Determination of the top mass at the LHC with emphasis on the theoretical uncertainties

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Based on:
Juste, Mantry, Mitov, Penin, Skands, Varnes, Vos, Wimpenny ’13
Frederix, Frixione, Mitov; to appear.

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

- ✓ Precision EW tests: the place in collider physics that is most sensitive to m_{top} .
  With the discovery of the (presumably SM) Higgs boson the SM is complete and the tests are over-determined. Everything looks good. The "bottleneck" is the uncertainty on the 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} .

- ✓ However: there is 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, say $O(M_{Plank})$.

- ✓ Two types of uncertainties appear:

  - ✓ Due to running itself

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

  - ✓ Due to boundary condition at EW. It is here m_{top} is crucial.

- ✓ Examples:

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

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

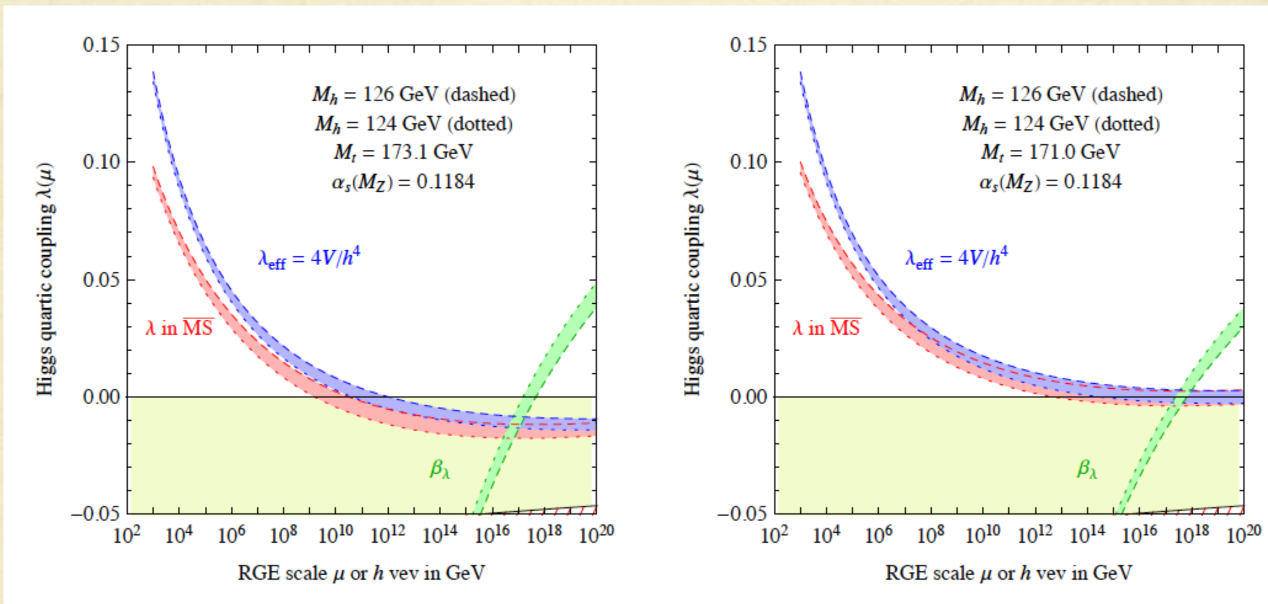
The fate of the Universe might depend on 1 GeV in M_{top}!

Higgs mass and vacuum stability in the Standard Model at NNLO.

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

Vacuum stability condition: $$V_{\rm eff} = -\frac{m^2}{2}h^2 + \frac{\lambda}{4}h^4 + \Delta V$$

Quantum corrections (included)



<u>Possible implication</u>:
For the right values of the SM parameters (and we are right there) SM might survive the Desert.

✓ Currently a big push for better understanding of the top mass. Precision is crucial here…

Introduction: goals regarding top mass determination at hadron colliders

- ✓ The apparent sensitivity to m_{top} requires convincing m_{top} determination
- ✓ What do I mean by convincing?
  - ✓ m_{top} is not an observable; cannot be measured directly.
  - ✓ It is extracted indirectly, through the sensitivity of observables to m_{top}

$$\sigma^{\mathrm{exp}}(\{Q\}) = \sigma^{\mathrm{th}}(m_t, \{Q\})$$

  - ✓ The implication: the "determined" value of m_{top} is as sensitive to theoretical modeling as it is to the measurement itself

- ✓ The measured mass is close to the pole mass (top decays …)
- ✓ One needs to go beyond the usual MC's to achieve theoretical control
- ✓ Lots of activity (past and ongoing). A big up-to-date review:

Juste, Mantry, Mitov, Penin, Skands, Varnes, Vos, Wimpenny '13

Introduction: goals regarding top mass determination at hadron colliders

- A worry: can there be an additional systematic O(1 GeV) shift in m_{top} ?

- 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 is not accounted for on the theory side. Basically, a kind of bias again.

Issues in top mass determination

✓ 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.

✓ 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

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: 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	$5 fb^{-1}$	$100 fb^{-1}$	$300 fb^{-1}$	$3000 fb^{-1}$
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

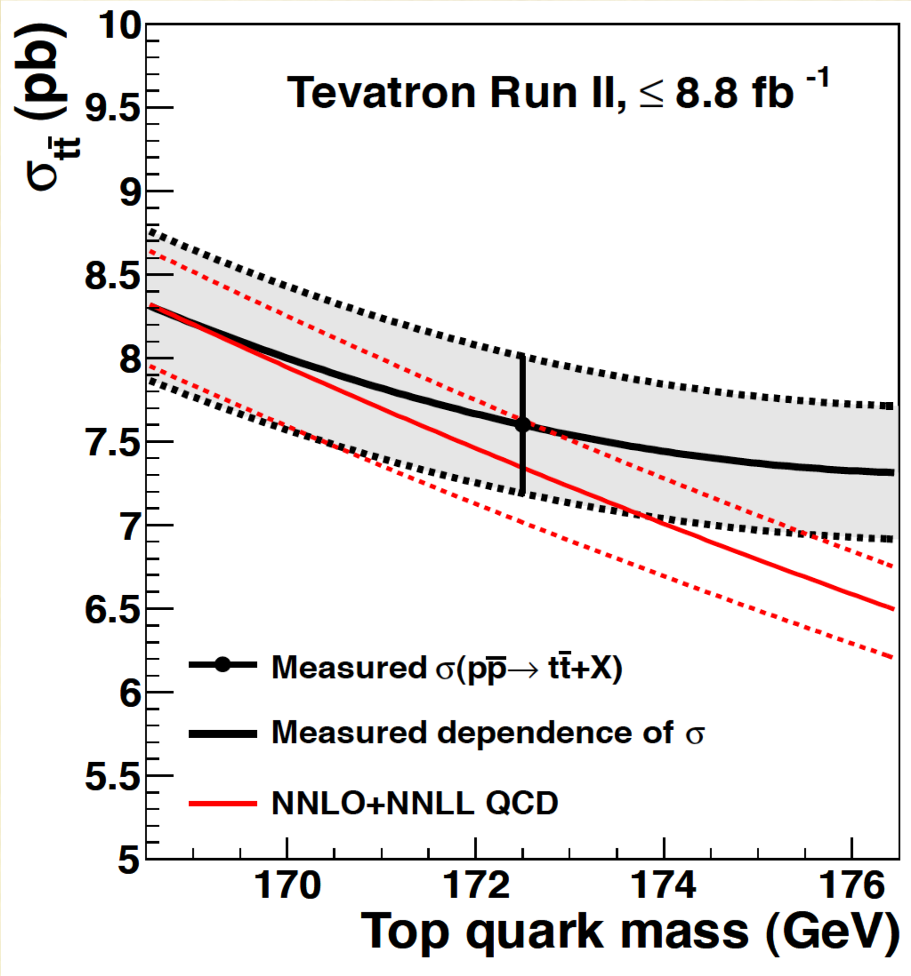
NNLO accuracy assumed in some extrapolations.

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} .



Latest Tevatron Combination: 1309.7570

➢ 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.

✓ 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

Frederix, Frixione, Mitov, in progress. <<< Second part of the talk

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 more years of waiting …

New Physics contributions to m_{top}

- ✓ One hardly mentioned problem!

- ✓ There is the possibility that undetected corrections to top production might shift the top mass measurements (measure top+bSM but theory assumes pure SM).

  Example: stop -> top+X

  If the stop is light, the event looks top-like!

- ✓ The strongest constraint on bSM contributions to m_{top} comes from the CMS end-point method

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

- ✓ The method is kinematic: it measures the position of the end-point of the spectrum of top decay products. This is independent of the top production mechanism.

- ✓ The total error from the measurement is just above 2.0 GeV and agrees with the world average

- ✓ From here we can conclude that bSM contributions to mtop are not larger than ~2GeV.

- ✓ Dedicated studies are welcome. Likely they will be model dependent; any model-independent arguments would be very valuable.

Top mass from leptonic distributions

Frederix, Frixione, Mitov; to appear

The message I'd like to convey: the questions I raised so far are not "academic".

Example: look at the spread across current measurements

arXiv:1403.4427

- Current World Average: m_{top}= 173.34±0.76 GeV
- New CMS (l+j): m_{top}= 172.04 ± 0.19 (stat.+JSF) ± 0.75 (syst.) GeV. TOP-14-001

Comparable uncertainties; rather different central values!

This is possible in the context of my discussion: different theory systematics.

In order to properly understand and estimate the theory systematics we propose a particular observable

$$pp \to t\bar{t} + X$$

$$t \to W + b + X$$

$$W \to \ell + \nu_\ell$$

These are ttbar dilepton events, subject to standard cuts:

$$|\eta_\ell| \leq 2.4 \ , \ |\eta_b| \leq 2.4 \ ,$$

$$p_{T,\ell} \geq 20 \text{ GeV} \ , \ p_{T,b} \geq 30 \text{ GeV}$$

- Construct the distributions from leptons only
- Require b-jets within the detector (i.e. integrate over)

The definition of the observable possesses several important properties:

- It is inclusive of hadronic radiation, which makes it well-defined to all perturbative orders in the strong coupling,
- It does not require the reconstruction of the t and/or $\bar{t}$ quarks (indeed we do not even speak of t quark),
- Due to its inclusiveness, the observable is as little sensitive as possible to modelling of hadronic radiation. This feature increases the reliability of the theoretical calculations.

The top mass is extracted from the shapes of the following distributions: (not normalizations)

kinematic distribution
$p_T(\ell^+)$
$p_T(\ell^+\ell^-)$
$M(\ell^+\ell^-)$
$E(\ell^+) + E(\ell^-)$
$p_T(\ell^+) + p_T(\ell^-)$

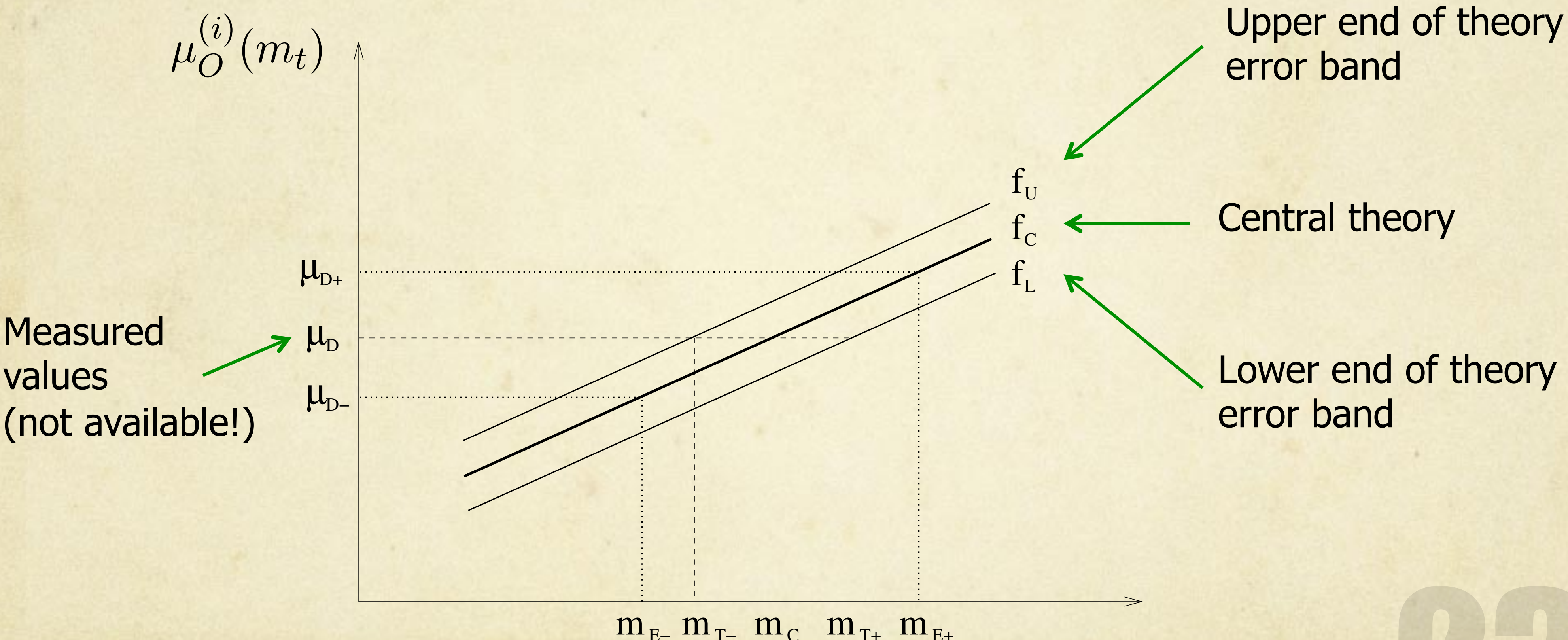
Working with distributions directly is cumbersome.
Instead, utilize the first 4 moments of each distribution

$$\sigma = \int d\sigma \qquad \mu_O^{(i)} = \frac{1}{\sigma}\int d\sigma\, O^{\,i} \qquad \mu_O^{(0)} = 1\,, \qquad \mu_O^{(1)} = \langle O \rangle$$

Note: both are subject to cuts (or no cuts); we tried both.

Here is how it all works:

1) Compute the dependence of the moments $\mu_O^{(i)}(m_t)$ on the top mass
2) Measure the moment
3) Invert 1) and 2) to get the top mass (would be the pole mass, since this is what we use)

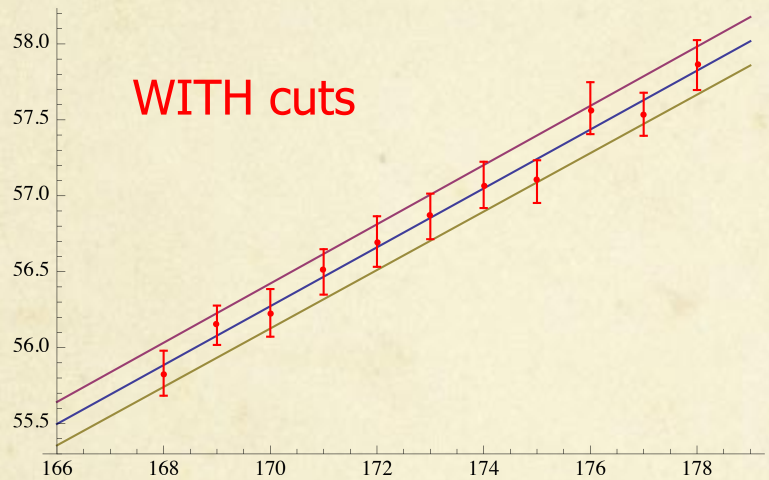


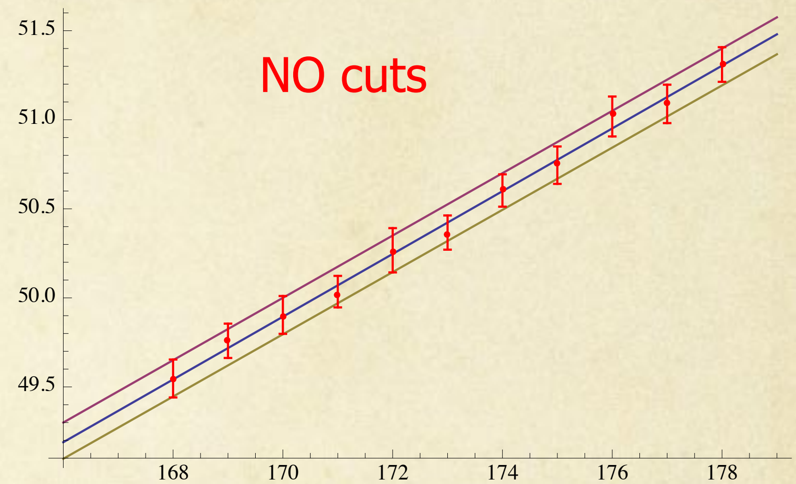
How to compute the theory error band for $\mu_O^{(i)}(m_t)$?

- Compute $\mu_O^{(i)}(m_t)$ for a finite number of m_t values: $m_t = (168, 169, \ldots, 178)$ GeV

  Then get best straight line fit (works well in this range).

Example:
- Single lepton P_T
- Subject to cuts





✓ Errors: pdf and scale variation; restricted independent variation

$$0.5 \leq \xi_F, \xi_R \leq 2 \qquad \xi_{F,R} = \mu_{F,R}/\hat{\mu} \text{ and } \hat{\mu} \text{ is a reference scale}$$

✓ There are statistical fluctuation (from MC even generation) No issue for lower moments 1M events; 30% pass the cuts.

Theory systematics

- We access them by computing the observables in many different ways.
- For a fair (albeit biased) comparison across setups and moments we use pseudodata (PD) generated by us
- Compare the systematics by comparing the top mass "extracted" by each setup from PD.

6 Setups:

label	fixer order accuracy	parton shower/fixed order	spin correlations
1	LO	PS	-
2	LO	PS	MS
3	NLO	PS	-
4	NLO	PS	MS
5	NLO	FO	-
6	LO	FO	-

3 F,R Scales:

$$\hat{\mu}^{(1)} = \frac{1}{2}\sum_i m_{T,i} \ , \ i \in (t,\bar{t}) \, ,$$

$$\hat{\mu}^{(2)} = \frac{1}{2}\sum_i m_{T,i} \ , \ i \in \ \text{final state} \, ,$$

$$\hat{\mu}^{(3)} = m_t \, ,$$

All is computed with aMC@NLO (with Herwig)

Theory systematics: impact of shower effects

obs.	$m_t^{(3)} - m_t^{(5)}$	$m_t^{(3)} - m_t^{\rm pd}$	$m_t^{(1)} - m_t^{(6)}$	$m_t^{(1)} - m_t^{\rm p}$
1	$-0.35^{+1.14}_{-1.16}$	$+0.12$	$-2.17^{+1.50}_{-1.80}$	-0.67
2	$-4.74^{+1.98}_{-3.10}$	$+11.14$	$-9.09^{+0.76}_{-0.71}$	$+14.19$
3	$+1.52^{+2.03}_{-1.80}$	-8.61	$+3.79^{+3.30}_{-4.02}$	-6.43
4	$+0.15^{+2.81}_{-2.91}$	-0.23	$-1.79^{+3.08}_{-3.75}$	-1.47
5	$-0.30^{+1.09}_{-1.21}$	$+0.03$	$-2.13^{+1.51}_{-1.81}$	-0.67

NLO

LO

label	fixer order accuracy	parton shower/fixed order	spin correlations
1	LO	PS	-
2	LO	PS	MS
3	NLO	PS	-
4	NLO	PS	MS
5	NLO	FO	-
6	LO	FO	-

- Setups 2,3 are anomalous (More later).
- Clearly big impact of NLO corrections (shower matters more at LO).

NOTE: proper PS study would require Pythia etc. Not done here.

Theory systematics: impact of NLO vs LO effects

obs.	$m_t^{(4)} - m_t^{(2)}$	$m_t^{(4)} - m_t^{\text{pd}}$	$m_t^{(3)} - m_t^{(1)}$	$m_t^{(3)} - m_t^{\text{pd}}$	$m_t^{(5)} - m_t^{(6)}$	$m_t^{(5)} - m_t^{\text{pd}}$
1	$+1.16^{+1.43}_{-1.60}$	$+0.41$	$+0.79^{+1.43}_{-1.60}$	$+0.12$	$-1.03^{+1.22}_{-1.43}$	$+0.47$
2	$-2.79^{+1.27}_{-1.65}$	-1.18	$-3.05^{+1.35}_{-1.64}$	$+11.14$	$-7.41^{+1.64}_{-2.72}$	$+15.87$
3	$-0.73^{+3.21}_{-3.45}$	$+0.84$	$-2.18^{+3.03}_{-3.30}$	-8.61	$+0.09^{+2.42}_{-2.91}$	-10.13
4	$+1.74^{+3.27}_{-3.78}$	$+0.16$	$+1.23^{+3.10}_{-3.61}$	-0.23	$-0.70^{+2.79}_{-3.09}$	-0.38
5	$+0.99^{+1.42}_{-1.72}$	$+0.25$	$+0.70^{+1.40}_{-1.72}$	$+0.03$	$-1.13^{+1.23}_{-1.33}$	$+0.33$

PS+MS

PS

-

label	fixer order accuracy	parton shower/fixed order	spin correlations
1	LO	PS	-
2	LO	PS	MS
3	NLO	PS	-
4	NLO	PS	MS
5	NLO	FO	-
6	LO	FO	-

- Setups 2,3 are anomalous (More later).
- Clearly big impact of NLO corrections.

Theory systematics: impact of Spin-Correlations effects

obs.	$m_t^{(4)} - m_t^{(3)}$	$m_t^{(4)} - m_t^{\rm pd}$	$m_t^{(2)} - m_t^{(1)}$	$m_t^{(2)} - m_t^{\rm pd}$
1	$+0.29^{+1.17}_{-1.14}$	$+0.41$	$-0.08^{+1.66}_{-1.96}$	-0.75
2	$-12.32^{+1.62}_{-2.13}$	-1.18	$-12.58^{+0.90}_{-0.94}$	$+1.60$
3	$+9.45^{+2.36}_{-2.16}$	$+0.84$	$+8.00^{+3.74}_{-4.26}$	$+1.57$
4	$+0.39^{+2.93}_{-3.16}$	$+0.16$	$-0.11^{+3.42}_{-4.16}$	-1.58
5	$+0.22^{+1.12}_{-1.28}$	$+0.25$	$-0.06^{+1.65}_{-2.07}$	-0.73

NLO+PS

LO+PS

label	fixer order accuracy	parton shower/fixed order	spin correlations
1	LO	PS	-
2	LO	PS	MS
3	NLO	PS	-
4	NLO	PS	MS
5	NLO	FO	-
6	LO	FO	-

- NOTE setups 2,3 Huge dependence on spin correlations (the place with strongest sensitivity to spin-correlations known!)
- NLO corrections make a difference.

"Best" Theory Predictions (NLO+PS+MS): choice of scale and Moment

$m_t^{\mathrm{pd}} = 174.32$ GeV ξ^2 per d.o.f.

scale	$i=1$	$i=1\oplus 2$	$i=1\oplus 2\oplus 3$	$i=1\oplus 2\oplus 3\oplus 4$
1	$174.48^{+0.73}_{-0.77}[5.0]$	$174.55^{+0.72}_{-0.76}[5.0]$	$174.56^{+0.71}_{-0.76}[5.1]$	$174.06^{+0.67}_{-0.71}[7.2]$
2	$174.73^{+0.77}_{-0.80}[4.3]$	$174.74^{+0.76}_{-0.79}[4.3]$	$174.91^{+0.75}_{-0.79}[4.1]$	$175.51^{+0.73}_{-0.79}[4.0]$
3	$172.54^{+1.03}_{-1.07}[1.6]$	$172.46^{+0.99}_{-1.05}[1.6]$	$172.22^{+0.95}_{-1.04}[1.38]$	$171.90^{+0.92}_{-0.98}[1.3]$
$1\oplus 2\oplus 3$	$174.16^{+0.81}_{-0.85}$	$174.17^{+0.80}_{-0.84}$	$174.17^{+0.78}_{-0.84}$	$174.08^{+0.75}_{-0.80}$

All 5 observables
NLO+PS+MS

scale	$i=1$	$i=1\oplus 2$	$i=1\oplus 2\oplus 3$	$i=1\oplus 2\oplus 3\oplus 4$
1	$174.67^{+0.75}_{-0.77}[3.0]$	$174.67^{+0.75}_{-0.77}[3.0]$	$174.61^{+0.74}_{-0.77}[3.17]$	$174.14^{+0.71}_{-0.73}[5.2]$
2	$174.81^{+0.83}_{-0.80}[6.2]$	$174.80^{+0.82}_{-0.80}[6.2]$	$174.85^{+0.82}_{-0.80}[6.1]$	$175.31^{+0.80}_{-0.80}[5.5]$
3	$172.63^{+1.85}_{-1.16}[0.2]$	$172.64^{+1.82}_{-1.15}[0.2]$	$172.58^{+1.81}_{-1.15}[0.2]$	$172.30^{+1.80}_{-1.07}[0.2]$
$1\oplus 2\oplus 3$	$174.44^{+0.92}_{-0.87}$	$174.44^{+0.92}_{-0.87}$	$174.43^{+0.91}_{-0.86}$	$174.32^{+0.88}_{-0.83}$

Observables 1,4,5
NLO+PS+MS

scale	$i=1$	$i=1\oplus 2$	$i=1\oplus 2\oplus 3$
1	$174.73^{+0.80}_{-0.79}[0.2]$	$174.73^{+0.80}_{-0.79}[0.2]$	$174.72^{+0.80}_{-0.79}[0.2]$
2	$174.78^{+0.90}_{-0.90}[0.6]$	$174.78^{+0.90}_{-0.90}[0.6]$	$174.78^{+0.90}_{-0.90}[0.6]$
3	$172.73^{+2.0}_{-1.2}[0.5]$	$172.73^{+1.96}_{-1.19}[0.5]$	$172.73^{+1.96}_{-1.19}[0.5]$
$1\oplus 2\oplus 3$	$174.46^{+0.99}_{-0.92}$	$174.46^{+0.99}_{-0.92}$	$174.45^{+0.99}_{-0.92}$

Observable 1
NLO+PS+MS

$$\hat{\mu}^{(1)} = \frac{1}{2}\sum_i m_{T,i}\ ,\ i \in (t,\bar{t})\,,$$
$$\hat{\mu}^{(2)} = \frac{1}{2}\sum_i m_{T,i}\ ,\ i \in \text{ final state}\,,$$
$$\hat{\mu}^{(3)} = m_t\,,$$

Theory systematics: Predictions

observable; setup	$i=1$	$i=1\oplus 2$	$i=1\oplus 2\oplus 3$
all; LO+PS	$187.90^{+0.6}_{-0.6}[428.3]$	$187.71^{+0.60}_{-0.60}[424.2]$	$187.83^{+0.58}_{-0.60}[442.8]$
all; LO+PS+MS	$175.98^{+0.63}_{-0.69}[16.9]$	$176.05^{+0.63}_{-0.68}[17.8]$	$176.12^{+0.61}_{-0.68}[18.9]$
all; NLO+PS	$175.43^{+0.74}_{-0.80}[29.2]$	$176.20^{+0.73}_{-0.79}[30.1]$	$175.67^{+0.73}_{-0.76}[31.2]$
all; $\mathrm{NLO_{FO}}$	$174.41^{+0.72}_{-0.73}[96.6]$	$174.82^{+0.71}_{-0.73}[93.1]$	$175.44^{+0.70}_{-0.68}[94.8]$
all; $\mathrm{LO_{FO}}$	$197.31^{+0.42}_{-0.35}[2496.1]$	$197.19^{+0.42}_{-0.35}[2505.6]$	$197.48^{+0.36}_{-0.35}[3005.6]$
1,4,5; LO+PS	$173.68^{+1.08}_{-1.31}[0.8]$	$173.68^{+1.08}_{-1.31}[0.9]$	$173.75^{+1.08}_{-1.31}[0.9]$
1,4,5; LO+PS+MS	$173.61^{+1.10}_{-1.34}[1.0]$	$173.63^{+1.10}_{-1.34}[1.0]$	$173.62^{+1.10}_{-1.34}[1.0]$
1,4,5; NLO+PS	$174.40^{+0.75}_{-0.81}[3.5]$	$174.43^{+0.75}_{-0.81}[3.5]$	$174.60^{+0.75}_{-0.79}[3.2]$
1,4,5; $\mathrm{NLO_{FO}}$	$174.73^{+0.72}_{-0.74}[5.5]$	$174.72^{+0.71}_{-0.74}[5.6]$	$175.18^{+0.64}_{-0.71}[4.6]$
1,4,5; $\mathrm{LO_{FO}}$	$175.84^{+0.90}_{-1.05}[1.2]$	$175.75^{+0.89}_{-1.05}[1.2]$	$175.82^{+0.89}_{-1.04}[1.2]$

$m_t^{\mathrm{pd}} = 174.32\ \mathrm{GeV}$

ξ^2 per d.o.f.

Conclusions

- ✓ New developments have resurrected the interest in knowing m_{top} precisely
  - ✓ Vacuum Stability in SM
  - ✓ Higgs Inflation
- ✓ There are many dedicated hadron collider measurements.
  They return consistent values around m_{top} = 173 GeV
  and uncertainty (mostly on the measurement!) of below 1 GeV.
- ✓ Questions remain: can there be a significant additional theoretical systematics O(1 GeV) ?
- ✓ This is not an abstract problem: m_{top} is not an observable and so is a theoretically defined concept.
- ✓ The issue of various mass definitions is a non-issue at present for hadron colliders.
- ✓ e+e- colliders offer the real possibility of measuring m_{top} with x10 precision, i.e. O(100 MeV)
  But how long would we have to wait for a ttbar threshold scan?
- ✓ New physics contributions to m_{top} are a totally open question. Upper limit of O(2 GeV) likely can be placed at present.
- ✓ Proposed new method, with emphasis on control over theory systematics.
  NLO vs LO: 1 GeV; spin correlations crucial. Awaiting the measurement (100k events exist!).