High precision measurement of the top quark mass from CMS

LHC seminar

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Introduction

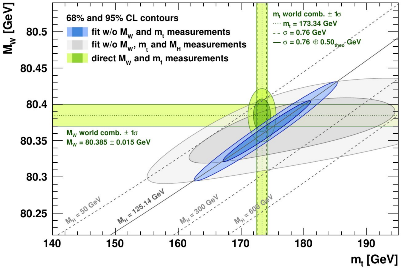
This seminar talk will present the two latest measurements of the top quark mass by the CMS collaborations.

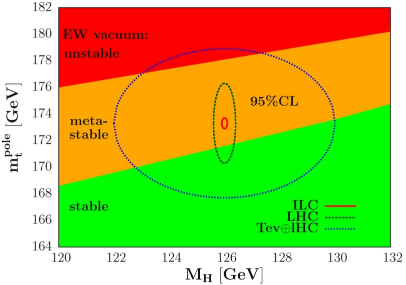
"A profiled likelihood approach to measure the top quark mass in the lepton+jets channel at $\sqrt{s} = 13\,\mathrm{TeV}$"
CMS-PAS-TOP-20-008

"Measurement of the top quark pole mass using $t\bar{t}$+ jet events in the dilepton final state at $\sqrt{s} = 13\,\mathrm{TeV}$"
CMS-PAS-TOP-21-008

The top quark

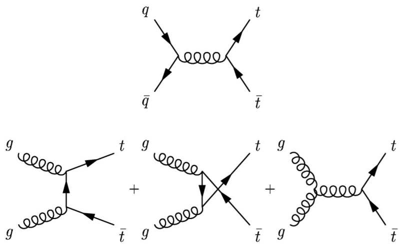
- Heaviest fundamental particle observed
- Life time smaller than hadronization time, so bare quark properties can be measured
- Loops contribute to the Higgs boson and W boson mass
- Top quark mass (m_t) is a prominent input for SM consistency checks

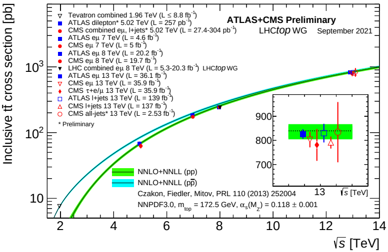




Top quark production

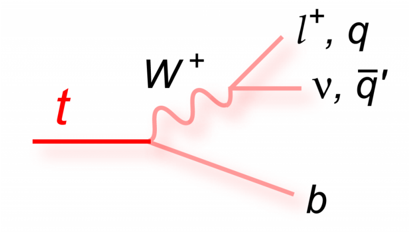
At the $\sqrt{s} = 13\,\text{TeV}$ proton-proton collisions of the LHC top quark-antiquark pairs are produced mainly from gluon-gluon fusion.

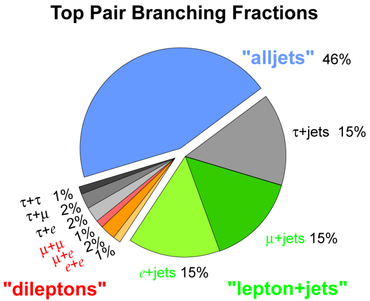




Top quark decay

Top quarks decay in 99.8% into a bottom quark and a W boson (in leading order).
Their decay is categorized by the subsequent decay of the W boson.

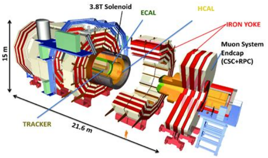


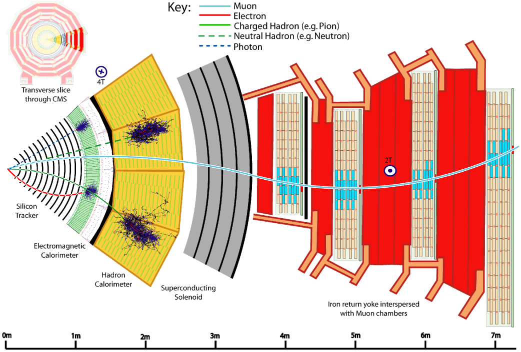


The quarks subsequently decay into showers of hadronic particles.

CMS detector

- track electromagnetic charged particles
- collect all energy around the collision point
- use combination of sub-systems for the identification of particles
- measure energy and momenta at high precision





Top quark mass definitions

Direct measurement:

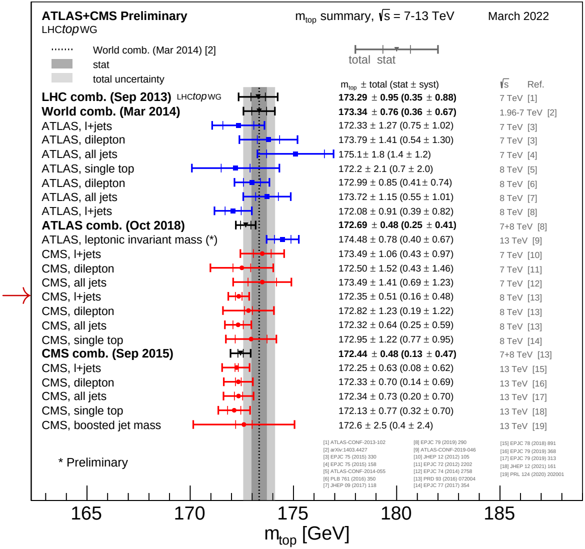
- rely on parton shower simulation
- build templates that dependent on the top quark mass (m_t) parameter in simulation
- yield small uncertainties
- relation to a theoretically well defined mass has an uncertainty of O(0.1–1 GeV)

theoretical mass of the top quark depends on the renormalization scheme, choice is the pole mass m_t^{pole}

$$\frac{i}{\not{p} - m_0} \Rightarrow \frac{i}{\not{p} - \underbrace{m_0(\Lambda)}_{\text{'bare' mass}} - \underbrace{\delta m_0(\Lambda)}_{\text{divergent}} - \underbrace{\Sigma' m_0(\Lambda)}_{\text{finite}}} := \frac{i}{\not{p} - m^{pole}}$$

- extracted via differential cross sections
- non-perturbative corrections must be added
- unfolding procedure yield typically bigger uncertainty than direct measurement

Direct mass measurements

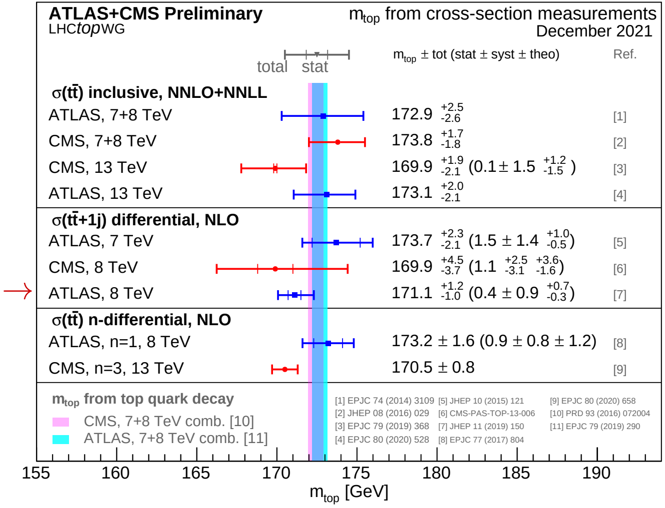


among the most precise measurements at the LHC

the most precise m_t measurement uses the $t\bar{t} \to \ell + \text{jets}$ channel

so far not surpassed with 13 TeV data

Pole mass measurements

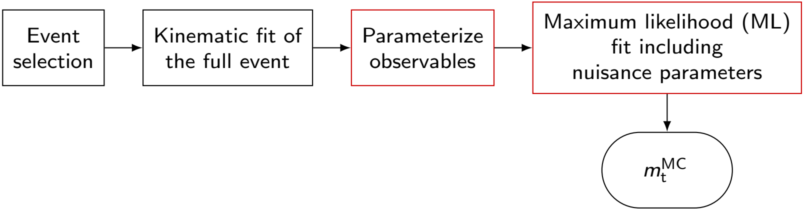


Improved a lot through more data and better methods for $\sqrt{s} = 13\,\text{TeV}$.
The $t\bar{t}+$ jet approach as performed by ATLAS for 7 and 8 TeV looks promising for a precise measurement.

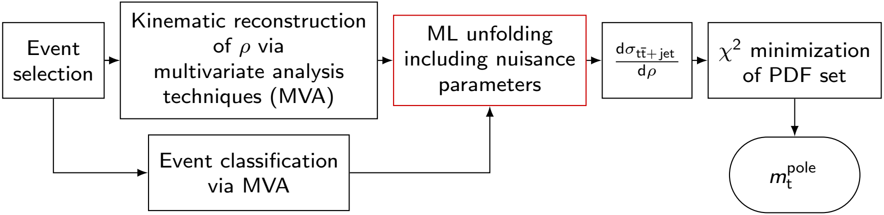
Analyses structure

Structure of the new measurements:

Direct mass measurement:



Pole mass measurement:



New direct mass measurement

$t\bar{t} \to \ell +$ jets channel was used in the most precise m_t measurement (PRD 93, 0720)

Useful channel for precision measurements due to

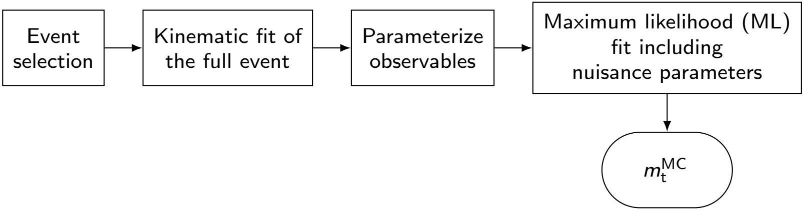
- branching ratio
- easy to trigger
- only one ν

The last analysis on data with $\sqrt{s} = 13\,\mathrm{TeV}$ (EPJC-78-891) could not surpass it with the same analysis approach.

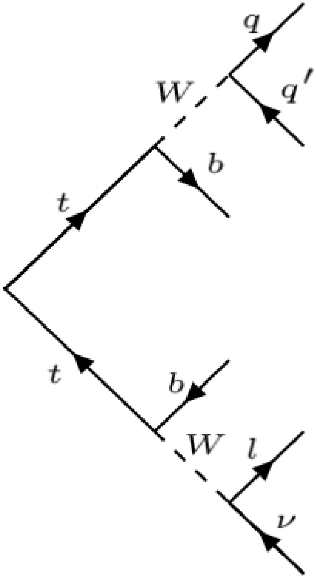
This new measurement expects a more accurate uncertainty than the prior analyses due to

- CP5 UE tune
- More events in simulation variation samples
- Use more observables
- Include all sources of uncertainty as nuisance parameters in the likelihood

Analysis structure of the direct mass measurement



Event selection



- $36\,\mathrm{fb}^{-1}$ of $\sqrt{s} = 13\,\mathrm{TeV}$ pp-collision data recorded by CMS in 2016
- trigger on single isolated muons and electrons
- anti-$k_t^{R=0.4}$ jets with $p_T > 30\,\mathrm{GeV}$, $|\eta| < 2.4$
- at least two b-tagged jets via *DeepJet* (WP: 1% mis-tag)

Kinematic reconstruction

Fit the full event kinematics to a $t\bar{t}$ hypothesis.

Inputs: p_T and angles of the jets and lepton and missing p_T

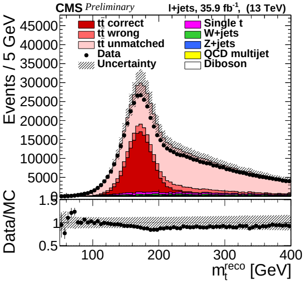
Constraints: ▶same invariant mass of both top quark candidates

▶$m_W^{fit} = 80.4\,\text{GeV}$ ▶p_T balance

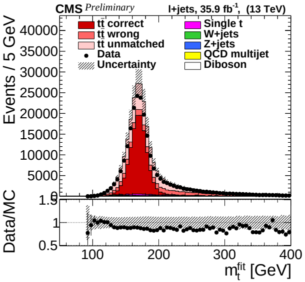
Use goodness-of-fit $P_{gof} = \exp(-\frac{1}{2}\chi^2)$ to assign jets to parton candidates

$P_{gof} \geq 0.2$ selection reduces background fraction to 5% and increases correct jet-parton assignments

invariant mass before kin. fit (m_t^{reco})



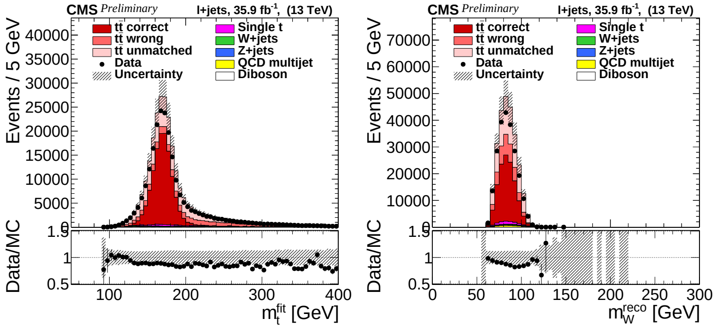
invar. mass after the kin. fit and $P_{gof} \geq 0.2$ sel (m_t^{fit})



Observables

use $P_{\text{gof}} \geq 0.2$ selection, "fit" denotes the kinematic after the kin. fit, "reco": kinematic before the kin. fit

- m_t^{fit} main observable
- m_W^{reco} reduces jet energy correction (JEC) uncertainties



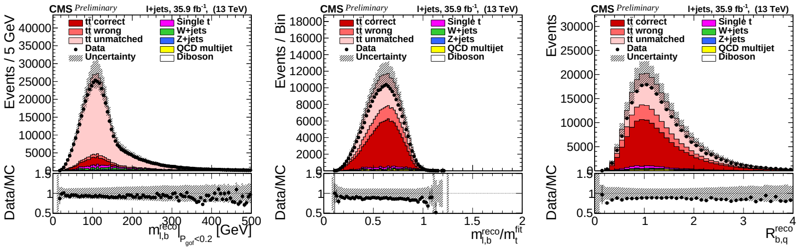
Observables

- $m_{l,b}^{reco}|_{P_{\text{gof}}<0.2}$ additional information on m_{t} not used in prior analyses

new observable $m_{l,b}^{reco} = \sqrt{\left(P_{lepton}^{reco} + P_{b}^{reco}\right)^2}$,inspired by $t\bar{t} \rightarrow$ di-lepton, but different jet-parton assignment

de-correlate $m_{l,b}^{reco}$ from m_t^{fit} as $m_{l,b}^{reco}/m_t^{fit}$

- $m_{l,b}^{reco}/m_t^{fit}$
- $R_{b,q}^{reco} = \frac{p_{T_{b1}}^{reco}+p_{T_{b2}}^{reco}}{p_{T_{q1}}^{reco}+p_{T_{q2}}^{reco}}$ reduces flavor dependent JEC uncertainties



Maximum likelihood

A negative log-likelihood is minimized to extract m_{t} .

Use custom implementation to include analytic parameterizations of observable distributions.

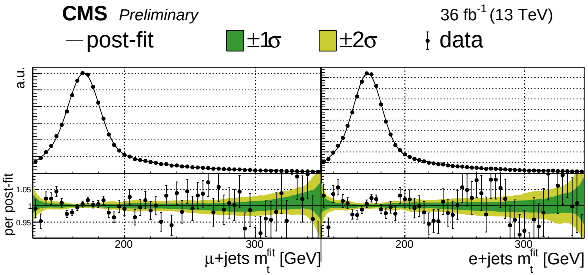
The $m_{\mathrm{t}}^{\mathrm{fit}}$ distribution is parameterized with a Voigt profile (convolution of Gauss and Breit-Wigner profiles) plus Chebychev polynominals.
For each of the other observables eight bins of equal integral are used. The parameterized distributions are used normalized.

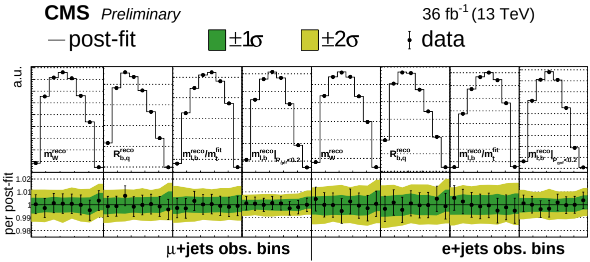
Each variable is parameterized linear in m_{t} , the nuisance parameters are implemented factorized approach.

$$\alpha_k(m_{\mathrm{t}}\,,\vec{\theta}) = \left(\alpha_k^0 + s_k^0\,(m_{\mathrm{t}}\, - 172.5\,\mathrm{GeV})\right)\prod_l \left(1 + s_k^l\theta_l\right)$$

The α_k are the free variables of the observable parameterization. Include all uncertainty sources l as nuisance parameters θ_l in this parameterisation with slopes s_k^l that are derived from simulation. The default simulation corresponds to $\vec{\theta} = \vec{0}$. The nuisance parameters are Gaussian constrained

Post-fit distributions



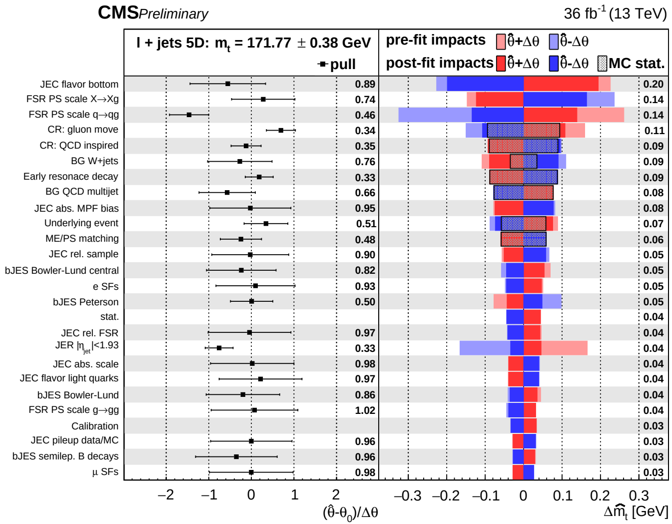


Post-fit probability density functions with error bands, compared to data

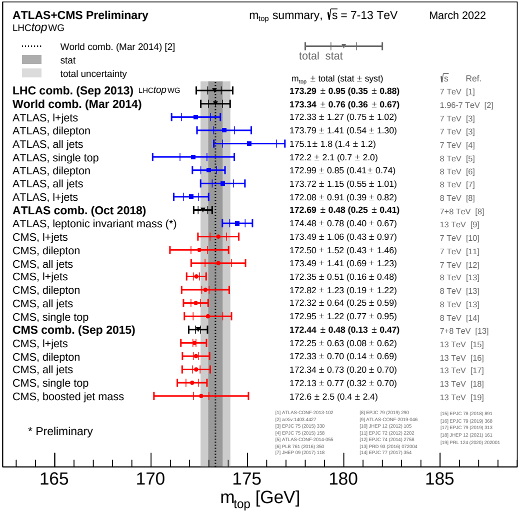
The distributions can describe the data well.

Result and impacts

$m_t^{MC} = 171.77 \pm 0.38\,\text{GeV}$, this includes $\sigma_{stat} = 0.04\,\text{GeV}$



Comparison to prior m_t measurements



The new result $m_t = 171.77 \pm 0.38\,\mathrm{GeV}$ is compatible with the prior ℓ+jets measurements.

Summary of the direct mass measurement

▶Inclusion of nuisances parameters in the fit helps to hone in on systematic uncertainties on the top quark mass.

▶Including $m_{\ell b}^{\text{reco}}$ for events formerly excluded by the P_{gof} cut, $m_{\ell b}^{\text{reco}}/m_{t}^{\text{fit}}$ and $R_{\text{bq}}^{\text{reco}}$ decreases the uncertainty in the direct measurement by additional 150 MeV

The final result is:

$$m_{t}^{\text{MC}} = 171.77 \pm 0.38\,\text{GeV} \; \left(\frac{\sigma_{m_t}}{m_t} = \pm 0.22\%\right)$$

This includes $\sigma_{\text{stat}} = 0.04\,\text{GeV}$ and $\sigma_{\text{calibration}} = 0.03\,\text{GeV}$
▶Its biggest uncertainty source is JEC flavor bottom as in prior analyses.
▶The limit from simulation statistic of variation samples still considerable.

This result surpasses the prior measurement on the same data by 0.25 GeV and is the most precise top quark mass measurement by 0.12 GeV.

Pole mass measurement

$t\bar{t} \to \ell\ell b\bar{b} + 1$ add. jet channel
The additional jet increases the sensitivity.

Measure norm. diff. $t\bar{t}+$ jet cross section as a function of the ρ

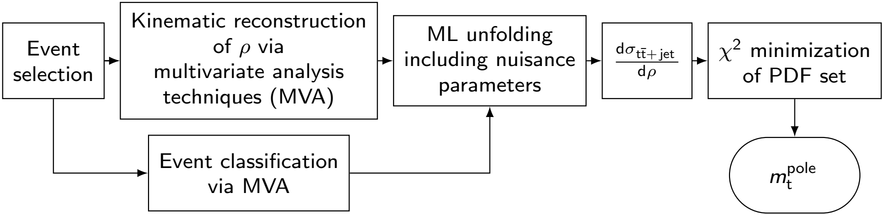
$$\rho = \frac{2m_0}{m_{t\bar{t}+\text{jet}}},\ m_0 = 170\,\text{GeV}$$

▶used before by ATLAS (20.2 fb^{-1}@8 TeV) JHEP11(2019)150
▶first measurement with this approach in this channel, at 13 TeV, and with CMS data

▶use multivariate analysis techniques (MVA) to improve ρ reconstruction and event categorization

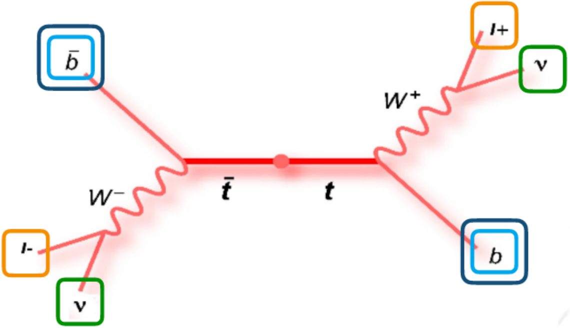
▶include dependencies on systematic uncertainty sources as nuisance parameters in the likelihood unfolding

Analysis structure of the pole mass measurement



Event selection

- $36\,\text{fb}^{-1}$ of $\sqrt{s}$ =13TeV pp-collision data recorded by CMS in 2016
- trigger on single isolated muons and electrons, and on di-leptons anti-$k_t^{R=0.4}$ jets with $p_T > 30\,\text{GeV}$, $|\eta| < 2.4$
- use *DeepCSV* b-tagging (WP: 10% mis-tag), additional b-jet energy regression



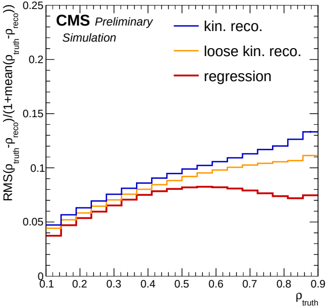
Kinematic reconstruction

ρ^{gen} is reconstructed via MVA regression.
The most import inputs of the network are:

- Loose kinematic reconstruction:
  - solve only $t\bar{t}$ system without m_t constraint, ▶$m_{\ell b}^{\text{reco}} < 180\,\text{GeV}$, ▶$m(W^+W^-) \geq 2 \cdot 80.4\,\text{GeV}$, ▶$m(\nu\bar{\nu}) \geq 0\,\text{GeV}$
- Full kinematic reconstruction:
  - solve top and anti-top decays individually, ▶total p_T conservation, ▶$m_W^{\text{fit}} = 80.4\,\text{GeV}$, ▶$m_t^{\text{fit}} = 172.5\,\text{GeV}$

Further inputs are:
- p_T of the subleading lepton
- MET
- invariant masses of different lepton and jet combinations

The regression improves the resolution of ρ.



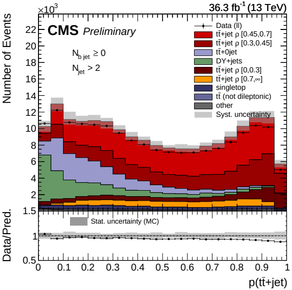
Classification

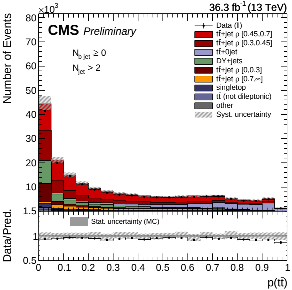
Use MVA to classify events into $t\bar{t}$ +1jet, $t\bar{t}$ +0jet and DY+jets.
(De-correlate from ρ via Unsupervised Domain Adaptation by Backpropagation)

The MVA inputs are:

- p_T of the additional jet from the full kin. reco., the hardest and third hardest jets, the dilepton system and the leading lepton
- invariant masses of the dilepton system, the leading lepton,the subleading lepton
- MET and the number of reconstructed jets

The signal responses $R_{\mathrm{NN}} = \frac{p(t\bar{t}+\mathrm{jet})}{p(t\bar{t}+\mathrm{jet})+p(t\bar{t}+0\,\mathrm{jet})}$ is used as observable in the main unfolding categories.





Maximum likelihood unfolding

Use maximum likelihood unfolding to get the signal strength

$$\boxed{r_k = \frac{\sigma^k_{\mathrm{t\bar{t}+jet}}}{\sigma^k_{\mathrm{t\bar{t}+jet}}(\mathrm{MC})}} \text{ for } \sigma^k_{\mathrm{t\bar{t}+jet}} = \int_{\rho^k_{\mathrm{low}}}^{\rho^k_{\mathrm{high}}} \frac{\mathrm{d}\sigma_{\mathrm{t\bar{t}+jet}}}{\mathrm{d}\rho}\mathrm{d}\rho.$$

r_k is the signal strength in different bins k of the ρ distribution. $\rho^k_{\mathrm{high/low}}$ denotes the high/low edge of this bins

- All uncertainty source are included as nuisance parameters in the likelihood.
- Uncertainties from simulation statistic are considered with dedicated nuisances a-la Barlow-Beeston-lite for all bins and processes.

Categories for ML unfolding

Categories for the ML unfolding independent for the different lepton channels.

The ρ bins are chosen for purity and stability.

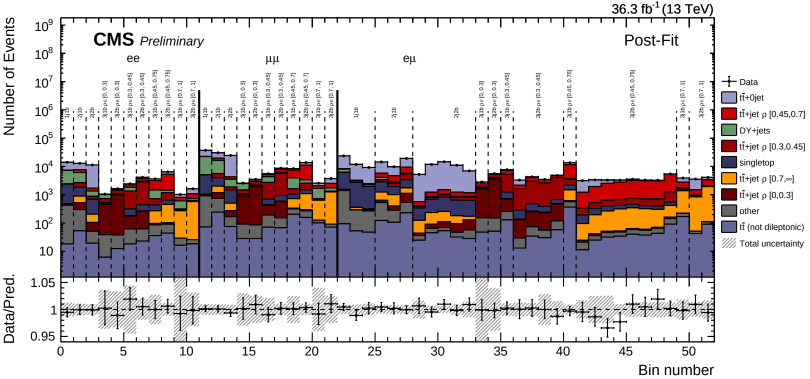
	reconstructed ρ				no reco. ρ	
	$N_{jet} = 3$				$N_{jet} \leq 1$	$N_{jet} = 2$
	$\rho < 0.3$	$0.3 < \rho < 0.7$	$0.45 < \rho < 0.7$	$\rho > 0.7$		
$N_{b\,jet} = 1$	R_{NN}	R_{NN}	R_{NN}	R_{NN}	p_T 1st jet	p_T 2nd jet
$N_{b\,jet} \geq 2$	R_{NN}	R_{NN}	R_{NN}	R_{NN}	-	$m_{\ell b}^{min}$

$R_{NN} = \frac{p(t\bar{t}+\text{jet})}{p(t\bar{t}+\text{jet})+p(t\bar{t}+0\,\text{jet})}$ is taken from the MVA event classification

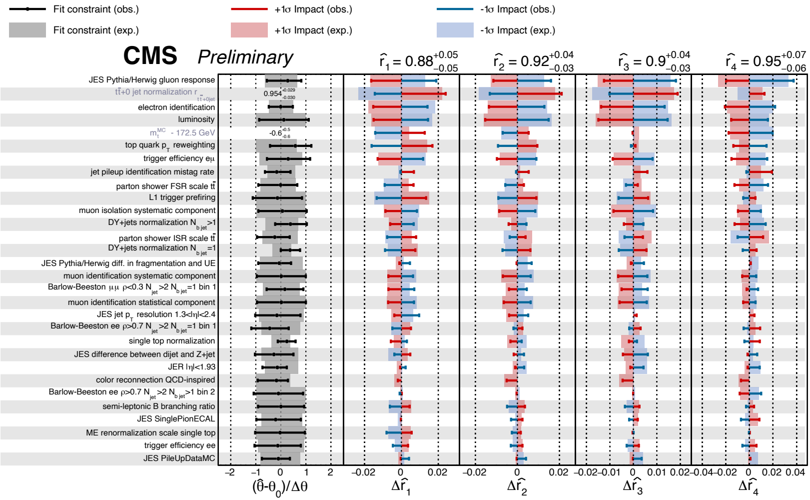
- $N_{b\,jet} = 1$, $N_{jet} < 3$ categories help to constrain the background and syst. uncertainty
- $N_{b\,jet} \geq 1$, $N_{jet} = 2$ category constraints m_t^{MC}

Post-fit distribution

For the same-flavor lepton combinations only the number of events in the category is used.



Signal strengths and impacts



$r_k = \dfrac{\sigma^k_{t\bar{t}+\text{jet}}}{\sigma^k_{t\bar{t}+\text{jet}}(\text{MC})}$, $k \in \rho$-bins, final uncertainties will be reduced by normalization that take the full correlations into account

Result of the pole mass measurement

m_t^{pole} is extracted by a χ^2 fit of different PDF sets to $\frac{1}{\sigma_{t\bar{t}+\text{jet}}} \cdot \frac{d\sigma_{t\bar{t}+\text{jet}}}{d\rho}$

from ABMP16NLO:

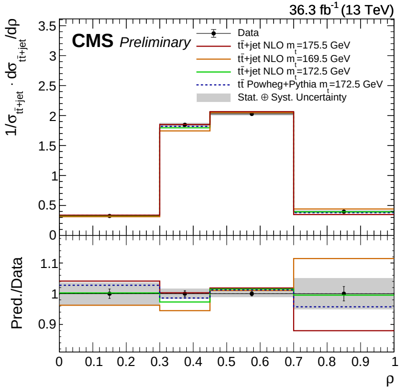
$m_t^{pole} = 172.94 \pm 1.27(\text{fit+PDF+extr}) \pm^{0.51}_{0.43} (\text{scale})$ GeV

from CT18NLO:

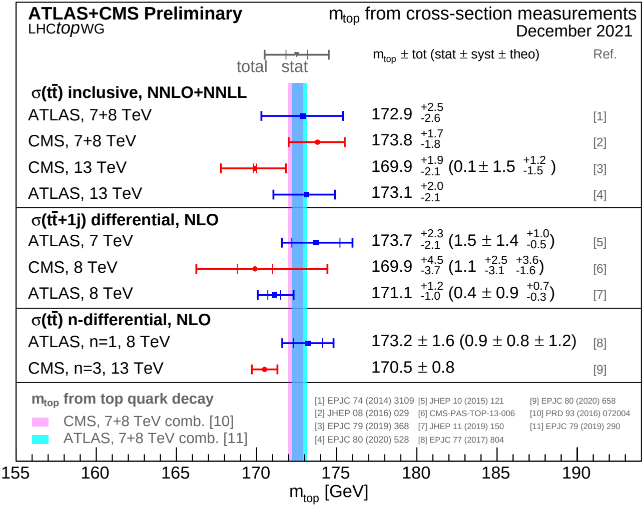
$m_t^{pole} = 172.16 \pm 1.35(\text{fit+PDF+extr}) \pm^{0.50}_{0.40} (\text{scale})$ GeV

Using normalized $\frac{d\sigma_{t\bar{t}+\text{jet}}}{d\rho}$ reduces some systematic uncertainties.

This is the first m_t measurement using the new NLO theory prediction with $H_T/2$ as dynamical scale.



Comparison to former m_t measurements



The new result $m_t = 172.9 \pm 1.4\,\text{GeV}$ is compatible with most former measurements.

Summary of the pole mass measurement

The additional jet and the highest ρ bin yield a high sensitivity in m_t .

The top quark pole mass was measured the first time in $t\bar{t}+$ jet events from the CMS experiment at $\sqrt{s} = 13\,\text{TeV}$ resulting in

$$m_t^{\text{pole}} = 172.94^{+1.37}_{-1.34}\ \text{GeV}\ \left(\frac{\sigma_{m_t}}{m_t} = \pm 0.8\%\right)$$

▶novel ABMP16NLO PDF set with dynamic scale
▶new MVA methods for observable reconstruction and event classification to maximize its sensitivity
▶includes uncertainties as nuisance parameters in the unfolding.

Summary

The two presented top quark mass measurements extract the mass of the top quark for different mass definition with different leading uncertainties.

Both have a phenomenal precision in their respective category.

$$m_{\mathrm{t}}^{\mathrm{pole}} = 172.94^{+1.37}_{-1.34}\,\mathrm{GeV}$$

$$m_{\mathrm{t}}^{\mathrm{MC}} = 171.77 \pm 0.38\,\mathrm{GeV}$$

Thank you for your attention!