Sensitivities to PDFs in parton shower MC generator reweighting and tuning

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Evaluating parton density systematic uncertainties in Monte Carlo event generator predictions has long been achieved by reweighting between the original and systematic PDFs for the initial state configurations of the individual simulated events. This weighting is now preemptively performed in many generators, providing convenient weight factors for PDF and scale systematics – including for NLO calculations where counterterms make the weight calculation complex. This note attempts a pedagogical discussion and empirical study of the consequences of neglecting the effects of PDF variations on the beyond-fixed-order components of MC models, and the implications for parton shower & MPI tuning strategies. We confirm that the effects are usually small, for well-understood reasons, and discuss the connected issue of consistent treatment of the strong coupling between PDFs and parton showers, where motivations from physical principles and the need for good data-description are not always well-aligned.

Introduction

Parton shower Monte Carlo (MC) event generators are a key tool for modelling of collider events beyond fixed perturbative order, and in particular for producing simulated fully exclusive events which closely resemble those found in real-world collider experiments. The leading shower MCs include non-perturbative effects and complex phase-space effects not available to, for example, analytic resummation calculations.

The price of such realism is the addition of free parameters which must be tuned to data, an expensive process in both computational and manpower terms. A cottage industry between shower MC developers and collider experiments has grown up around this problem [1], and several generations of tunes, particularly for the PYTHIA shower MC family, have evolved from the LEP and Tevatron eras up to the present point early into the second run of the Large Hadron Collider (LHC) [2, 3].

The last ten years of developments in shower MC technology have led to fully exclusive event generation in which the parton shower (PS), and usually also non-perturbative modelling
aspects such as hadronization and multiple partonic interactions (MPI), are smoothly matched to matrix element (ME) calculations significantly improved over the leading-order Born level. These include both “multi-leg LO”, exemplified by the Alpgen [4], MadGraph [5], and Sherpa 1 [6] codes, the “single-emission NLO” codes such as POWHEG [7] and (a)MC@NLO [8, 9], and the latest generation in which both modes are combined into shower-matched multi-leg NLO: Sherpa 2 and MadGraph5-aMC@NLO [10].

This computational frontier does not come without downsides: the integration and efficient sampling of many-leg phase space is slow, as is the computation, integration and subtraction of the matrix element terms required for finite NLO calculations. The major benefit of NLO calculations in particular is the expected robustness of total cross-sections and many differential quantities, to be explicitly confirmed by constructing envelopes for variation of renormalization & factorization scales, and parton density functions (PDFs) in the calculations. The high CPU cost of the state-of-the-art calculations means that explicit consistent re-running of the shower-matched simulation for all PDF and scale variations is unfeasible: instead, internal construction of pre-shower event weights for each systematic variation has become the standard approach.\footnote{Construction of PDF reweighting factors is more complicated at NLO, due to the need for subtraction counter-terms with different initiating parton flavours and kinematics. The weight computation is hence done inside the NLO matching generator rather than by post hoc construction of single PDF ratios as for LO events.}

While computationally necessary, this approach neglects the effect of these systematic variations on the tuned components of the simulation; in particular the parton shower (which naively should be configured consistently with the PDF and scale choices of the matrix element) and the MPI model (which is not connected to the hard scattering by perturbative QCD, but does display significant PDF dependence).

The same issues apply to shower MC tuning, for LO as well as NLO simulations: strictly a different tune should be constructed and used for each matrix element PDF and scale variation, but again this is computationally impractical and a single shower MC tune tends to be used for all matrix element variations.

Evaluating the rationale and empirical support for this factorized approach, with particular respect to PDF variations, is the topic of this brief note. This is neither novel ground nor particularly surprising, but since a review of available literature finds surprisingly little material on the topic it is hoped that this survey makes a useful contribution.

1 PDF dependence of parton showers

We will spend most of this study considering the effect of PDF variations on initial-state parton shower algorithms, producing initial-state radiation (ISR). The typical ISR algorithm evolves backwards from the hard process’ incoming legs towards the initial state hadrons, and produces only a few splittings per event as contrasted with the hundreds of branchings in the typical...
final-state radiation (FSR) simulation. These few branchings, however, are usually high-energy compared to the FSR splittings which produce internal structure, and they are the dominant mechanism by which the collinear parton shower formalism can produce additional isolated jets – albeit at a rate usually less than in data and in dedicated higher-order matrix element calculations.

As the matrix element calculation includes PDF factors in its partonic hard process amplitudes, QCD evolution of the initiating parton legs must correct those PDF factors for the changes in initial parton flavour and Björken momentum fraction produced by the sequential ISR branchings, as well as the usual strong coupling and splitting function terms of a FSR shower splitting. The ISR Sudakov form factor (the probability of no QCD splitting in evolution of a parton between scales $q$ and $Q$ is hence

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\Delta_{ISR}^b(q^2, Q^2; x) \sim \exp \left\{ -\sum_b \int_{q^2}^{Q^2} \frac{d\tilde{q}^2}{\tilde{q}^2} \int_{q_0^2/q^2}^{1-q_0^2/q^2} dz \frac{\alpha_S(\tilde{q}^2)}{2\pi} \frac{x' f_b(x', \tilde{q}^2)}{x f_a(x, \tilde{q}^2)} P_{ba}(z, \tilde{q}^2) \right\}
$$

for shower cutoff scale $q_0 \sim 1$ GeV, splitting function $P_{ba}$ going (backwards) from initial parton flavour $a$ to $b$, and the PDF $x f_i$ terms as indicated for $x$ and $x' = x/z$ momentum fractions on the original and new initial splittings respectively.

The key feature of eq. (1) from our perspective is that the PDFs enter the (non-)splitting probability in a ratio between the same PDF at two momentum fractions $x$ and $x' = x/z$. Hence a change in hard process PDF which is unmatched by the same change to the ISR PDF will introduce deviations proportional to the double ratio of the two different PDFs between the two $x$s. As we shall demonstrate empirically, this double ratio is a more stable quantity than the bare ratio of two PDFs and hence the effects are not as large as a pure change of PDFs in the hard process matrix element. Of course, the PDF effect on a single Sudakov is not the effect on the whole event, since the splitting is iterated, but the fact that ISR evolution typically only introduces one or two initial-state splittings per incoming parton means that this effect is not large – and by construction it is limited to the production rates and kinematics of subleading jets not modelled by the hard process.

The effect of PDF systematics and $\alpha_S$ variations on ISR Sudakov factors was studied a decade ago [11], concluding that the effects of PDF uncertainties are small compared to other sources of uncertainty, except in certain isolated high- and low-$x$ regions where PDFs are unconstrained and their uncertainties inflate. In the sections that follow, we shall reprise the spirit of that study with new PDF fits, and focus on the PDF (double) ratios entering the Sudakov terms.
1.1 PDFs between shower splittings

In Figure 1 we show the distribution of $x$ ratios between initial state shower splittings in Pythia 8 dijet simulation. It can be seen that these take the form of a power law, with most splittings close together. To achieve a balance between the close-together splittings at the low-scale end of the spectrum and the larger gaps between hard emissions, and to avoid a proliferation of similar plots, in this section we will use an $x$ ratio of $1/2$ (equivalent to 2 according to the definition in Figure 1). Ratio constructions with a factor of 10 produced very similar results, which are hence elided in the interests of brevity.

First, we look at the differences between the latest leading order (LO) and next-to-leading order (NLO) PDFs from the three major global fit collaborations: CTEQ [12], MMHT [13] (the latest incarnation of the MRST / MSTW group), and NNPDF [14, 15]. These are shown in Figures 2 and 3 for gluon PDFs $x f_g$ and the sum of light (anti)quark PDFs $\sum_{i \in \text{light}} x f_i$ as functions of $x$ at several scales from the semi-soft to the very hard. These plots were made using the LHAPDF 6 parton density library [16].

We see that the overall scale of deviations between PDF fits are relatively small – on these logarithmic scales they are only really visible at very low values of $x$, where the MMHT PDFs in particular tend to have higher sea contributions for both quarks and gluons, and for the high-$x$.

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2Adding light quark PDFs together for presentation as a single line is implicitly a probabilistic interpretation, and hence not strictly valid beyond LO. However, it is useful here since negative PDF values only appear in restricted regions of phase space, and because a LO interpretation is precisely how they are used in parton shower splitting and MPI models.
Figure 2: Comparing gluon PDFs from CTEQ, MMHT, and NNPDF at LO (left) and NLO (right).

Figure 3: Comparing summed light quark PDFs from CTEQ, MMHT, and NNPDF at LO (left) and NLO (right).

The gluon where the CTEQ PDFs in particular tend to be at odds with the other two families at both LO and NLO.

We now look at the ratios of each of these PDFs between different emission scales, i.e. the PDF ratio term with different $x$ values on numerator and denominator which appears in eq. (1). We define this ratio for parton flavour $i$ in PDF $p$ as

$$R_i^{(p)}(x, \tilde{q}, z) = x/z f_i(x/z, \tilde{q}) / x f_i(x, \tilde{q}).$$

In Figure 2, we show this ratio as a function of scale $\tilde{q}$ for the CTEQ and MMHT PDFs which mostly defined the envelope of PDFs in Figures 2 and 3, for a fixed splitting fraction $z = 1/2$ – this nominal $z$ value is taken for illustration, since a full integration over splitting phase space...
Figure 4: Comparing gluon (left) and light quark (right) PDF ratios between CTEQ/MMHT and LO/NLO, with splitting fraction $z = 1/2$.

and splitting functions is best done in an MC shower generator itself and we shall do just that in Section 2.

These ratios are clearly quite large, ranging from $\sim 20\%$ deviation from unity at low values of $x$ and $\tilde{q}$, to 75% and 35% deviations at high $x$ and $\tilde{q}$ for gluons and light quarks respectively. The Sudakov dependence is stronger in $x$ than in $\tilde{q}$, as expected from Figures 2 and 3: QCD scale evolution of PDFs is logarithmic, while the $x$ dependence of the PDFs is quite strong, and becomes more so for the gluon PDF at high-$x$. The potentially large size of these ratios is not a problem but rather the driver of ISR emission physics; in the next section we look at the double ratios which reflect the magnitude of neglected shower effects when reweighting or changing a hard process PDF without a change of parton shower configuration.

### 1.2 PDF double ratios

In Figures 5 and 6 we finally see the ratios of Sudakov form factor PDF terms which correspond to the effect of switching the parton shower PDF without changes in shower cutoff (or $\alpha_S$, which can be modified both by use of the $\alpha_S$ evolution for that PDF, and by tuning fudge factors [17] and QCD-derived scalings [18]). These are again shown for our ad hoc fixed splitting fraction $z = 1/2$, and between the CTEQ and MMHT latest LO and NLO fits.

Figure 5 shows the double ratios obtained by reweighting / switching between the CTEQ and MMHT families. These are typically constrained to within 5% of unity, and better than that for most of the range. A mild exception is seen for reweighting between the NLO PDFs at low $x$ and $\tilde{q}$, where such PDFs are little constrained; and a very large anomalous deviation of up to 20% for high-$x$ LO PDFs, particularly at low scales. It is expected that these high-$x$ effects will be dealt with in the hard process rather than the parton shower, and also will use NLO rather than LO.
Figure 5: Comparing gluon (left) and light quark (right) PDF double ratios between CTEQ/MMHT, with splitting fraction $z = 1/2$.

Figure 6: Comparing gluon (left) and light quark (right) PDF double ratios between LO/NLO, with splitting fraction $z = 1/2$. 
PDFs when matrix elements are available, but the potential effect is worth noting.

Typically shower algorithms, being based on leading order splitting functions, use leading order PDFs. However, in the case of matching showers to NLO matrix elements there is a school of opinion that the shower should match the matrix element in PDF choice to avoid discontinuities across the ME/PS hand-over. An argument has also been made for using NLO PDFs in leading-order multi-leg matrix elements on the basis that multi-leg MEs include ISR evolution effects which would be absorbed into the fitting of an LO PDF, and this has similarly been used to argue that LO matching would require use of NLO shower PDFs. We may ask whether it is “allowed” to reweight between LO and NLO PDFs, and this is addressed in Figure 6: larger effects up to \( \pm 10\% \) are seen in LO/NLO gluon PDF reweighting of a \( z = 1/2 \) Sudakov than in LO or NLO reweighting between PDF families, but the light quarks are still within a few percent of unity.

In most typical use-cases the effect of either neglecting shower PDF effects in reweighting, or of using the same shower tune with different PDFs, is hence expected to be on the order of 5–10\%, comparable to the typical systematic uncertainty of shower algorithms (typically evaluated by variation of parton shower starting scales and \( \alpha_S \) evolution). This justifies the usual approach of neglecting explicit shower PDF effects, effectively absorbing them into shower systematics instead, since the effort required for an explicit evaluation would be disproportionate to the improvement in predictivity or uncertainty coverage.

## 2 PDF effects on parton showered observables

In this section we study the real-world effect of PDF changes in the Pythia 8 shower MC generator [17], for two important processes: inclusive jet production, and \( W+\text{jet} \) production in the Run 2 LHC \( pp \) configuration with \( \sqrt{s} = 13 \) TeV.

Pythia 8 allows separate PDFs to be used for the hard (matrix element) and soft (parton showers & MPI) components of the event simulation, so to compare the effects of PDF changes in the soft modelling we use the default Monash 2013 \( pp \) tune [2] and fix the hard process PDF to NNPDF2.3 LO [14], then change the soft PDF to the CTEQ6L1 [19] and MMHT2014 LO [13] leading order fits, as well as the NNPDF 3.0 NLO [15], CT10 NLO [12] and MMHT2014 NLO [13] next-to-leading-order central PDFs. While use of NLO PDFs in soft simulation is discouraged by MC experts [20], it is not unknown and we believe that an empirical demonstration of the effects is useful.

2 million events were generated for each configuration, and were analysed using the Rivet [21] MC\_JETS and MC\_WJETS validation analyses, with jets defined by an anti-\( k_T \) algorithm with \( R = 0.4 \) and \( p_T > 20 \) GeV. The results are shown in Figures 7-9 for the inclusive jets process, and Figures 10 and 11 for the inclusive \( W+\text{jet} \) process. The LO and NLO soft modelling PDF choices
are respectively rendered as solid lines with blue/green colouring, and as dashed lines with red/orange colouring to allow easy identification of the natural PDF groupings.

These figures show several expected effects. First, the effects of switching between leading order shower and MPI PDFs are small, on the roughly expected scale of a few percent and less than 10% in all statistically well-populated regions of the plots. The use of NLO PDFs in shower & MPI modelling produces large differences with respect to the LO baseline setup, with variations of up to 20% in many observables, and rarely less than 10%.

Secondly, the kinematics of objects such as the leading two jets in inclusive jet production (which are dominated by the matrix element partons) are in fact fairly stable even when NLO PDFs are used for showering, but extra jets in both processes (dominated by initial state shower emissions) are more strongly affected. The jet multiplicities are similarly strongly affected – particularly for the NLO shower PDFs at high multiplicities.

Further effects are seen when NLO PDFs are used for soft QCD simulation, notably the strong reduction of multi-jet rates and the 20% difference in jet masses below \( \sim 30 \text{ GeV} \). These motivate further discussion of \( \alpha_S \) treatment and multi-parton interactions modelling, and are considered in the next section.

Broadly, these empirical data support several conventional rules of thumb:

- the effects of the particular leading-order parton shower PDF choice (without shower retuning) are limited to a few percent when considering perturbative QCD objects in the bulk of phase space;

- reversing this observation, providing specific retunes of parton showers for different LO matrix element PDFs can only provide benefits of at most a few percent in some phase space regions;

- we cannot directly conclude from this data about shower-PDF sensitivity in event simulation with NLO matrix elements, but as it is well-known that LO Pythia 8 configurations can perform well in connection with NLO hard process events from POWHEG-BOX [22] or aMC@NLO [9], the potential performance gain is again expected to be on the few-percent scale.

### 2.1 \( \alpha_S \) (in)consistency

So far we have only considered the effect of changing parton density values, without regard for the strong coupling \( \alpha_S \), whose boundary conditions and evolution are linked to the PDF evolution.
Figure 7: PYTHIA 8 jet $\eta$ distributions.
Figure 8: PYTHIA 8 jet $p_T$ distributions.
Figure 9: PYTHIA 8 jet mass and N_{jet} distributions.
Figure 10: PYTHIA 8 $W + \text{jet}$ $\eta$, $\Delta R$ and $p_T$ distributions.
Figure 11: PYTHIA 8 $W +$ jet jet mass, $H_T$ and $N_{jet}$ distributions.
2.1.1 PDF $\alpha_S$ ratios

Ratios of $\alpha_S$ between PDF families and LO/NLO are shown in Figure 12 for a wide range of $\tilde{q}$ scales from $10$–$1000$ GeV. Unsurprisingly, the biggest differences (up to 15%) are between LO and NLO PDFs’ $\alpha_S$ values; and similarly unsurprisingly the second biggest differences are between the two LO sets. The differences between NLO PDF $\alpha_S$ values are a relatively flat $\sim 2\%$ across the scale range. For many purposes this means that reweighting NLO MC samples between two NLO PDFs with not-exactly-matching PDF couplings will induce acceptably small deviations from a full resimulation. Between LO samples the $\alpha_S$ values may vary more significantly, and whether ignoring this effect is acceptable depends on both the PDFs and generators involved. LO SHERPA, HERWIG++, MADGRAPH and ALPGEN all do use the PDF $\alpha_S$ in their matrix element evaluation, but Pythia 8 does not (the fixed ME default is $\alpha_S(M_Z) = 0.130$, the same as most LO PDFs) and hence there may be no effect at all due to an $\alpha_S$ mismatch in reweighting. Reweighting, and indeed any attempt at naive exchange, between LO and NLO PDFs is very strongly discouraged!

2.1.2 $\alpha_S$ effects in lowest-order simulation

Unlike its predecessor, version 8 of the Pythia parton shower generator does not automatically change the $\alpha_S$ values in its parton showers (or the matrix element, cf. above) to match that of the PDF used in initial-state showering; instead the user is left free to choose whichever $\alpha_S(M_Z)$ values (and evolution orders) they like for not only the ISR and FSR showers independently,

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3LHAPDF 6 warns by default if reweighting is attempted between PDFs whose $\alpha_S(Q)$ differ by more than 2%.

4Although use different tunes for the two PDFs may well change the ME $\alpha_S$ parameter – *caveat emptor.*
but also the MPI matrix element and hadronization. The Herwig++ generator offers similar freedom, and of the three most commonly used shower generators, only Sherpa enforces full $\alpha_S$ consistency.

This freedom to use different $\alpha_S$ values in different parts of MC simulations gives MC tuning studies extra degrees of freedom to best describe observables (such as jet shapes) which should fall within the range of validity of the parton shower approach. The validity of this flexibility is argued from the limited (leading logarithmic) predictivity of current parton shower algorithms, which is most important for lowest-order simulation such as the Pythia 8 built-in hard processes. The use of this approach in MC tuning has motivated the approach taken here, where we have considered purely the effect of the PDF itself and not the associated QCD parameters.

This is perhaps surprising, since naively the parton shower $\alpha_S$ configuration must match that of the hard process PDF and matrix element, to avoid inconsistency. Unlike PDF values themselves, there is no “double ratio protection” for $\alpha_S$ mismatches in parton shower evolution. But for “Born-level” leading-order simulation this inconsistency can again be absorbed into the leading-log uncertainty of the shower formalism, allowing the mismatch to be countered by other tunable shower parameters such as flexibility in evolution start & cutoff scales: historically this is exactly what has been done to achieve acceptable data description.

In Figures 9 and 11 the 20% lower rate of multijet production with NLO shower PDFs seems consistent with the significantly lower $\alpha_S(M_Z)$ used in those PDFs, until one realises that this is a purely PDF effect and that re-achieving good data description through shower tuning with an NLO shower PDF would require use of extremely high shower $\alpha_S$ values – into a debatably unphysical regime with even larger ME/shower $\alpha_S$ mismatches than already gave concern.

It is also worth noting that the large values of $\alpha_S(M_Z) \sim 0.13–0.14$ often resulting from parton shower tuning are not badly inconsistent with the $\alpha_S$ values used in leading-order PDFs – one of many arguments in favour of using LO PDFs for LO matrix elements, at least at lowest order if not for multi-leg hard processes.

2.1.3 Beyond Born-level

The rise of more complete QCD calculations has cast a spanner into this machinery, however. In NLO and multi-leg LO ME/PS matching, it is key that parton emissions from shower or matrix element can be considered as interchangable, with the additional (beyond Born) partons from the matrix element being neatly assimilated into the shower evolution as improved splitting functions. An inconsistency in ME and shower coupling breaks this equivalence to some degree, leading to perverse effects such as the increased/reduced hardness of ALPGEN events when the shower $\alpha_S$ is respectively reduced/increased [23]. While this is not directly a PDF effect in the parton shower, the strict requirement of PDF/ME consistency in $\alpha_S$ and the matching requirement of interchangable shower and ME partons.
In practice this effect is often tolerable for LO matched simulations – especially when traded against the pragmatic gains from tuning the LL shower model to data – due to the similarity of $\alpha_S$ values in LO PDFs and in tuned shower configurations. But it should be far less ignorable if either NLO PDFs are used for the LO multi-leg ME calculation or for NLO matched configurations (obviously also using NLO PDFs), since the NLO $\alpha_S \sim 0.118$ value is much smaller than the "natural" value in the parton shower. It is surprising, then, that in general matched NLO simulation tunes have not paid great attention to this issue – however, unambiguous NLO matching configurations have yet to be established for POWHEG-BOX [22] or aMC@NLO [9], the NLO matched generators (unlike Sherpa) for which the parton shower configuration is not fully constrained, and hence for now we may be conflating $\alpha_S$ consistency issues into that larger issue of configurational optimisation.

We conclude by noting two potentially useful tools in the MC simulation kit: first, the argument from Catani, Marchesini & Webber (CMW) [18] that for consistency with full analytic resummation calculations, the $\alpha_S$ in parton showers should be modified – in the original formulation by $N_f$-dependent upward rescaling of $\Lambda_{QCD}$. This provides a motivation for using a shower $\alpha_S$ larger than that in the PDF & matrix element, but it remains unclear how this can be made consistent with the requirements of matching schemes. And secondly, an "LO" PDF with an "NLO-like" $\alpha_S = 0.118$ already exists – the CT09MCS set [24]. Whether this is a panacea for NLO matching configurations is not clear, however, since previous use of "modified LO" PDFs – albeit from the MRST family rather than the CTEQ one – led to unwanted artefacts in soft event features such as underlying event: explicit study of this configuration is needed to understand whether such effects are induced at a problematic level by the CT09MCS set.

In summary, at lowest order there is significant freedom to choose special $\alpha_S$ values for parton shower evolution without mismatches to the PDF coupling inducing anomalous behaviours more significant than the intrinsic uncertainty of the shower formalism. Once ME/PS matching is involved, things become more complicated, but for multi-leg LO simulation the freedom is again tolerable because of the substantial scale uncertainty of the ME and shower and because typical shower values for $\alpha_S$ are not far from those used in LO PDF fits. Matched NLO calculations, and particularly state-of-the-art multi-leg-NLO ones, are now the front-line in this long-running battle between the ugly pragmatism of tuning and the theoretical requirements of full QCD consistency – the state-of-the-art hence may not describe data as well as LO+LL simulations tuned to data, but the increasing ability to calculate QCD processes from first principles (and accordingly predictivity in so-far unmeasured phase spaces) can only be welcomed.
2.2 PDFs in multi-parton interactions

The demonstrations and arguments above make a compelling case that we should not be overconcerned about PDF consistency between PDFs & matrix elements and parton showers, because of the relative stability of the PDF ratios which appear in the ISR Sudakov form factor, eq. (1).

But a surprising effect in this Pythia 8 study is seen in the jet mass plots of Figures 11 and 9. Given that the the shower couplings are not automatically affected by the shower PDF, and that perturbative jet mass dominantly arises from the broadening effects of the final-state shower (whose Sudakov factor includes no PDF terms at all), the observed large effect seems perverse. But we have also to consider the effects of PDFs in multi-parton interactions (MPI).

It is well known that as the minimum parton/jet scale, $\hat{p}_T^{\text{min}}$, is reduced in jet cross-section calculations, the resulting cross-section diverges and eventually exceeds the total $pp$ cross-section. In the usual eikonal approach to MPI modelling, the ratio of calculated partonic to hadronic collision cross-sections – i.e. the factor by which unitarity is naively violated – is interpreted as the mean number of partonic interactions in each $pp$ collision, $\mu_{\text{int}}$. Each $pp$ event then samples from a Poisson distribution with mean $\mu_{\text{int}} - 1$ to choose how many soft QCD partonic interactions, $n_{\text{int}}$, will accompany the hard scatter. Since $\mu_{\text{int}}$ depends on the partonic cross-section at low-$p_T$, which is sensitive to low-$x$ PDFs, changes of PDF can have a very significant effect on levels of MPI activity (i.e. underlying event), even when restricted to LO fits as is recommended [20].

It is hence most plausible that underestimation of the level of partonic multiple scattering, in particular due to the smaller low-$x$ gluon in NLO PDFs, and the absence of a retune of MPI model cutoffs and suppression factors is responsible for the large effects of “shower” PDF choice on jet mass observables in Pythia simulation.

A switch of PDF in the “soft” (i.e. non-hard-process) components of an event generator will hence in general need to retune the MPI model. This may be necessary even if restricting to LO PDFs with the same $\alpha_S$, since different PDF families can have significantly different low-$x$ gluon distributions for the same strong coupling: the changes in Figures 9 and 11 are not always negligible within the LO group, especially below $m \sim 30$ GeV. Luckily, previous tuning experience with the Pythia model has shown that the maximum “plateau” level of MPI activity can be adjusted with minimal impact on more detailed underlying event observables, or the parton shower, via a simple 1-parameter tune of the $p_T^0$ screening scale. It is hence possible to switch soft-process PDFs with only a simple – perhaps by-hand – retuning, rather than needing to re-employ the more comprehensive machinery needed for a full shower+MPI generator tune.
3 Summary

This note has presented empirical evidence for the usual approaches to reweighting and retuning Monte Carlo parton shower event generators for use with different PDFs, along with discussion of some of the observable artefacts and physical principles involved. We hope these plots and discussion will prove useful, particularly as a pedagogical introduction and to highlight areas where a 100% satisfying solution to shower configuration ambiguities has yet to be found.

Several popular rules of thumb are supported by this presentation. For unambiguously leading-order hard process simulation, the use of LO PDFs is recommended not only because of the compensation for missing LO matrix element effects built into the PDF fit but also for closer equivalence of the PDF $\alpha_S$ value to the values typically obtained in parton shower tuning to $e^+e^-$ and hadron collider data. PDF reweighting between LO and NLO sets – thankfully rare in practice, although not unheard of – is seen to induce severe effects due to both PDF and $\alpha_S$ effects and is strongly discouraged.

The smallness of differences between LO and particularly between NLO PDF ratios and the corresponding $\alpha_S$ suggest that reweighting at ME-level only, and hence neglecting their effects on parton showers, should be an acceptable approximation – provided that the neglected effects will be covered by the systematic uncertainties inherent in the parton shower formalism. Explicit simulation confirms this, with neglected deviations within the group of major LO PDFs being restricted to $\sim 5\%$ at most. Even observables sensitive to multiple initial state emissions, such as $H_T$ do not show more significant effects. This argument in favour of “naïve” reweighting can also be used to justify switching of shower PDFs in generator configurations without a need for detailed shower parameter retuning – although the typically associated change of multi-parton interactions PDF will necessitate some simple tune modification to account for sensitivity to low-$x$ parton distribution differences. The relative insensitivity of parton showers to PDFs is good news insofar as it suggests that a single shower MC tune made with a given leading-order PDF/ME/shower/MPI PDF can be reused with many different hard-process PDFs rather than needing a family of tunes to cover all hard process simulation options.

More substantial than PDF values themselves may be the corresponding variations in the strong coupling, $\alpha_S$. If propagated to the parton shower, $\alpha_S$ changes can have a significant effect on many observables, particularly at LO. While generator codes may allow for inconsistency in both PDF and $\alpha_S$ treatment, this pragmatic freedom can easily prove counterproductive once higher-order hard process calculations are used – as is these days the norm for simulation of Standard Model processes. The CMW [18] argument from resummed calculations for $\alpha_S$ enhancement in parton showers has some purchase but does not obviously play well with the need for equivalence of shower & ME parton emission in ME/PS-matched calculations. The convenience of PDF reweighting and weight-based systematics without explicitly incorporating
the effects on parton showers is for now a clear win for pragmatism, but as hard process modelling becomes more and more sophisticated we must ensure to monitor its evolving validity.

**Apologies**

*My apologies to all those to whom I promised I would write up these studies more than 18 months ago. I hope late really has proven to be better than never!*

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