PROCEEDINGS OF SCIENCE

A PYTHIA-8 underlying event tune from RHIC to the LHC

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General purpose Monte Carlo event generators are a vital component of the feedback loop between experimental measurement, where they are used to model detector effects and correct for them, and theory, where comparisons to data can inform further improvements in the models. However, most tuning exercises are performed on LHC or Tevatron data, with the most recent RHIC tune being the single-parameter modification of the PYTHIA-6 Perugia 2012 tune that is typically used in STAR. We present a new underlying event tune – the "Detroit" tune – of PYTHIA-8 suitable for pp collisions at RHIC and LHC energies, and compare to a variety of measurements at midrapidity at RHIC, as well as at the LHC and the Tevatron. We find, in general, that the Detroit tune offers an improvement on the default PYTHIA-8 Monash tune at RHIC energies, and outperforms Monash at large transverse momenta at LHC energies. At forward rapidities, neither tune is adequate to describe pion cross sections from BRAHMS and STAR. This leads to future opportunities to develop a refined parameter set that can describe both regions simultaneously.

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1. Introduction

A proton-proton (pp) collision has many features which must be included in simulations for them to accurately and simultaneously describe a range of observables in various kinematic regimes. Some of these features – typically at low transverse momentum (p_T), or "soft" – cannot be calculated from first principles, and require phenomenological models. The number of parameters related to these processes in so-called general purpose Monte Carlo event generators, which aim to provide a realistic description of pp collisions, is on the order of 100 [1]. Selecting the appropriate parameter values, for which there is often a limited physical intuition *a priori*, is a computationally intensive multi-dimensional optimization. Once the model is "tuned" to data in a given kinematic regime, the parameters may be extrapolated to another kinematic regime using some functional form. However, it is possible to overfit the data used in this procedure, resulting in limited universality of the tuned model. The STAR Collaboration found [2] that the Monte Carlo model PYTHIA-6 [3] with the default Perugia-2012 tune [4] overpredicted low-p_T π yields by up to 30%. This was remedied by reducing the PARP(90) parameter, which controls the energy scaling of the low-p_T regularization, by 11.25% to produce a "RHIC" tune which described a wide range of RHIC data well (see e.g. Ref. [5]).

With the advent of the LHC, PYTHIA-8 [1] (the successor to PYTHIA-6) was tuned mainly on the LHC data. Some constraints on extrapolating to low energies were provided by UA5 $p\bar{p}$ data at $\sqrt{s}$ = 200 GeV in the Monash 2013 tune (the default since PYTHIA-8.200), but no RHIC data were included. PYTHIA-8 with this Monash 2013 tune exhibits significant disagreements with STAR data (see e.g. Refs. [5, 6]). For this reason, a task force within STAR was formed to produce a RHIC tune of PYTHIA-8 using the Monash 2013 tune as a starting point, resulting in the "Detroit" tune [7].

2. Tuning procedure

The set of parameters selected for adjustment were exclusively related to multi-parton interactions (MPI). In PYTHIA, these control the behavior of secondary, softer partonic scatterings, and the rules for reconnecting bare color between nearby MPI. Additionally, the parton distribution function (PDF) set was updated from NNPDF 2.3 [8] to NNPDF 3.1 [9]. The full list of parameters, and the ranges over which they were allowed to vary, can be found in Tab. 1 of Ref. [7]. One parameter to note is "ecmRef" which is the reference center-of-mass energy from which the energy extrapolation is carried out. This energy extrapolation modifies, for instance, the exchanged transverse momentum regularization of the perturbative $2 \to 2$ partonic hard cross section, $\hat{\sigma}$, which is accomplished using the phenomenological $p_{T,0}$ parameter with the form [10]:

$$\hat{\sigma} \propto \frac{1}{p_T^2 + p_{T,0}^2}. \tag{1}$$

This prevents the hard cross section from diverging as $p_T \to 0$ and producing an unphysical number of soft MPI. When the center-of-mass energy is equal to ecmRef, there is no scaling of the regularization of the hard cross section at low p_T:

$$p_{T,0} = p_{T,0}^{\text{ref}} (\sqrt{s}/\sqrt{s}_{\text{ref}})^{\text{ecmPow}}. \tag{2}$$

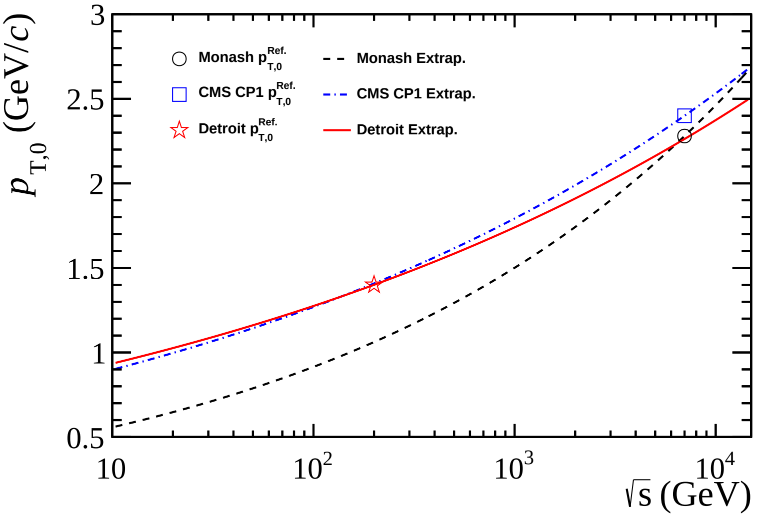

Figure 1: Scaling of the PYTHIA-8 regularization parameter $p_{\mathrm{T},0}$ with center-of-mass energy for the Detroit tune (red solid line), the CMS CP1 tune [11] (dot-dashed blue line), and the Monash tune (dashed black line).

The value of ecmRef in Monash 2013 is 7 TeV, while for this tune, the value is taken to be 200 GeV. Combined with updated values of ecmPow and $p_{\mathrm{T},0}^{ref}$, this results in a difference of roughly 30% of $p_{\mathrm{T},0}$ at nominal RHIC energy, as shown in Fig. 1. This increase in the $p_{\mathrm{T},0}$ parameter relative to Monash 2013 should decrease the contribution from MPI resulting in a smaller underlying event (UE) contribution.

Parameters such as ecmPow were adjusted simultaneously using the Professor-2.3.3 package [12]. In this approach, parameters are sampled randomly within their allowed ranges and the event generator is re-run each time. Histograms for all observables are produced, and the response of the generator to changes in the parameter values is interpolated with a (third-order) N-dimensional polynomial, where N is the number of parameters. The χ^2 of the comparison of data with the parametrized PYTHIA prediction is then minimized to produce an optimal set of parameters. Professor is an improvement over manual tuning (such as the PYTHIA-6 RHIC tune mentioned in Sec. 1) as the latter is difficult to optimize in such a high-dimensional parameter space, among other drawbacks. Professor is also an improvement over brute force tuning. By fitting the response of the generator to variations in tune parameters, a computationally expensive grid sampling approach can be avoided, resulting in a running time determined mostly by the time taken to run the generator for each sampled parameter set.

Comparisons between the Professor PYTHIA-8 runs and the data are facilitated by the Rivet framework [13], which contains analysis libraries and methods. Analyses in Rivet are done on HepMC objects [14] which makes simulation runs agnostic to the generator tune. The STAR analyses included in this tuning procedure which were not originally included in Rivet were added for the first time and can be found at Ref. [15]. The data (all at midrapidity) included in the tuning procedure were, at 200 GeV, STAR $\pi^{\pm}$ cross sections [16], PHENIX Drell-Yan di-muons [17], STAR underlying event multiplicities [5], STAR SoftDrop-groomed [18] jet substructure [6], and STAR jet mass and groomed jet mass [19]; and at energies ranging from 0.3 to 1.96 TeV, CDF

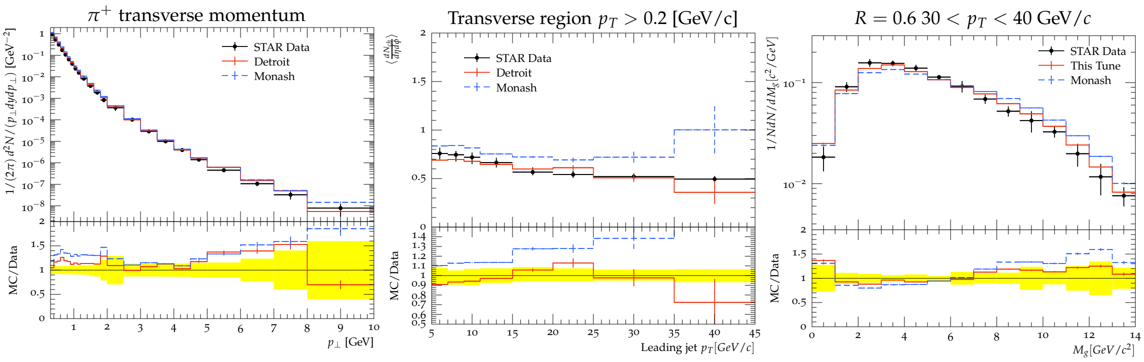

Figure 2: Comparison, for a representative selection of observables (from left to right: π^+ yield as a function of p_T, underlying event multiplicity as a function of the p_T of the leading jet, and SoftDrop-groomed jet mass), between PYTHIA-8 (red line: Detroit tune, blue line: Monash 2013 tune) and STAR data (black markers) at $\sqrt{s} = 200$ GeV.

underlying event multiplicities and average p_T [20]. These data span a broad variety of physical processes including non-perturbative and perturbative QCD physics.

3. Results

The global χ^2/ndf of the final parameter set is $611/493 \approx 1.24$. The resulting Detroit tune exhibits consistently improved agreement with the data compared to the Monash 2013 tune. Figure 2 shows this comparison for a representative selection of observables which were used in the tuning procedure, including π yields, underlying event multiplicity, and jet substructure, all at nominal RHIC energy of 200 GeV. It is interesting to note that even the agreement with jet substructure observables improved when only the MPI parameters and PDF set were changed.

Using the updated scaling of the low-p_T regularization gives an improved description of CDF underlying event data [20] (used in the tuning procedure) at higher energies as well (Fig. 3). The value of $p_{\mathrm{T},0}$ is still much larger in Detroit compared to Monash 2013 at these energies (see Fig. 1). Although no LHC data were included in the tuning procedure, the Detroit tune also offers reasonable predictions of 7 TeV and 13 TeV observables. For example, underlying event observables at 13 TeV are at least as well described by Detroit as Monash 2013 for leading track p_T above roughly 5 GeV/c (Fig. 4).

4. Conclusion and outlook

PYTHIA-8 is an important tool for high energy physics, and it is desirable that it can describe data from varying kinematics, across the entire phase space. The Detroit tune, presented here, improves this universality by describing RHIC and CDF data more accurately than the Monash 2013 tune, and retaining a good description of the LHC data above a certain p_T. This tune should certainly be used for comparison in future RHIC and even LHC publications at midrapidity. However, it was also seen [7] that predictions for forward rapidity STAR [21] and BRAHMS [22] data were inaccurate with the new tune (and to a lesser extent, the Monash 2013 tune). This presents

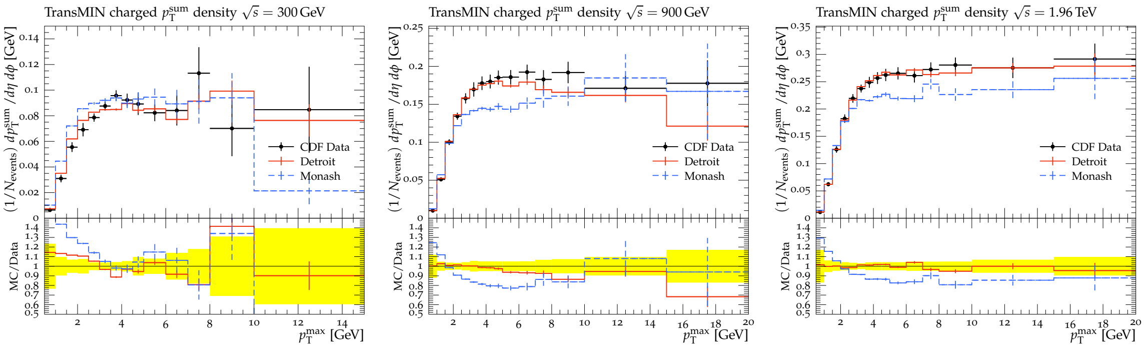

Figure 3: Comparison of an underlying event observable, the scalar p_T^{sum} of charged particles as a function of the highest charged particle p_T in the transverse region with lowest p_T^{sum} (TransMIN), between PYTHIA-8 (red line: Detroit tune, blue line: Monash 2013 tune) and CDF data (black markers) at (from left to right) $\sqrt{s}$ = 0.3, 0.9, 1.96 TeV.

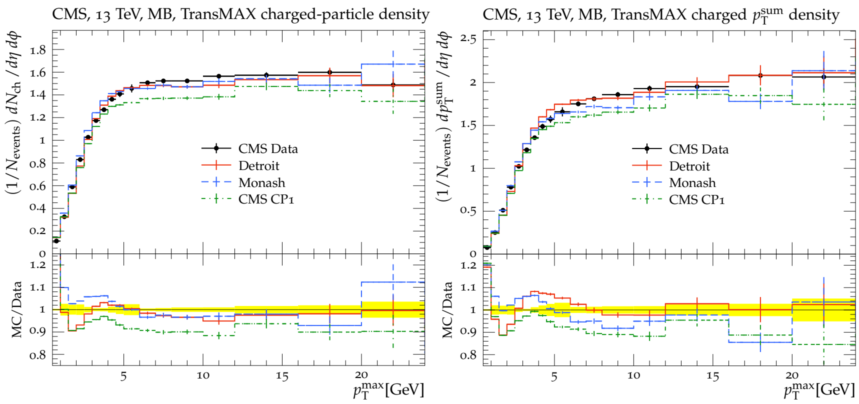

Figure 4: Comparison of an underlying event observable, the scalar p_T^{sum} of charged particles as a function of the highest charged particle p_T in the transverse region with highest p_T^{sum} (TransMAX), between PYTHIA-8 (red line: Detroit tune, blue line: Monash 2013 tune, green dot-dashed line: CMS CP1 tune [11]) and CMS data (black markers) at $\sqrt{s}$ = 13 TeV.

an opportunity for future improvement, which will be necessary when data from the STAR forward upgrade from 2022 is analyzed, and with the EIC on the horizon.

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