herwig tunes are in good agreement with LHC data, however, they are not typically designed for center-of-mass energies below  $\sqrt{s} = 300$  GeV. The tunes presented in this study can describe midrapidity data collected at the nominal RHIC energy of  $\sqrt{s} = 200$  GeV as well as higher center-of-mass energies utilized by experiments at the LHC and Tevatron. The base “New Haven” tune is developed by fitting minimum-bias simulations of proton-proton ( $pp$ ) collisions to midrapidity identified hadron and jet data from the STAR experiment. The “Nashville” tune includes a separate set of parameters developed by tuning to Tevatron proton-antiproton ( $p\bar{p}$ ) data at  $\sqrt{s} = 300, 900$  and 1960 GeV from CDF, and LHC  $pp$  measurements from CMS at  $\sqrt{s} = 7$  TeV, in addition to the STAR measurements. Both new tunes demonstrate significant improvements over the recommended default tune currently included in the latest version of Herwig for minimum bias production. As such, we advocate using these tunes for future simulation studies at midrapidity by experimental collaborations at RHIC (STAR and sPHENIX) and the LHC (ALICE, ATLAS, and CMS).

DOI: [10.1103/cnck-wtbh](https://doi.org/10.1103/cnck-wtbh)

## I. INTRODUCTION

Monte Carlo (MC) event generators, which simulate collisions involving relativistic lepton-lepton, lepton-hadron, and hadron-hadron interactions play a critical role in high-energy particle and nuclear physics. Theoretically, MC models help test our fundamental understanding of the Standard Model, particularly quantum chromodynamics (QCD), providing a framework for the initial and final states of collision systems. Experimentally, MCs are a vital part of the simulation process, not only in reproducing realistic spectra for determining detector acceptance and resolution corrections or studying systematic effects in experimental data, but also as a powerful tool for gaining insights into physics measurements. Popular event generators, such as Pythia [1,2], Sherpa [3], and Herwig/Herwig++ [4,5], are extensively used to simulate collisions at the Large Hadron Collider (LHC) and the Relativistic

Heavy-Ion Collider (RHIC). These simulations treat various QCD physics processes, including a perturbative hard scattering regime and evolution via a parton shower that incorporates both initial state radiation (ISR), i.e., emissions prior to the hard scattering, and final state radiation (FSR), i.e., emissions after the hard scattering. Additionally, they account for nonperturbative components such as hadronization, the creation of particles in the underlying event (UE), and multiparton interactions (MPI).

The aforementioned MC event generators use multiple free parameters that are determined by fits to experimental data. The Herwig7 MC event generator discussed in this study has undergone numerous tuning exercises over the years and is successful in describing data at the LHC [6,7]. However, significant discrepancies remain when describing data from collisions at lower center-of-mass energies. These disagreements are mainly attributed to incorrect modeling of the low-energy QCD interactions in the underlying event, which arise from the extrapolation of the center-of-mass energy used. Currently, the set of parameters from Ref. [8] is the recommended option for the simulation of minimum bias and underlying event data. This set of parameters is obtained in the following manner. First, the authors tune MPI parameters explicitly responsible for determining the soft/hard (low/high transverse momentum) emission threshold, which has a power-law

\*Contact author: [uqureshi@cern.ch](mailto:uqureshi@cern.ch)

†Contact author: [luke.mozarsky@cern.ch](mailto:luke.mozarsky@cern.ch)

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dependence on  $\sqrt{s}$ . These parameters are tuned to data taken with center-of-mass collision energies ranging from  $\sqrt{s} = 200$  GeV to  $\sqrt{s} = 13$  TeV, one energy at a time. The authors then fit the aforementioned power law to the emission thresholds produced by these tunes to extract MPI parameters that, in principle, describe multiple-parton interactions well across the entire range of  $\sqrt{s}$ . It is important to note that while the power-law fit includes the tune values from 200 GeV–13 TeV, it is also forced to pass through the central values from the tunes at 7 and 13 TeV, which the authors note leads to improved tune performance at higher center-of-mass while resulting in a suboptimal description of data at  $\sqrt{s} = 200$  GeV. Finally, the remaining MPI model and color reconnection parameters are tuned to minimum bias and underlying event data taken at  $\sqrt{s} = 7$  and 13 TeV. We find that this tune, in addition to other existing Herwig tunes, does not provide a satisfactory description of data with energy around  $\sqrt{s} = 200$  GeV. In particular, this limits the utility of Herwig as a tool for the STAR and sPHENIX experiments at RHIC, and eventually for experiments studying QCD at the Electron-Ion Collider.

In this work, we use underlying event multiplicity data from RHIC at  $\sqrt{s} = 200$  to develop two distinct Herwig7 tunes: the “New Haven” tune, which is fitted exclusively to STAR minimum-bias pp measurements at  $\sqrt{s} = 200$ , and the “Nashville” tune, which in addition incorporates Tevatron  $p\bar{p}$  data at CDF at energies of  $\sqrt{s} = 300, 900$  and 1960 GeV from CDF and LHC pp measurements at  $\sqrt{s} = 7$  TeV from CMS. Both tunes achieve improved performance at  $\sqrt{s} = 200$  GeV while maintaining a good description of data at higher center of mass energies. A similar dedicated Pythia8 tune was developed in Ref. [9], and was seen to significantly improve the description of experimental data.

This paper is organized as follows: Section II details the Professor toolkit and its parametrization-based tuning procedure. Section III describes the data and its implementation through the RIVET framework. Section IV presents the results for our new tunes. Section V compares the new Herwig7 tune predictions with selected data distributions. We conclude with a discussion in Sec. VI that summarizes our findings.

## II. TUNING METHODOLOGY

The Herwig Monte Carlo (MC) event generation framework consists of both perturbative and nonperturbative components. The hard component of an event refers to the particles produced through the showering process of the partons that emerge from the primary hard  $2 \rightarrow n$  scattering. In contrast, the underlying event comprises particles originating from the hadronization of beam remnants and MPI, as well as their ISR and FSR. Beam-beam remnants are made up of hadrons that arise from the fragmentation of remnant

partons, which participate minimally in the momentum transfer during the collision. “MPI” refers to additional parton-parton scatterings (2-to-2 interactions) occurring within the same hadronic collision but characterized by a lower transverse momentum compared to the primary hard scattering event.

In addition to hard-scattering processes, several other mechanisms contribute to the inelastic cross section in hadron-hadron collisions. These include single-diffractive dissociation (SD), double-diffractive dissociation (DD), and central diffraction (CD). For a detailed description of these mechanisms, see Ref. [10].

The term “minimum bias” (MB) refers to a broad class of events that are selected with minimal requirements on the detector activity, effectively capturing a large fraction of the overall inelastic cross section. MB data are frequently used in studies of the underlying event (UE) because they provide an inclusive sample of inelastic collision events.

For this study, we adopt a parametrization-based tuning procedure via the Professor (v2.4.2) toolkit [11]. This process involves sampling our parameters of interest multiple times within a specified range, and, for each sample of parameters, generating Herwig7 Monte Carlo (MC) events. The resulting predictions of these MC simulations are then compared to data using RIVET [12]. For each bin of each data observable, Professor constructs a third-degree polynomial to parametrize the Herwig7 predictions as a function of the  $P$  tuning parameters, with numerically computed coefficients. Finally, a  $\chi^2$  fit of the polynomial to the data is performed using the Minuit framework [13] which identifies the optimal set of parameters.

The parameters we determined to tune in the report are described as follows. As a starting point, we use the default tune [8] (which we label as “Default”) with an updated set of leading-order parton distribution functions (PDFs) (NNPDF3.0 [14]). The Herwig7 MPI model [15] is determined primarily by the two parameters  $p_T^{\min}$  and  $\mu^2$ . Emissions with  $p_T > p_T^{\min}$  are considered as hard, while those below are considered soft. The first set of our tuning parameters ( $p_{T,0}^{\min}, b, c$ ) governs the energy-scaling of  $p_T^{\min}$ , which follows a power-law function

$$p_T^{\min}(\sqrt{s}) = p_{T,0}^{\min} \left( \frac{b + \sqrt{s}}{E_0} \right)^c \quad (1)$$

Where  $E_0$  is the reference energy scale. The parameter  $E_0$  is arbitrary, and thus we set  $E_0 = 200$  GeV rather than its default value of 7 TeV. Meanwhile, the parameter  $\mu^2$  is the (squared) inverse of the proton radius, i.e., the transverse spatial extension of the partonic point cloud that enters the collision. Another set of parameters ( $N_{\text{ladder}}, B_{\text{ladder}}$ ) governs the production of soft particles in a ladder graph. The average expected number of particles  $\langle N \rangle$  is parametrized such that the number  $N$  of the particles in the soft

TABLE I. Comparison of Herwig7 settings and tuning ranges for parameters between the default tune and the tunes presented in this study.

| Setting             | Default | Our tunes |
|---------------------|---------|-----------|
| $E_0$               | 7 TeV   | 200 GeV   |
| PDFSet              | CT14LO  | NNPDF30   |
| Parameter           | Default | Range     |
| $c$                 | 0.31    | 0.15–0.50 |
| $b$                 | 622     | 500–950   |
| $p_{T,0}^{\min}$    | 2.82    | 2.00–5.00 |
| $\mu^2$             | 1.1     | 0.68–2.50 |
| $N_{\text{ladder}}$ | 0.6838  | 0.2–0.8   |
| $p_{\text{reco}}$   | 0.970   | 0.2–1.0   |
| $R_{\text{diff}}$   | 0.187   | 0.18–0.40 |

ladder is drawn from a Poisson distribution with mean  $\langle N \rangle$  given as

$$\langle N \rangle = N_{\text{ladder}} \ln \left[ \frac{(p_{r1} + p_{r2})^2}{m_{\text{rem}}^2} \right] + B_{\text{ladder}} \quad (2)$$

Where  $p_{r1,2}$  are the momenta of the beam remnants and  $m_{\text{rem}}$  is the constituent mass of the remnant. Following the guidelines in Ref. [8], we set the parameter  $B_{\text{ladder}}$  to zero and only tune the  $N_{\text{ladder}}$ . Meanwhile, the diffractive ratio parameter  $R_{\text{diff}}$  gives the fraction of the diffractive cross section with respect to the nondiffractive cross section.

The last of our tuning parameters is the color reconnection probability  $p_{\text{reco}}$ , which determines the likelihood of rearranging the color topology between clusters or QCD dipoles to minimize the total invariant cluster mass. It is worth noting here that while there are four color-reconnection algorithms (see Ref. [16]) in Herwig7: plain (default), statistical, baryonic, and baryonimesonic, our tune uses the plain color reconnection scheme. The baryonic and baryonimesonic schemes include an additional parameter,  $p_{\text{reco}}^{\text{baryonic}}$ . Since our tune employs the plain algorithm exclusively,  $p_{\text{reco}}^{\text{baryonic}}$  remains inactive and therefore is not tuned the fits. A more detailed description of the above tuning parameters is given in Ref. [8]. All the tuning parameters and their respective ranges are listed in Table I.

For our procedure with 7 tunable parameters, a third-degree polynomial has 120 coefficients, thereby requiring a minimum of 120 samples in parameter space. To over-sample by at least a factor of two as recommended by the Professor authors [11], we require 240 or more points. Hence, we sample 300 multidimensional points from the tuning parameters phase-space as listed in Table I within the specified ranges to be used as anchor points in the generator response polynomial parametrization. For each sampling, we generate 10 million minimum bias inelastic events to ensure the MC statistics are sufficient as compared to the data. The optimal vector of tuned parameters  $\theta_0$  is determined by minimizing the weighted  $\chi^2$ , where the optimization is over all parameter vectors  $\theta \in \Theta$

$$\theta_0 = \underset{\theta \in \Theta}{\operatorname{argmin}} \chi^2(\theta) \quad (3)$$

Where the  $\chi^2$  for a single parameter vector  $\theta$  is computed as

$$\chi^2(\theta) = \sum_{i \in I} w_i (f_i(\theta) - d_i) C_i^{-1} (f_i(\theta) - d_i) \quad (4)$$

The summation index,  $i$ , is over the set  $I$  with size determined by the number of data points  $d_i$ ;  $w_i$  is the weight for each data point;  $f_i(\theta)$  is the corresponding interpolated Herwig response parametrized by a vector  $\theta$ .  $C_i$  is the covariance matrix considering just experimental uncertainties, and we assume no significant bin-by-bin correlations.

### III. DATA AND SIMULATION

For this tuning exercise, we utilize midrapidity data in  $pp$  collisions from the STAR and CMS experiments, as well as  $p\bar{p}$  collisions from the CDF experiment. We choose datasets for the tuning procedure to represent three main categories of measurements: identified particle spectra, which track specific particle types and their invariant yields; event multiplicities, which count the number of particles in some specified kinematic phase-space produced in collisions; and jet substructure measurements, which examine the radiation patterns in phase space of the hard scattered partons. These categories and the specifics of experiments used are summarized in Table II.

TABLE II. Summary of experiments and observables used in the new tunes.

| Experiment | $\sqrt{s}$ (GeV) | Observable                                            | Nashville | New Haven | Figure  | Reference |
|------------|------------------|-------------------------------------------------------|-----------|-----------|---------|-----------|
| STAR       | 200              | $\pi^\pm$ and $p$ , $\bar{p}$ cross sections vs $p_T$ | ✓         | ✓         | 5       | [17]      |
| STAR       | 200              | Charged particle multiplicities and $p_T$             | ✓         | ✓         | 4       | [18]      |
| CDF        | 300, 900, 1960   | Charged particle density and $\sum p_T$               | ✓         | ...       | 7, 8, 9 | [19]      |
| CMS        | 7000             | Charged particle density and $\sum p_T$               | ✓         | ...       | 10      | [20]      |
| STAR       | 200              | SoftDrop groomed jet substructure ( $z_g, R_g$ )      | ✓         | ✓         | 6       | [21]      |
| STAR       | 200              | Invariant and groomed jet mass                        | ✓         | ✓         | 6       | [22]      |

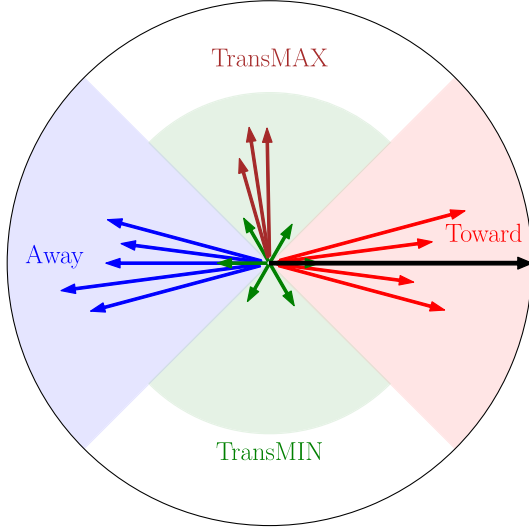


FIG. 1. An illustration of a hadron-hadron collision in which a hard parton-parton collision has occurred, and the leading object is taken to be the charged particle of largest  $p_T$  in the event. The black arrow in the toward direction indicates the leading object direction. Figure adapted from [24].

The identified hadron spectra measurements from STAR [17] focuses on  $\pi^\pm$ ,  $p$ , and  $\bar{p}$  yields at RHIC. These spectra are measured at midrapidity with  $|y| < 0.5$  over the range  $0.3 < p_T < 10$  GeV/c, utilizing particle identification techniques based on ionization energy loss in the time projection chamber (TPC), along with time-of-flight (ToF) measurements. The spectra are particularly sensitive to the UE since the UE contributes substantially to the production of low- and intermediate- $p_T$  particles.

For the UE multiplicity data from STAR [18,23], CDF [19], and CMS [20], the charged particle with the highest transverse momentum is defined as the leading object. Charged particles with  $p_T > 0.5$  GeV/c and  $|\eta| < 0.8$  are then used to describe the UE for the CDF and CMS measurements while  $p_T > 0.2$  GeV/c and  $|\eta| < 0.4$  are used for the STAR data. The leading object direction is used to divide the detector  $\eta - \phi$  space into four distinct regions on an event-by-event basis. The “toward” and “away” regions are defined relative to the leading object direction. The two transverse regions are then labeled as TransMAX or TransMIN, as depicted in Fig. 1. The TransMAX (TransMIN) regions are defined on an event-by-event basis as the regions with the greatest (least) number of charged particles, or larger (smaller)  $p_T$  sums. The average transverse density TransAVE is the average of the TransMAX and the TransMIN densities while TransDIF is the difference between TransMAX and TransMIN densities. Hard initial or final-state radiation may also result in a third jet in the TransMAX region. Both the TransMAX and TransMIN regions receive contributions from multiparton interactions and beam-beam remnant components. The TransMIN region is very sensitive to the multiparton interactions

and beam-beam remnant components of the UE, while the TransDIF is very sensitive to initial and final-state radiation.

Measurements of jet substructure from STAR [21], such as the shared momentum fraction  $z_g$  and the groomed jet radius  $R_g$ , as defined by the SoftDrop algorithm, are also used. These substructure observables are measured differentially for jets with varying resolution parameters from  $R = 0.2$  to  $0.6$  within a transverse momentum range of  $15 < p_T < 60$  GeV/c. Finally, inclusive measurements of the invariant and SoftDrop-groomed jet mass [22] by the STAR experiment are also considered. All jet substructure measurements are fully corrected for detector effects and reported differentially in both the jet transverse momentum and jet radius parameters. Particle within the momenta, energy, and rapidity ranges  $0.2 < p_T < 30$  GeV/c,  $0.2 < E_T < 30$  GeV/c, and  $|\eta| < 1$  are included in the analysis. While jet substructure observables are not inherently very sensitive to UE, the authors of Ref. [9] saw improvements from including them. This is likely because the inclusion of jet substructure helps fine-tune the extrapolation of  $p_T^{\min}$  since the energy cutoff dictates the particle multiplicity in a jet. As a whole, the selected data offer a robust metric to evaluate the tune’s performance in capturing both the nonperturbative and perturbative components of hadronic collisions.

The MC runs for all energies and beam types over all samples are then analyzed using the RIVET framework. The resulting output yoda files are processed by the Professor code to determine the minimum  $\chi^2$ . RIVET analyses for each of the measurements mentioned above are publicly available at [25].

#### IV. NEW Herwig7 TUNES

In this study, we provide two distinct parameter sets. The base New Haven tune is developed by fitting minimum-bias simulations of proton-proton ( $pp$ ) collisions to midrapidity identified hadron and jet data from the STAR experiment. The Nashville tune includes a separate set of parameters developed by tuning to Tevatron  $p\bar{p}$  data at  $\sqrt{s} = 300, 900$  and  $1960$  GeV from CDF, and LHC  $pp$  measurements from CMS at  $\sqrt{s} = 7$  TeV, in addition to the STAR measurements. Figure 2 shows the  $\chi^2$  profiles for each tuning parameter around the global minimum (offset such that  $\chi^2 = 0$  at the minimum) for the Nashville tune. The  $\chi^2$  statistic for the New Haven tune shows similar sensitivity to variations in the tuning parameters.

Table III lists the optimal values of the tuning parameters considered in the new Nashville and New Haven tunes. Generally, the errors on these central values derived from Minuit are negligible ( $< 1\%$ ), do not affect the shape of the resulting MC responses, and are, therefore, omitted. However, they may be seen in the  $\chi^2$  profile plots depicted in Fig. 2. The best fit  $\chi^2$  per degree of freedom  $\chi^2/\nu$  is

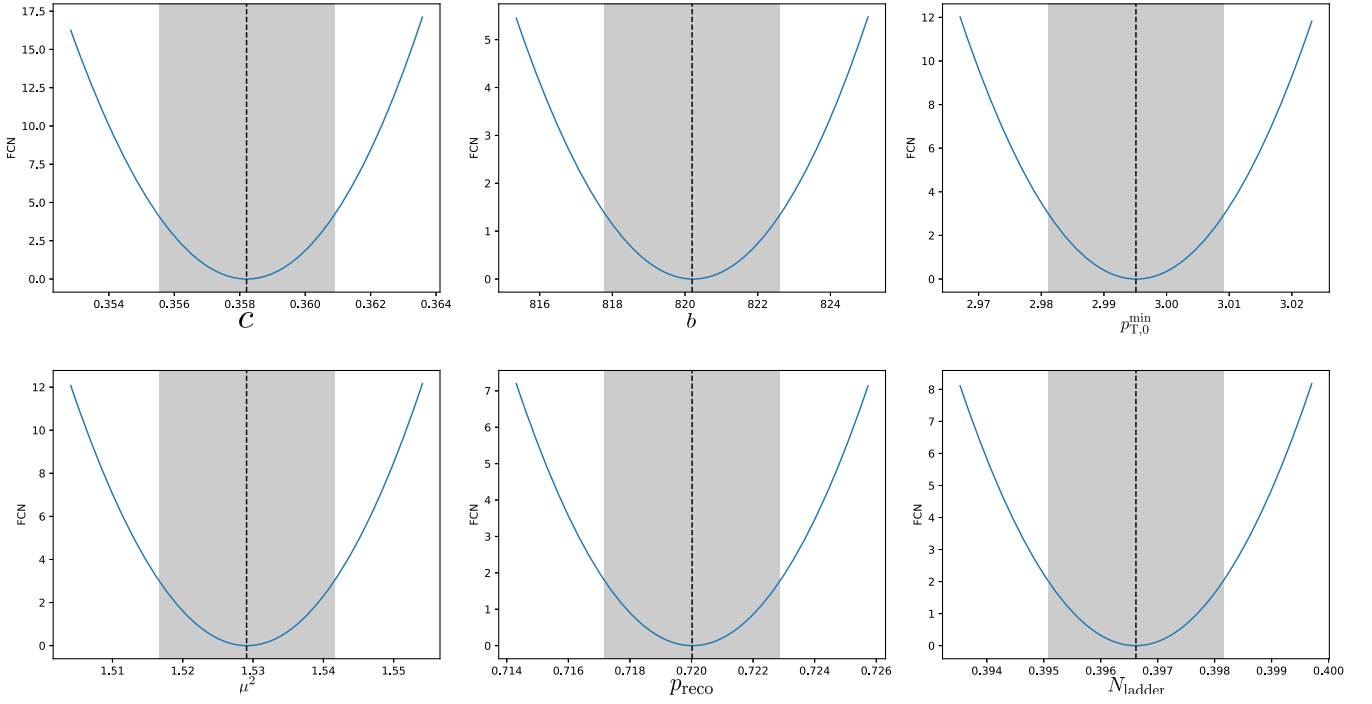


FIG. 2. Minimum-subtracted  $\chi^2$  profiles of the Nashville tune parameters in the vicinity of the best-fit value. The gray-shaded regions indicate the  $1\sigma$  uncertainties in the optimal parameters.

$3727/1055 \approx 3.53$  for the Nashville tune and  $1451/518 \approx 2.80$  for the New Haven tune.

Figure 3 shows the extrapolation of  $p_T^{\min}$  as dictated by Eq. (1) for the default, New Haven, Nashville, and Pythia8 Detroit tunes. We remind the reader that all tunes set the reference energy  $E_0 = 200$  GeV except the default tune which uses  $E_0 = 7$  TeV.

We observe that for both the Nashville and New Haven tunes, the new  $p_T^{\min}$  value is roughly a factor of 2.5 to 3 larger compared to the default. The Detroit and default tune extrapolations are very comparable at  $\sqrt{s} = 200$  GeV energies and separate as collision energy increases or decreases. Between the Nashville and New Haven tunes, there is about a constant 20%–25% percent difference in the value of  $p_T^{\min}$  from 0 to 200 GeV, which then increases

slightly at  $\mathcal{O}(\text{TeV})$ . We attribute much of the offset between the two new tunes and the default Herwig tune to the fact that the reference energy  $E_0$  was changed from 7 TeV to 200 GeV. We also note that while the default Herwig and Pythia8 Detroit tune have fairly similar dependence of  $p_{T,\min}$  on  $\sqrt{s}$  many of their other tunable parameters are significantly different, as are their hadronization models, so care

TABLE III. Comparison of Herwig7 tuned parameters between the default and the new Nashville and New Haven tunes.

| Parameter           | Default | Nashville | New Haven |
|---------------------|---------|-----------|-----------|
| $c$                 | 0.31    | 0.36      | 0.23      |
| $b$                 | 622     | 820       | 551       |
| $p_{T,0}^{\min}$    | 2.82    | 2.99      | 3.01      |
| $\mu^2$             | 1.10    | 1.53      | 1.11      |
| $N_{\text{ladder}}$ | 0.6838  | 0.3966    | 0.5690    |
| $p_{\text{reco}}$   | 0.970   | 0.720     | 0.522     |
| $R_{\text{diff}}$   | 0.187   | 0.299     | 0.262     |

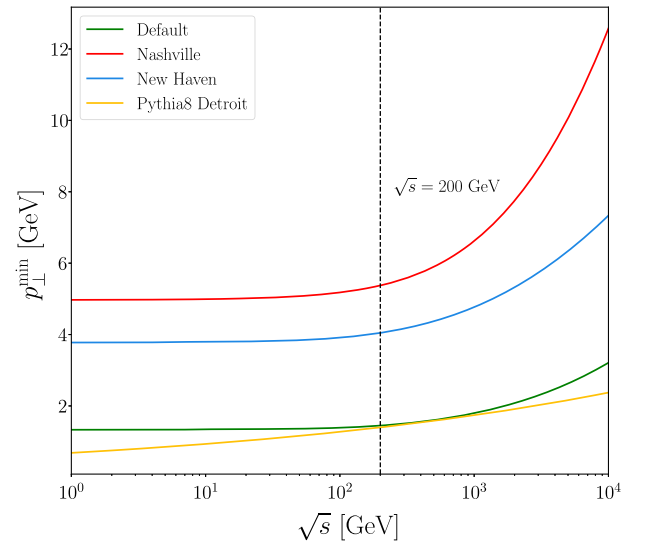


FIG. 3. The energy extrapolations of  $p_T^{\min}$  for the default, Nashville, New Haven, and Pythia Detroit tunes are shown as the solid green, red, blue, and orange curves, respectively. The black dashed line is drawn for reference at  $\sqrt{s} = 200$  GeV.

should be taken about drawing strong conclusions from this apparent agreement.

The comparison of Herwig7 tuned parameters between the default, Nashville, and New Haven tunes reveals several differences. First we consider the parameters responsible for setting the soft/hard particle cutoff used by the MPI model. For the parameter  $c$ , Nashville requires a larger value (0.36) compared to the default (0.31), an increment of approximately 16%. However, New Haven exhibits a significant decrease, with  $c = 0.225$ , which is about 17.5% lower than the default and 38% lower than Nashville. The parameter  $b$

shows a large increase of about 32% in Nashville (820) compared to the default (622). In New Haven,  $b$  decreases to 551, which is roughly 33% lower than in Nashville and 11% lower than the default tune. Note that these changes manifest as the observed difference in the  $p_T^{\min}$  extrapolation. The parameter  $p_{T,0}^{\min}$  shows slight increases across both tunes, with Nashville (2.99) being about 6% higher than the default (2.82) and New Haven (3.005) showing an approximately 6.6% increase over the default. This is evidence of the fact that our tunes predict a greater proportion of soft particle emissions than the default and Detroit tunes.

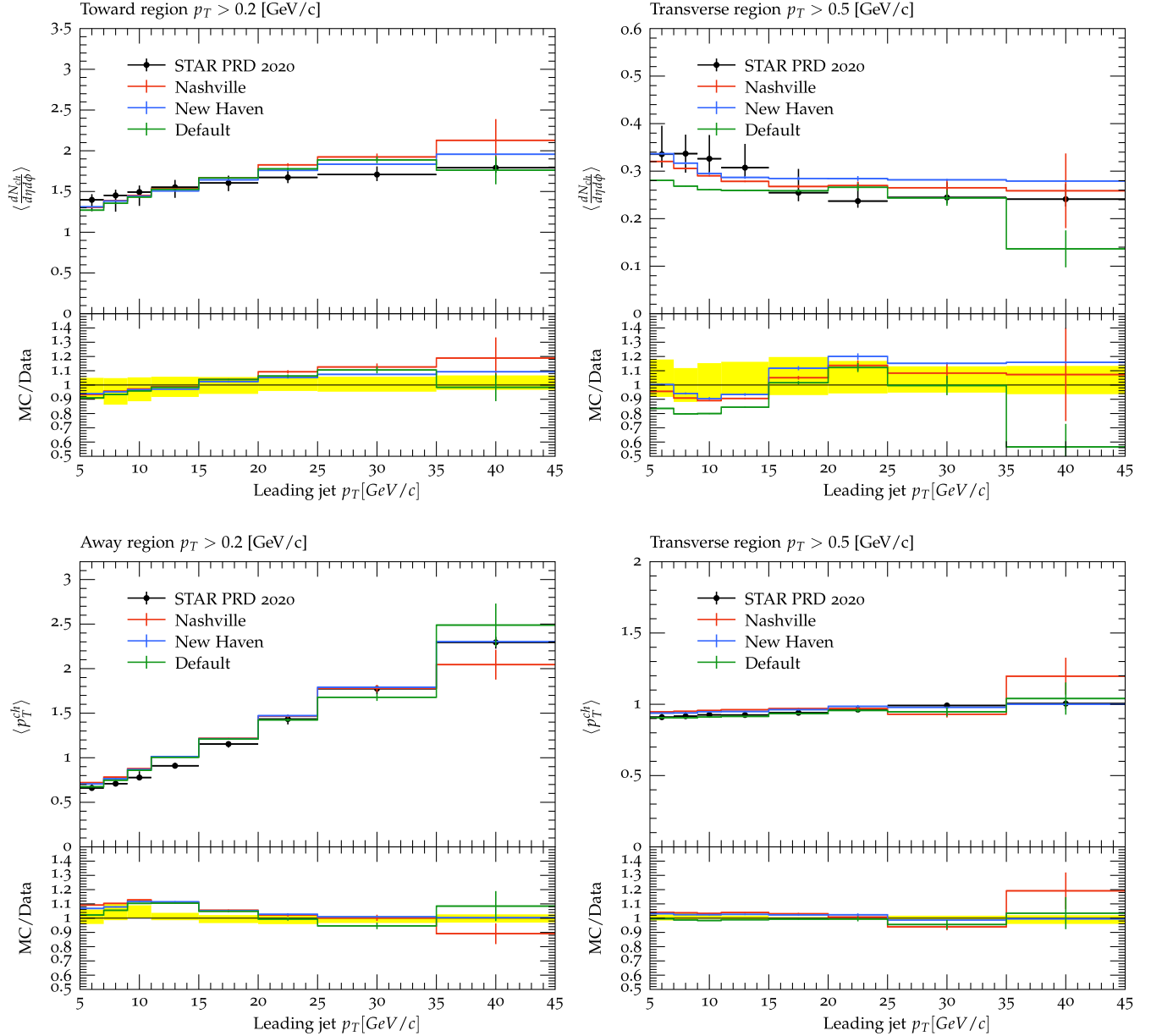


FIG. 4. UE observables as a function of leading jet  $p_T$  from STAR measurements in  $pp$  collisions at  $\sqrt{s} = 200$  GeV. The top left and right show the charge particle density in the toward and transverse regions, respectively. The bottom left and right figures show the average  $p_T$  for the away and transverse regions, respectively. The bottom panels in each plot show the ratio of the Monte Carlo predictions to measured data and the yellow-shaded region indicates the experimental uncertainties.

The parameter  $\mu^2$  increases significantly in Nashville (1.53) compared to the default (1.1), a rise of about 40%, whereas New Haven shows a more modest increase to 1.11, only about 1% higher than the default but 27.5% lower than Nashville. While  $\mu^2$  is described as the (squared) inverse proton radius, it more specifically describes the inverse radius of the cloud of incoming colored particles that may participate in MPI interactions for a given event. The increase in  $\mu^2$  (representing a decrease in the radius of the cloud) seen in both new tunes compared to the default is not surprising, as we expect proportionally greater soft particle production, or, equivalently, less hard particle production through MPI.

The diffractive fraction of the inelastic cross section,  $R_{\text{diff}}$ , is also larger in both Nashville (0.299) and New Haven (0.262) compared to the default (0.187), representing increases of about 60% and 40%, respectively. These results are consistent with the observation that  $\mu^2$  increases in both new tunes: one would expect that having smaller partonic clouds leads to decreased hard particle production and therefore to a greater proportion of particles produced through diffraction for a given UE multiplicity.

Finally,  $N_{\text{ladder}}$ , governing the number of soft particles produced in each ladder, shows a significant reduction in Nashville (0.3966) compared to the default (0.6838),

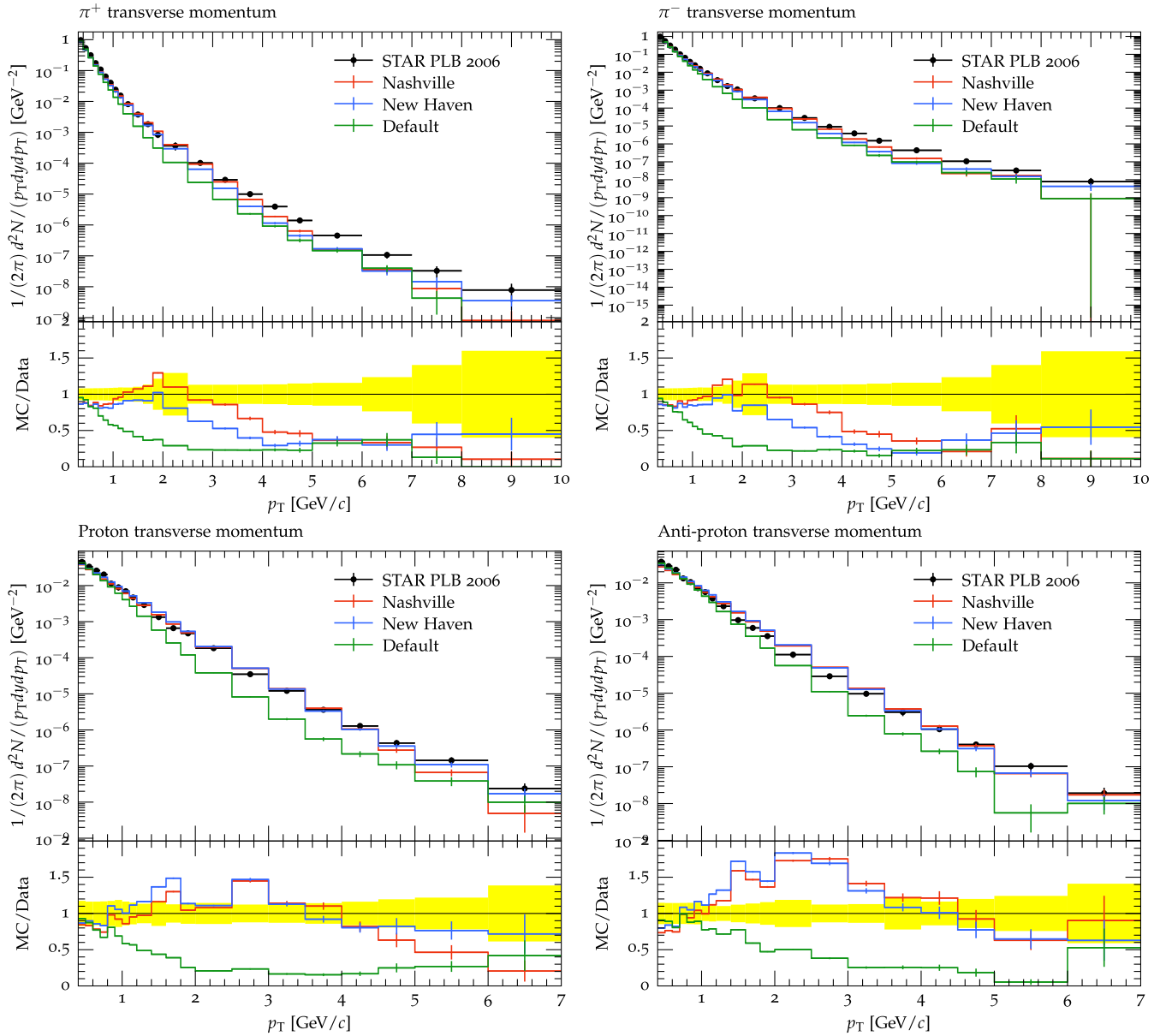


FIG. 5. Invariant yields of  $\pi^+$  (top left),  $\pi^-$  (top right),  $p$  (bottom left) and  $\bar{p}$  (bottom right) as a function of  $p_T$  from STAR measurements in  $pp$  collisions at  $\sqrt{s} = 200$  GeV. The bottom panels in each plot show the ratio of the Monte Carlo predictions to measured data and the yellow-shaded region indicates the experimental uncertainties.

representing a decrease of approximately 42%. In New Haven,  $N_{\text{ladder}}$  rises to 0.569, which is still about 17% lower than the default but 43% higher than Nashville. For the parameter  $p_{\text{reco}}$ , Nashville decreases to 0.720 from the default 0.970, a reduction of about 26%. In New Haven, this value decreases further to 0.522, which is about 46% lower than the default and 28% lower than Nashville. For a given partonic configuration, the decrease in color reconnection probability represents an increase in charged particle multiplicity and therefore a lower average transverse momentum per particle [26]. However, while a greater

proportion of soft particles are produced as compared to the default tune, the reduction in  $N_{\text{ladder}}$  indicates that fewer particles are produced per soft particle ladder.

## V. COMPARISONS WITH DATA

Figure 4 compares the underlying event (UE) observable distributions in the toward, away, and transverse regions. In the top left plot, the distribution of charged particle density as a function of leading jet  $p_T$  in the toward region ( $p_T > 0.2$  GeV/ $c$ ) is shown. All three tunes

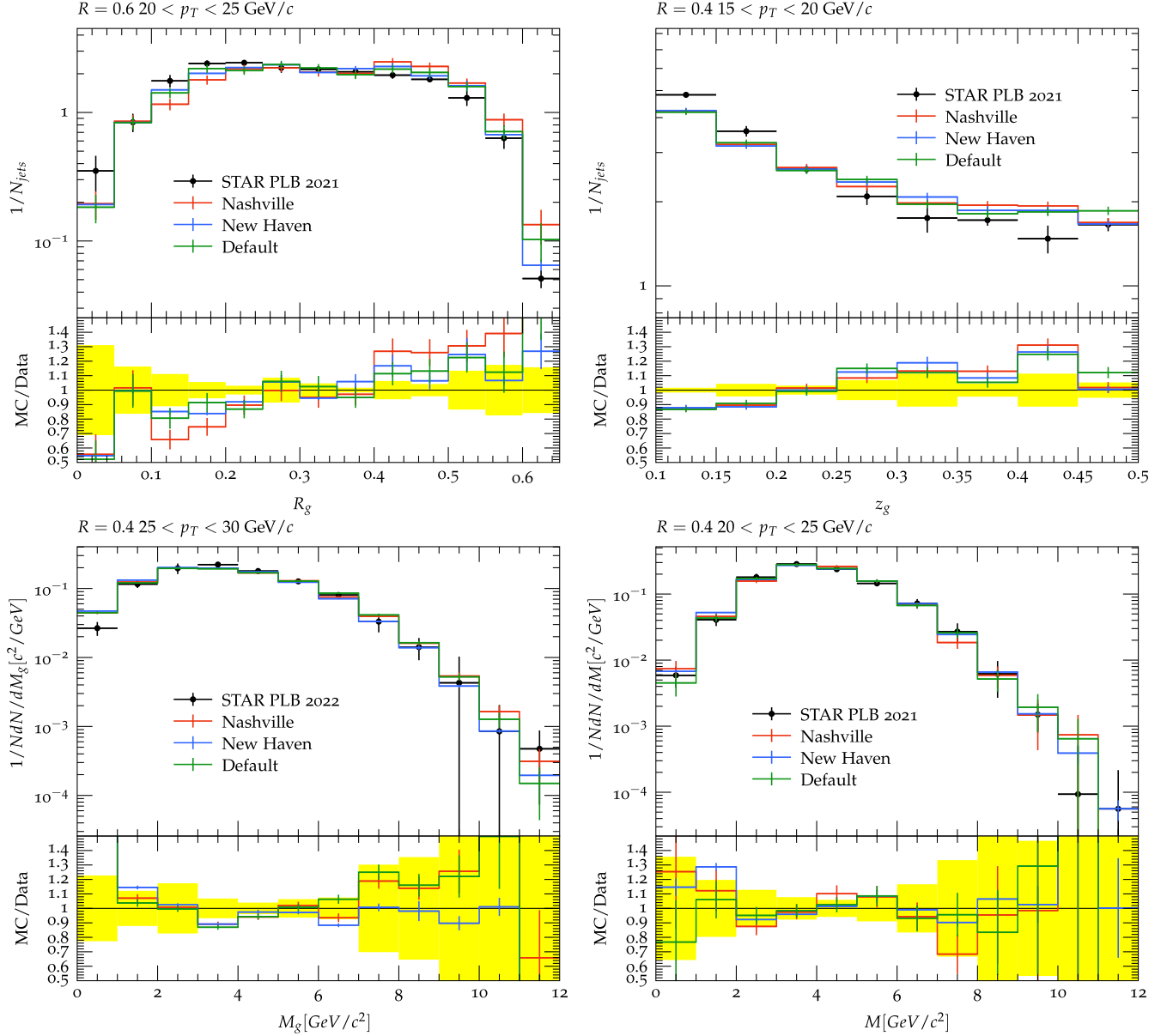


FIG. 6. Distributions of the SoftDrop groomed jet radius  $R_g$  (top left), shared momentum fraction  $z_g$  (top right), and groomed and invariant jet masses  $M_g$  and  $M$  (bottom left and right, respectively) from STAR measurements in  $pp$  collisions at  $\sqrt{s} = 200$  GeV. The bottom panels in each plot show the ratio of the Monte Carlo predictions to measured data and the yellow-shaded region indicates the experimental uncertainties.

follow the data reasonably well across the entire  $p_T$  range. The top right plot shows the same observable but in the transverse region with  $p_T > 0.5$  GeV/c. The Nashville and New Haven tunes provide the best agreement across the  $p_T$  range, with the Nashville tune following the data better. At low and high leading jet  $p_T$ , the default tune deviates from the data, more drastically in the latter region than the former.

In the bottom plots, the average charged particle  $p_T$  distributions as a function of the leading jet  $p_T$  in the

away (left) and transverse (right) regions are shown, with minimum charged particle  $p_T$  cuts of 0.2 and 0.5 GeV/c, respectively. All three tunes demonstrate strong agreement with the data across the full leading jet  $p_T$  ranges, with mild overestimation by all three tunes between 10 and 15 GeV/c in the Away region, and slight under/overprediction by the Nashville tune in the transverse region only for the highest  $p_T$  selection measured, above 35 GeV/c.

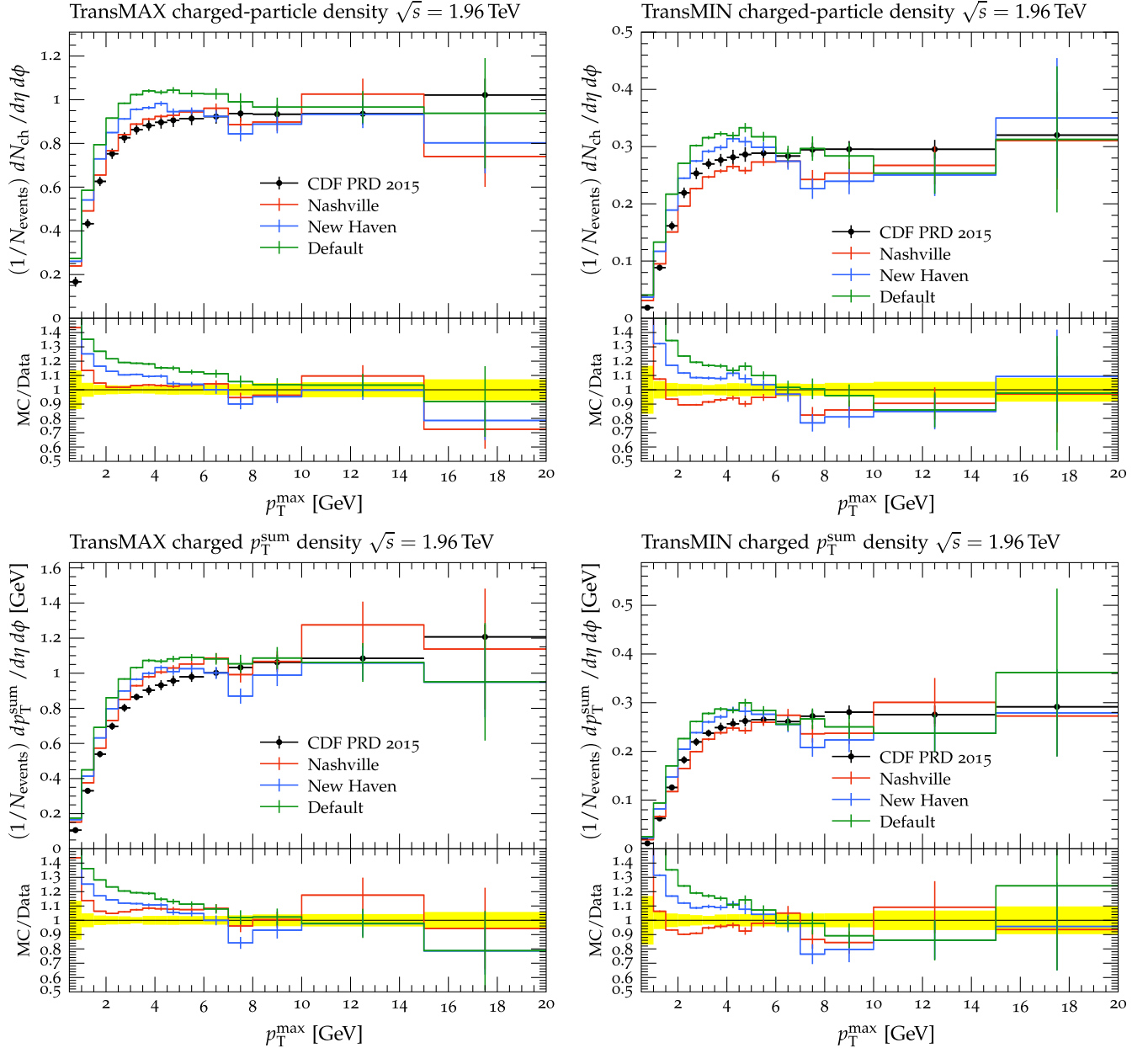


FIG. 7. UE observables as a function of leading hadron  $p_T$  from CDF measurements in proton-antiproton collisions at  $\sqrt{s} = 1.96$  TeV. The top left and right show the charge particle multiplicity in the transMAX and transMIN regions (see text for definitions), respectively. The bottom left and right figures show the charged particle  $p_T$  sum for the transMAX and transMIN regions, respectively. The bottom panels in each plot show the ratio of the Monte Carlo predictions to measured data and the yellow-shaded region indicates the experimental uncertainties.

Figure 5 shows the charged pion, proton, and antiproton transverse momentum spectra at  $\sqrt{s} = 200$  GeV. In the  $\pi^\pm$  distributions (top), the Nashville tune provides the best overall agreement with the data across the entire  $p_T$  range. The New Haven tune also follows the data reasonably well but deviates slightly more than Nashville, especially where  $2 \lesssim p_T \lesssim 6$  GeV/c. At the lowest transverse momentum ( $p_T \lesssim 1$  GeV/c), all three tunes agree with data. Otherwise, tune consistently under-predicts,

showing noticeable discrepancies from the data throughout the  $p_T$  spectrum. At higher  $p_T$  values (above 4 GeV/c), all tunes begin to diverge significantly from the data. In the proton transverse momentum distribution (bottom left), similar trends are observed, though the New Haven tune remains more closely aligned with data even up to the highest  $p_T$  bins. In the antiproton spectrum (bottom right), we see better agreement between the Nashville and New Haven tunes with the data at  $p_T \gtrsim 4$  GeV/c than the

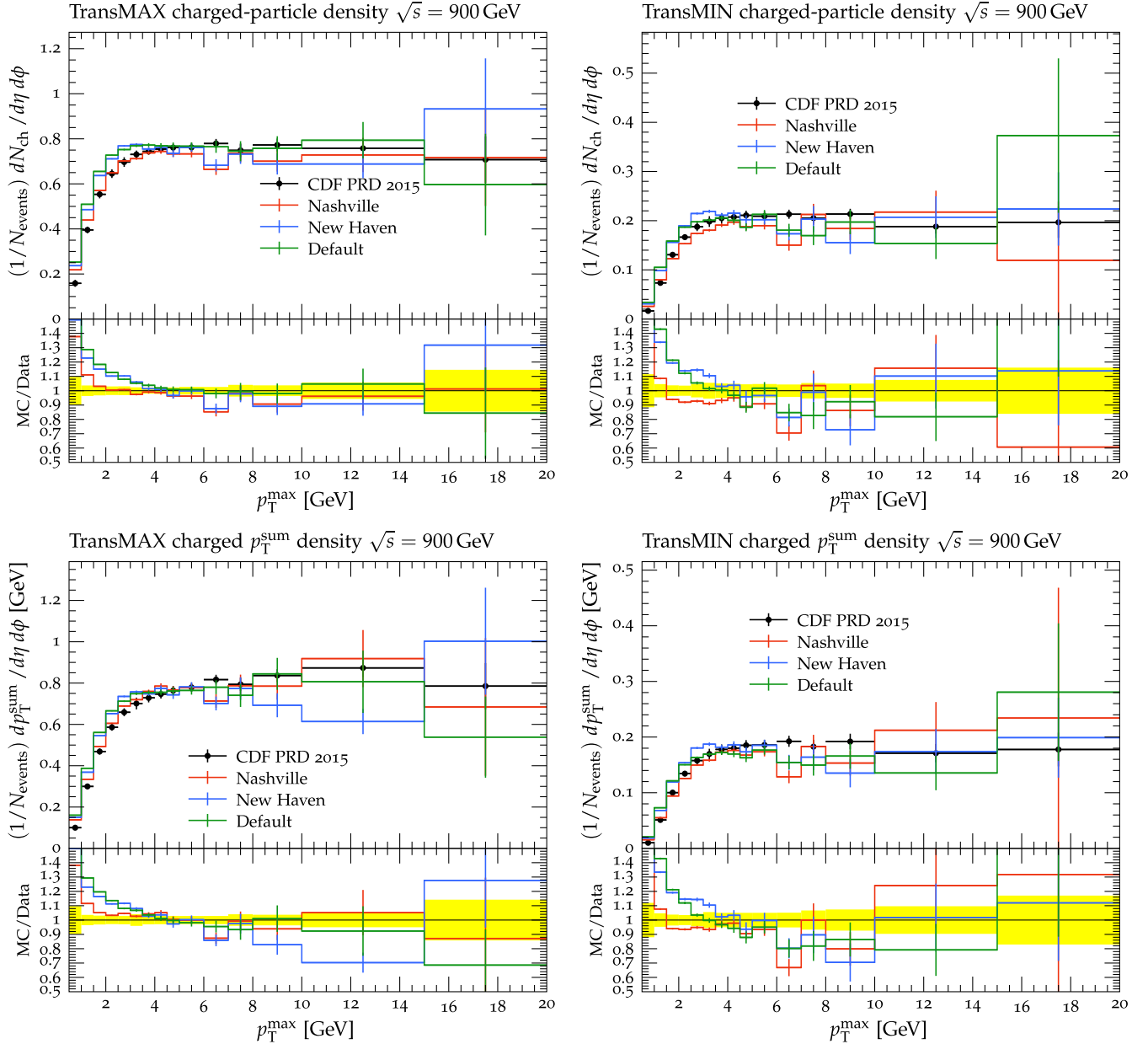


FIG. 8. UE observables as a function of leading hadron  $p_T$  from CDF measurements in proton-antiproton collisions at  $\sqrt{s} = 900$  GeV. The top left and right show the charge particle multiplicity in the transMAX and transMIN regions (see text for definitions), respectively. The bottom left and right figures show the charged particle  $p_T$  sum for the transMAX and transMIN regions, respectively. The bottom panels in each plot show the ratio of the Monte Carlo predictions to measured data and the yellow-shaded region indicates the experimental uncertainties.

default tune. In both the proton and antiproton spectra, the Nashville and New Haven tunes tend to over-predict the data in the region  $1.5 \lesssim p_T \lesssim 3 \text{ GeV}/c$  (more so in the latter spectrum than the former), while the default tune tends to underpredict across most of the  $p_T$  range as in the  $\pi^\pm$  spectra. We defer from diagnosing these differences in the baryon spectra since the hadronization model has a significant effect on their production and this is something not considered for tuning in this study.

Finally, it is interesting to note that the *ratio* of the proton and antiproton spectra produced by the Nashville and New Haven tunes agree reasonably well with the measured ratio across the entire  $p_T$  range considered.

Figure 6 shows the distributions of the SoftDrop groomed jet radius  $R_g$ , shared jet momentum fraction  $z_g$ , groomed jet mass  $M_g$  and invariant jet mass  $M$ , with different requirements on jet  $p_T$  and resolution parameter  $R$  (denoted at the top of each plot). In the groomed radius

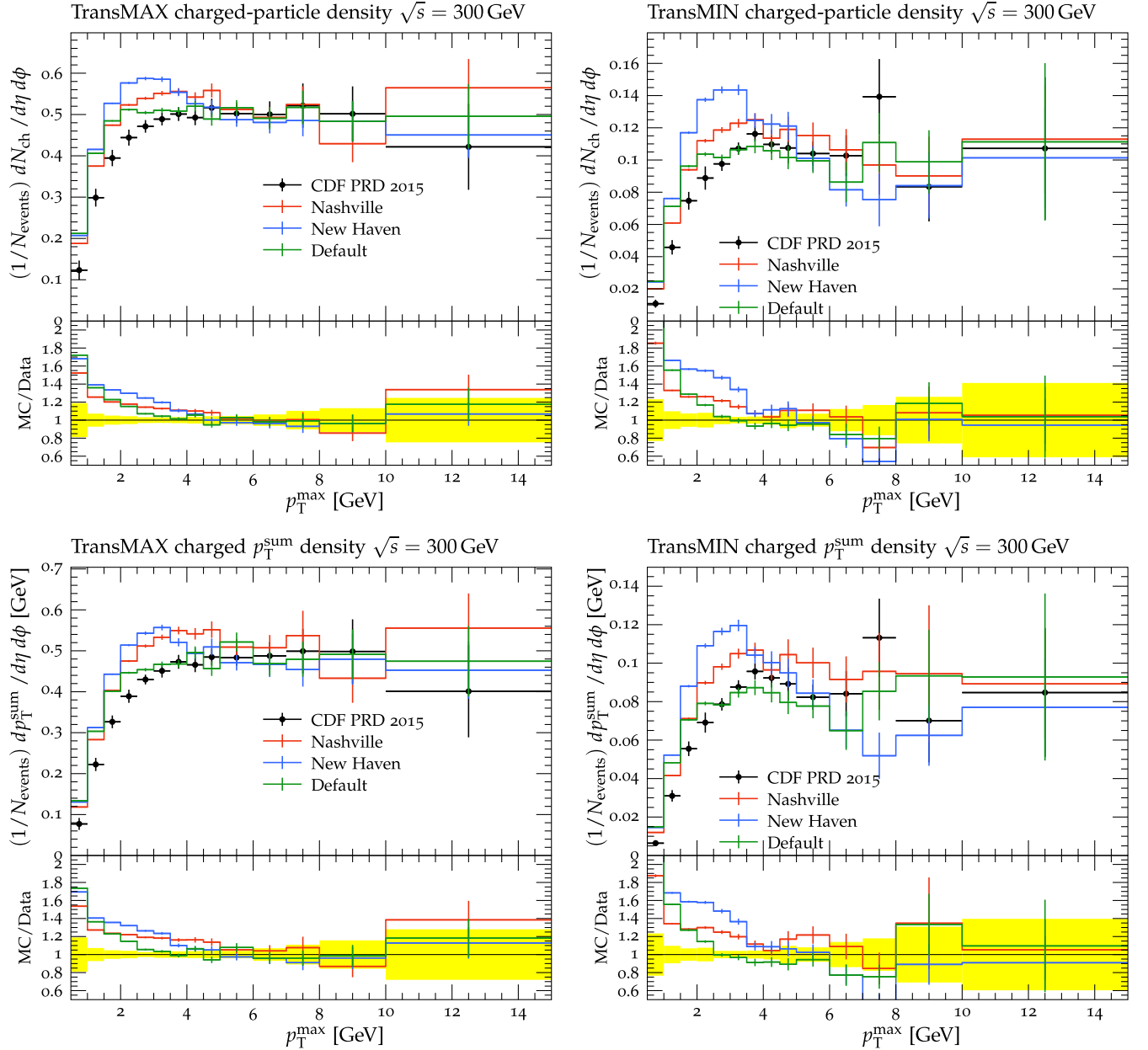


FIG. 9. UE observables as a function of leading hadron  $p_T$  from CDF measurements in proton-antiproton collisions at  $\sqrt{s} = 300 \text{ GeV}$ . The top left and right show the charge particle multiplicity in the transMAX and transMIN regions (see text for definitions), respectively. The bottom left and right figures show the charged particle  $p_T$  sum for the transMAX and transMIN regions, respectively. The bottom panels in each plot show the ratio of the Monte Carlo predictions to measured data and the yellow-shaded region indicates the experimental uncertainties.

distribution (top left), all tunes exhibit similar behavior, tracking the data well. The Nashville tune tends to slightly underestimate the data at lower  $R_g$  and overpredicts at higher  $R_g$ , while New Haven Tune provides the best overall agreement across the full range. In the shared jet momentum fraction distribution (top right), all tunes follow the trend of the data, with some slight underprediction for  $0.1 \lesssim z_g \lesssim 0.2$  and slight overprediction at higher  $z_g$ . In the groomed jet mass distribution (bottom left), all three tunes

agree with the data across the full  $M_g$  range, with the New Haven tune in closest agreement. Finally, in the invariant jet mass distribution (bottom right), all three tunes show agreement with data up to  $M \lesssim 5 \text{ GeV}/c^2$ ; at greater  $M$ , the New Haven tune matches the data, while limitations in statistics prevent us from making conclusions about the performance of the Nashville and default tunes.

Figure 7 shows the underlying event (UE) observables from CDF measurements in  $p\bar{p}$  collisions at  $\sqrt{s}=1.96 \text{ TeV}$ .

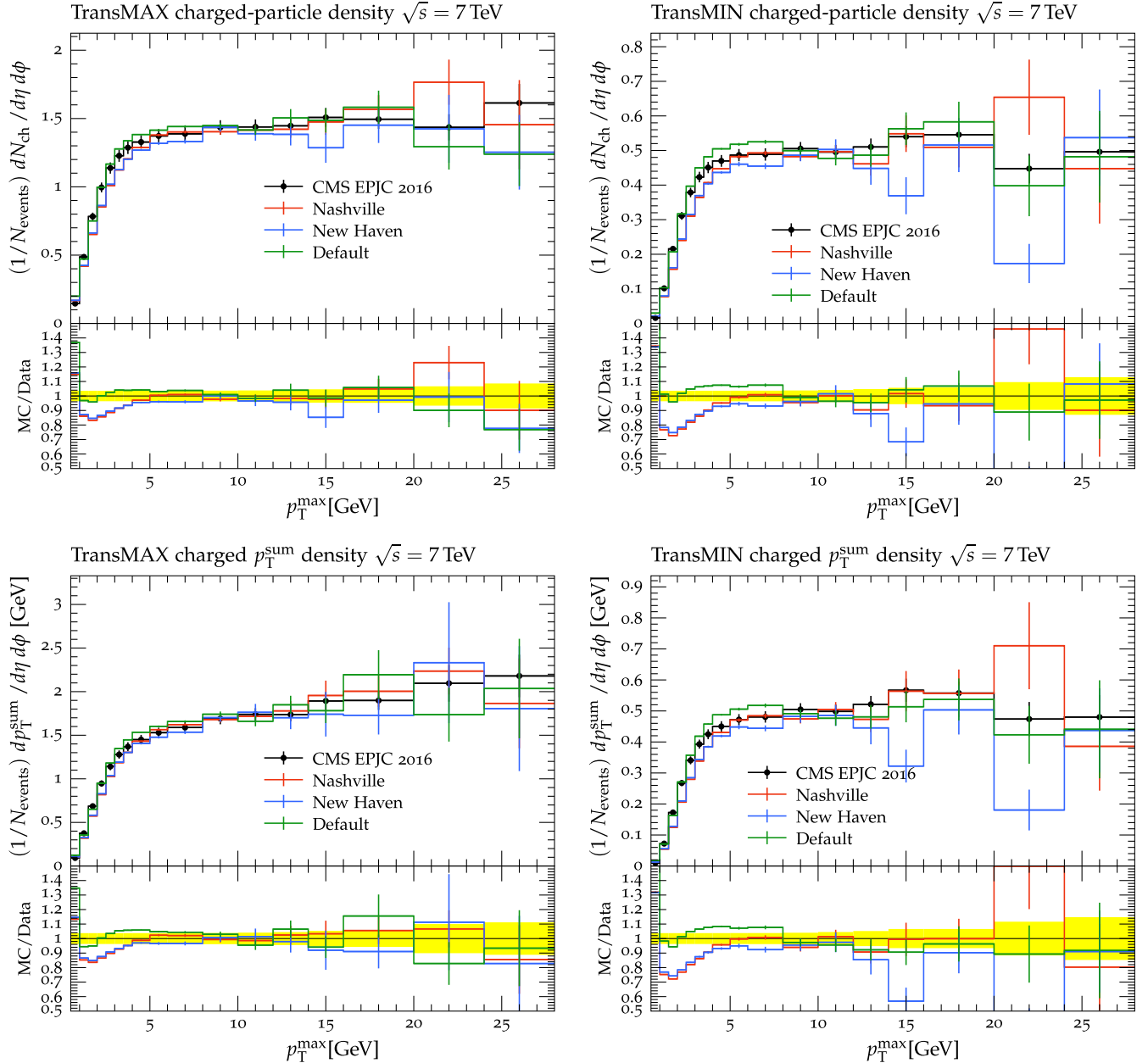


FIG. 10. UE observables as a function of leading hadron  $p_T$  from CMS measurements in  $pp$  collisions at  $\sqrt{s} = 7 \text{ TeV}$ . The top left and right show the charge particle multiplicity in the transMAX and transMIN regions (see text for definitions), respectively. The bottom left and right figures show the charged particle  $p_T$  sum for the transMAX and transMIN regions, respectively. The bottom panels in each plot show the ratio of the Monte Carlo predictions to measured data, and the yellow-shaded region indicates the experimental uncertainties.

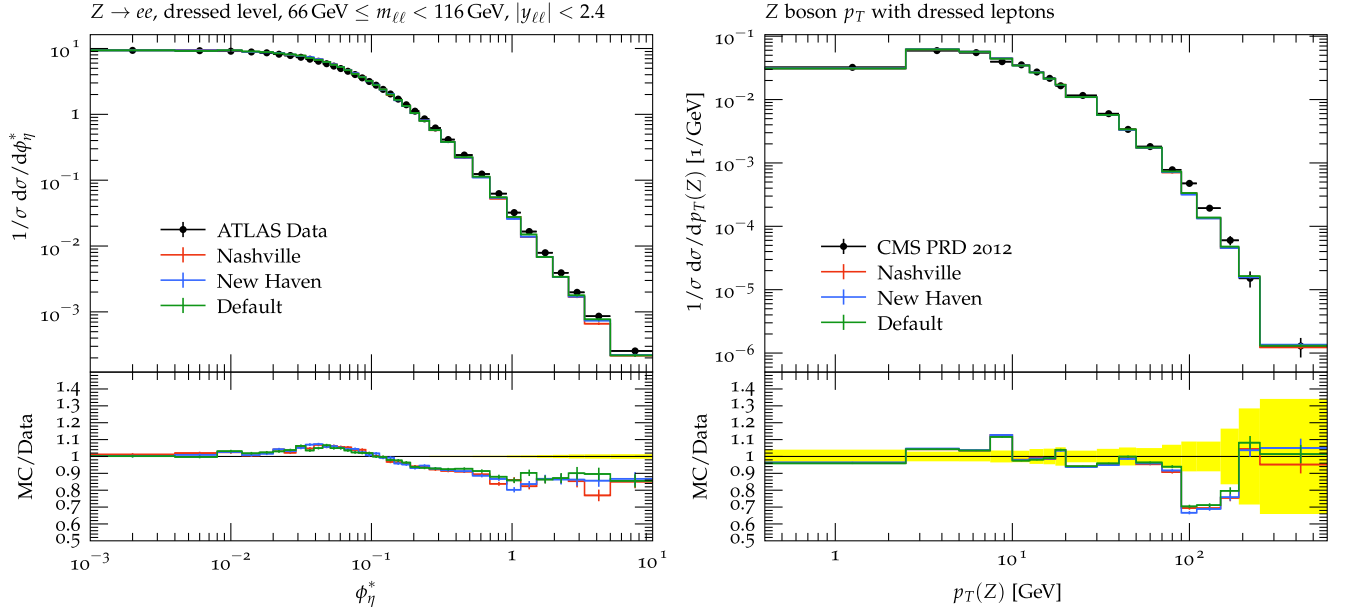


FIG. 11. Dressed-level distributions of the Z-boson  $\phi_\eta^*$  from ATLAS (left) and  $p_T$  from CMS (right) from measurements of Drell-Yan lepton pairs in  $pp$  collisions at  $\sqrt{s} = 8$  TeV and  $\sqrt{s} = 7$  TeV. The bottom panels in each plot show the ratio of the Monte Carlo predictions to measured data, and the yellow-shaded region indicates the experimental uncertainties.

A similar trend is observed in both the TransMAX and TransMIN regions, with respect to both the charged-particle density and charged  $p_T^{\text{sum}}$  density: all three tunes tend to lie within the experimental uncertainty of the data, except at low  $p_T^{\text{max}}$ . In this region ( $p_T^{\text{max}} \lesssim 6$  GeV/c), New Haven and the default tune overpredict the data somewhat, while Nashville shows the closest agreement, only very slightly over-predicting (underpredicting) in the TransMAX (TransMIN) regions. Additionally, there is a slight but significant underprediction from both Nashville and New Haven in the region  $6 \lesssim p_T^{\text{max}} \lesssim 10$  GeV/c in all observables, emphasized in the TransMIN region. Overall, we observe that both the New Haven and Nashville tunes provide a better description of the UE data recorded by CMS at  $\sqrt{s} = 1.96$  TeV than the default tune. Similar trends can be seen in Figs. 8 and 9, which shows UE observables from CDF measurements in  $p\bar{p}$  collisions at  $\sqrt{s} = 900$  and  $\sqrt{s} = 300$  GeV. At  $\sqrt{s} = 900$  GeV (Fig. 8), Nashville maintains the best performance out of the three tunes, with New Haven and the default tune performing similarly, particularly at low  $p_T^{\text{max}}$ . As we decrease the center-of-mass energy further to  $\sqrt{s} = 300$  GeV (Fig. 9), Nashville performs best in the very lowest  $p_T^{\text{max}}$  bins (up to  $\sim 2$  GeV/c), while the default tune performs better in the intermediate region. For  $p_T^{\text{max}} \gtrsim 6$  GeV/c, all three tunes converge and perform similarly well compared to the data.

Moreover, Fig. 10 shows UE observables from CMS measurements in  $pp$  collisions at  $\sqrt{s} = 7$  TeV. In the lowest  $p_T^{\text{max}} \lesssim 3$  GeV/c bins, the default tune demonstrates excellent agreement with the data, outperforming the other tunes. However, this improved agreement in the low- $p_T$

region comes at the expense of overshooting the data at intermediate  $p_T$  values (approximately  $3 \text{ GeV}/c \lesssim p_T^{\text{max}} \lesssim 5 \text{ GeV}/c$ , or up to  $\sim 7 \text{ GeV}/c$  for transMIN). For  $p_T^{\text{max}} \gtrsim 7 \text{ GeV}/c$ , all tunes converge and show good agreement with the data.

Finally, noting that our tunes target the UE and utilize an updated NNPDF3.0 PDF set instead of the default Herwig7 PDFs, we validate that the initial-state parton-shower description remains robust by comparing our tunes against LHC Z-boson production measurements that were not included in the tuning. In particular, we validate our tunes against the Z-boson  $\phi_\eta^*$  distributions from ATLAS measurements of Drell-Yan lepton pairs in  $\sqrt{s} = 8$  TeV  $pp$  collisions [27] and  $p_T$  distributions normalized to the measured cross section from CMS measurements of  $\sqrt{s} = 7$  TeV  $pp$  collisions [28]. We compare our tunes with the Default tune and data as shown in Fig. 11. The tunes remain within uncertainty compared to the Default tune, confirming that they also provide an accurate description of the initial-state parton shower.

## VI. DISCUSSION AND CONCLUSIONS

This study presents new underlying event (UE) tunes for the Herwig7.3 Monte Carlo event generator, specifically developed to improve the description of UE observables at RHIC energies while maintaining strong performance at higher energies, such as those probed by CDF and CMS. The default Herwig7 tune, designed primarily for high-energy data, struggles with predicting particle production at the lower collision energies studied by the RHIC

experiments. This study introduces two new tunes, Nashville and New Haven, that address this limitation by better capturing the dynamics at these lower energies.

The tuning process involved fitting the parameters of the Herwig7 model using the Professor toolkit, utilizing a  $\chi^2$ -based fit to experimental data from STAR, CDF, and CMS. The Nashville tune was developed primarily based on RHIC data but also includes Tevatron and LHC data, resulting improved accuracy across a wide range of collision energies with a trade-off affecting reproducing particle spectra yields at RHIC. The New Haven tune, meanwhile, was tailored exclusively to RHIC conditions, ensuring enhanced performance at  $\sqrt{s} = 200$  GeV.

Results demonstrate that at the nominal RHIC energy of  $\sqrt{s} = 200$  GeV, both new tunes surpass the default Herwig tune. At this center-of-mass energy, the Nashville tune appears to provide the greatest improvement in describing charged particle spectra, while the New Haven tune offers better descriptions of jet substructure observables. Both tunes provide slightly better predictions of charged particle and charged  $p_T$  densities at  $\sqrt{s} = 200$  GeV when compared to the default tune.

At higher center-of-mass energies, the Nashville tune consistently provides the closest alignment with experimental data, especially in the TransMAX and TransMIN regions of charged particle density and  $p_T^{\text{sum}}$  density, across both low and high  $p_T^{\text{max}}$  ranges. The New Haven tune also performs well for these observables (albeit with slight deviations in some regions) given the fact these data were not used during the fitting process for the New Haven tune. It is worth noting that the fact that the New Haven tune's

ability to describe the data slightly worsens as one increases energy from 300 to 900 to 1960 GeV is not unexpected, as the New Haven tune was constructed only using data taken at  $\sqrt{s} = 200$  GeV. At the highest center-of-mass energy considered in our study ( $\sqrt{s} = 7$  TeV), all three tunes offer comparable performance, demonstrating the new tunes' versatility. Future studies that include forward rapidity data will be important for further improving our understanding to the entire dynamics of a pp collision.

## ACKNOWLEDGMENTS

The authors would like to thank Simon Platzer (Uni-Graz) and Stefan Gieseke (KITP) for helpful discussions on the various parameters and implementation within the Herwig UE model. The authors also thank John Lajoie (ORNL) for testing the new tune independently and for helpful feedback on the draft. R. K. E. and U. S. Q. would like to thank the Vanderbilt ACCRE computing facility. R. K. E. would like to acknowledge funding by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under Grant No. DE-SC0024660. HLC, IAM, and LJM thank the Yale Center for Research Computing. HLC and IAM acknowledge funding by the Office of Nuclear Physics of the U.S. Department of Energy under Award No. DE-SC004168 (HLC and IAM) and BNL/DOE-424803 (IAM).

## DATA AVAILABILITY

The data that support the findings of this article are openly available [29].

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