The top quark mass

Sonny Mantry, Alexander Mitov, Peter Skands and Erich Varnes

Summary on top quark mass for the first meeting of the top quark group in preparation for Snowmass 2013

Outline:

- Document the need for precision top mass determination in the LHC era
- Discuss the main issues arising in precision top mass determination
- Collect and document existing results on top determination at hadron colliders
- Map the prospects for future precision top mass determination

- The top mass is not an observable. Being a formal parameter, it is up to us to define it.
- Observables are not affected by this choice (of definition).
- To extract the top mass *in any given scheme* invert the relation:

$$\sigma^{\rm exp}(\{Q\}) = \sigma^{\rm th}(m_{\rm top}, \{Q\})$$

- This relation is not exact, however:
  - Theory errors
    - higher order perturbative,
    - Non-Perturbative,
    - Top/W widths;
  - Experimental errors
    - the obvious ones, quoted in measurements
    - in practice, there could also be some TH input and mild m_top dependence in EXP

All of these have to be controlled to achieve claimed precision.

Top mass definition

- A large number of schemes exist: pole, MSbar, 1S, etc.
- The idea is they can be related to each other:

$$m_{\rm top}^{\rm pole} = m_{\rm top}(R,\mu) + \delta m_{\rm top}(R,\mu) \qquad \delta m_{\rm top}(R,\mu) = R\sum_{n=1}^{\infty}\sum_{k=0}^{n} a_{nk}\left[\alpha_s(\mu)\right]^n \ln^k\left(\frac{\mu^2}{R^2}\right)$$

- Relation between pole mass and MSbar mass is known through 3 loops in QCD

[4] K. G. Chetyrkin and M. Steinhauser, Phys. Rev. Lett. **83**, 4001 (1999) [hep-ph/9907509].
[5] K. Melnikov and T. v. Ritbergen, Phys. Lett. B **482**, 99 (2000) [hep-ph/9912391].

- Numerically large EW corrections reported recently:

[6] F. Jegerlehner, M. Y. .Kalmykov and B. A. Kniehl, arXiv:1212.4319 [hep-ph]

Note: could be very important; but is it is the same MSbar mass?

The bottom line: how to relate the experimental measurements to a particular top mass scheme (could be any one, in principle).

Top mass: the numbers

- Currently, the top mass $\delta m_{\rm top} \lesssim 1\,{\rm GeV}$

  Tevatron, (LHC close behind)

- Ultimately, ILC/CLIC can reach $\delta m_{\rm top} \lesssim 100\,{\rm MeV}$ or better

  See talk by Sasha Penin

- See also recent CLIC studies: LCD Note-2012-013

  hlp://cds.cern.ch/record/1498599/files/LCD-2012-013.pdf

Where does the top mass precision matter?

- Current O(1 GeV) does not appear to be limiting factor in collider physics <u>at present</u>
- EW precision fits restricted by the W mass, not m_top
- But could matter for:
  - Vacuum stability of the Standard Model

    [19] G. Degrassi, S. Di Vita, J. Elias-Miro, J. R. Espinosa, G. F. Giudice, G. Isidori and A. Strumia, JHEP **1208**, 098 (2012) [arXiv:1205.6497 [hep-ph]].

  - Cosmology (Higgs Inflation)

    [21] F. L. Bezrukov and M. Shaposhnikov, Phys. Lett. B **659**, 703 (2008) [arXiv:0710.3755 [hep-th]].
    [22] A. De Simone, M. P. Hertzberg and F. Wilczek, Phys. Lett. B **678**, 1 (2009) [arXiv:0812.4946 [hep-ph]].

Issues in precision top mass determination at hadron colliders

- MC modeling
- Reconstruction of the top pair
- Unstable top and finite top width effects.
- Bound-state effects in top pair production at hadron colliders.
- Renormalon ambiguity in top mass definition.
- Alternative top mass definitions.
- Higher-order corrections.
- Non-perturbative corrections.
  NOTE: new options in Pythia 6.4.27 for controlling color reconnections

More details on the above can be found in the writeup.

Methods for top mass determination

- Matrix element methods
  - The "classics". So far takes input from LO QCD. To be extended to NLO:

[57] J. M. Campbell, W. T. Giele and C. Williams, JHEP **1211**, 043 (2012) [arXiv:1204.4424 [hep-ph]].

- Extraction from the total cross-section σ_{tot}
  - Somewhat clean approach with good theory control. Not as sensitive to m_top.

- The J/ψ method

[58] A. Kharchilava, Phys. Lett. B **476**, 73 (2000) [hep-ph/9912320]

  - theoretically very well defined; does not rely on reconstruction of hadronic final state. With enough statistics, could be competitive with the best measurements. Known in full NLO:

[46] S. Biswas, K. Melnikov and M. Schulze, JHEP **1008**, 048 (2010) [arXiv:1006.0910 [hep-ph]]

- Dilepton-specific methods.
  - Look at the distributions of the leptons in dileptonic events. Theoretically well defined. Not sensitive to modeling of hadronic radiation. Known in full NLO:

[33] A. Denner, S. Dittmaier, S. Kallweit and S. Pozzorini, JHEP **1210**, 110 (2012) [arXiv:1207.5018 [hep-ph]]; A. Denner, S. Dittmaier, S. Kallweit and S. Pozzorini, Phys. Rev. Lett. **106**, 052001 (2011) [arXiv:1012.3975 [hep-ph]].
[34] G. Bevilacqua, M. Czakon, A. van Hameren, C. G. Papadopoulos and M. Worek, JHEP **1102**, 083 (2011) [arXiv:1012.4230

Related past measurements:

CDF, arXiv:1101.4926
CMS, arXiv:1211.2220

Prospects for precision top mass determination

- Extraction of the top mass with new methods that have alternative systematics (like J/ψ method and dilepton measurements).
  - ✓ Such extractions will either validate the current precision in the available measurements or highlight the need for additional scrutiny.
  - ✓ Further phenomenological and experiment studies of these new methods are needed.

- Decreasing the perturbative uncertainty in currently used Matrix Element methods by applying future extension of

  [57] J. M. Campbell, W. T. Giele and C. Williams, JHEP **1211**, 043 (2012) [arXiv:1204.4424 [hep-ph]].

  - ✓ It remains an open question if top width effects and non-pert effects can also be reduced

- Improved understanding of the relation between MC mass and standard quark masses, such as the pole mass. Work along these lines has been reported in

  [2] A. H. Hoang and I. W. Stewart, Nucl. Phys. Proc. Suppl. **185**, 220 (2008) [arXiv:0808.0222 [hep-ph]].

  [23] A. Buckley, J. Butterworth, S. Gieseke, D. Grellscheid, S. Hoche, H. Hoeth, F. Krauss and L. Lonnblad *et al.*, Phys. Rept. **504**, 145 (2011) [arXiv:1101.2599 [hep-ph]].

Summary

- Current precision O(1 GeV) of m_{top} is already impressive.
- Motivation for improvements from Cosmology or from New Physics discovery at the LHC.
- Significant increase in precision ($\delta m_{top} < 100$MeV): at a lepton collider.

Real current issue:

> Relationship between the top quark mass measured at hadron colliders and a well-defined quark mass, like the pole mass.

Will likely require:

- ✓ application of several current and novel experimental methods that are sensitive to different effects,
- ✓ advances in the theoretical understanding of the relationship between the measured and fundamental quantities.

What can be achieved by mid-summer 2013?

- Theoretical progress towards MEM at NLO.
- The current status of ATLAS and CMS on the J/ψ method measurements ?
- Theory work, ideally with ATLAS and CMS, on measuring m_top in dilepton events.
- For experiments: try out the new Color Reconnection modifications in PYTHIA 6.4.27.