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Non-perturbative QCD effects and the top mass at the Tevatron

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Abstract. We present a new, universally applicable toy model of colour reconnections in hadronic final states. The model is based on hadronising strings and has one free parameter. We next present an implementation of this model in the PYTHIA event generator and provide several parameter sets ('tunes'), constrained by fits to Tevatron minimum-bias data. Finally, we consider the sensitivity of a simplified top mass analysis to these effects, in exclusive semi-leptonic top events at the Tevatron. A first attempt at isolating the genuine non-perturbative effects gives an estimate of order $\delta m_{\text{top}} \sim \pm 0.5$ GeV from non-perturbative uncertainties, and a further $\delta m_{\text{top}} \sim \pm 1$ GeV from shower effects.

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1 Introduction

With increasing statistics and improved analysis techniques, a truly precise measurement of the top quark mass now seems feasible at the Tevatron experiments, reaching a final uncertainty at or below 1.5 GeV [1]. This is all the more impressive given that the top mass is a highly non-trivial observable, involving both jets and leptons. Moreover, it furnishes an important motivation to reconsider which theoretical aspects are relevant, at the 1 GeV level, and whether they are sufficiently well under control. Ultimately, this question will also be relevant for a range of proposed high-precision measurements at the LHC.

In particular for hadronic final states, a sophisticated array of corrections are applied to the experimental raw data before the actual observable is evaluated [1–3]. Due to the increasingly advanced procedures mandated by high precision, it is not straightforward to predict how uncertainties in the modelling affect the final answer; instead, dedicated studies are required to establish whether theoretical models are sufficiently well constrained and/or whether modified measurement strategies could ultimately be more fruitful.

On the theoretical side, techniques for consistent matching between perturbative parton showers and fixed-order calculations have been improved and generalised in recent years (for reviews see e.g. [4–6]), with some work focusing specifically on top production [7–10]. The structure of the underlying event (UE) has also received increasing attention [11–16], with theoretical developments here focusing on resummations of multiple perturbative interactions (MPI) [17–20]. Non-perturbative aspects, on the other hand, still suffer from being hard to quantify, hard to test, and hard to calculate. In this study, we focus on one particular such source of uncertainty: colour reconnection effects in the final state.

We begin by briefly discussing some general aspects of colour reconnections, including the role they already play in current descriptions of hadron collisions. We next present several explicit models, with parameters constrained by Tevatron minimum-bias distributions. Finally, we apply the models in the context of semileptonic top events at the Tevatron and study the sensitivity of simplified top mass estimators to the model variations. Some previous work leading up to this report can be found in [21, 22].

2 Colour reconnections

In a first study of colour rearrangements, Gustafson, Pettersson, and Zerwas (GPZ) [23] observed that, e.g., in hadronic WW events at LEP, colour interference effects and gluon exchanges can cause 'crosstalk' between the two W systems. In the GPZ picture, the corresponding changes occurred already at the perturbative QCD level, leading to predictions of quite large effects.

Sjöstrand and Khoze (SK) [24, 25] subsequently argued against large perturbative effects and instead considered a scenario in which reconnections occur only as part of the non-perturbative hadronisation phase. Starting from the Lund string fragmentation model [26], SK argued that, if

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two QCD strings overlap in space and time, there should be a finite possibility for them to fuse or cut each other up (see e.g. [27]). However, since it is not known whether the QCD vacuum more resembles a (chromomagnetic) type I or type II superconductor, SK presented two limiting-case models, referred to as SK-I and SK-II, respectively. Both models resulted in effects much smaller than for GPZ, leading to a predicted total uncertainty on the W mass from this source of $\sigma_{M_W} < 40$ MeV. SK also performed a study of QCD interconnection effects in $t\bar{t}$ production [28], but only in the context of e^+e^- collisions.

Subsequently, a number of alternative models have also been proposed, most notably the ones proposed by the Lund group, based on QCD dipoles [29–31], and one based on clusters by Webber [32]. Apart from WW physics, colour reconnections have also been proposed to model rapidity gaps [33–36] and quarkonium production [37].

Experimental investigations at LEP did not find conclusive evidence of the effect [38–41], but were limited to excluding only the most dramatic scenarios, such as GPZ and versions of SK-I with the recoupling strength parameter close to unity. Furthermore, in hadron collisions the initial state contains soft colour fields with wavelengths of order the confinement scale. The presence of such fields, unconstrained by LEP measurements, could impact in a non-trivial way the formation of colour strings at the time of hadronisation [33, 34]. And finally, the underlying event produces an additional amount of displaced colour charges, translating to a larger density of hadronising strings between the beam remnants. It is not known to what extent the collective hadronisation of such a system differs from a sum of independent string pieces.

As the starting point for a concrete model, we take the description of hadron collisions developed in [17, 19, 20], as implemented in the PYTHIA event generator [42]. In particular, this implies that the underlying event is obtained by a resummation of perturbative QCD $2 \to 2$ scatterings. The required multi-parton luminosities are obtained from the standard 1-parton ones, augmented with impact-parameter dependence and imposing flavour and momentum conservation [19].

The system of coloured partons emerging from the perturbative phase is dual to a set of colour-singlet QCD dipoles [43, 44], with the transformation between the two being uniquely determined in the large-N_c limit (modulo a small ambiguity between the hard scattering and underlying event initiators [19]). In the absence of colour reconnections or other collective phenomena, each such dipole translates directly to a hadronising string piece.

Colour reconnections can then be introduced by defining a finite probability $\mathcal{P}_{\text{reconnect}}$ for each dipole to undergo some form of modification before it hadronises. We shall here define the probability for the dipole to 'survive' as

$$\mathcal{P}_{\text{keep}} = 1 - \mathcal{P}_{\text{reconnect}} = \prod_{i=1}^{n_{\text{int}}} (1 - \xi_R) = (1 - \xi_R)^{n_{\text{int}}} , \quad (1)$$

where ξ_R represents an averaged probability for the dipole/string to interact and the scaling with the number of multiple interactions n_{int}, is intended to give a rough representation of a scaling with the number of strings between the remnants, each of which the dipole could have interacted with. In principle, we could have gone further, noting that a dipole cannot interact with itself ($n_{\text{int}} \to n_{\text{int}} - 1$), that gluon exchange stretches two strings, rather than one, between the remnants ($n_{\text{int}} \to 2n_g + n_q$), the possibility to interact with the background vacuum ($n_{\text{int}} \to n_{\text{int}} + c$), etc. Given the uncertainties, the present scaling should be a reasonable first approximation, leaving the possibility open that future studies may require a more sophisticated behaviour.

By consequence, for e^+e^- collisions the effective reconnection probability is simply ξ_R, while it grows from a minimum value close to ξ_R for low-multiplicity (peripheral) hadron collisions to larger values in harder, more central collisions, such as the high-multiplicity tail of min-bias or top production. The model thus yields some of the expected qualitative behaviour while leaving only a single free parameter, ξ_R, to be determined from data.

The dipoles which do not survive define an overall colour neutral system of (anti-)triplet charges (a gluon is represented as the sum of a triplet and an antitriplet in the $N_c \to \infty$ limit) for which a new string topology is to be determined. The basis of our model is an annealing-like algorithm [21] which attempts to minimise the total potential energy, as represented by the string length measure Λ [45, 46], here given for massless partons for simplicity:

$$\Lambda = \prod_{i=1}^{N} \frac{m_i^2}{M_0^2} , \quad (2)$$

where i runs over the number of string pieces, N, with invariant masses m_i, and M_0 is a constant of order the hadronisation scale. The actual measure used by the algorithm is the four-product of the momentum vectors of the dipole endpoints. We note that the minimisation of a similar measure also lies at the heart of an earlier model for string re-interactions proposed by Rathsman [35], the generalized area law (GAL), to which we plan to return in a future study.

More aggressive models could still be constructed, e.g., by reducing the risk of the annealing procedure getting trapped in shallow local minima, but we do not consider this a critical issue. One could also be more selective about which dipoles to include in the annealing; here, we simply select a random set of 'active' dipoles, whereas in a more aggressive model one could have introduced a preference for dipoles which have the most to gain in Λ. Conversely, less aggressive models could be motivated by arguing that fairly long-lived resonances should be able to 'escape' the mayhem and hadronise independently. Presumably, this would be particularly relevant for colour singlet resonances, such as the W, and in a more sophisticated treatment a gradual suppression with distance from the central hadronising region, or, more precisely, the distance between a pair of interacting dipoles, would be expected. However, since both the top and W have decay lengths of order 0.1 fm , for the present we treat their decay products as fully participating in the swapping of colours.

Below, we investigate three variants of the algorithm; type 0 in which the collapse of the colour field is driven by free triplets only (gluons are sequentially attached to string systems starting from quarks), which naturally suppresses the formation of small closed gg string loops and is simultaneously numerically the fastest, type 1 in which gg loops are suppressed by brute force, and type 2 in which gg loops are not suppressed. The physical question behind this issue is, very briefly stated, whether, at the non-perturbative transition level, gluons should be interpreted merely as representations of transverse excitations (or 'kinks') on strings whose main topology is defined by their quark endpoints, or whether the gluons should be allowed to play a more independent dynamical role. Neither is likely to be the full answer, and so by these variations we seek to explore some measure of the associated uncertainty.

The strength parameter ξ_R remains to be determined. In principle, the constraints from LEP and diffractive processes would be prime candidates for this task. However, since we are here explicitly concerned with possible breakdowns of jet universality, the applicability of such constraints to hard inelastic hadron collisions would be, at least, questionable. Thus, although these connections are certainly worth exploring in more depth, we note that a smaller extrapolation relative to the process we are interested in can be obtained by simply using non-top Tevatron data. Here we consider minimum-bias (inelastic, non-diffractive) events at run II of the Tevatron, the large-multiplicity tail of which should be fairly directly related to top production. In a more elaborate study, this should be extended to include also Drell–Yan and dijet data, particularly with $Q^2 \sim m_{\mathrm{top}}^2$.

The complex nature of hadron collisions, and, in particular, the uncertainties associated with the underlying event, imply that we cannot just correlate a single distribution with ξ_R and be done with it. Instead, the colour reconnection strength must be determined as part of a more general fit or 'tune' to several minimum-bias distributions simultaneously. As a first step, we here use the charged hadron multiplicities, $P(N_{\mathrm{ch}})$, and the mean $p_\perp$ as a function of multiplicity, $\langle p_\perp \rangle (N_{\mathrm{ch}})$.

The naive expectation from an uncorrelated system of strings decaying to hadrons would be that $\langle p_\perp \rangle$ should be independent of N_{ch}, and to first approximation equal to the LEP fragmentation $p_\perp$ width. (With PYTHIA, the best fit for the non-perturbative component of this is $\langle p_\perp \rangle_{\mathrm{NP}} \sim$ 0.36 GeV, to give the order of magnitude.) Already at $Sp\bar{p}S$, however, and more recently at RHIC and the Tevatron, such a constant behaviour has been convincingly ruled out. Currently, models which successfully describe the $\langle p_\perp \rangle (N_{\mathrm{ch}})$ distribution, such as R. Field's 'Tune A' and others [12, 13, 16], do so by incorporating very strong ad hoc correlations between final-state partons from different interactions. We emphasise that these correlations are not chosen at random but are constructed to minimise the resulting string length, i.e., similarly to our models here. Thus, although colour reconnections are not explicitly part of these models, an implicit effect with similar consequences is still needed, at a seemingly large magnitude. This observation alone serves as a significant part of the motivation for our study.

Table 1. PYTHIA parameters [42], divided into a few main categories: UE (underlying event), ISR (initial state radiation), FSR (final-state radiation), BR (beam remnants), and CR (colour reconnections). The UE reference energy for all models is PARP(89) = 1800 GeV, and all dimensionful parameters are given in units of GeV. MSTP(95) = 2, 4, 6 corresponds to CR types 1, 2, and 0, respectively, in the text

Parameter (PYTHIA v.6408+)		DW	A	A_{PT}	A_{CR}	S_0	S_1	S_2	NOCR
UE model	MSTP(81)	1 ('old' [17])				21 ('new' [20])			
UE infrared regularisation scale (at $\sqrt{s} = 1800$ GeV)	PARP(82)	1.9	2.0	2.1	2.0	1.85	2.1	1.9	2.05
-"-, scaling power with $\sqrt{s}$	PARP(90)	0.25 ('fast')				0.16 ('slow')			
UE hadron transverse mass distribution	MSTP(82)	4 ('double Gaussian')				5 ('ExpOfPow')			
-"- parameter 1	PARP(83)	0.5				1.6	1.4	1.2	1.8
-"- parameter 2	PARP(84)	0.4				n/a			
UE total gg fraction	PARP(86)	1.0	0.95	0.95	0.66	n/a			
ISR infrared cutoff	PARP(62)	1.25	1.0	1.0	1.0	(≡ PARP(82))			
ISR renormalisation scale prefactor	PARP(64)	0.2	1.0	1.0	1.0	1.0			
ISR Q^2_{max} factor	PARP(67)	2.5	4.0	4.0	4.0	n/a			
ISR infrared regularisation scheme	MSTP(70)	n/a				2	0	2	2
ISR FSR off ISR scheme	MSTP(72)	n/a				0	1	0	0
FSR model	MSTJ(41)	2	2	12	2	($p_\perp$-ordered)			
FSR Λ_{QCD}	PARJ(81)	0.29	0.29	0.14	0.29	0.14			
BR colour scheme	MSTP(89)	n/a				1	1	1	2
BR composite x enhancement factor	PARP(79)	n/a				2	2	2	3
BR primordial k_T width $\langle \lvert k_T \rvert \rangle$	PARP(91)	2.1	1.0	1.0	1.0	n/a			
BR primordial k_T UV cutoff	PARP(93)	15.0	5.0	5.0	5.0	5.0			
CR model	MSTP(95)	n/a			6	6	2	4	1
CR strength ξ_R	PARP(78)	n/a			0.25	0.2	0.35	0.15	0.0
CR gg fraction (old model)	PARP(85)	1.0	0.9	0.9	0.0	n/a			

Given the good agreement between Tune A and Tevatron data, and given the difficulty in obtaining the data itself, we constrain the new models simply by comparing to Tune A. Table 1 gives a list of 8 different PYTHIA (v.6408) parameter sets, which almost unavoidably combine variations of both perturbative and non-perturbative aspects. However, we have chosen the models such that, by comparing all of them, it should be possible to separate the perturbative from the non-perturbative components, at least to a first approximation.

Tunes A and DW both pertain to the 'old' UE model [17] and are the result of careful comparisons to CDF data [12, 13, 16], for Tune A including underlying event only, and for Tune DW also Drell–Yan data. We again emphasise the large role played by non-trivial colour correlations in these tunes, which was originally introduced to improve the fit to the high-$p_\perp$ tail of hadron spectra [47]. The A_{PT} model is a re-tune of Tune A, with the original virtuality-ordered final-state showers replaced by the new $p_\perp$-ordered ones [20] (with Λ_{QCD} obtained from a fit to ALEPH data [48]). We note that, by default, both choices of ordering variable incorporate matrix element merging for hard jet radiation [7] for both top and W decays. We, thus, expect differences in the out-of-cone effects from hard perturbative radiation to be small. Similarly, A_{CR} is again identical to Tune A, except that it starts from uncorrelated UE string systems and then applies the type 0 colour annealing model presented here as an afterburner. The S_α models pertain to the 'new' interleaved UE model [20], with $p_\perp$-ordered showers and type α colour annealing, respectively – constrained using the distributions in Fig. 1 and, for the FSR Λ_{QCD}, ALEPH event shape data [48]. The NOCR model is shown for reference only. It is the only one that does not incorporate explicit non-trivial colour correlations, and even then care has been taken to exploit the initial-state colour ambiguity mentioned above to the fullest.

In Fig. 1, the eight models in Table 1 are compared on the N_{ch} and $\langle p_\perp \rangle (N_{\mathrm{ch}})$ distributions. A good description of the charged multiplicity distribution is obtained in all cases. Simultaneous good agreement with $\langle p_\perp \rangle (N_{\mathrm{ch}})$ is only obtained for the models incorporating non-trivial colour correlations – the notable exception being the NOCR model which exhibits the close-to-constant behaviour of uncorrelated string decays discussed above. We interpret this behaviour as representing a concrete example of a data-driven motivation to develop ideas of hadronisation beyond the current cluster/string models, which have remained essentially frozen since the LEP era. This is not to imply that these models are intrinsically unsatisfactory or that hadronisation at LEP should be perceived as being a completely separate story, but only that 1) we expect that the many recent improvements on the perturbative side imply that there is less 'wriggle' room for the non-perturbative physics, and hence the latter could presumably be better constrained today than a decade ago, and 2) the size of possible differences between non-perturbative effects in different environments should be more fully explored, where current models are normally limited to the assumption of jet universality.

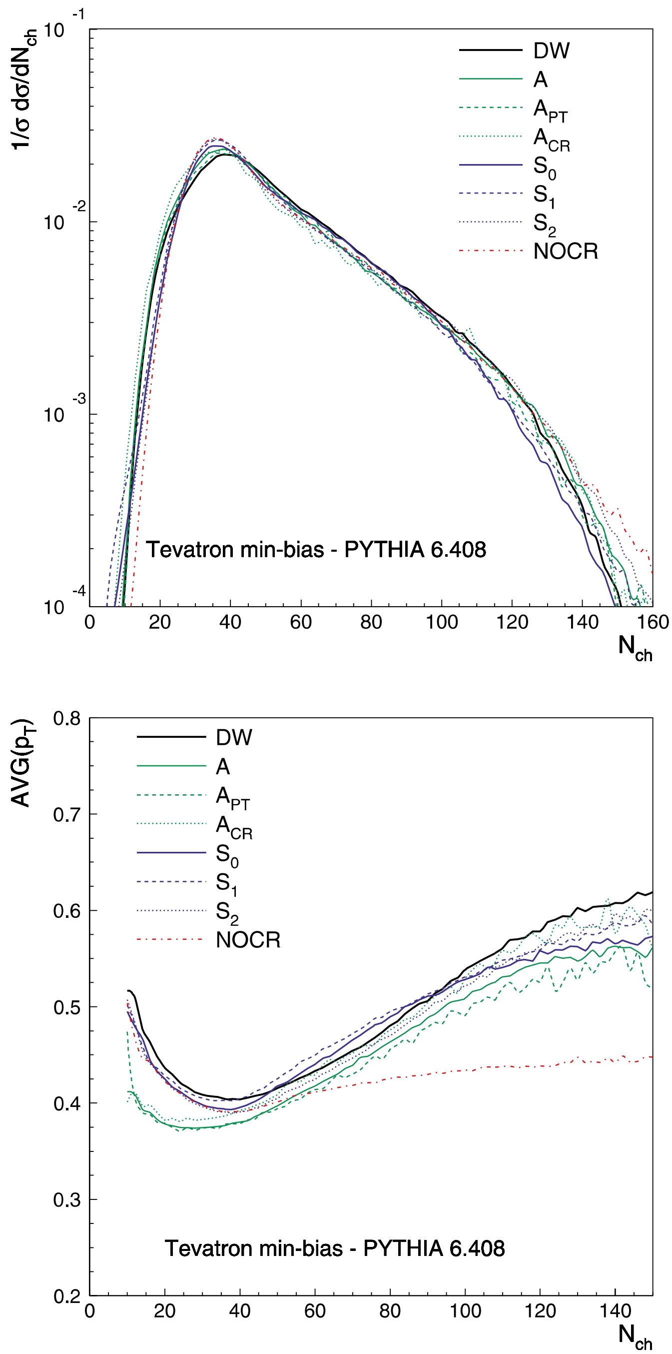

Fig. 1. Comparison of the models/tunes discussed in the text. Inelastic non-diffractive (min-bias) events in $p\bar{p}$ collisions at $\sqrt{s} = 1960$ GeV. *Top*: Charged multiplicity distribution. *Bottom*: Mean $p_\perp$ in GeV, as a function of charged multiplicity. The main point is not the precise predictions for each tune, but rather that they all roughly agree, with the notable exception of the NOCR one

Returning to the question at hand, we find that the remaining models in Table 1 all describe the two distributions in Fig. 1 within an acceptable margin, at least as gauged by the spread between the two more elaborate Tevatron tunes, A and DW.

3 The top mass at the Tevatron

Assuming the in situ extrapolation discussed above to be at least moderately reliable, we now apply the same models and parameters in the context of top production at the Tevatron. More specifically, we concentrate on semileptonic $t\bar{t}$ events, i.e., $t\bar{t} \to b\bar{b}q\bar{q}\ell\nu$. As a first step towards estimating the sensitivity of experimental top mass observables, we consider the impact on a simplified measurement which roughly approximates the key ingredients used in current Tevatron analyses. As already mentioned, it is not possible to cleanly separate the CR effect from other sources of variation in these models. Nonetheless, by grouping models with similar parton showers and studying both the variations within and between the groups, we are able to make some headway. Differences between the results obtained using the same parton shower but different CR models for the same generated top mass may then be interpreted as a first estimate of the uncertainty on m_{top} due to genuine non-perturbative effects, while the uncertainty between groups with different shower models is interpreted as having a perturbative origin.

3.1 Real top mass measurement

To set the stage for the subsequent analysis, let us first summarise the methods used in actual top mass reconstructions at the Tevatron, focusing on the ingredients they employ to go from detector level events to a reconstructed top mass. The relevant measurements performed in the semileptonic channel by the CDF and DØ collaborations [49–53] use one of three methods.

The *template method* compares the distribution of kinematically reconstructed top mass values to templates obtained for various nominal top mass values from simulation with full detector description (including background). The *matrix element method* computes the event-by-event likelihood that the observed kinematic configurations stem from events of a given top mass. Maximising the total likelihood of the observed sample yields the final result. Finally, the *ideogram method* reconstructs top mass values in each event and then builds the likelihood of observing that value with the given resolution as a function of the true value. Again, maximising the total likelihood of the observed sample yields the final result.

All three methods are based on so-called reconstructed physics objects, i.e., jets, identified charged leptons, and missing transverse energy, which fulfil certain selection criteria. For the methods with explicit reconstruction of the top mass an assignment of jets to one of the two top quarks has to be made. Often constrained fits are used to improve the experimental resolution by requiring that the two reconstructed top masses are equal and that the known W-mass is reconstructed in the decay of each of the top quarks. In this case an assignment of each jet to the W-boson or b-quark within each top decay product is also required.

The methods are calibrated, i.e., the performance of a given implementation is measured on fully simulated events. Any deviation of the reconstructed from the generated top masses is corrected for; this implies that the top mass measurement is limited by the precision of the simulation used for the calibration.

Since summer 2005 all methods have been extended to tackle the dominant experimental systematic uncertainty, the jet energy scale (JES), by simultaneously fitting the top mass and the jet energy scale, with the additional constraint that the reconstructed mass of the hadronically decaying W present in each event should be consistent with the known m_W.

The main features of a top mass measurement are thus utilisation of reconstructed physics objects, assignment of each jet to a specific top decay product, correction for an overall JES factor, and calibration of the method. We shall now construct a simplified top mass estimator which embodies these four ingredients.

3.2 Toy top mass measurement for generator level

To obtain an estimate of the influence of the above CR/UE models on top mass measurements, a toy mass measurement on events generated by PYTHIA was implemented. The study is performed at the generator level, here meaning after hadronisation and hadron decays but without detector simulation.

In this simplified analysis electrons and neutrinos are 'identified' by looking at the generator truth. Jets are reconstructed on final-state particles using cone jets of $\Delta R = 0.5$ [54, 55] and are required to have a $p_T > 15$ GeV. Only semileptonic events with exactly four reconstructed jets are considered for further analysis.

Jets are assigned to the top decay parton with the lowest ΔR distance. Events without a unique one-to-one assignment are discarded. In the samples used here, between 25% and 27% of the semileptonic events fulfil these requirements.

The top mass is now computed event by event from the sum of the four-momenta of the three jets from the hadronically decaying top in the event. The top mass for the full sample is then obtained by fitting a Gaussian to the distribution of reconstructed masses. To minimise the importance of the tails of the distribution, the fit range is restricted to a window of ± 15 GeV around the top mass. This width corresponds approximately to the experimental resolution observed in current measurements. The fit is iterated until it settles on a range symmetric around the final result, $m_{\text{top}}^{\text{fit}}$.

The same method can also be applied for measuring the W-mass from the two jets assigned to the partons from the W decay. The resulting W-mass measurement can be used to compute a JES correction factor: $s_{\text{JES}} = 80.4\,\text{GeV}/m_W$. The fitted top mass above can then be corrected by this factor, to produce a JES-scaled top mass value, $m_{\text{top}}^{\text{scaled}} = s_{\text{JES}} \cdot m_{\text{top}}^{\text{fit}}$.

This full procedure is repeated for several different values of the generated top mass, between 165 and 185 GeV, in steps of 1 GeV. Both the scaled and unscaled fitted top masses exhibit a completely linear dependence on the input top mass. Observed slopes are consistent with 1 at the 2% level. This indicates that the fit procedure is indeed stable and has the desired dependence on the physical quantity, cf. Fig. 2.

3.3 Differences from different models

In real mass measurements, the offset and slope of the straight line that describes the reconstructed vs. the generated top mass is used to calibrate the given top mass procedure. However, this calibration must necessarily use only one specific CR/UE model. By virtue of the tuning we performed, there is a genuine ambiguity of which model to choose. Differences between the individual model calibrations therefore lead to uncertainties on the top mass results. As an example, Fig. 2 shows the calibration curve obtained for Tune A before JES rescaling.

Figure 3 summarises our central results. It shows the offsets before (left) and after (right) scaling with the JES correction factor. The offsets, Δm_{top}, for each model are obtained from a straight line fit to the calibration curve evaluated at $m_{\mathrm{top}}^{\mathrm{gen}} = 175\,\mathrm{GeV}$, and have statistical precisions (determined from the spread of the data points) of $\sim 0.1\,\mathrm{GeV}$.

The top masses in the uncorrected fits (dots, left column) come out somewhat lower than the input mass, principally due to out-of-cone corrections. Including the JES correction, i.e., scaling all jets by the factor necessary to get the right hadronic W mass, the points move to the right (squares), even to the point of over-correcting the top mass.

Again, our central point is that, while for any particular model a further, constant offset would be sufficient to calibrate the measurement to coincide with the input mass, the spread between models cannot be dealt with in this way. It is the ambiguity coming from not knowing *which* offset value to correct for that we interpret as the uncertainty on the top mass.

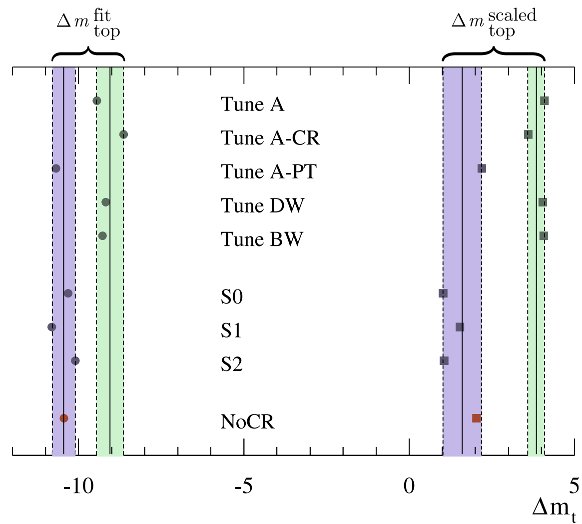

Fig. 3. Comparison of calibration offsets obtained for each model, in GeV, here including an additional parameter set, 'BW', from Rick Field. *On the left* are the results obtained before JES rescaling (*dots*) and *on the right* after rescaling (*squares*). The *shaded bands* group models with the same final-state shower *light*(*green*): virtuality-ordered, *dark*(*blue*): $p_\perp$-ordered. The statistical precision due to the finite number of generated events is at the 0.1 GeV level

It, therefore, seems significant that the various models exhibit differences of about ± 1.1 GeV and ± 1.5 GeV for the offsets of $m_{\mathrm{top}}^{\mathrm{fit}}$ and $m_{\mathrm{top}}^{\mathrm{scaled}}$, respectively. Explicit checks varying both the fit range and fit function produced variations no larger than $\sim 20\%$ in these numbers, hence at this level the effect appears genuine. Without additional constraints from data, it translates directly into an uncertainty on the reconstructed top mass.

To extricate the genuinely non-perturbative part of this, we note that the models fall into two broad classes: those that utilise the "old" virtuality-ordered final-state parton shower and those that utilise the "new" $p_\perp$-ordered one. The largest component of the difference is *between* these two classes, hinting at a perturbative origin for most of it, which, at least to some extent, should already be present in Tevatron analyses via the PYTHIA-HERWIG systematic.

Within each class, we still observe differences roughly of order ± 0.5 GeV on the top mass, which we are more confident in assigning a non-perturbative origin. Note, however, that this still lumps genuine CR effects together with other infrared ambiguities, such as infrared regularisation and renormalisation procedures, the treatment of beam remnants, etc.

Real mass analyses may have a different sensitivity to the model differences. The size of the effect in this first study, however, suggest a need for further in depth analyses. If the sensitivity we observe here is confirmed for real mass analyses, we hope the question may be turned around, and that in situ measurements can be used to gain

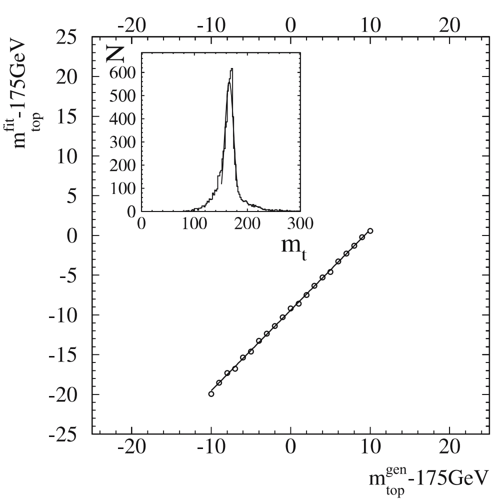

Fig. 2. Calibration curve obtained for Tune A, before JES rescaling. A similar plot was made for each model in Table 1 and their relative offsets compared, both before and after JES rescaling. The *inset* shows the Gaussian fit to the distribution reconstructed top masses from the hadronic event side for the specific point $m_{\mathrm{top}}^{\mathrm{gen}} = 175$ GeV

further information about the interesting physics effects that may be present.

4 Summary and conclusion

We have presented a set of new, universally applicable models to study colour reconnection (CR) effects in hadronic final states. The models are based on hadronising strings and apply an annealing-like algorithm to minimise a measure of the classical potential energy, with a freely varying strength parameter running from zero to unity. A scaling is included such that the survival probability of a given string piece decreases as a function of the number of perturbative scatterings in the underlying event. The models are implemented in a publicly available version (v.6408+) of the PYTHIA event generator.

To constrain the CR strength parameter we have used Tevatron minimum-bias distributions, specifically $P(N_{\mathrm{ch}})$ and $\langle p_\perp \rangle (N_{\mathrm{ch}})$. Taking the results obtained with the CDF 'Tune A' as a benchmark, we present several alternative parameter sets exploring the possible combinations of showers, underlying-event modelling, and colour reconnections. As a further, data-driven motivation, we argue that current underlying-event descriptions, including 'Tune A', already include strong non-trivial colour correlations.

As a first application, we have investigated the influence of changing the underlying physics model, including CR, UE, and shower effects, on a range of simplified Tevatron top mass measurements. The models we consider exhibit individual variations of about ± 1.5 GeV on the reconstructed top mass. While this is comparable to systematic uncertainties quoted for present top mass measurements, it has so far only partly been considered in the current analyses.

Of the total variation we attribute about ± 1 GeV to perturbative effects and about ± 0.5 GeV to non-perturbative sources.

Our conclusion for the present is thus twofold: firstly, colour reconnections in hadron collisions appear to be a both experimentally and theoretically motivated possibility, one which should be explored as part of developing a more detailed picture of hadron collisions. Secondly, it appears that non-perturbative uncertainties, among which colour reconnections hold a prominent place, are likely to be relevant in the drive towards sub-GeV uncertainties on the top mass at the Tevatron.

It is important to now verify the size of the observed uncertainties in real mass measurements and to increase the amount of non-top data used to constrain the models; Drell–Yan production, and in particular its high-mass tail, is likely to be useful in reducing the initial-state shower ambiguities, while the infrared effects could be further probed by expanding on the number of minimum-bias distributions, as well as including underlying-event studies in dijet and Drell–Yan production, again in particular when $Q \sim m_{\mathrm{top}}$ where the required extrapolation is presumably minimal. The connection with the LEP data (and, possibly, diffractive physics) should also be explored, although as we have noted the assumption of jet universality should probably not be treated as inviolate in this context.

On the theoretical side, we hope that the arguments we have presented will stimulate curiosity, and eventually activity, in this now somewhat dormant field. Along the intersection of the two communities, it would be interesting to explore alternative measurement strategies and, as a last resort, a combined tuning and top mass fit. A final follow-up we envision is to extrapolate in energy to evaluate the impact on precision studies at the LHC.

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