Recoil uncertainty in top mass measurement

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Abstract
We present the effect of treating the top quark as the recoiler during gluon emission in $t \to bW$ decay on direct top quark mass measurements. We study this effect using the Pythia8 Monte Carlo event generator within the CMSSW framework, and compare to recoil configurations used during LHC Run 2 and legacy Pythia8 configurations. We implement various analyses using the Rivet analysis toolkit to study this effect. The top mass is extracted from the lepton+jet hadronic top mass distribution, normalized jet mass in boosted top quark decays, the lepton+soft muon invariant mass distribution, and the invariant lepton+bottom quark mass distribution. The strong coupling constant α_s is tuned to CMS data separately for each of the three recoil configurations using the highly correlated variable ΔR_g. For each of the recoil models with and without tuned α_s, we extract a mass from each of the mentioned mass distributions, and calculate the difference between models. This process is done for both the Pythia8 Monash and CP5 tunes, as well as POWHEG+Pythia8 matching. Our study suggests that recoiling to the top quark introduces a systematic shift of at least -200 MeV shift to Run 2 top mass measurements.

Keywords
CERN Summer Student Report

1 Introduction

Precision measurement of the top quark mass has implications for the vacuum stability of our universe, as well as on which energy scales we may uncover new physics. Previous modeling of gluon emission recoil during top quark decay has raised theoretical concerns, as out of cone radiation and phase space may not be physically represented [2]. Recoil, or the redistribution of energy-momenta between a designated recoiler and radiator, impacts our reconstruction of invariant mass. We study the impact of changing our recoil model in top quark mass measurements.

In early releases of Pythia8 and LHC Run 2, particles W and b were designated as recoilers in coloured resonance decay, respectively. We refer to recoiling to W as RTW, and recoiling to bottom as RTB. A new Pythia8 Userhook allows us to treat the top quark as our recoiler, in an attempt to rectify the radiation and phase space concerns raised by earlier models. This new tool is hypothesized to provide results most consistent with theory expectations [3]. Recoiling to the top quark (RTT) was first used in analysis by a 2022 ATLAS top mass measurement, in which they reported an uncertainty of +/- 0.25 GeV due to recoil [4]. We aim to explore the effect of RTT on CMS measurements, as well as cross check the uncertainty reported by ATLAS. We perform this study for different top quark mass reconstruction methods using the Pythia8 Monte Carlo event generator in CMSSW. This study is then repeated across multiple Pythia8 generator setups, including but not limited to, POWHEG+Pythia8 matching and the updated CMS CP5 tune.

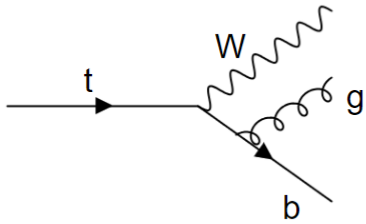
The outline of our paper is as follows. Section 2 discusses further the theory upon which we base our study of recoil uncertainty. Sections 3 and 4 explain the production and validation of the Monte

*Summer Student 2023

Carlo samples used in our analysis. Section 5 explains the changes in CMS analysis tools implemented by our analysis. In section 6 we discuss our extraction of a top mass value and comparison between recoil models. Finally, section 7 summarizes our work and discusses implications on future results.

2 Background

Broadly speaking, changes in gluon emission modeling impact all coloured resonance decays, however this study focuses on $t \to bW$ as our antenna shower. As the top quark decays to a bottom quark and a W boson, gluon emission can occur. How we model the subsequent showers determines how we accurately we can reconstruct the original top quark.



Gluon emission results in a change in energy-momentum, however we must distribute this to other particles in the system to ensure that conservation laws are preserved. We designate the gluon's particle of origin as the radiator, and the particle which assumes the difference in energy-momentum as the recoiler. As the top decay contains three final state particles, models of our shower can designate any of the three to be recoilers. It is important to note that the initial gluon emission is fixed to treat the W boson as the recoiler, so the changes we study impact only second and subsequent gluon emissions [3].

Our choice of recoiler greatly impacts the emission phase space. If we recoil off of the W, as in the initial gluon emission, the entire phase space remains accessible, however the W boson receives too much of this energy-momentum, and the radiation can be unphysical. If we recoil off of the b, i.e. combining radiator and recoiler, our phase space is collapsed, and the resulting emission trends towards collinearity with the b-jet. This corrects the unphysical radiation pattern from RTW, however this can result in too little out of cone radiation, mass peaks which are probably too narrow, and the W receiving very little kick (likely too little). Treating the top quark as our recoiler is very similar to RTW, however it introduces an eikonal factor which is weighted by the top mass. The phase space is smaller than RTW's, but not as collinear with the b-jet as RTB's. This likely still overestimates the 'kick' to the W, however it has been suggested as a good starting point, since these phase space effects suggest RTT will be somewhere in between RTB and RTW [2].

RTB is treated as the primary, default comparison, due to its usage in LHC Run 2 measurements. Both RTT and RTW allow for wider gluon emissions than RTB, thus we expect changes in observables used in mass reconstruction. Notably, in RTT and RTW we predict reduced b-jet energy, hardened b-hadron momenta, and a mild impact on W p_t [4].

3 Sample production and tuning

Monte Carlo generated samples form the basis of our study. We produce ttbar samples with Pythia settings (including the strong coupling constant α_s^{FSR}) in four difference configurations (3.1), for each of RTB, RTW, and RTT. All of our analyzed samples are produced using Pythia 8.309 within the CMSSW Generator Interface framework. Each of our primary samples contain at least 10 million events.

Initially, we work in Pythia8 with the default settings, which correspond to the Monash tune. We then produce samples at both the default $\alpha_s = 0.1365$ setting, as well as our own extracted tuned α_s values (unique for each recoil model). This process is also done in Pythia8 using updated CP5 tune settings, where default $\alpha_s = 0.118$, and from which we also extract another α_s tuning. The latter pair of

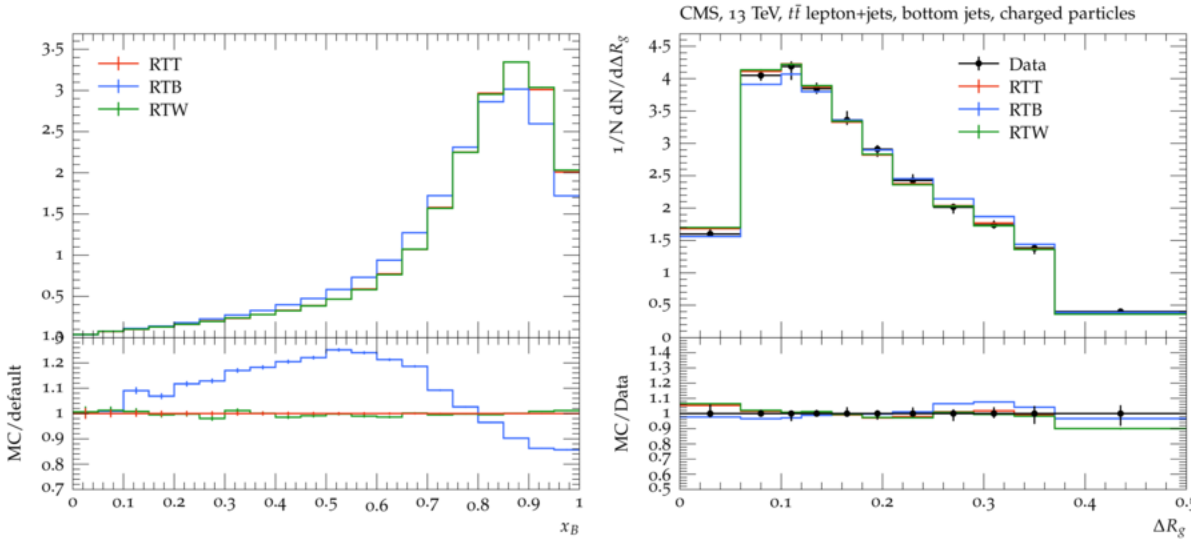


Figure 1: Key observables for measuring the impact of our recoil modes. Note the differences between recoil modes.These plots correspond to the default Pythia8 configuration (Monash).

settings are also used in generating POWHEG+Pythia8 samples matching the parton shower to an NLO matrix-element calculation for the hard process.

Initial samples yield statistically significant differences in key observables. The differential B hadron momenta fraction x_B and the measure between the hardest two prongs of the b-jet, ΔR_g, are sensitive to the recoil setting, especially since the gluon should be the first emission. A difference in these observables should be reflected later with differences in extracted top mass. They are shown in Fig. 1.

3.1 Tuning the strong coupling constant α_s^{FSR}

To explore the correlation of the strong coupling constant to a recoil models, we perform a series of α_s scans. We use the HEPdata entry and covariance matrix from CMS-TOP-17-013, and minimize χ^2 on the highly correlated observable ΔR_g [5]. The observable is selected as it is very sensitive to α_s, as well as it is independent from the top mass. Most importantly, we have data measurements against which to tune.

The plots displayed in Fig. 2 correspond to the χ^2 between CMS-TOP-17-013 data and MC as a function of α_s as labelled for each recoil mode. For each model we apply 4 different fits: B-spline, quadratic fit, quadratic fit with reduced input range, and polyfit, and average the extracted minimum to

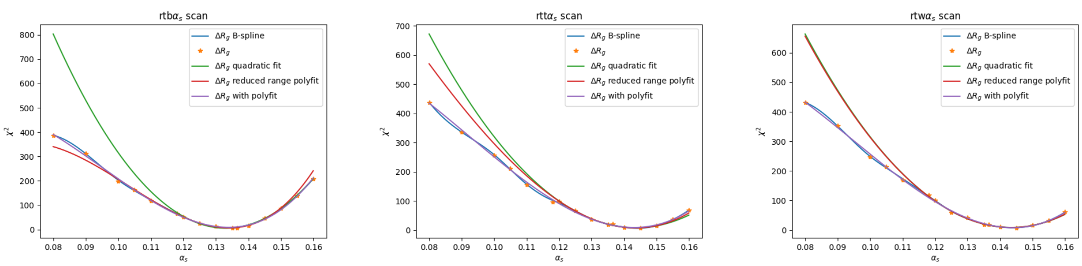


Figure 2: χ^2 minimization plots for default Pythia8 configuration (Monash).

Table 1: Results of α_s tuning procedure, Pythia 8 default settings, $\alpha_{s,default} = 0.1365$

Recoil option	**Tuned α_s**	**Uncertainty**
RTB	0.1336	0.0004
RTT	0.1436	0.0004
RTW	0.1437	0.0003

Table 2: Results of α_s tuning procedure, CP5 settings, $\alpha_{s,default} = 0.118$

Recoil option	**Tuned α_s**	**Uncertainty**
RTB	0.1264	0.0004
RTT	0.1344	0.0004
RTW	0.1346	0.0008

determine the optimal α_s for each respective recoil mode.

We perform this scan twice for each recoil mode, once for the Pythia8 Monash tune, and once for the Pythia8 CP5 tune (B.2). Significantly, RTT and RTW behave very similarly, however they diverge from the default α_s^{FSR} values of $\alpha_s^{FSR} = 0.1365$ for the Monash tune, and $\alpha_s^{FSR} = 0.118$. RTB also diverges, but not to the scale of the other recoil modes. For the remainder of the study, tuned α_s refers to the strong coupling constant values reported in tables 1 and 2.

3.2 Qualitative tuning results

Initial results from tuning α_s are promising, as we see better agreement in our key observables after tuning. However, quantitative comparisons are necessary between all of our mass models.

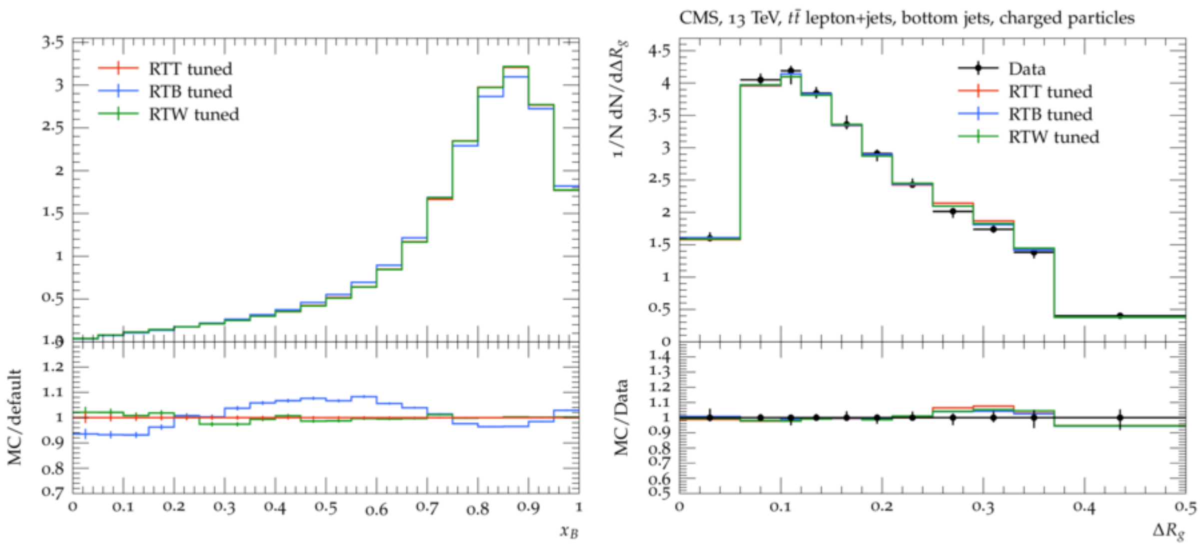


Figure 3: Key observables for measuring the impact of our recoil modes. Note the reduced differences between recoil modes. These plots correspond to the default Pythia8 configuration (Monash).

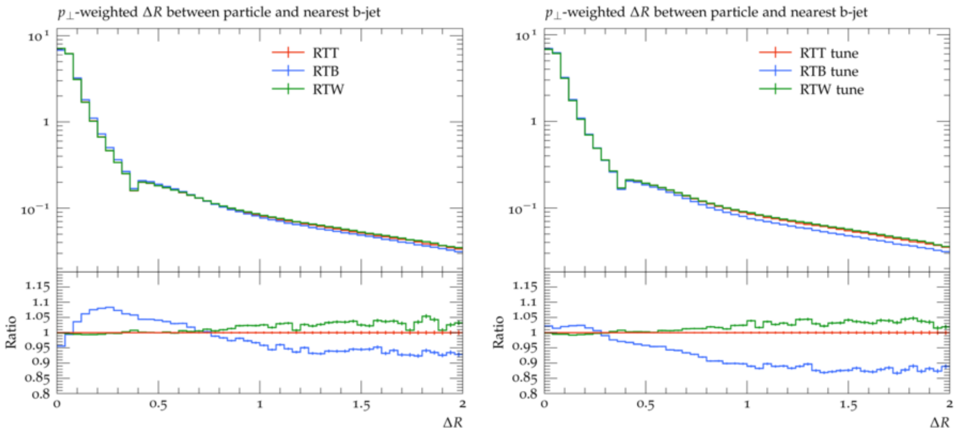


Figure 4: p_T-weighted ΔR at $E_{COM} = 500$ GeV

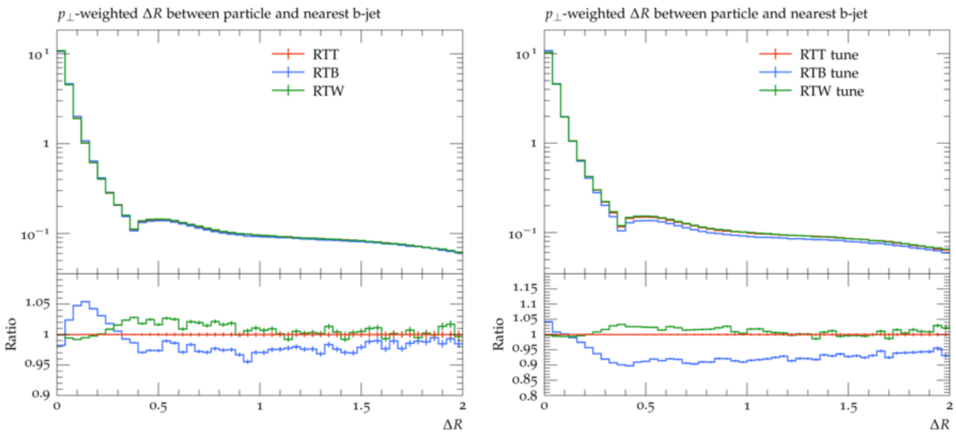


Figure 5: p_T-weighted ΔR at $E_{COM} = 1$ TeV

4 Additional studies

To confirm that our recoil modes are behaving as expected, and to ensure we are performing an inclusive study without missing any major effects, we conduct a series of extra studies.

4.1 Jet substructure and radiation effects

Most importantly, we wish to see that the three recoil modes behave as expected, relative to one another. This means that we expect to see higher b-jet energy in RTB than in RTT, and higher b-jet energy in RTT than in RTW. Similarly, RTB should have very little wide-angle radiation.

In order to evaluate this effect, we produce MC samples for e^+e^- collisions producing ttbar events in the dilepton decay channel because these events are very clean for studying b-jets from top quark decays. Samples are produced at $E_{COM} = 500$ GeV and $E_{COM} = 1$ TeV, and use the same settings as we see in the Monash tune, and thus the same tuned α_s^{FSR} values as extracted earlier.

Initially, the p_T-weighted ΔR between particles in the shower and the nearest b-jet demonstrates that radiation in RTB is emitted at smaller angles than in the other recoil models, especially when ΔR is larger than the jet radius. Importantly, this trend is amplified as both center of mass energies increase, and after tuning. Note this effect in Fig. 4 and Fig. 5.

We look one step further to see how the ratio of energy in the b-jet changes as we vary the maximum ΔR. We almost immediately see expected energy relationships between recoil modes. Before

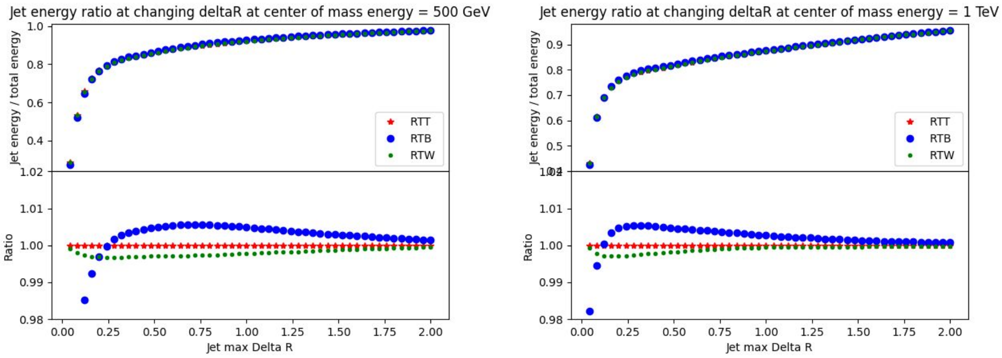


Figure 6: Jet energy ratios before applying tuned α_s.

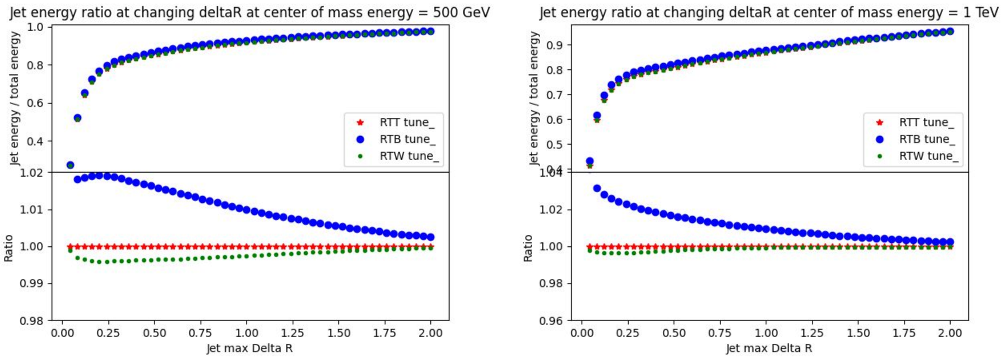


Figure 7: Jet energy ratios after applying tuned α_s.

tuning, at both $E_{COM} = 500$ GeV and $E_{COM} = 1$ TeV, we see that the b-jet energy in RTB is very focused within a narrow jet radius, and has a higher energy than both RTT and RTW (Fig. 6).

Our samples with tuned α_s reflect this same trend of RTB having higher b-jet energy than the other modes, and RTT being more energetic than RTW. However, we note that the ratio plot shape of RTB changes from the default α_s settings, losing the peak seen in Fig. 6. This is shown in Fig. 7.

4.2 Further effects of α_s tuning

A brief check on the impacts of tuning the strong coupling constant on measured observable data is presented. We see that some jet substructure observables are more impacted by α_s than our recoil modes, as seen in the τ_{32} distributions shown in Fig. 8.

Further, we mention that our tuning of α_s worsens our description of light jet observables, as shown in Figure 9. The light jet pairs are constrained to the W mass for top mass measurements, so it does not raise concern for our analyses. This may merit further analysis, especially as CMS considers new tunes of the strong coupling constant.

4.3 Deadcone effect

We also explore the impact of wide angle suppresion on the differences between recoil models [2]. Wide angle suppresion via the 'recoilDeadCone' option in Pythia8 is switched on by default. We evaluate the impact of switching off this wide-angle suppresion, i.e. allowing 'primary' gluon emissions to be found in the dead cone region.

A comparison across the L+jets mass extraction method yields a difference in top mass which is

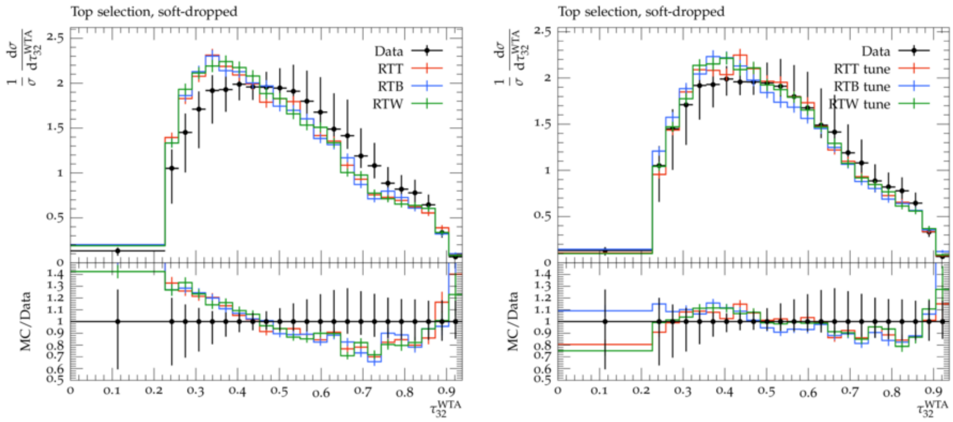


Figure 8: τ_{32} distributions in the default and tuned POWHEG+Pythia8 configurations. Note how the differences in the first bin mimic the relative behavior of the three tuning values for α_s.

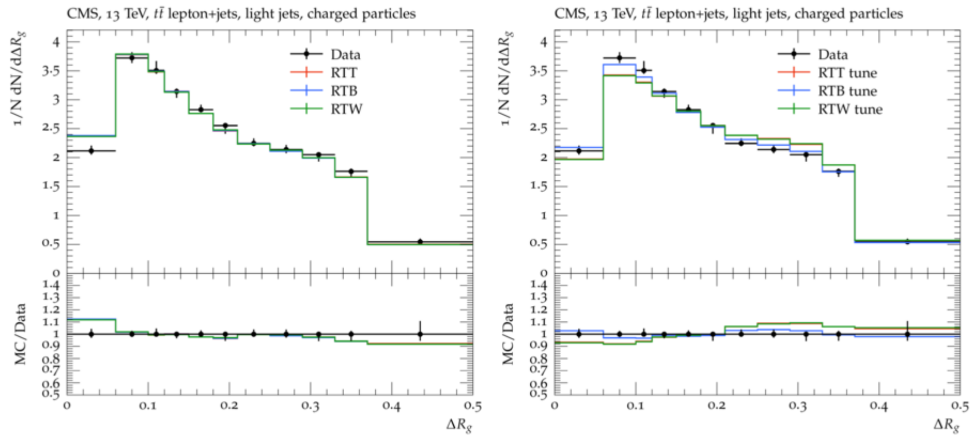


Figure 9: Comparison of ΔR_g light jet observable with default and tuned values of α_s and POWHEG+Pythia8 configuration.

not significant with respect to the reported statistical uncertainty. This holds for both the default and tuned values of α_s^{FSR} in the Pythia8 default setup (Monash tune). We deem this adequate to disregard the impact of the wide-angle suppression, as the L+jets analysis is our most statistically precise mass measurement method.

4.4 Vincia

Pythia8 is often interfaced with other modeling software, and the Vincia plugin can be used in place of the internal Pythia8 parton cascades [6]. As such, we expect our recoil modes to be ignored when it is switched on. Across low statistics (approx. 1 million events), we see that our key observables ΔR_g and

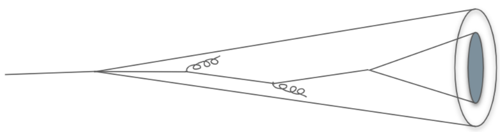


Figure 10: Sketch of wide angle suppression setting. When switched on, the shown gluons respect the dead cone demarcated by the grey region.

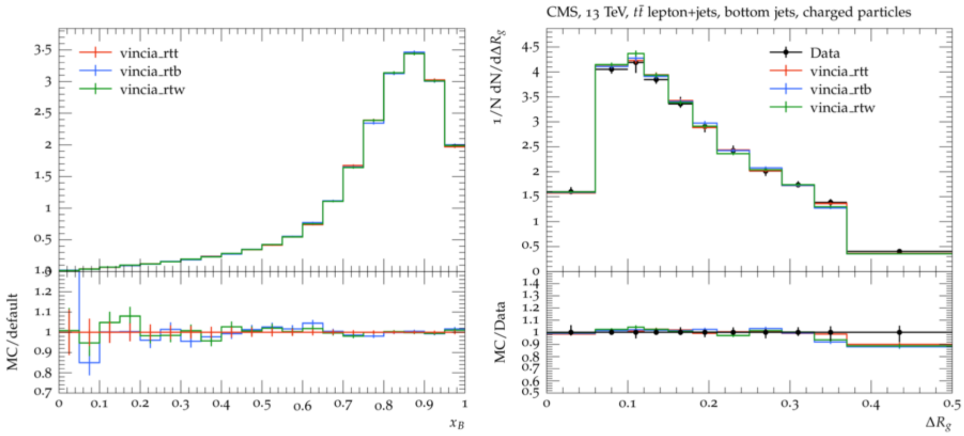


Figure 11: Key observables when Vincia plugin is switched on.

x_B behave as expected, i.e. all three recoil modes match, since they are not used in the simulation. The Vincia comparisons are shown in Fig. 11.

5 Technical review of recoil tools

A substantial amount of computational effort was devoted to development of the framework needed to perform comparisons across recoil modes.

5.1 Current status

A summary of the recoil tools available prior to June 2023.

Throughout Run 2, recoil to bottom has been the default setting in gluon recoil modeling. Prior to Pythia 8.160, only recoil to W was available. These were selected by setting 'recoilToColoured = on/off', where the 'on' setting corresponds to what we call RTB.

Wide angle suppresion via the 'recoilDeadCone' option mentioned earlier is turned on by default in Pythia 8.309.

Our input top mass defaults to be set at 172.5 GeV.

The strong coupling constant α_s^{FSR} defaults to 0.1365 for the default Pythia8 configuration, and defaults to 0.118 when the global CP5 settings are applied.

5.2 Updates to CMSSW Pythia8 interface

The recoilToTop Userhook provided by Pythia authors is now integrated into the CMSSW Pythia8Interface. This can be switched on by setting 'TopRecoilHook:doTopRecoilIn = on'. We also provide a configuration script for testing.

5.3 Analysis implementation in Rivet

A new Rivet [9] analysis with which to extract the top mass via combination of the invariant mass of the primary lepton and a soft muon in top quark decay, is now implemented and merged. This is referred to as *MC_TOPMASS_LSMT*.

6 Results

With confirmation that the recoil modes behave as expected, relative to one another, we proceed to quantitatively assessing the difference between RTT, RTB, and RTW in top mass extractions.

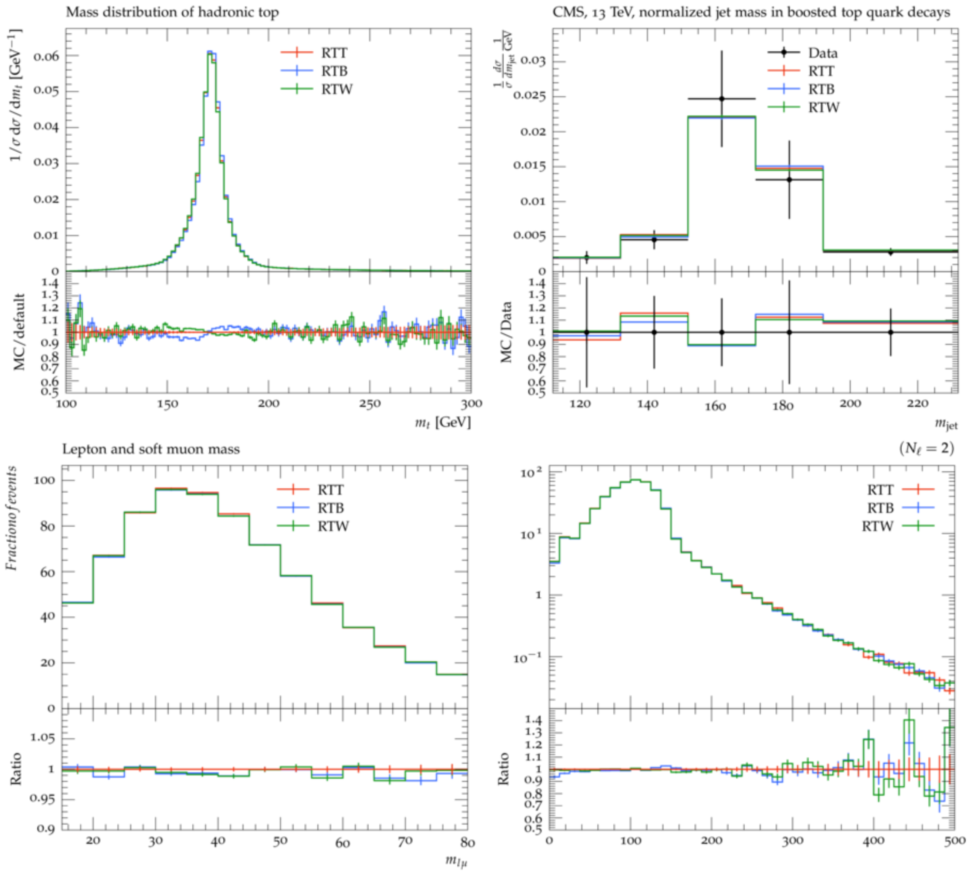


Figure 12: Mass distributions for recoil options in POWHEG+Pythia8 using the CP5 tune. Default α_s is used. In order of left to right, and top to bottom, mass distribution plots for L+jets, boosted top, L+ soft muon, and m(lb) are shown.

6.1 Extraction of top mass fit

In order to compare between models, we must extract a calibrated top mass from each mass measurement method, as L+jet, L+soft muon, boosted top decay jets, and m(lb) all measure different mass distributions.

First, we extract mass values from each mass distributions by fitting either a Breit-Wigner function (in the case of L+jets and boosted) or a Gaussian function (in the case of m(lb)), or by taking the mean value of the distribution (in the case of L+soft muon). The calibration is done by plotting this extracted mass peak from our distributions against the input mass while we perform a mass scan. This plot has a linear fit applied to it, as shown in Fig 14, and the returned fit parameters are used to get a calibrated, extracted mass. We apply the fit from RTB (as our current Pythia8 default), to the other two models, and compare the differences. Again, this process is repeated twice for each Pythia8 configuration (default, CP5 settings, and POWHEG+Pythia8), as we wish to compare differences between α_s variations as well.

6.2 Comparison between models

We make three primary comparisons between models. We take the calibrated, extracted masses as found in the previous section, and for input mass at 172.5 GeV we find the differences $RTB - RTT$, $RTW - RTT$, and $RTB - RTW$. These differences, as well as propagated uncertainties, are presented in Appendix B.1.

We take special notice of the $RTB - RTT$ comparison mode, as it is the correction from most cur-

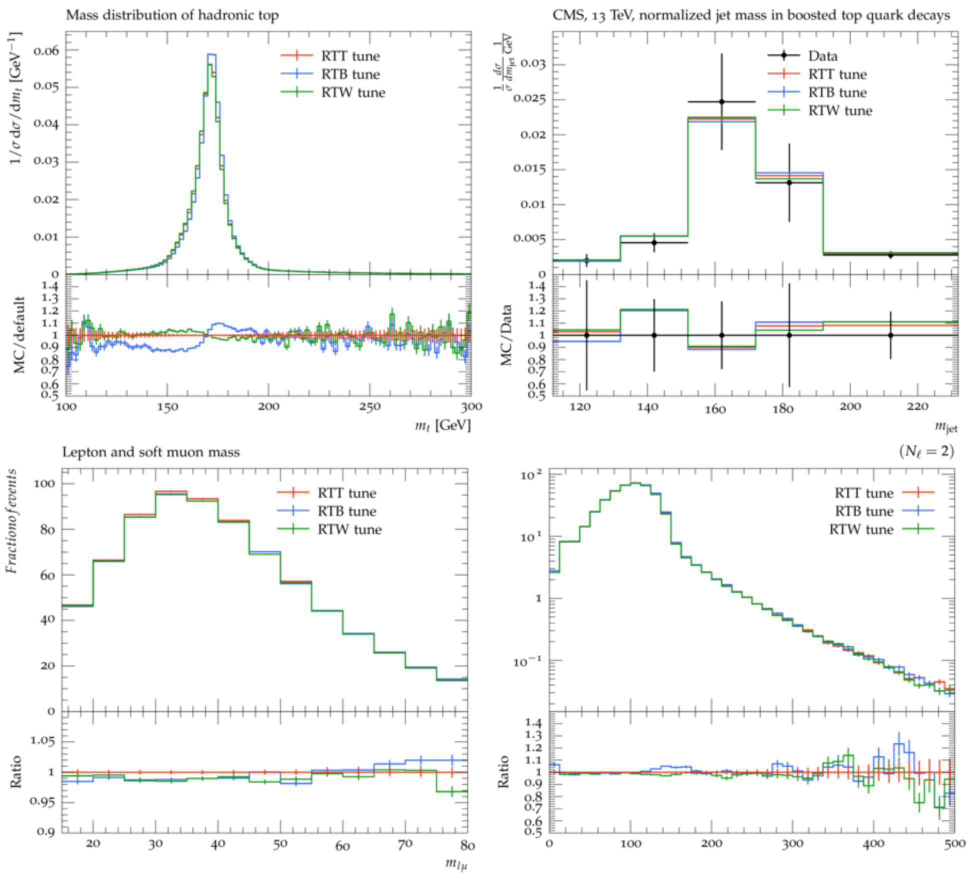


Figure 13: Mass distributions for recoil options in POWHEG+Pythia8. Tuned α_s is used. In order of left to right, and top to bottom, mass distribution plots for L+jets, boosted top, L+ soft muon, and m(lb) are shown.

rent Run 2 top mass measurements to the new recoilToTop model. From our mass comparison modes, the L+jets mass has the least statistical uncertainties, and is used in the most precise top mass measurements. Of the Pythia8 configurations, POWHEG+Pythia8 matching is used in the most precise current analyses (B.5, B.6). This setup minimizes the difference in $RTB - RTT$, and we see a shift of approximately 200 MeV.

The general behavior between models, with the exception of the untuned L+SMT, is in agreement between mass measurements. We observe that tuning increases the difference between models, however it increases the agreement between Pythia8 configurations and between mass measurements. Of our mass measurements, we most seriously consider the shift values from L+jet and Boosted, as the reduced statistical uncertainty means the mass shifts are significant.

7 Summary and outlook

The mass shifts due to changes in modeling gluon emission are very relevant in context of current top quark mass measurements. The shift between RTB and RTT in POWHEG+Pythia8 matching is on the same scale as reported experimental uncertainties in Run 2 measurements [8]. The L+jets and Boosted measurements show this with high confidence.

In order to further implement this result in CMS measurements, we have submitted samples for central production. We hope this will allow us to define the shift caused by recoilToTop with more confidence (i.e. continue to reduce stat. uncertainty), and actually apply said shift to future studies. Further studies should also include a better understanding of the effect of POWHEG on final state radiation

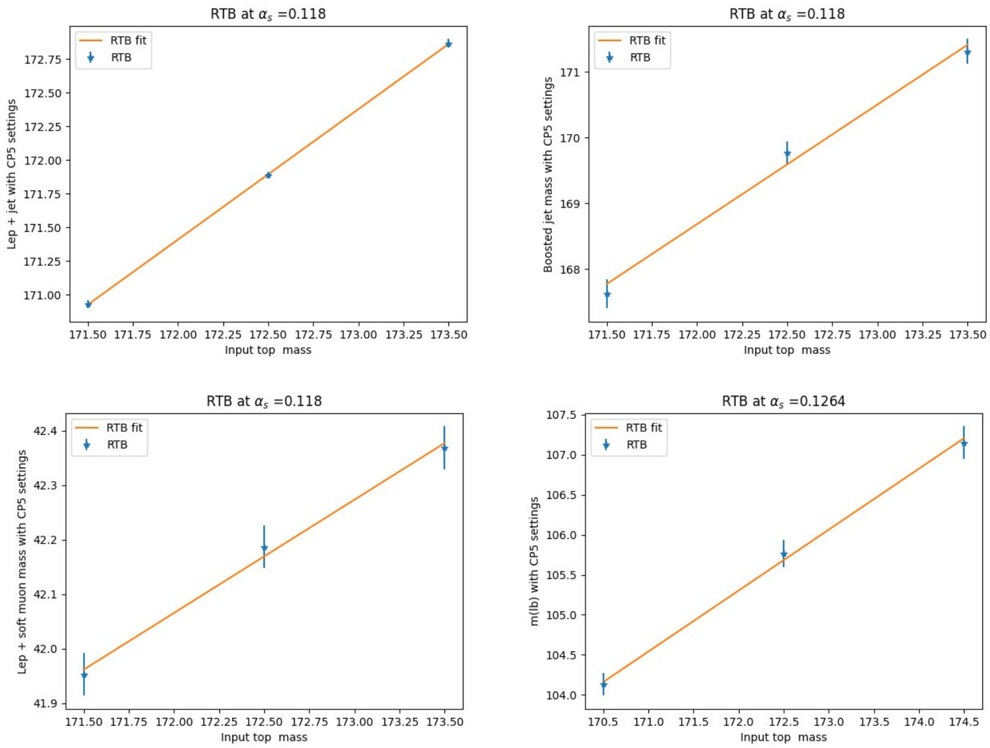


Figure 14: Example of calibration plots. RTB plots for POWHEG+Pythia8 are shown.

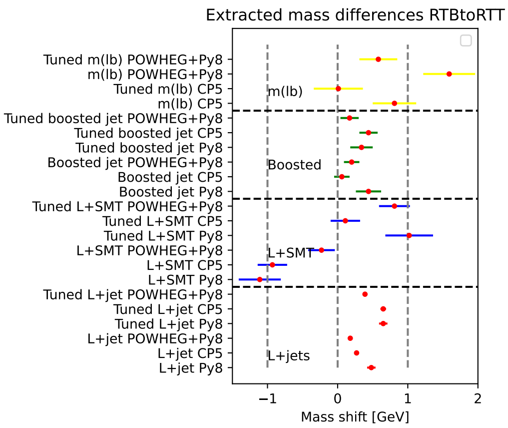


Figure 15: Full display of RTB - RTT shifts.

(FSR).

Future e^+e^- colliders will provide the best insight into how our jet substructures and showers behave, as clean observable data yields exciting opportunities to further improve our modeling of coloured decay resonances.

We look forward to continued collaboration and feedback from the top mass community, as we continue to explore the broader effects of changing the gluon recoil model.

Acknowledgements

This project was made possible by the CERN Summer Student Program 2023. Special thanks go to Karlis Dreimanis for comments and support during this process.

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Appendix

A Updates to Pythia8 and Rivet

A concise reference to find the changes made to Pythia8 and Rivet within CMS framework.

A.1 Pythia8Interface

Initial implementation of recoilToTop as an analysis plugin in ’GeneratorInterface/Pythia8Interface’ is done in PR #42180.This was implemented in Pythia 8.309. Beginning with Pythia 8.310, the recoilToTop Userhook and recoilToColoured option were combined and integrated in a new Pythia setting called *recoilStrategyRF* by Pythia authors.

A.1.1 Backports

As per maintainer requests, we provide backports of the plugin to previous versions of CMSSW to allow for legacy analysis.

- Backport to CMSSW_10_6_X in PR #42202
- Backport to CMSSW_13_0_X in PR #42338
- Backport to CMSSW_13_1_X in PR #42337
- Backport to CMSSW_13_2_X in PR #42332

A.2 Rivet

Initial CMS Rivet routine for extracting the invariant dilepton mass of the primary lepton and soft muon in top quark decay, for use in top mass reconstruction, is found in merge request 228.

The selection criteria for the L+SMT Rivet analysis is as listed below:

- Primary lepton cuts: $|\eta| < 2.5$, $p_T > 27$ GeV, prompt (from W decay)
- Soft muon cuts cuts:$|\eta| < 2.5$, $p_T > 8$ GeV, not prompt (from hadron decay)
- Jet cuts: $|\eta| < 2.5$, $p_T > 25$ GeV
- Additional requirements: $\Delta R_{l,\mu} < 2$, $\Delta R_{j,\mu} < 0.4$, $\Delta R_{l,j} > 0.4$, 15 GeV $< m_{l,\mu} <$ 80 GeV

B Additional plots

B.1 Further comparisons for mass shifts

The full tables containing all of the mass shifts values are attached in this section. All values are reported in GeV. Plots describing the global shifts $RTW - RTT$ and $RTB - RTW$ are also included.

Table B.1: Recoil model difference with top input mass at 172.5 GeV and default Pythia8 settings

Comparison mode	α_s **setting**	**L+jet**	**L+soft muon**	**Boosted**
RTB-RTT	Default α_s	+0.48	-1.11	+0.44
	Tuned α_s	+0.65	+1.02	+0.34
RTW-RTT	Default α_s	-0.18	-0.42	+0.12
	Tuned α_s	-0.24	+0.12	-0.23
RTB-RTW	Default α_s	+0.65	-0.69	+0.32
	Tuned α_s	+0.89	+0.91	+0.57

Table B.2: Statistical uncertainty in recoil model differences at 172.5 GeV input mass and default Pythia8 settings

Comparison mode δ	α_s **setting**	δ **L+jet**	δ **L+soft muon**	δ **Boosted**
RTB-RTT	Default α_s	± 0.06	± 0.30	± 0.18
	Tuned α_s	± 0.06	± 0.34	± 0.16
RTW-RTT	Default α_s	± 0.06	± 0.31	± 0.19
	Tuned α_s	± 0.07	± 0.36	± 0.17
RTB-RTW	Default α_s	± 0.06	± 0.29	± 0.18
	Tuned α_s	± 0.06	± 0.33	± 0.17

Table B.3: Recoil model difference with top input mass at 172.5 GeV and CP5 settings

Comparison mode	α_s setting	L+jet	L+soft muon	Boosted	m(lb)
RTB-RTT	Default α_s	+0.27	-0.93	+0.06	+0.81
	Tuned α_s	+0.65	+0.11	+0.44	+1.59
RTW-RTT	Default α_s	-0.12	-0.41	-0.14	-0.57
	Tuned α_s	-0.25	-0.35	-0.21	-0.36
RTB-RTW	Default α_s	+0.39	-0.52	+0.20	+1.38
	Tuned α_s	+0.90	+0.46	+0.65	+1.95

Table B.4: Statistical uncertainty in recoil model differences with CP5 settings at 172.5 GeV input mass

Comparison mode δ	α_s setting	δ L+jet	δ L+soft muon	δ Boosted	0m(lb)
RTB-RTT	Default α_s	± 0.03	± 0.21	± 0.11	± 0.31
	Tuned α_s	± 0.04	± 0.21	± 0.13	± 0.37
RTW-RTT	Default α_s	± 0.03	± 0.22	± 0.11	± 0.33
	Tuned α_s	± 0.05	± 0.22	± 0.14	± 0.42
RTB-RTW	Default α_s	± 0.03	± 0.21	± 0.11	± 0.33
	Tuned α_s	± 0.04	± 0.22	± 0.13	± 0.39

Table B.5: Recoil model difference with top input mass at 172.5 GeV and POWHEG+Pythia8 matching

Comparison mode	α_s setting	L+jet	L+soft muon	Boosted	m(lb)
RTB-RTT	Default α_s	+0.18	-0.23	+0.20	+0.01
	Tuned α_s	+0.39	+0.81	+0.17	+0.58
RTW-RTT	Default α_s	-0.09	-0.10	-0.04	-0.31
	Tuned α_s	-0.13	+0.04	-0.18	-0.47
RTB-RTW	Default α_s	+0.27	-0.13	+0.24	+0.32
	Tuned α_s	+0.52	+0.78	+0.36	+1.04

Table B.6: Statistical uncertainty in recoil model differences at 172.5 GeV input mass and POWHEG+Pythia8 matching

Comparison mode δ	α_s setting	δ L+jet	δ L+soft muon	δ Boosted	m(lb)
RTB-RTT	Default α_s	± 0.03	± 0.19	± 0.11	± 0.35
	Tuned α_s	± 0.03	± 0.22	± 0.13	± 0.27
RTW-RTT	Default α_s	± 0.03	± 0.19	± 0.11	± 0.35
	Tuned α_s	± 0.04	± 0.23	± 0.13	± 0.28
RTB-RTW	Default α_s	± 0.03	± 0.19	± 0.11	± 0.35
	Tuned α_s	± 0.03	± 0.22	± 0.13	± 0.28

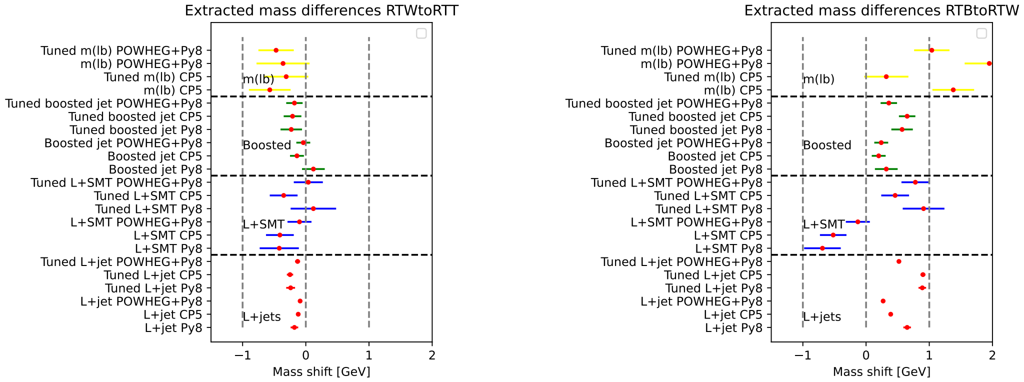
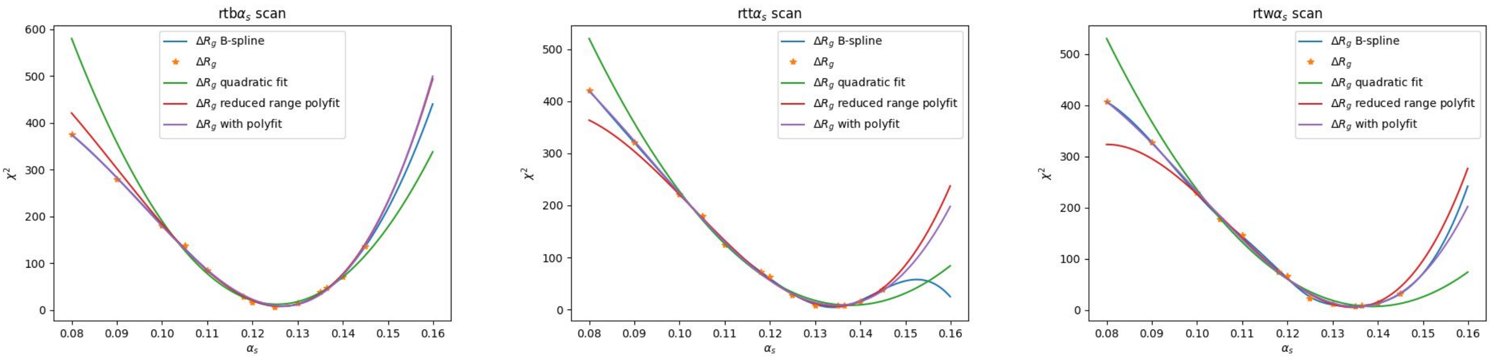


Figure B.1: Full display of RTW - RTT, and RTB - RTW shifts.

B.2 Additional α_s tuning plots

Strong coupling constant scan plots for the Pythia8 CP5 tune are included in this section. We also include plots for key observables x_B and ΔR_g in the POWHEG+Pythia8 with CP5 settings configuration.



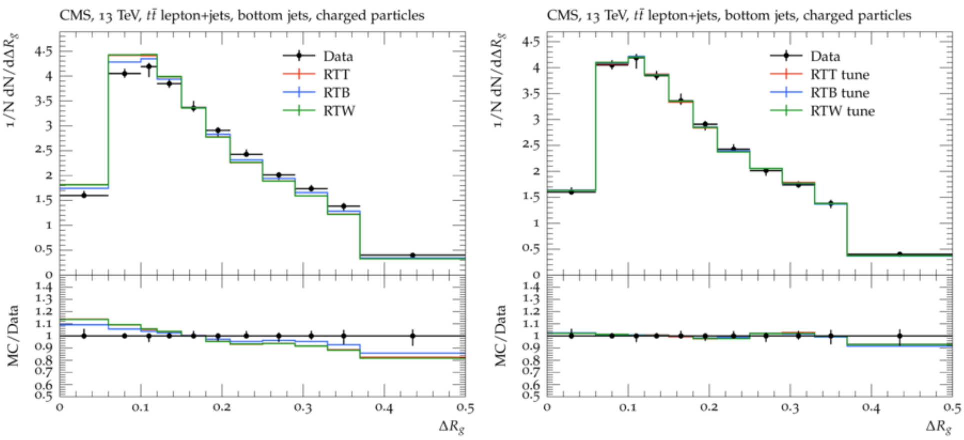


Figure B.2: ΔR_g for bottom jets in the POWHEG+Pythia8 configuration. Note how the observable is much better described after tuning.

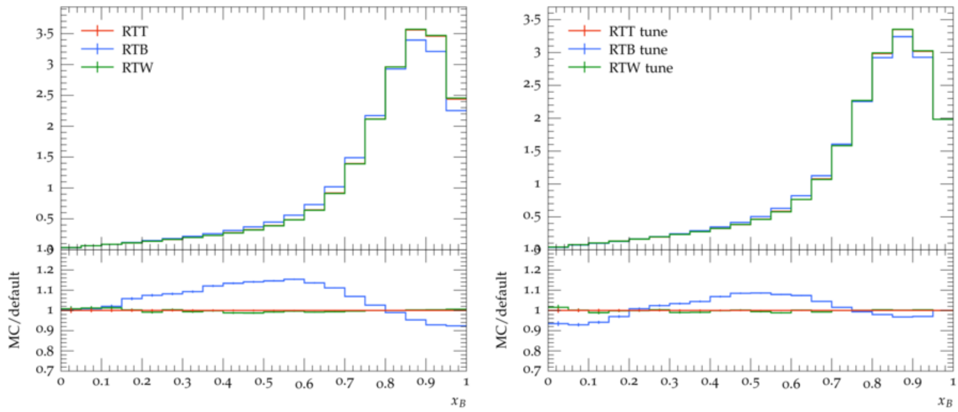


Figure B.3: x_B distribution for POWHEG+Pythia8 configuration.

B.3 Ttbar mass distributions

Ttbar mass distributions for the POWHEG+Pythia8 configuration are included in this section.

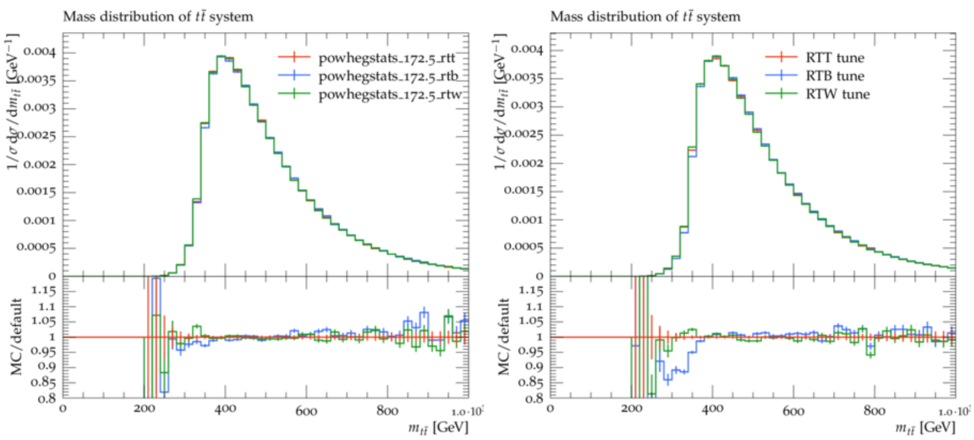


Figure B.4: Ttbar mass distributions for POWHEG+Pythia8 matching.