Recoil uncertainty in top mass measurement

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Introduction

- Studying simulation of top quark decays with gluon emissions

- $t \rightarrow bW$
  - Need to assign ‘recoil’ from gluons to other final state particles
  - Recoil to bottom (RTB), recoil to top (RTT), recoil to W (RTW)
  - Recoil uncertainty = how much does change in recoiler assignment impact extracted top mass

- Expectations in RTT and RTW observables:
  - b-jet energy reduced
  - b-hadron momenta hardened
  - $W p_t$ mildly impacted

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Objective

- Evaluate effect of new recoilToTop option on generator level top mass measurements in CMS
  - L + jets hadronic top mass (L+jet)
  - Lepton + soft muon mass (L+SMT)
  - Boosted top decay normalized jet mass (Boosted)
- Integrate RTT into CMSSW Pythia8Interface and Rivet
- 2022 ATLAS paper uses this in their analysis, reports uncertainty of \( \pm 0.25 \) GeV from recoil \(^4\)
  - We want to cross check this on different top mass measuring methods!

\(^4\) ATLAS Collaboration, “Measurement of the top-quark mass using a leptonic invariant mass in \( pp \) collisions at \( \sqrt{s} = 13 \) TeV with the ATLAS detector”, September 2022
Impact on b jet observables

- Difference **visible** between different recoil options!
  - Observables directly connected to b hadron momentum most impacted
  - Quite literally… b-hadron momentum fraction ($x_B$), b-jet internal angles
Tuning strong coupling constant $\alpha_s$

- Perform $\alpha_s$ scan using HEPdata entry from CMS-TOP-17-013 [5]
  - minimize $\chi^2$ on highly correlated observable delta $\Delta R_g$
  - Independent of input top mass

![Graphs showing $\alpha_s$ scan results]

<table>
<thead>
<tr>
<th>Returned $\alpha_s$</th>
<th>RTB = 0.1336</th>
<th>RTT = 0.1436</th>
<th>RTW = 0.1437</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1\sigma$</td>
<td>0.0004</td>
<td>0.0004</td>
<td>0.0003</td>
</tr>
</tbody>
</table>

Qualitative tuning results

- Better agreement to observable data and other recoil schemes AFTER tuning
Qualitative tuning results

- Better agreement to observable data and other recoil schemes AFTER tuning

Post tune
Jet substructure and radiation effects

- Confirmation via study of e+e- at $E_{\text{COM}} = 500$ GeV
  - Behavior between models as expected from theory
    - Much less wide-angle radiation in RTB
    - More energy in RTB jet, jet less focused after tune
Top mass comparisons

L+jet

Pre-tune

L+SMT

Post-tune

Boosted
Top mass calibration

- Need to calibrate BEFORE we evaluate top mass shift
- Plot input mass vs. mass plot peak
  - Fit to $y = a*(x-172.5)+b$ and use fit parameters $a$ and $b$ to get extracted masses
- Apply fit from RTB to both RTT and RTW
  - Compare differences!

Example plots:

- **L+jets**: RTB at $\sigma_t = 0.1365$
- **L+SMT**: RTB at $\sigma_t = 0.1365$
- **Boosted**: RTB at $\sigma_t = 0.1365$
Top mass results

- Notable shifts between recoil models
  - RTT and RTW behave very similarly (expected)
  - RTB to RTT have bigger shift
  - Importance of $\alpha_s$ tuning
    - Big impact on lep + soft muon method

- Technical work:
  - RecoilToTop implemented as Pythia8 plugin [6]
    - Backported to older CMSSWs for Run 2 analysis
  - Rivet routine for L+soft muon implemented

<table>
<thead>
<tr>
<th>$\alpha_s$ setting</th>
<th>L+Jet</th>
<th>L+SMT</th>
<th>Boosted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Default $\alpha_s$</td>
<td>+0.48 GeV</td>
<td>-1.11 GeV</td>
<td>+0.44 GeV</td>
</tr>
<tr>
<td>Tuned $\alpha_s$</td>
<td>+0.65 GeV</td>
<td>+1.02 GeV</td>
<td>+0.34 GeV</td>
</tr>
</tbody>
</table>

RTB - RTT at 172.5 GeV input mass

[6] PR #42180
Backup!
Continuation of work

- Implement Powheg matching
- Perform tunes using current CMS data (CP5 tune), check if shift consistent
- Central production
Additional studies: dead cone effect

- Compare default setting with switching off wide angle suppression via recoilDeadCone
- Comparison on L+jets yields only statistical difference, i.e. no change!
  - Reported statistical uncertainty in L+jets sample of 30 MeV
  - Default tune: Approximately 30 MeV change between sample with and without wide angle suppression
  - Tuned $\alpha_s$: < 10 MeV less difference between samples with and without dead cone setting

Emissions from these ‘primary’ gluons also respect dead cone
Tuning strong coupling constant $\alpha$

- Mimic procedure used in CMS-TOP-17-013 [5]
  - $\Delta R_g$ observable very sensitive to $\alpha_s$ AND independent of top mass

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[5] CMS Collaboration, “Measurement of jet substructure observables in ttbar events from proton-proton collisions at $s\sqrt{=} 13\text{ TeV}$”, December 2018
Scaling procedure fits

Default Pythia8:

<table>
<thead>
<tr>
<th>Reco type</th>
<th>L+soft muon</th>
<th>L+jet</th>
<th>Boosted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fit params</td>
<td>a=0.21 +/- 0.01 b=41.62 +/- 0.02</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>a=0.97 +/- 0.01 b=171.48 +/- 0.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>a=0.86 +/- 0.17 b=183.28 +/- 0.29</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Scaling procedure fits

Tuned:

<table>
<thead>
<tr>
<th>Reco type:</th>
<th>L+soft muon</th>
<th>L+jet</th>
<th>Boosted top jet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fit params:</td>
<td>a=0.19 +/- 0.01 b=41.73 +/- 0.01</td>
<td>a=0.97 +/- 0.01 b=171.48 +/- 0.01</td>
<td>a=0.67 +/- 0.09 b=183.43 +/- 0.19</td>
</tr>
</tbody>
</table>
Differences between recoil models

- RTB - RTT: correction for Run 2 measurements to RTT scheme
- RTB - RTW: correction for Run 2 measurements to Run 1 setup
- RTW - RTT: correction for Run 1 measurements to RTT scheme

<table>
<thead>
<tr>
<th>Comparison mode</th>
<th>α_s setting</th>
<th>L+jet</th>
<th>L+soft muon</th>
<th>Boosted</th>
</tr>
</thead>
<tbody>
<tr>
<td>RTB-RTT</td>
<td>Default α_s</td>
<td>+0.48</td>
<td>-1.11</td>
<td>+0.44</td>
</tr>
<tr>
<td></td>
<td>Tuned α_s</td>
<td>+0.65</td>
<td>+1.02</td>
<td>+0.34</td>
</tr>
<tr>
<td>RTW-RTT</td>
<td>Default α_s</td>
<td>-0.18</td>
<td>-0.42</td>
<td>+0.12</td>
</tr>
<tr>
<td></td>
<td>Tuned α_s</td>
<td>-0.24</td>
<td>+0.12</td>
<td>-0.23</td>
</tr>
<tr>
<td>RTB-RTW</td>
<td>Default α_s</td>
<td>+0.65</td>
<td>-0.69</td>
<td>+0.32</td>
</tr>
<tr>
<td></td>
<td>Tuned α_s</td>
<td>+0.89</td>
<td>+0.91</td>
<td>+0.57</td>
</tr>
</tbody>
</table>
Important plots not otherwise shown
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- Note minimal difference, so b momenta is primary factor in xB
Tuning effect on light jets

- Tune might have negative effect on light jets
  - Need independent alpha_s tunes for light and bottom jets?