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RESUMMATION AND SHOWER STUDIES*

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1. INTRODUCTION

The transverse momentum of a colour-singlet massive particle produced in a hadronic collision provides important information on perturbative and nonperturbative effects. A process like $\mathrm{q\overline{q}} \to \mathrm{Z}^0$ corresponds to a $p_{\perp \mathrm{Z}} = 0$, while higher-order processes provide $p_\perp$ kicks as the Z^0 recoils against quarks and gluons. At large $p_{\perp \mathrm{Z}}$ values the bulk of the $p_\perp$ comes from one hard emission, and perturbation theory is a reasonable approach. In the small-$p_{\perp \mathrm{Z}}$ region, on the other hand, many emissions can contribute with $p_\perp$ kicks of comparable size, and so the order-by-order approach is rather poorly convergent. Furthermore, in this region nonperturbative effects may start to become non-negligible relative to the perturbative ones.

The traditional solution has been to apply either an analytical resummation approach or a numerical parton-shower one. These methods to some extent are complementary. The norm today is for showers to be based on an improved leading-log picture, while resummation is carried out to next-to-leading logs. However, resummation gives no information on the partonic system recoiling against the Z^0, while showers do, and therefore can be integrated into full-fledged event generators, allowing accurate experimental studies. In both approaches the high-$p_\perp$ tail is constrained by fixed-order perturbation theory, so the interesting and nontrivial region is the low-to-medium-$p_\perp$ one. Both also require nonperturbative input to handle the low-$p_\perp$ region, e.g. in the form of a primordial $k_\perp$ carried by the initiator of a shower.

One of the disconcerting aspects of the game is that a large primordial $k_\perp$ seems to be required and that the required value of this primordial $k_\perp$ can be dependent on the kinematics of the process being considered. Confinement of partons inside the proton implies a $\langle k_\perp \rangle \approx 0.3$ GeV, while fits to Z^0 data at the Tevatron favour ≈ 2 GeV [1] (actually as a root-mean-square value, assuming a Gaussian distribution). Also resummation approaches tend to require a non-negligible nonperturbative contribution, but that contribution can be determined from fixed-target data and then automatically evolved to the kinematical region of interest. In this note we present updated comparisons and study possible shower modifications that might alleviate the problem. We will use the two cases of $\mathrm{q\overline{q}} \to \mathrm{Z}^0$ and $\mathrm{gg} \to \mathrm{H}^0$ (in the infinite-top-mass limit) to illustrate differences in quark and gluon evolution, and the Tevatron and the LHC to quantify an energy dependence.

2. COMPARISON STATUS

A detailed comparison of analytic resummation and parton showers was presented in [1]. For many physical quantities, the predictions from parton shower Monte Carlo programs should be nearly as precise as those from analytical theoretical calculations. In particular, both analytic and parton shower Monte Carlos should accurately describe the effects of the emission of multiple soft gluons from the incoming partons.

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Parton showers resum primarily the leading logs, which are universal, i.e. process-independent, depending only on the initial state. An analytic resummmation calculation, in principle, can resum all logs, but in practice the number of towers of logarithms included in the analytic Sudakov exponent depends on the level to which a fixed-order calculation was performed for a given process. Generally, if a NNLO calculation is available, then the $B^{(2)}$ coefficient (using the CSS formalism [2]) can be extracted and incorporated. If we try to interpret parton showering in the same language then we say that the Monte Carlo Sudakov exponent always contains a term analogous to $A^{(1)}$ and $B^{(1)}$ and that an approximation to $A^{(2)}$ is also present in some kinematic regions.

In Ref. [1], predictions were made for both Z^0 and Higgs production at the Tevatron and the LHC, using both resummation and parton shower Monte Carlo programs. In general, the shapes for the $p_\perp$ distributions agreed well, although the PYTHIA showering algorithm typically caused the Higgs $p_\perp$ distribution to peak at somewhat lower values of transverse momentum.

3. SHOWER ALGORITHM CONSTRAINTS

While customarily classified as leading log, shower algorithms tend to contain elements that go beyond the conventional leading-log definition. Specifically, some emissions allowed by leading log are forbidden in the shower description. Taking the PYTHIA [3, 4] initial-state shower algorithm [5, 6, 7] as an example, the following aspects may be noted (see [8] for further details):
(i) Emissions are required to be angularly ordered, such that opening angles increase on the way in to the hard scattering subprocess. That is, non-angularly-ordered emissions are vetoed.
(ii) The z and Q^2 of a branching $a \to bc$ are required to fulfill the condition $\hat{u} = Q^2 - \hat{s}(1-z) < 0$. Here $\hat{s} = (p_a + p_d)^2 = (p_b + p_d)^2/z$, for d the incoming parton on the other side of the event. In the case that b and d form a Z^0, say, and c is the recoiling parton, $\hat{u}$ coincides with the standard Mandelstam variable for the $a + d \to (\mathrm{Z}^0 = b + d) + c$ process. In general, it may be viewed as a kinematics consistency constraint.
(iii) The evolution rate is proportional to $\alpha_\mathrm{s}((1-z)Q^2) \approx \alpha_\mathrm{s}(p_\perp^2)$ rather than $\alpha_\mathrm{s}(Q^2)$. Since $p_\perp^2 < Q^2$ by itself this implies a larger α_s and thus an increased rate of evolution. However, one function of the $Q_0 \approx 1$ GeV nonperturbative cutoff parameter is to avoid the divergent-α_s region, so now one must require $(1-z)Q^2 > Q_0^2$ rather than $Q^2 > Q_0^2$. The net result again is a reduced emission rate.
(iv) One of the partons of a branching may develop a timelike parton shower. The more off-shell this parton, the less the $p_\perp$ of the branching. The evolution rate in x is unaffected, however.
(v) There are some further corrections, that in practice appear to have negligible influence: the non-generation of very soft gluons to avoid the divergence of the splitting kernel, the possibility of photon emission off quarks, and extra kinematical constraints when heavy quarks are produced.
(vi) The emission rate is smoothly merged with the first-order matrix elements at large $p_\perp$. This is somewhat separate from the other issues studied, and the resulting change only appreciably affects a small fraction of the total cross section, so it will not be considered further here.

The main consequence of the first three points is a lower rate of x evolution. That is, starting from a set of parton densities $f_i(x, Q_0^2)$ at some low Q_0^2 scale, and a matching Λ, tuned such that standard DGLAP evolution provides a reasonable fit to data at $Q^2 > Q_0^2$, the constraints above lead to x distributions less evolved and thus harder than data. If we e.g. take the CTEQ5L tune [9] with $\Lambda^{(4)} = 0.192$ GeV, the $\Lambda^{(4)}$ would need to be raised to about 0.23 GeV in the shower to give the same fit to data as CTEQ5L when the angular-ordering cut in *(i)* is imposed. Unfortunately effects from points *(ii)* and *(iii)* turn out to be process-dependent, presumably reflecting kinematical differences between $\mathrm{q} \to \mathrm{qg}$ and $\mathrm{g} \to \mathrm{gg}$. There is also some energy dependence. The net result of the first three points suggests that PYTHIA should be run with a $\Lambda^{(4)}$ of about 0.3 GeV (0.5 GeV) for Z^0 (H^0) production in order to compensate for the restrictions on allowed branchings.

One would expect the increased perturbative evolution to allow the primordial $k_\perp$ to be reduced. Unfortunately, while the total radiated transverse energy, $\sum_i |\mathbf{p}_{\perp i}|$, comes up by about 10% at the Teva-

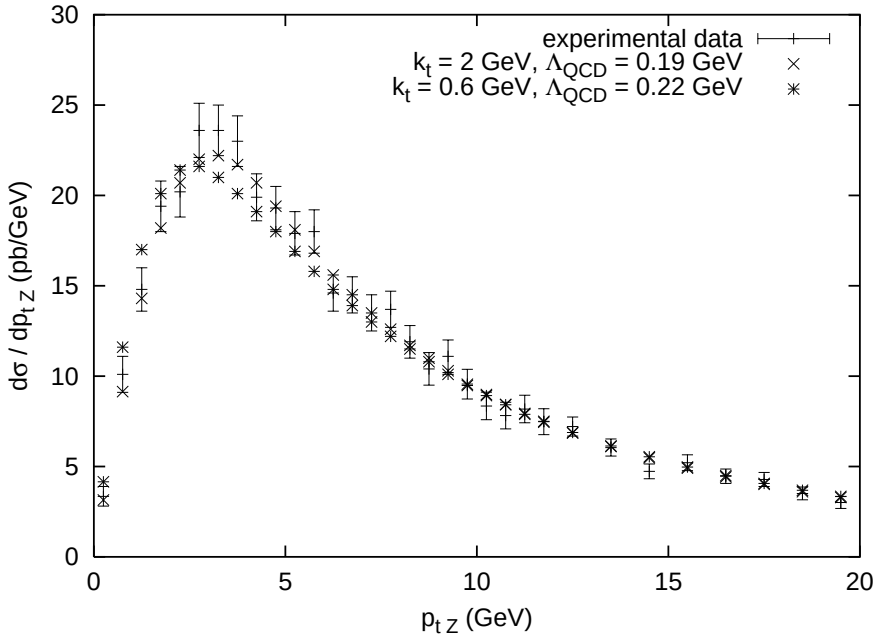

Fig. 1: Comparison of the CDF $p_{\perp \mathrm{Z}}$ spectrum with the new shower algorithm for two parameter sets.

tron, this partly cancels in the vector sum, $\mathbf{p}_{\perp \mathrm{Z}} = -\sum_i \mathbf{p}_{\perp i}$. For a 2 GeV primordial $k_\perp$ the shift of the peak position of the $p_{\perp \mathrm{Z}}$ spectrum is negligible. Results are more visible for $p_{\perp \mathrm{H}}$ at the LHC.

Note that a primordial $k_\perp$ assigned to the initial parton at the low Q_0^2 scale is shared between the partons at each shower branching, in proportion to the longitudinal momentum fractions a daughter takes. Only a fraction $x_{\mathrm{hard}}/x_{\mathrm{initial}}$ of the initial $k_\perp$ thus survives to the hard-scattering parton. Since the typical x evolution range is much larger at the LHC than at the Tevatron, a tuning of the primordial $k_\perp$ is hardly an option for H^0 at the LHC, while it is relevant for Z^0 at the Tevatron. Therefore an increased Λ value is an interesting option.

We now turn to the point *(iv)* above. By coherence arguments, the main chain of spacelike branchings sets the maximum virtuality for the emitted timelike partons, i.e. the timelike branchings occur at longer timescales than the related spacelike ones. In a dipole-motivated language, one could therefore imagine that the recoil, when a parton acquires a timelike mass, is not taken by a spacelike parton but by other final-state colour-connected partons. A colour-singlet particle, like the Z^0 or H^0, would then be unaffected by the timelike showers.

The consequences for $p_{\perp \mathrm{Z}}$ and $p_{\perp \mathrm{H}}$ of such a point of view can be studied by switching off timelike showers in PYTHIA, but there is then no possibility to fully simulate the recoiling event. A new set of shower routines is in preparation [10], however, based on $p_\perp$-ordered emissions in a hybrid between conventional showers and the dipole approach. It is well suited for allowing final-state radiation at later times, leaving $p_{\perp \mathrm{Z}}$ and $p_{\perp \mathrm{H}}$ unaffected at that stage. Actually, without final-state radiation, the two approaches give surprisingly similar results overall. Both are lower in the peak region than the algorithm with final-state radiation, in better agreement with CDF data [11]. The new one is slightly lower, i.e. better relative to data, at small $p_{\perp \mathrm{Z}}$ values.

A combined study [8], leaving both the primordial $k_\perp$ and the Λ value free, still gives some preference to $\langle k_\perp \rangle = 2$ GeV and the standard $\Lambda^{(4)} = 0.192$ GeV, but differences relative to an alternative with $\langle k_\perp \rangle = 0.6$ GeV and $\Lambda^{(4)} = 0.22$ GeV are not particularly large, Fig. 1.

4. FURTHER COMPARISONS

Returning to Higgs production at the LHC, in Fig. 2 are shown a number of predictions for the current standard PYTHIA shower routines. Using CTEQ5M rather than CTEQ5L results in more gluon radiation and a broader $p_\perp$ distribution due to the large value of Λ. Likewise turning off timelike showers for gluons radiated from the initial state also results in the peak of the $p_\perp$ distribution moving outwards.

We can now compare the results with resummation descriptions and other generators, Fig. 3 [12]. As we see, the new PYTHIA routines agree better with resummation descriptions than in the past [1], attesting to the importance of various minor technical details of the Monte Carlo approach. One must note, however, that some spread remains, and that it is not currently possible to give an unambiguous prediction.

5. CONCLUSIONS

We have studied $p_{\perp\mathrm{Z}}$ and $p_{\perp\mathrm{H}}$ spectra, as a way of exploring perturbative and nonperturbative effects in hadronic physics. Specifically, we have pointed out a number of ambiguities that can exist in a shower approach, e.g. that the shower goes beyond the simpleminded leading-log evolution and kinematics, while still making use of leading-log parton densities. Attempts to correct for mismatches in general tend to increase the perturbative $p_{\perp\mathrm{Z}}$. The need for an unseemly large primordial $k_\perp$ in the shower approach is thus reduced, but not eliminated. There is still room for, possibly even a need of, perturbative evolution beyond standard DGLAP at small virtuality scales.

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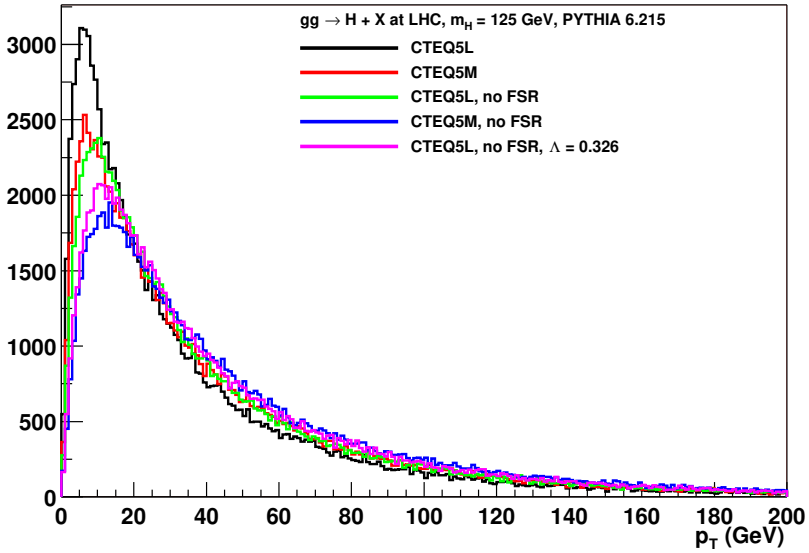

Fig. 2: Comparison of the PYTHIA $p_\perp$ distributions for Higgs production at the LHC using LO and NLO pdf's and turning timelike parton showering off (no FSR) and on.

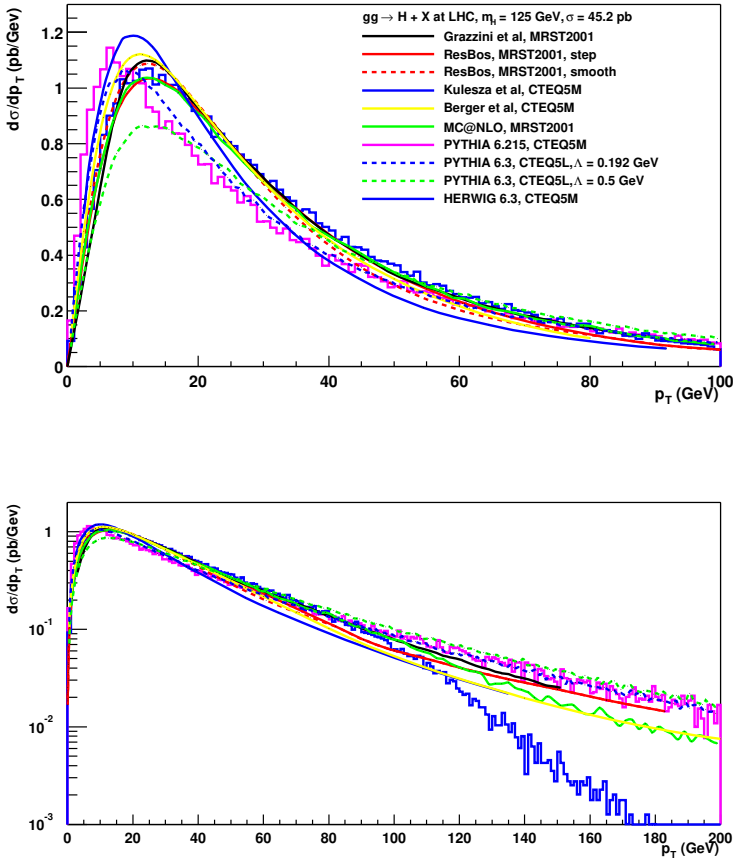

Fig. 3: Comparison of various $p_\perp$ distributions for Higgs production at the LHC. The curves denoted Grazzini [13], ResBos [14], Kulesza [15] and Berger [16] are resummation descriptions, while MCNLO [17, 18], HERWIG [19] and PYTHIA are generators, PYTHIA 6.3 referring to the new algorithm outlined above.

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