ATLAS+CMS TOP MASS: CURRENT RESULTS AND FUTURE MEASUREMENTS

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The LHC experiments are fast catching up with Tevatron on the accuracy of the top quark mass (m_t) measured using standard methods, with the latest CMS combination reaching an accuracy of 0.66 GeV compared to 0.64 GeV for Tevatron. The future prospects look promising as both ATLAS and CMS have commissioned new methods (3D-R_{bq}, Z+b / Z+jet ratio) to address the leading systematic uncertainty from b-jet energy scale (bJES). At this level of precision the agreement between generator mass m_t^{MC} and the theoretical pole mass m_t^{pole} becomes relevant, and alternative methods are also explored.

1 Introduction

The top quark mass m_t is a fundamental parameter of the standard model, and together with the W boson mass M_W and the Higgs boson mass M_H it provides a strong self-consistency check of the electroweak theory. Using input values of $m_t = 173.34 \pm 0.76$ GeV,[1] $M_W = 80.385 \pm 0.015$ GeV and $m_H = 125.14$ GeV in a global electroweak fit,[2] the three parameters are compatible within 1.5 σ.

The top quark also provides a unique opportunity to directly probe a colored particle that decays before it has time to hadronize, helping to better understand QCD. Top quarks are mostly produced in $t\bar{t}$ pairs, and for almost 100% of the cases, the top and anti-top quark decay into a W boson and a b or $\bar{b}$ quark. The W bosons further decay into a $q\bar{q}'$ pair or a lepton and a neutrino, while the b quark and light quarks form jets. The fast decay of the top quark makes the measurement of the top quark mass theoretically and experimentally challenging. For example, there is a difference between the theoretical top quark pole mass $m_{t,\mathrm{pole}}$ and the definitions $m_{t,\mathrm{MC}}$ used in the MC generators used to calibrate the measurements. The b and anti-b quarks also experience color re-connection that can affect experimental measurements.

The measurement of the top quark mass is done in a very rich hadronic environment, and has multiple spin-offs that can benefit other measurements. The b jets produced in top decays offer a clean sample for studying b quark hadronization, with the m_t and $t\bar{t}$ kinematics offering a reference point for the initial energy at the parton level. The m_W and m_t can also be turned into constraints on the light quark and b quark jet energy scales, JES and bJES, respectively.

Comparison of the measured top quark and Higgs boson masses to standard model predictions has suggested that we may inhabit a meta-stable vacuum.[3] There is considerable debate about this conclusion, which assumes stability of the SM vacuum up to the Planck scale, an unlikely assumption in itself. There is also some tension between the recent results from the Tevatron[4] and CMS,[5] and uncertainty in the relation between the theoretical pole mass m_t^{pole} used in the stability calculation and the MC generator mass m_t^{MC} measured by the experiments. Nevertheless, the "fate of the universe" implied by vacuum meta-stability has been a fertile ground for discussions.

2 Standard reconstruction

The invariant mass of the top quark can be reconstructed from the decay products of the top quark, which include leptons (μ, e), jets and missing transverse energy $E_{T,\mathrm{miss}}$. The top quark mass measurements are traditionally divided by the decay channels of the two W bosons: dilepton events with both W boson decaying into a lepton and a neutrino (5% of all $t\bar{t}$ events), lepton+jets events with one W boson decaying semi-leptonically and the other into $q\bar{q}'$ (30%), and all-jets events (45%) with only hadronic decays of the W bosons.

The so-called standard measurements measure top quark mass relative to the MC generator mass m_t^{MC} by first building an estimator for m_t (*e.g.* invariant mass of the top quark daughters), then parameterizing this estimator versus m_t^{MC} and possibly other variables such as JES and bJES. The single-variable measurement of m_t is typically referred to as 1D, while the combination of m_t and JES is referred to as 2D and m_t, JES and bJES as 3D. The top quark mass is finally extracted by performing a maximum likelihood fit to data. It is also possible to combine multiple estimators per event in the likelihood.

The LHC experiments CMS[6] and ATLAS[7] have collected about 5 fb^{-1} of data at 7 TeV in 2011, corresponding to about 800,000 $t\bar{t}$ pairs, and about 20 fb^{-1} at 8 TeV in 2012, corresponding to about five million $t\bar{t}$ pairs. Measurements are available from CMS in all channels on both data sets,[8,9,10,11,12,13,14] and from ATLAS on the 7 TeV data set.[15,16] In this article we report the most recent 8 TeV resuls from CMS, and the latest 7 TeV results from ATLAS.

2.1 Dilepton events

The signature of the dilepton channel is two b jets, two leptons and $E_{T,\mathrm{miss}}$ from two neutrinos. This topology is underconstrained due to the two ν, requiring some external information for solving m_t. The dilepton m_{lb} measurement,[11] which is the first blind m_t measurement from CMS, uses the invariant mass m_{lb} of a lepton and b jet as the estimator for m_t. Another complementary technique called Analytical Matrix Weighting Technique (AMWT)[12] uses the full event kinematics with multiple solutions for m_t. Both measurements have JES (0.4–0.6 GeV) and b fragmentation (0.6–0.7 GeV) among the leading systematic uncertainties. The AMWT is very sensitive to theory scale uncertainty (0.87 GeV), while m_{lb} is less sensitive to theory scale (0.55 GeV), but adds uncertainty from top p_T modeling (0.66 GeV).

The **new** ATLAS dilepton measurement[15] also used the m_{lb} method, with leading systematics from JES (0.75 GeV), bJES (0.68 GeV) and hadronization plus underlying event (0.53 GeV). Compared to the CMS measurement ATLAS has slightly larger JES uncertainty and less events, but benefits from an in-depth study of correlations with the lepton+jet measurement, which reduces the later ATLAS combination uncertainty. The three results are summarized in Table 1.

2.2 Lepton+jets events

The signature of the lepton+jets channel is two b jets, two other jets and $E_{T,\mathrm{miss}}$ from a single neutrino. This topology is often referred to as the golden channel as it has very clean event

Table 1: Results from dilepton events.

$m_{t,\mathrm{AMWT}}(\mathrm{CMS})$	$=$	$172.5 \pm 0.2(\mathrm{stat}) \pm 1.4(\mathrm{syst})$ GeV
$m_{t,m_{lb}}(\mathrm{CMS})$	$=$	$172.3 \pm 0.3(\mathrm{stat}) \pm 1.3(\mathrm{syst})$ GeV
$m_{t,m_{lb}}(\mathrm{ATLAS})$	$=$	$173.8 \pm 0.5(\mathrm{stat}) \pm 1.3(\mathrm{syst})$ GeV

kinematics and can be used to constrain the JES in-situ with the hadronic W boson decay using the W boson mass $m_W = 80.4$ GeV as a constraint. ATLAS has developed a novel technique of constraining also the bJES in-situ using the R_{bq} variable, shown in Fig. 1(left), defined approximately as the ratio of the b jet p_T to the W boson p_T.

In the **new** 3D ATLAS lepton+jet measurement at 7 TeV[15] the JSF (JES scale factor) is measured as JSF-1$= +1.9 \pm 2.7\%(\mathrm{syst} + \mathrm{stat})$ and bJSF (bJES scale factor relative to JES) as bJSF-1$= +0.3 \pm 2.4\%(\mathrm{syst} + \mathrm{stat})$. The leading systematic uncertainties are 0.67 GeV *statistics-limited* uncertainty for bJES, 0.58 GeV for JES and 0.50 GeV for b tagging, for a total systematic uncertainty of 1.0 GeV. Given the statistical limitations, this measurement is expected to substantially improve in the future.

The CMS 2D lepton+jet measurement[13] at 8 TeV shown in Fig. 1(right) is the most precise LHC result to date, with 0.8 GeV total uncertainty. It measures m_t together with in-situ JSF using the m_W constraint, finding JSF-1$= +0.7 \pm 1.2\%(\mathrm{syst} + \mathrm{stat})$. The leading systematics are bJES (0.41 GeV) and signal modelling (0.35 GeV), with the rest divided evenly among multiple smaller uncertainties. The measured m_t has been carefully studied versus event kinematics to verify good modelling of the data by the central MadGraph[17]+Pythia 6[18] tune Z2* MC simulation, and by several other MC generators. The studied variables include N_{jet}, ΔR_{xx}, $p_{T,x}$, $|\eta|_x$ *etc.*, where x is q, b, t or W. All variables are found to be in good agreement with simulation. The CMS and ATLAS results are summarized in Table 2.

Table 2: Results from lepton+jets events.

$m_{t,\mathrm{2D}}(\mathrm{CMS})$	$=$	$172.0 \pm 0.2(\mathrm{stat}) \pm 0.8(\mathrm{syst})$ GeV
$m_{t,\mathrm{3D}}(\mathrm{ATLAS})$	$=$	$172.3 \pm 0.8(\mathrm{stat}) \pm 1.0(\mathrm{syst})$ GeV

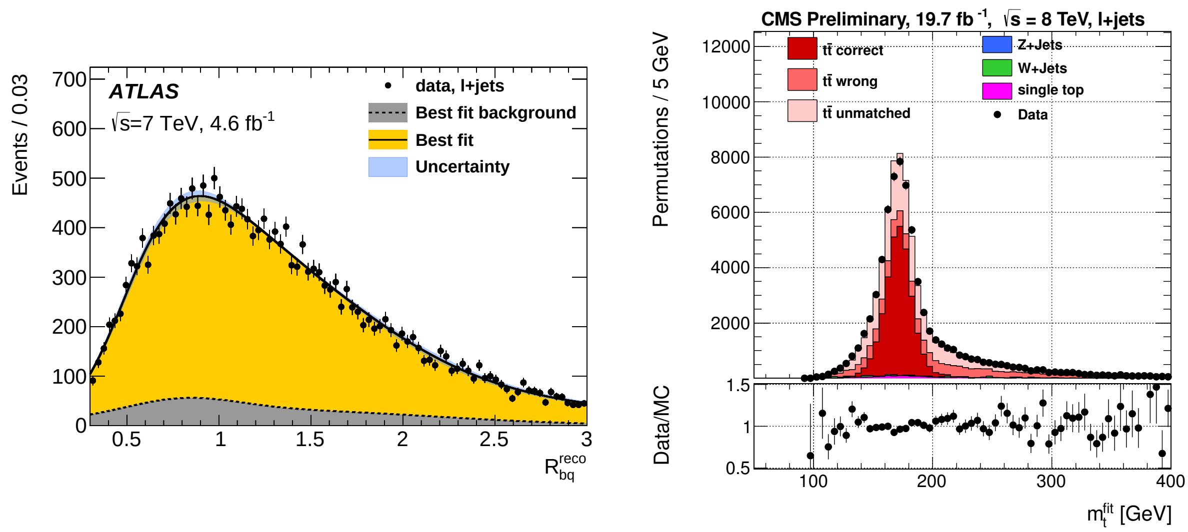


Figure 1 – Lepton+jet measurements at LHC: R_{bq} used for bJSF at ATLAS (left)[15], and fitted top quark mass m_t^{fit} at CMS (right)[13].

2.3 All-jets events

The all-jets signature is two b-tagged jets and at least four light jets. The methods employed for the CMS 8 TeV measurement[14] are the same as those used for the lepton+jet measurement, with similar systematics of 0.36 GeV for bJES and 0.29 GeV for signal modelling. The JSF-1= $+0.7 \pm 1.1\%(\mathrm{syst} + \mathrm{stat})$, in excellent agreement with the lepton+jet measurement. Despite high combinatorial background, the analysis reaches 78% purity with narrow signal peak afer cuts on goodness-of-fit $P_{\mathrm{GOF}} > 0.1$ and $\Delta R(b, b) > 2.0$.

The purity before cuts of 16% is very similar to that obtained by the ATLAS 7 TeV measurement[16] (17%), which determines m_t from a template fit to ratio of 3-jet mass to 2-jet mass $R_{3/2}$. This is in essence a 2D measurement as well, without explicit JSF. The leading systematics are 0.62 GeV for bJES, 0.51 GeV for JES and 0.50 GeV for hadronization for a total systematic uncertainty of 1.2 GeV, compared to 0.8 GeV at CMS. The CMS and ATLAS results are summarized in Table 3.

Table 3: Results from all-jets events.

$$\begin{aligned} m_{t,2\mathrm{D}}(\mathrm{CMS}) &= 172.1 \pm 0.4(\mathrm{stat}) \pm 0.8(\mathrm{syst})\ \mathrm{GeV}, \\ m_{t,R_{3/2}}(\mathrm{ATLAS}) &= 175.1 \pm 1.4(\mathrm{stat}) \pm 1.2(\mathrm{syst})\ \mathrm{GeV} \end{aligned}$$

2.4 Run I combinations

Both CMS and ATLAS have published new combinations of their m_t measurements that are competitive with the the World combination[1] from March 2014 (0.76 GeV uncertainty), or in the case of CMS even exceeding it. The Tevatron experiments have meanwhile released a new combination of their results[4] in July 2014, which currently holds the record precision, but only by a narrow margin (0.64 GeV total uncertainty at Tevatron versus 0.66 GeV at CMS).

The CMS combination uses dilepton and lepton+jets channels from 2010 (7 TeV, 36 pb^{-1}) and all three channels from both 2011 (7 TeV) and 2012 (8 TeV). There is good consistency between individual measurements and channels. The final result is dominated by the 2012 lepton+jets measurement (46.5% constrained BLUE combination coefficient), but with substantial contributions from the 2012 all-hadronic (23.0%), 2011 lepton+jets (14.6%) and other 2011 and 2012 measurements as well.

The **new** optimised ATLAS combination[15] uses only the new 7 TeV lepton+jet and dilepton measurements. The optimised treatment of correlated systematics between these two measurements leads to 28% gain relative to lepton+jet only, and the new measurements improve 36% relative to the previous ATLAS combination and 4% relative to the previous LHC combination (0.91 GeV versus 0.94 GeV). The leading systematics of the ATLAS combination are JES (0.41 GeV), bJES (0.34 GeV), hadronization and UE (0.35 GeV) and b tagging (0.25 GeV).

The Run I combinations from CMS and ATLAS are summarized in Fig. 2. Both experiments measure a value of m_t consistent with the previous world average of 173.34 ± 0.76 GeV, but lower than the new Tevatron combination of 174.34 ± 0.64 GeV,[4] which is dominated by a single new D0 measurement in the lepton+jet channel.[19] The tension between this D0 measurement and the corresponding 8 TeV lepton+jet measurement from CMS[13] is about 3 σ.

3 Alternative methods

The standard methods all share a few common features: (i) $t\bar{t}$ event reconstruction, (ii) mass calibration based on simulation ($m_t^{\mathrm{measured}} = m_t^{\mathrm{MC}}$), (iii) large sensitivity to JES and bJES uncertainties.

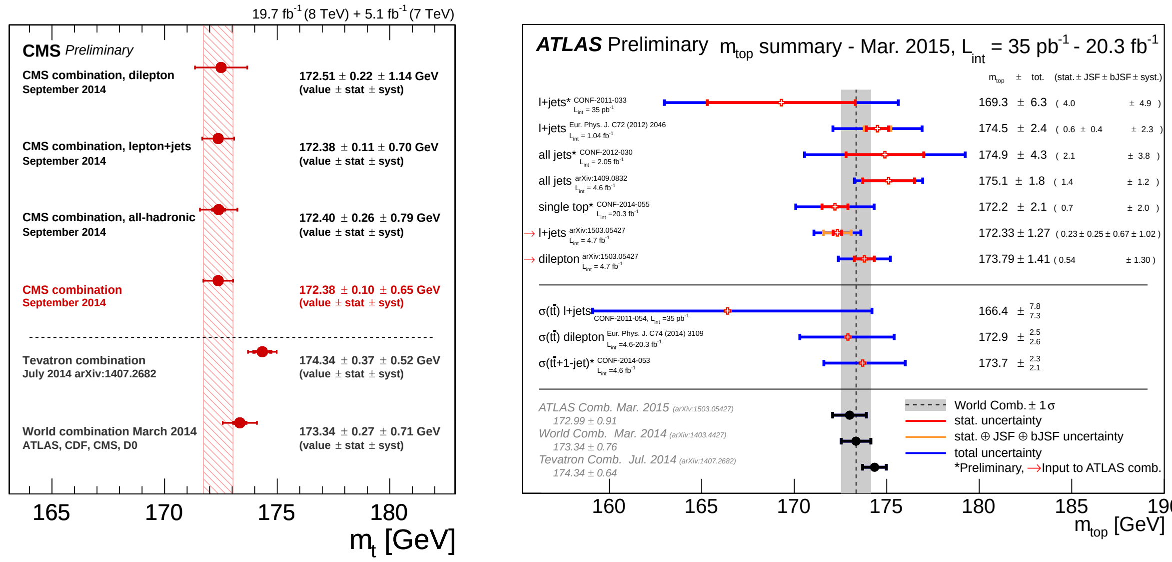


Figure 2 – Run I combinations for m_t from CMS (left)[5] and ATLAS (right) compared to latest world average and Tevatron combination. The ATLAS summary has been updated with the latest results for Moriond 2015.[15]

The alternative methods use observables and/or final states sensitive to different systematic uncertainties, and they often attempt to extract top quark mass in a well-defined renormalisation scheme to avoid dependence on MC generator definition of m_t. Recent alternative analyses include measurements using B-hadron lifetime,[20] kinematic end points,[21] and a propaedeutic study of $b \to J/\Psi$ channel and underlying event.[22] In this article we focus on single-top events in the t-channel[23] and extraction of m_t^{pole} from inclusive $t\bar{t}$ cross section[24,25] and from $t\bar{t}$+jet differential cross section.[26] Although not a m_t measurement, we also discuss the determination of bJES from data.[27]

3.1 *Single top in t-channel*

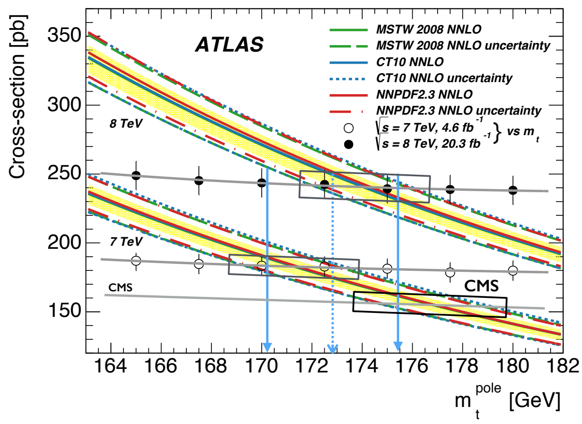
The signature of single top in t-channel is one lepton, one b jet, one light jet and $E_{T,\text{miss}}$ from a single neutrino. The ATLAS analysis[23] shares many similarities with the dilepton measurement in the $t\bar{t}$ channel, and the mass is also measured using m_{lb} template. The backgrounds are overall larger, but the presence of a single t reduces combinatorial background and having a single ν helps to avoid some issues involved in an underconstrained system. A neural network is used to enrich the t-channel, obtaining an expected purity of about 46%, with another 26% from $t\bar{t}$ and the rest 28% from other non-top quark backgrounds.

The main benefit of the single top is different sensitivity to color reconnection and a different Q^2 scale. The sample is also statistically independent from the $t\bar{t}$ measurements, which helps in m_t combinations. The dominant systematic uncertainties are similar to the dilepton channel in $t\bar{t}$: JES (1.5 GeV), hadronization (0.7 GeV) and backgrounds (0.6 GeV).

3.2 *Inclusive $t\bar{t}$ cross section*

The $t\bar{t}$ cross section depends on the theoretical pole mass m_t^{pole} in a well-defined way. This allows the cross section $\sigma_{t\bar{t}}$ to be re-interpreted as a measurement of m_t^{pole}. The dominant systematic uncertainties in this case are uncertainties from parton distribution functions (PDFs) and the theory scale uncertainty. The biggest challenge is reducing the theory uncertainties to the level where the difference between MC generator masses and pole mass is expected to matter: $\Delta(m_t^{\text{MC}}, m_t^{\text{pole}}) \leq 1$ GeV.

The pole mass has been measured by ATLAS from combined 7 and 8 TeV data,[25] and by CMS from the 7 TeV data.[24] There is still quite some variability in the results as shown in Fig. 3, with uncertainties of about 3 GeV on both experiments. The differences in the measured $m_t^{\rm pole}$ between CMS and ATLAS is a direct consequence of the difference in the 7 TeV cross section measurements by the two experiments.



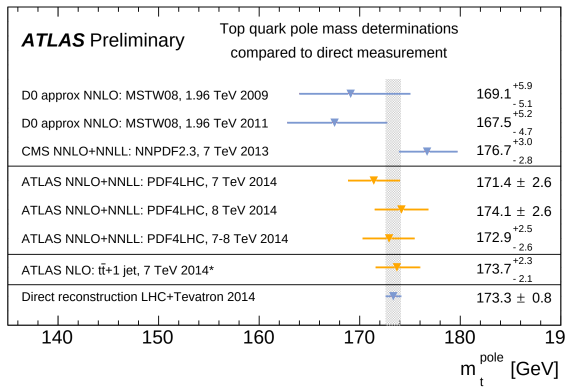


Figure 3 – (Left) Measurement of $m_t^{\rm pole}$ by ATLAS and CMS using inclusive $t\bar{t}$ cross section. The CMS 7 TeV result, cross section boxes and arrows for ATLAS combined result have been overlaid on the original ATLAS plot[25] for direct comparison. (Right) $m_t^{\rm pole}$ determinations compared to direct measurement.[25]

3.3 $t\bar{t}$+jet differential cross section

The most precise determination of $m_t^{\rm pole}$ to date comes from ATLAS,[26] using $t\bar{t}$+jet differential cross section $\sigma_{t\bar{t}+{\rm jet}}$ to enhance m_t sensitivity with respect to inclusive $\sigma_{t\bar{t}}$. The theoretical calculations have been performed at next-to-leading-order with parton shower (NLO+PS), compared to next-to-next-to-leading order (NNLO) for $\sigma_{t\bar{t}}$. The theory systematic uncertainties come primarily from the scale uncertainty (+0.93, -0.44 GeV). The experimental systematic uncertainties mainly from JES (0.94 GeV) are competitive with standard methods. The measurement is limited by statistical uncertainty (1.5 GeV) so the results will further improve with more data at 8 TeV.

4 Measurement of bJES from data

The bJES uncertainty stands out as a leading systematic in most methods, both standard and alternatives. Even if not directly quoted as bJES uncertainty, even alternatives often rely on the b quark fragmentation $p_{T,{\rm B-hadron}}/p_{T,{\rm b-jet}}$ in data. One of the most successful ways to measure bJES in data has been the ATLAS 3D method using R_{bq},[15] which effectively reduces the m_t uncertainty from bJES to 0.08(syst.) $\pm$ 0.67(stat.) GeV, altough the final quoted bJSF including additional systematic uncertainties is $1.003 \pm 0.008({\rm stat.}) \pm 0.023({\rm syst.})$.

A complementary way to study b-jet scale is to look at b jets produced in association with a Z boson. The Z+b events have kinematics quite similar to the W+b produced in top quark decays, making it possible to measure a single scale factor for bJES. The precision of this approach tested at CMS[27] is on par with the simulation-based bJES uncertainty from comparing Pythia 6[18] and Herwig++[28] at CMS, and with the 3D method used at ATLAS.

To cancel out common systematic uncertainties, the jet response from a b-tagged sample with a purity of about 80% is measured relative to the inclusive Z+jet sample used in determining the central JES. Many of the remaining systematic uncertainties are shared with the b in the W+b from top decays, *e.g.* the neutrinos produced in semileptonic decays, which are the dominant uncertainty (0.32%) for Z+b / Z+jet. The measurement is done with two different methods, missing E_T projection fraction (MPF) and p_T balance (R_{pT}),[29] and by either using a fixed cut on additional jet activity (face value) or extrapolating the additional activity to zero (fitted). All four approaches give fully consistent results, with the MPF face value having smallest total uncertainty and thus chosen as the central value: bJSF$= 0.998 \pm 0.004$(stat.) $\pm\, 0.004$(syst.) for b-to-light jet energy scale ratio relative to Pythia 6 tune Z2*.

5 Road to the future

A large drop in the m_t uncertainties is still expected in Run II, given the expected availability of a $t\bar{t}$ data sets of unprecedented size: more than twenty million $t\bar{t}$ pairs for the initial 30 fb^{-1} at 13 TeV.[30] Even though the most precise analyses are already systematics limited, the large data set should enable reducing systematic biases, and therefore uncertainties, that stand out at a level of 2–3 σ.

As shown in Fig. 4, the LHC experiments are well on track with their m_t measurements.[31] CMS has reduced standard method uncertainties with detailed kinematic studies and demonstrated a bJES measurement from Z+b / Z+jet ratio that is still statistics limited and should threfore become more powerful in Run II. ATLAS has shown promising paths for measuring m_t^{pole} from differential $\sigma_{t\bar{t}+\mathrm{jet}}$ and m_t^{MC} with bJES and JES using the 3D method. Both of these analyses are also statistics limited at 7 TeV.

The experiments reached an initial agreement on the common treatment of systematic uncertainties during the LHC and World combinations of m_t in 2014, with the details documented in a public summary.[32] The document also details areas that will need future improvement, putting the LHC top mass combinations on a solid ground in Run II.

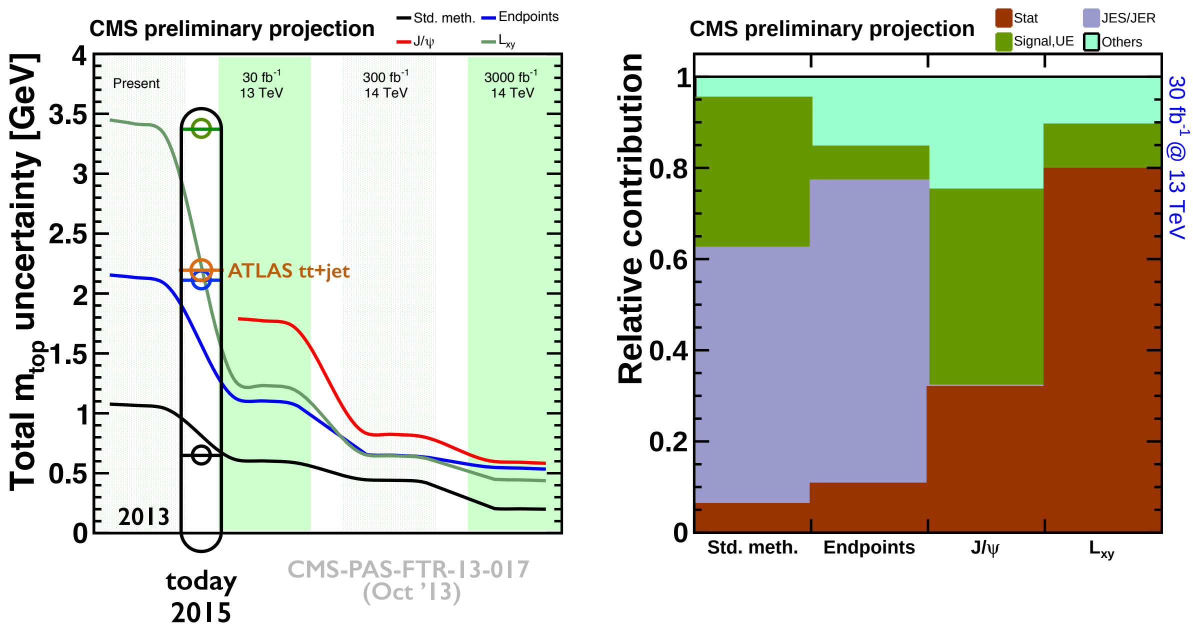


Figure 4 – (Left) Future projections of m_t uncertainties at CMS.[31] The current 2015 results have been overlaid for comparison. (Right) Contributions of various sources of uncertainty to the projected uncertainty in Run II.[31]

6 Conclusions

The past three years have seen rapid improvement in the precision of the top quark mass measurements at the LHC. The precision of the CMS measurements of m_t^{MC} is now on par with the Tevatron measurements: CMS has 0.66 GeV total uncertainty versus 0.64 GeV at the Tevatron. Run II prospects for top quark mass measurements look good with new methods to constrain the leading systematic uncertainty from bJES with a large number of $t\bar{t}$ and Z+jet events. ATLAS has demonstrated this with the 3D fit using R_{bq}, while CMS has measured bJES using ratio of Z+b and Z+jet events.

All standard measurements are currently systematics limited, but CMS experience with 7 TeV and 8 TeV data sets has shown that more data helps to reduce also the systematic uncertainties. Many alternative measurements are now available, and they complement the standard measurements by changing sensitivity to some of the leading systematic uncertainties. Especially the difference between MC generator mass $m_t^{\rm MC}$ and theoretical pole mass $m_t^{\rm pole}$ can perhaps be addressed in the future using cross-section based measurements of the top quark mass. ATLAS has shown with the differential $t\bar{t}$+jet measurement that it is possible to go beyond inclusive $\sigma_{t\bar{t}}$ in the sensitivity to $m_t^{\rm pole}$.

The current best measurements of the top quark mass are Tevatron combination[4] of $m_t = 174.34 \pm 0.64$ GeV (July 2014), CMS combination[5] of $m_t = 172.38 \pm 0.66$ GeV (September 2014) and ATLAS combination[15] of $m_t = 172.99 \pm 0.91$ GeV (March 2015). Two of these already exceed the precision of the world combination[1] of $m_t = 173.34 \pm 0.76$ GeV (March 2014) from only a year earlier, boding well for the future.

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