Top Quark Mass
Theory Developments

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Motivation update

Old phase diagram
(arXiv:1307.3536)

New phase diagrams
(1708.08124)

What changed?
• Complete instability boundary to NLO
• Stability boundary gauge invariant
• EW/QCD threshold effects included
• Proper handling of correlated errors
• Universe lifetime = $10^{139}$ years

Higgs mass uncertainty smaller than $\alpha_s$ uncertainty

For $3\sigma$ exclusion need
• $\Delta m_t < 250$ MeV or
• $\Delta \alpha_s < 0.00025$
Fine tuning?
Top mass schemes

Best measurements come from reconstructing hadronic top decays

CMS (7&8 TeV): $172.44 \pm 0.48$ GeV
ATLAS (8 TeV): $172.84 \pm 0.70$ GeV
PDG 2014: $173.1 \pm 0.6$ GeV

Is there an additional scheme ambiguity?

Monte Carlo mass
• Parameter in PYTHIA/Herwig
• Depends on tuning
• How to relate to theoretically precise mass (i.e. MSbar)?

Pole mass
• Well defined theory mass
• Translation to MSbar has a ~110 MeV ambiguity 1605.03609
  • Related to non-convergence of asymptotic series
• Equals MC mass at leading order

MSR mass
• Introduced by Hoang et al. 0803.4214
• Converts to MSbar mass without ambiguity
• Used in precision boosted top calculations e.g. 1708.02586
• Closer to MC mass?
  • Conversion depends on tuning
Higher-order QCD effects

Convergence better using MSR than pole for boosted tops (1608.01318)

Unboosted tops, should use pp → tt at NLO matched to parton showers
- Including interference and decay in PowhegBox (1607.04538)
- Uses NLO pole mass $m_t^{\text{pole}} \rightarrow m_t^{\overline{\text{MS}}}$
- Still tuning ambiguity induced by matching to PS
Reducing MC mass uncertainty

MC mass is not a single mass
- Depends on process (e⁺e⁻ vs pp)
- Depends on tuning
- Should be $m_t^{MC}(\alpha_s, \text{ISR, FSR, had-model}, \cdots)$

Estimate tuning uncertainty by varying tunes
- Use ATLAS A14 tunes, cross check with others
- Simulate top events, cluster, and fit shape to extract mass

$\Delta m_t^{MC} = 530 \text{MeV}$

**W calibration:**
- Corrects for Jet Energy Scale (exp. Issue)
- Also corrects for soft radiation
  - ISR, FSR, Underlying Event, Pileup...

$\Delta m_t^{MC} = 200 \text{MeV}$
Reducing MC mass uncertainty

Additional reduction with jet grooming

Jet Trimming (arXiv:0912.1342)
- Reclusters with kT
- Drops soft subjets or size $R_{sub}$

\[ p_{T,\text{sub}} < f_{cut} p_{T,\text{jet}} \]

Soft Drop (arXiv:1402.2657)
- Reclusters with Cambridge/Aachen
- Drops soft branches of tree

\[ \frac{\min(p_{T,1},p_{T,2})}{p_{T,1} + p_{T,2}} = z > z_{cut} \left( \frac{\Delta R_{12}}{R} \right)^\beta \]

Table 1: Optimal grooming parameters:

<table>
<thead>
<tr>
<th></th>
<th>Trimming ($f^<em>_\text{cut},R^</em>_\text{sub}$)</th>
<th>Soft Drop ($z^<em>_\text{cut},\beta^</em>$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>without $W$-calibration</td>
<td>-</td>
<td>(0.05,0.5)</td>
</tr>
<tr>
<td>with $W$-calibration</td>
<td>(0.02,0.2)</td>
<td>(0.1,1.0)</td>
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</tbody>
</table>
Reducing MC mass uncertainty

Figure 4: Comparison of $m_{MC}$ for subsets of A14 tunes, pp tunes and $e^+e^-$ tunes, for soft drop, trimming and no grooming for optimized grooming parameters.

Table 2: Uncertainties on $m_{MC}$ after various corrections are included. Percentage change from no grooming, without $W$-calibration is shown in parenthesis. We estimate around a 50 MeV uncertainty on these numbers due to statistical fluctuations and fitting inaccuracies.

| no grooming             | without $W$ calibration | with $W$-calibration | Soft-drop reduces uncertainty to $\Delta m_t^{MC} = 140 MeV$
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<tbody>
<tr>
<td>No grooming</td>
<td>530 MeV</td>
<td>200 MeV (−62%)</td>
<td></td>
</tr>
<tr>
<td>Trimming</td>
<td>530 MeV (0.0%)</td>
<td>170 MeV (−68%)</td>
<td></td>
</tr>
<tr>
<td>Soft drop</td>
<td>390 MeV (−26%)</td>
<td>140 MeV (−74%)</td>
<td></td>
</tr>
<tr>
<td>$e^+e^-$</td>
<td>110 MeV (−79%)</td>
<td>50 MeV (−90%)</td>
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Soft drop is theory-friendly

- Soft drop jets are process-independent (no event-wide color connections)
- Resummation known to NNLL level
- Active area of theory research
- CMS just measured soft-drop jet mass (SMP-16-010)

Jet mass theory
(arXiv 1603.06375)

Jet mass experiment
CMS (SMP-16-010)

Boosted top jet theory
(arXiv 1708.02586)
Summary

- Mass reconstruction in semileptonic top decays is currently the best method for top mass measurement.

Need $\Delta m_t < 250$ MeV to exclude absolute stability.

- May be possible convert to MC mass to well-defined mass (MSR mass) for boosted tops.
- Unboosted tops should use NLO top mass distribution, matched to MC:
  - Available in Powheg (see 1607.04538).
  - NLO reduces pure theory uncertainty.
  - Residual tuning uncertainty same as MC mass tuning uncertainty.

Converting between schemes is a theory problem.
Reducing sensitivity to tuning has to be done during measurement.

- Top MC mass is tuning dependent: $\Delta m_t^{MC} = 530$ MeV.
- Dependence reduced with:
  - W-Calibration (JES calibration): $\Delta m_t^{MC} = 200$ MeV.
  - Soft-drop jet grooming:
    - Theory friendly: $\Delta m_t^{MC} = 140$ MeV.