Top mass subgroup:

Summary of findings

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Based on two writeups (available on the Snowmass webpage):
http://www.snowmass2013.org/tiki-index.php?page=Fully+Understanding+the+Top+Quark

- ✓ General intro to the issues in top mass determination

  S.Mantry, A.Mitov, P.Skands, E.Varnes

- ✓ Various specific projections

  A.Mitov, M.Vos, S.Wimpenny

This presentation is the summary of both and will be the base for the White Paper.

Introduction

The top quark mass is not an observable. It is defined as the implicit solution of:

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

$\{Q\}$ - a set of kinematic variables and possibly other parameters

Issues:

- Insure common acceptance
- The equation is not exact due to uncertainties:
  - ✓ Higher order corrections
  - ✓ Finite top/W width
  - ✓ NP corrections
  - ✓ Experimental uncertainties

Measurements in different observables are affected differently by the above

Introduction

Like any "non-observable", m_{top} is scheme dependent, i.e. the mass we extract reflects the theoretically defined x-section σ^{th}. Common mass definitions are pole and Msbar. There are many others.

All mass schemes are formally equivalent to each other (up to missing higher orders). For example, a scheme "R" is related to the pole mass through:

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

Are all mass definitions "created equal"? Yes and no:

The pole mass is special, in that it gets additional NP correction: renormalon ambiguity

It is approximately 200MeV correction that cannot be controlled.

It is thus important to work with running masses (like Msbar, 1S, or many others) to be able to get precision of 200MeV or less.

Crucial for m_{top} determination at e^+e^- machine where $\Delta m_{top} \leq 100$ MeV is expected.

Not an issue at hadron collider where the present and future anticipated uncertainty is much larger, O(1 GeV). Therefore, will not dwell on this any more.

Introduction: Why do we care about the top quark mass?

It appears that the collider physics place that is most sensitive to m_{top} is the precision EW tests. After the discovery of the (presumably SM) Higgs boson the SM is complete and the tests are over-determined. Everything looks good, however the "bottleneck" is the uncertainty is W mass. Top mass will be competitive once the ultimate W mass precision (at LHC) is achieved.

All other places in collider physics are even less sensitive to m_{top} .

Very strong dependence on m_{top} in models that rely on bottom-up approaches. These Take some data at EW scale (measured) and then predict (through RG running) how the model Looks at much larger scales, like GUT and Plank.

Two types of uncertainties:

Due to running itself
Due to boundary condition at EW. Here m_{top} is crucial.

Chetyrkin, Zoller '12-13
Bednyakov, Pikelner, Velizhanin `13

Examples:

Higgs inflation. Model very predictive; relates SM and Λ_{CDM} parameters. Agrees with Planck data.

Bezrukov, Shaposhnikov '07-'08
De Simone, Hertzbergy, Wilczek '08

Vacuum stability in SM. Change of 1 GeV in m_{top} shifts the stability bound for SM from 10^{11} to the Plank scale.

Degrassi, Di Vita, Elias-Miro, Espinosa, Giudice, Isidori, Strumia '12

This is the place where high precision in m_{top} is needed most.

Introduction: short-term goals regarding top mass determination

- Clarify if it is possible to have additional "hidden" systematics in existing m_{top} determinations that are comparable in size to the "known" error on the best existing measurements.

- Two types of possible hidden errors:

✓ QCD related. As follows from the equation: $\sigma^{\text{exp}}(\{Q\}) = \sigma^{\text{th}}(m_{\text{top}}, \{Q\})$

the precision in m_{top} determination reflects the experimental uncertainty, as well as the error on the theory input. Unaccounted theory sources might have impact.

Typical situation: using a MC to construct a likelihood and find the likeliest value of m_{top}. Combine with other methods/measurements to improve errors, etc. etc.
At each step the error seemingly decreases. But this is not so, because we have irreducible error that the MC generator simply may not know about and no improvement in the measurement will take care of it. Such errors are the scariest since they are hidden (bias).

✓ bSM related. Unexplored territory. Conceptually the same as above, but the the role of higher order terms is now played by bSM physics: it contributes to the measurement but I not accounted for on the theory side. Basically, a kind of bias again.

✓ MC modeling.

Most methods for extraction of m_{top} rely on modeling the measured final state with typically LO+LL MC generators. The extracted mass then reflects the mass parameter in the corresponding MC generator. Identifying the nature of this mass parameter and relating it to common mass schemes, like the pole mass, is a non-trivial and open problem.
It may be associated with ambiguities of order 1 GeV.

Buckley, Butterworth, Gieseke et al Phys. Rep. '11

The effect of the top and bottom masses on parton-shower radiation patterns is generally Included already in the LO+LL MC's and they screen collinear singularities.

✓ Non-perturbative corrections:

Mostly affect the MC modeling of the final state. Includes hadronization, color reconnection, Underlying Event, final state interactions (especially with jet vetoes).

Many such systematics are accounted for through the JES.
Color reconnection small at e+e- but O(500 MeV) at hadron colliders.

Recommendation: try methods with alternative systematics (unrelated to MC).

Introduction: issues in top mass determination

✓ Reconstruction of the top pair.

Typically, the existing methods for extraction of the top quark mass implicitly or explicitly rely on the reconstruction of the top pair from final state leptons and jets.

This introduces uncertainties of both perturbative origin (through higher-order corrections) and non-perturbative origin (related to showering and non-factorizable corrections).

Methods that do not rely on such reconstruction are therefore complementary and highly desirable; two examples are J/Ψ methods and dilepton distributions.

✓ This is correlated with the attempt to define a pseudo top. How needed/useful is that?

✓ Alternative top mass definitions.

Alternative mass definitions that reflect the physics are beneficial (known from e+e-).
Less clear at hadron colliders.

✓ Renormalon ambiguity in top mass definition.

Pole mass of the top quark suffers from the so-called renormalon ambiguity. This implies an additional irreducible uncertainty of several hundred MeV's on the top pole mass.
Not an issue for short distance masses. Currently, at hadron colliders, this is a subdominant uncertainty.

✓ Higher-order corrections.

Important source of uncertainty. State of the art NLO QCD; not always included.

Introduction: issues in top mass determination

✓ Unstable top and finite top width effects.

Understood for e+e-.

Computed at NLO for hadron colliders. Could affect certain distributions.

G. Bevilacqua, M. Czakon, A. van Hameren, C. G. Papadopoulos and M. Worek, JHEP **1102**, 083 (2011) [arXiv:1012.4230

A. Denner, S. Dittmaier, S. Kallweit and S. Pozzorini, JHEP **1210**, 110 (2012) [arXiv:1207.5018

Melnikov, Schulze

Not really used so far in top mass studies.

✓ Bound-state effects in top pair production at hadron colliders.

When the ttbar pair is produced with small relative velocity (i.e. close to threshold) bound-state formation begins. These effects can affect the shape of differential distributions within few GeV away from the threshold. Special care must be taken if a measurement is sensitive to such effects.

In usual "inclusive" observables (like total x-section) this effect is diluted to about 1%.

Methods for m_{top} determination: Matrix Element Methods

✓ The backbone of the Tevatron studies as well as the most precise LHC ones. Performed in all final states.

✓ Measured objects are compared with expectations from the LO tt production and decay diagrams convoluted with the detector response.

✓ Method's power comes from the fact that the likelihood for each event to be consistent with both tt and background production is calculated; greater weight is assigned to events that are more likely to be from tt when measuring m_{top}.

✓ Issue: incorrect modeling due to missing theory corrections.

Methods for m_{top} determination: Matrix Element Methods

Projections based on CMS lepton-plus-jet analysis:

S. Chatrchyan *et al.* [CMS Collaboration], JHEP **1212**, 105 (2012) [arXiv:1209.2319

	Ref.[2]	Projections				
CM Energy	7 TeV	14 TeV				
Cross Section	167 pb	951 pb				
Luminosity	$5 fb^{-1}$	$100 fb^{-1}$		$300 fb^{-1}$		$3000 fb^{-1}$
Pileup	9.3	19	30	19	30	95
Syst. (GeV)	0.95	0.7	0.7	0.6	0.6	0.6
Stat. (GeV)	0.43	0.04	0.04	0.03	0.03	0.01
Total	**1.04**	**0.7**	**0.7**	**0.6**	**0.6**	**0.6**
Total (%)	0.6	0.4	0.4	0.3	0.3	0.3

Scenario	Dominant Uncertainties
Ref.[2]	Jet Energy Scale, Hadronization, Soft QCD, ISR/FSR
100 fb^{-1}/19 PU	Jet Energy Scale, Hadronization, Soft QCD, ISR/FSR
100 fb^{-1}/30 PU	Jet Energy Scale, Hadronization, Soft QCD, ISR/FSR, Pileup
300 fb^{-1}/19 PU	Jet Energy Scale, Hadronization, Soft QCD, ISR/FSR
300 fb^{-1}/30 PU	Jet Energy Scale, Hadronization, Soft QCD, ISR/FSR, PIleup
3000 fb^{-1}/95 PU	Jet Energy Scale, Hadronization, Soft QCD, ISR/FSR, PIleup

TABLE II: Dominant systemic uncertainties for each scenario

- ✓ Projections beyond 14 TeV require full detector simulation. Not done here.
- ✓ Pileup and UE become more important at higher energy/pileup.
- ✓ ISR/FSR become dominant uncertainties at high luminosity (unlike current measurements)
- ✓ Extra 300MeV uncertainty added by hand.

Methods for m_{top} determination: ATLAS 3-dimensional template fit method

[ATLAS Collaboration], "Measurement of the Top Quark Mass from s = 7 TeV ATLAS Data using a 3-dimensional Template Fit", ATLAS-CONF-2013-046.

- ✓ Similar method in lepton-plus-jets final state.
- ✓ Extracts m_{top} together with 2 other parameters:

$$m_t = 172.31 \pm 0.23\ (\text{stat}) \pm 0.27\ (\text{JSF}) \pm 0.67\ (\text{bJSF}) \pm 1.35\ (\text{syst})\ \text{GeV}$$

Methods for m_{top} determination: CMS endpoint method

S. Chatrchyan *et al.* [CMS Collaboration], arXiv:1304.5783

A kinematical method: utilizes the strong correlation between the maximum of the M_{bl} Distribution and m_{top}.

	Ref.[8]	Projections		
CM Energy	7 TeV	14 TeV		
Cross Section	167 pb	951 pb		
Luminosity	$5fb^{-1}$	$100fb^{-1}$	$300fb^{-1}$	$3000fb^{-1}$
Syst. (GeV)	1.8	1.0	0.7	0.5
Stat. (GeV)	0.90	0.10	0.05	0.02
Total	**2.0**	**1.0**	**0.7**	**0.5**
Total (%)	1.2	0.6	0.4	0.3

Scenario	Dominant Uncertainties
Ref.[8]	Jet Energy Scale, Hadronization, Soft QCD
100 fb^{-1}	Jet Energy Scale, Hadronization, Soft QCD
300 fb^{-1}	Jet Energy Scale, Hadronization, Soft QCD
3000 fb^{-1}	Jet Energy Scale, Hadronization

TABLE IV: Dominant systemic uncertainties for each scenario

- ✓ ISR/FSR and pileup do not play a role at high luminosity. (unlike conventional methods)
- ✓ Does not rely on MC for internal calibration (analytical with data-driven backgrounds).
- ✓ Less likely to be affected by bSM corrections.
- ✓ Nonetheless, higher order effects do affect the endpoint position (particularly top widths) NLO calculations do exist – not utilized.

G. Bevilacqua, M. Czakon, A. van Hameren, C. G. Papadopoulos and M. Worek, JHEP **1102**, 083 (2011) [arXiv:1012.4230

A. Denner, S. Dittmaier, S. Kallweit and S. Pozzorini, JHEP **1210**, 110 (2012) [arXiv:1207.5018

Methods for m_{top} determination: J/Ψ method

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

A different method: no reconstruction is involved. Known at NLO.

	Ref. analysis	Projections				
CM Energy	8 TeV	14 TeV			33 TeV	100 TeV
Cross Section	240 pb	951 pb			5522 pb	25562 pb
Luminosity	$20fb^{-1}$	$100fb^{-1}$	$300fb^{-1}$	$3000fb^{-1}$	$3000fb^{-1}$	$3000fb^{-1}$
Theory (GeV)	-	1.5	1.5	1.0	1.0	0.6
Stat. (GeV)	7.00	1.8	1.0	0.3	0.1	0.1
Total	-	**2.3**	**1.8**	**1.1**	**1.0**	**0.6**
Total (%)	-	**1.3**	**1.0**	**0.6**	**0.6**	**0.4**

TABLE VI: Extrapolations based on the J/Ψ method.

Estimates from NLO QCD.

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

(see also) A. Denner, S. Dittmaier, S. Kallweit and S. Pozzorini, JHEP **1210**, 110 (2012) [arXiv:1207.5018

NNLO accuracy assumed in some extrapolations.

Main source: B-fragmentation. Likely will be irreducible unless new e+e- data.

Methods for m_{top} determination: m_{top} from kinematic distributions

✓ Total cross-section:

Allows extraction with about 3% uncertainty due to limited sensitivity to m_{top} .

➢ Positive features:

Good theory control (NNLO)
Small non-perturbative and width effects

➢ Negatives:

Small sensitivity (unlikely to improve)

✓ At present there are inconsistently applied acceptance corrections (i.e. LO or NLO not NNLO).
Still, likely a small effect.

Methods for m_{top} determination: m_{top} from kinematic distributions

✓ Extraction suggested from tt+jet.

S. Alioli, P. Fernandez, J. Fuster, A. Irles, S. -O. Moch, P. Uwer and M. Vos, arXiv:1303.6415

Estimates for contributions from unknown corrections – below 1 GeV.

Method is MC dependent and involves t (tbar) reconstruction)

✓ Dilepton distributions

- No reconstruction
- Minimal shower and NP sensitivity. Reliably computable at fixed order.
- Potential for 14 TeV at 1.5 GeV.

  S. Biswas, K. Melnikov and M. Schulze, JHEP **1008**, 048 (2010) [arXiv:1006.0910
- Further studies in progress.

e+e- colliders

- ✓ The machine where the ultimate precision of 100MeV or less can be achieved.
- ✓ Best approach is threshold scan.
- ✓ Continuum production also possible.
- ✓ Similar at ILC and CLIC.
- ✓ Interesting question: is it possible to measure m_{top} at c.m. energy of, say, 250GeV, i.e. below the threshold?
- ✓ Given the presumed ILC schedule this might imply few years …

Summary

✓ For the LHC at 14 TeV top quark mass extraction with precision of 0.6 GeV can be achieved with conventional top mass determination techniques.
At integrated luminosity as high as 3000fb^-1 the CMS endpoint method has the potential for reaching similar precision.
Methods based on various kinematic distributions can lead to top mass extraction with mt = O(1 GeV), or better.

✓ For a pp collider with c.m. energy of 33 or 100 TeV projections based on the J/Ψ method have been made. We project top quark mass extraction with mt = O(1.0 GeV) and mt = O(0.6 GeV), respectively.

✓ The highest precision in top quark mass determination, with mt = O(100 MeV,) can be achieved from a dedicated tt threshold scan at a future lepton collider (like ILC and CLIC).

Conclusion

➢ All possible venues for m_{top} determination should be pursued.

➢ The goal is to ensure cross-check of the many sources of systematical uncertainty (mostly theory but also experiment) and thus arrive at a convincing mass extraction.