Recent measurements of the top-quark mass and Yukawa coupling using the ATLAS and CMS detectors at the LHC

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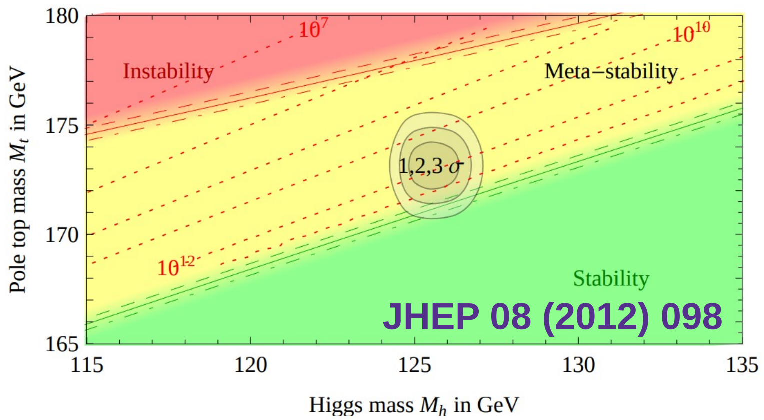
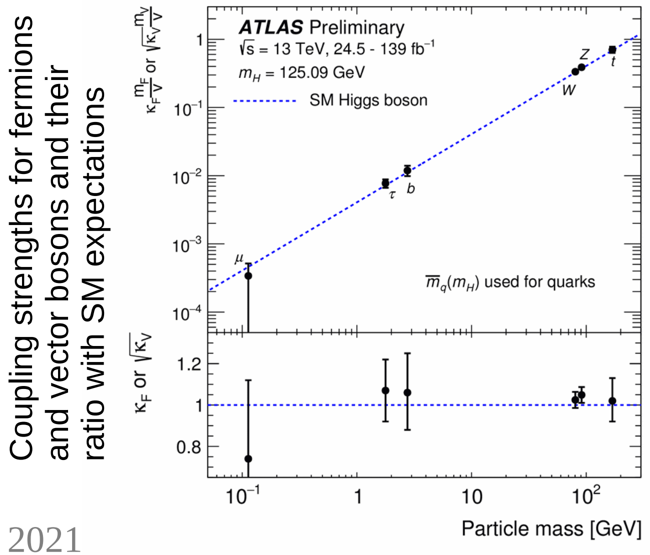
Top quark mass and Yukawa coupling

- The top quark is the heaviest elementary particle in the Standard Model
- m_t is an important parameter to assess the internal consistency of the SM at the EW scale and to make predictions up to very high scales (assuming the SM holds)
- The top quark, as well as all quarks, is not a free particle
  Its mass can be determined through comparison with theoretical calculations
- Yukawa coupling proportional to the mass of fermions.
  → Largest value ~1 for the top quark
  → Sensitive to new physics

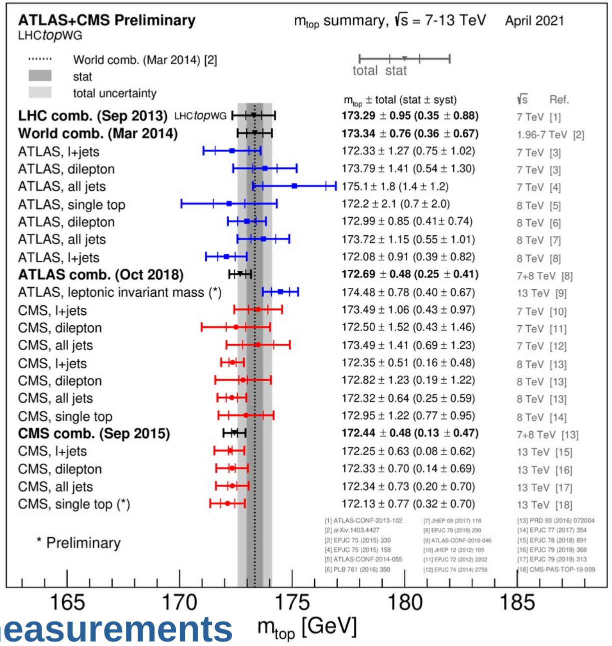




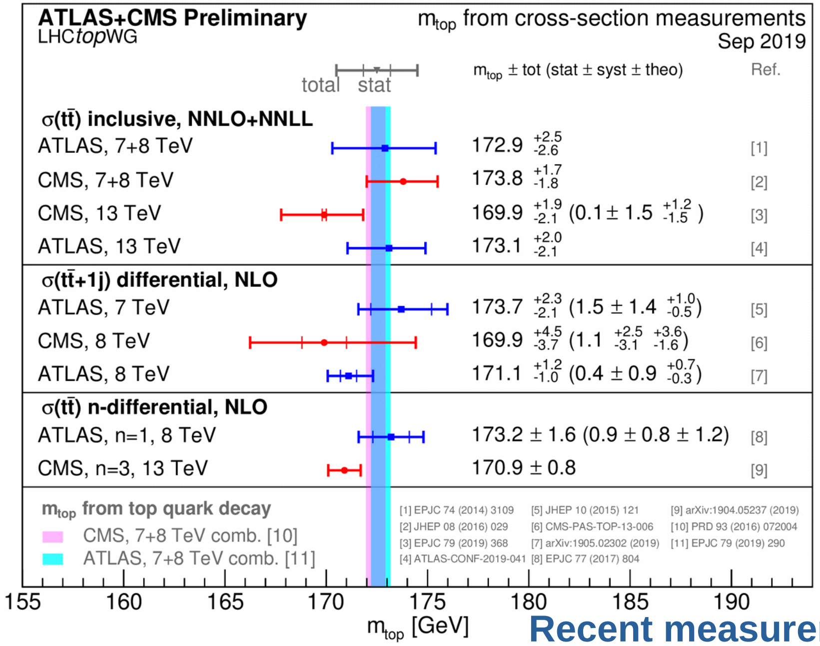
Measurements: overview

- **"Direct" measurements:** reconstruct invariant mass of decay products, or some other quantity highly sensitive to m_t, compare with MC calculations (template methods) → $\mathbf{m_t^{MC}}$
- **"Indirect" measurements:** measure production cross-section (also differential) that can be compared to first-principle calculations → $\mathbf{m_t^{POLE}}$, $\mathbf{m_t^{\overline{MS}}}$

Relation $m_t^{POLE} \leftrightarrow m_t^{\overline{MS}}$ calculated to 4-loops precision in QCD (Phys. Rev. Lett. 114 (2015) 142002)



Recent measurements → 0.3-0.4% uncertainty



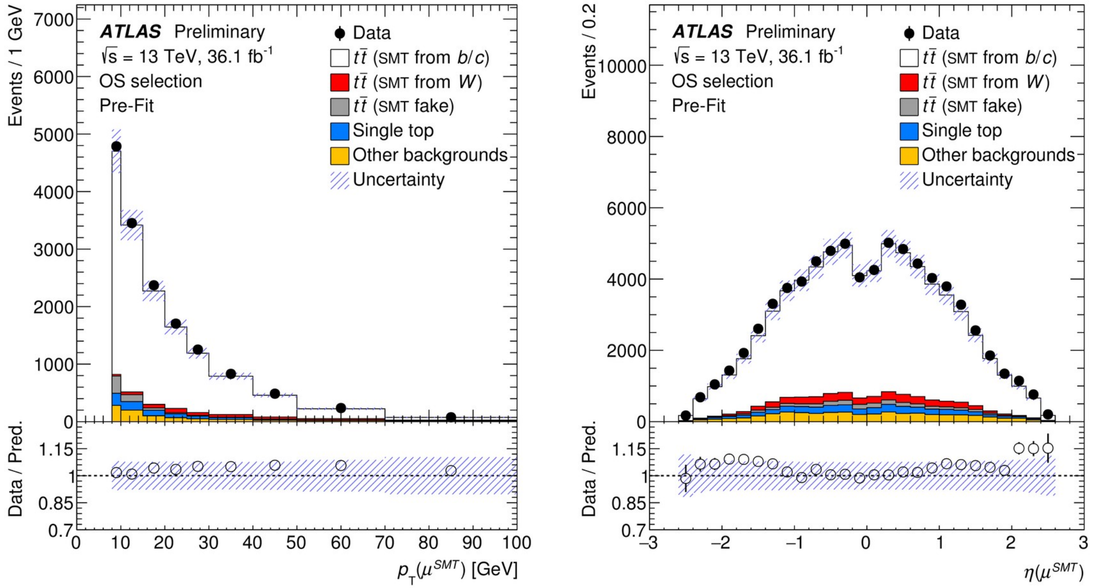
Recent measurements → 0.5% uncertainty

Top quark mass with Soft Muons

13 TeV - 36.1 fb^{-1} - ATLAS-CONF-2019-046

- l+jets events
- At least one SMT-tagged b-jet in the event → soft μ
- $m_{l\mu}$: invariant mass of the lepton from W-boson decay and the muon originated from a semileptonic b-hadron decay
- Reduced sensitivity to jet energy calibration and modeling of $t\bar{t}$ production kinematics (boost-invariant quantity, although distribution affected by top kinematics)

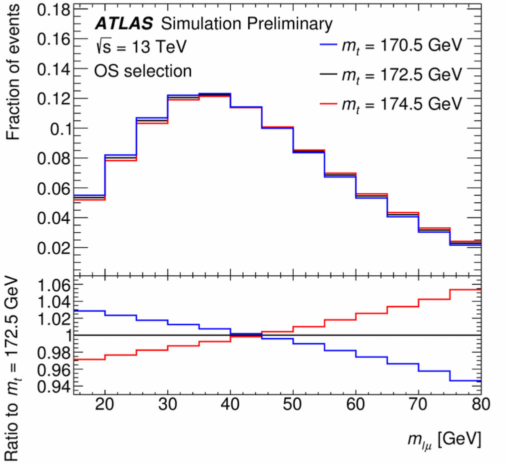
Soft Muon Tagging for b-jets: presence of a muon candidate within a distance ΔR <0.4 of a selected jet candidate

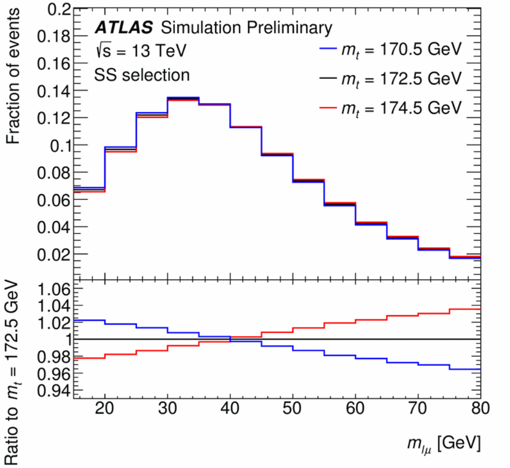


Soft muon kinematics

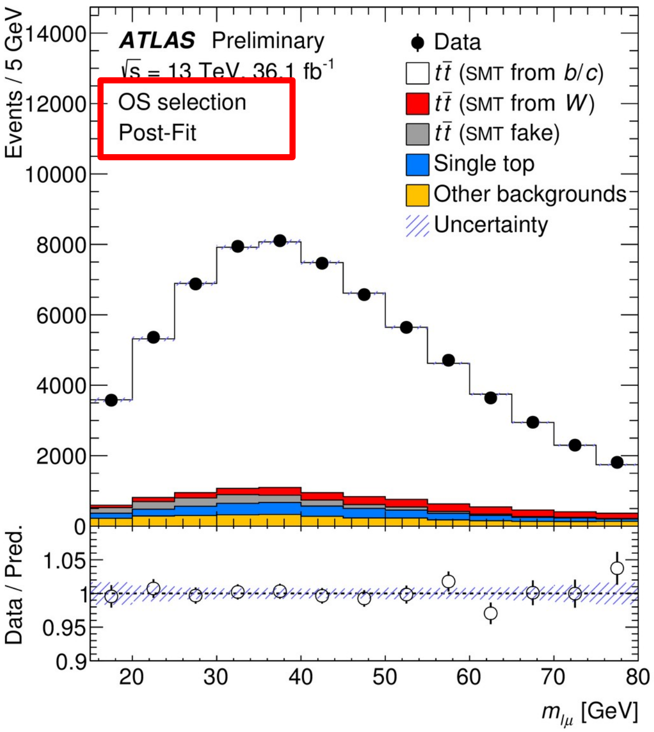
Top quark mass with Soft Muons

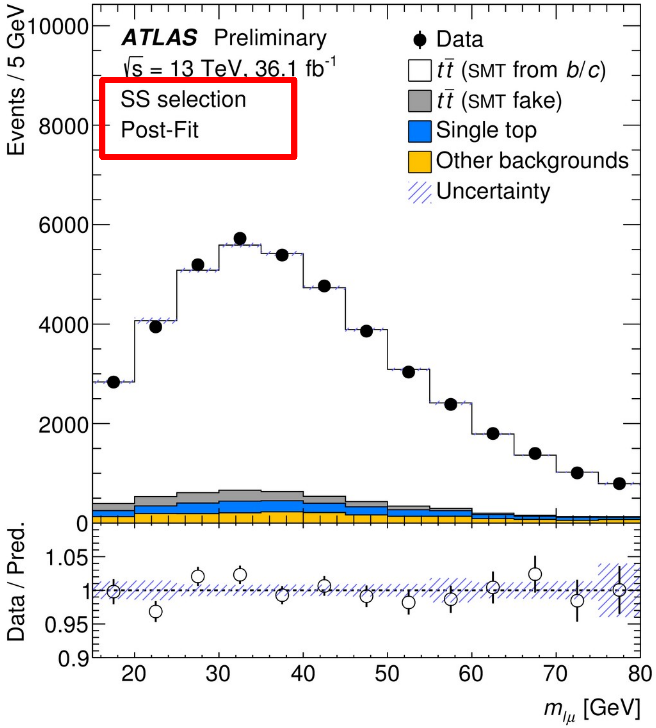
13 TeV - 36.1 fb^{-1} - ATLAS-CONF-2019-046





Both Opposite Sign (mainly b→μX) and Same Sign (mainly b→cX→μX') events sensitive to the top quark mass





Top quark mass with Soft Muons

13 TeV - 36.1 fb^{-1} - ATLAS-CONF-2019-046

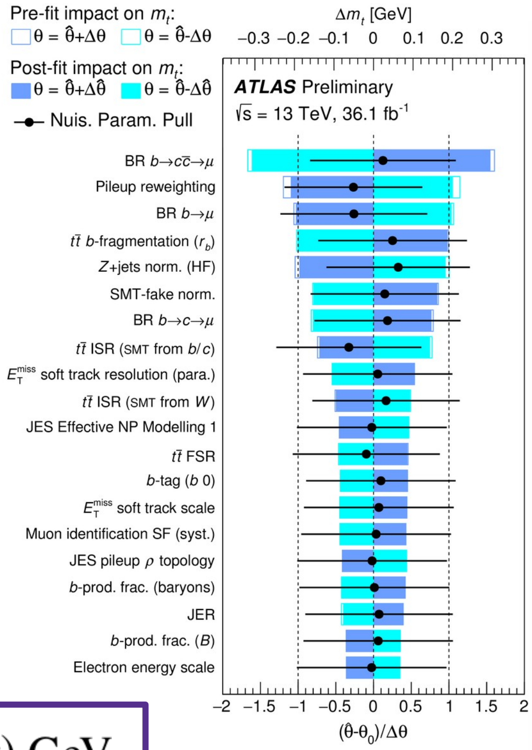
$m_{l\mu}$ distribution used to determine m_t^{MC} through profile likelihood fit:

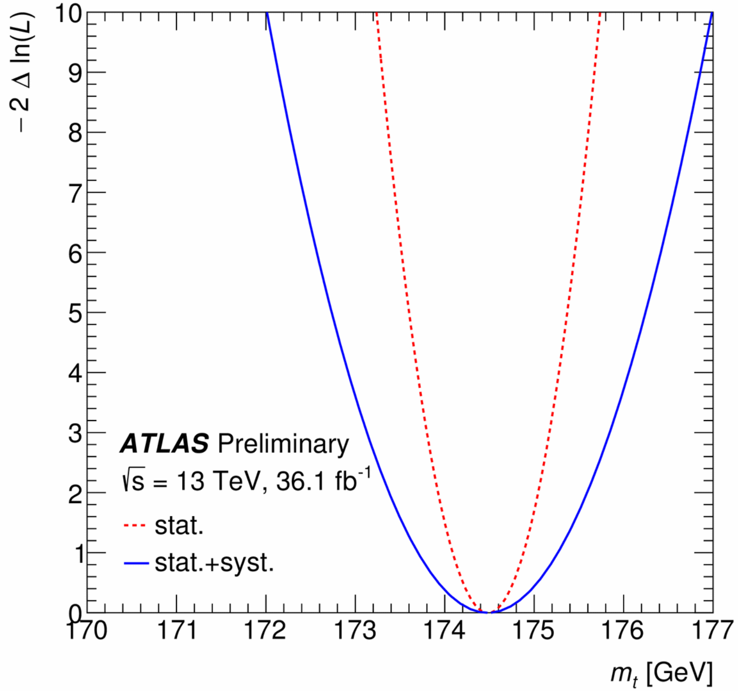
- free parameters: SS and OS $t\bar{t}$ normalizations and m_t^{MC} (model $m_{l\mu}$ distribution)
- no constraint observed on systematic uncertainty nuisance parameters

Systematic uncertainties are dominated by signal modeling.
Main one: b fragmentation and decay.

$$m_t = 174.48 \pm 0.40\,(\text{stat}) \pm 0.67\,(\text{syst})\ \text{GeV}$$

Total uncertainty: 0.78 GeV (0.45%)

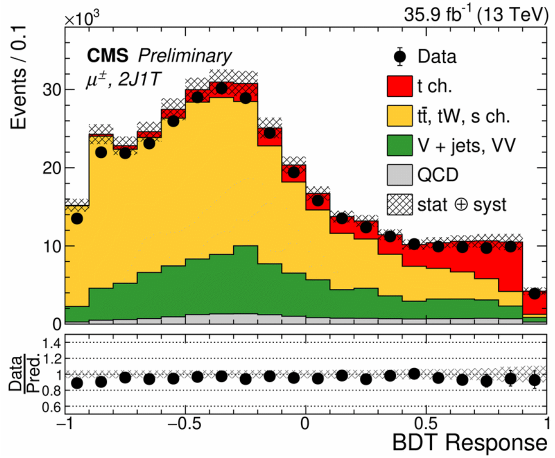




Top quark mass from single top events NEW!

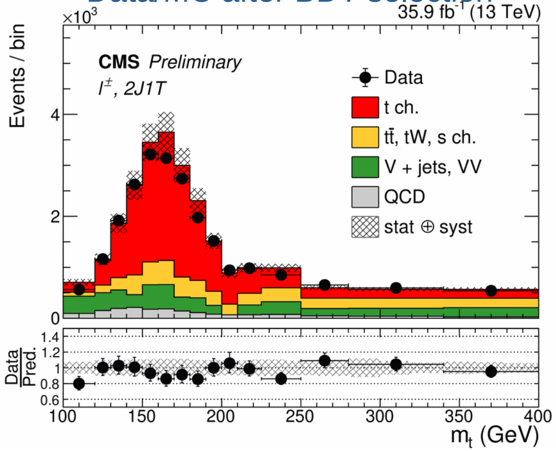
13 TeV - 35.9 fb^{-1} - CMS-PAS-TOP-19-009

- Top quark mass usually measured using $t\bar{t}$ events
- New techniques and complementary phase spaces can be affected by different systematic effects and help in the combinations
- Clean sample of single top events with leptonic top decays, selected with BDT (BDT resp. > 0.8 → purity ~60%)
  - BDT input variables uncorrelated with m_t

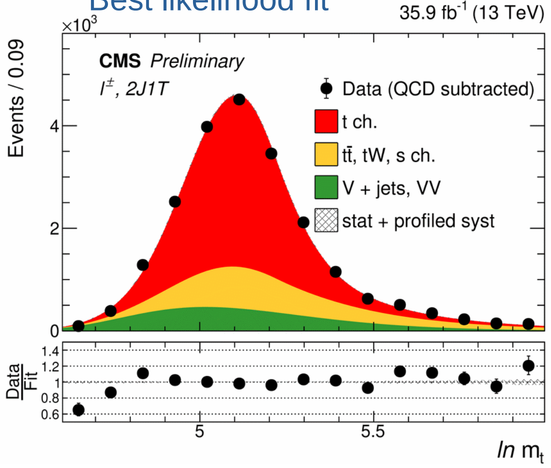


- m_t extracted with max-likelihood fit using a parametric 1D model to determine the peak position
- Separate fits done on events with positive and negative leptons → determination of top-antitop mass ratio and difference

Data/MC after BDT selection



Best likelihood fit

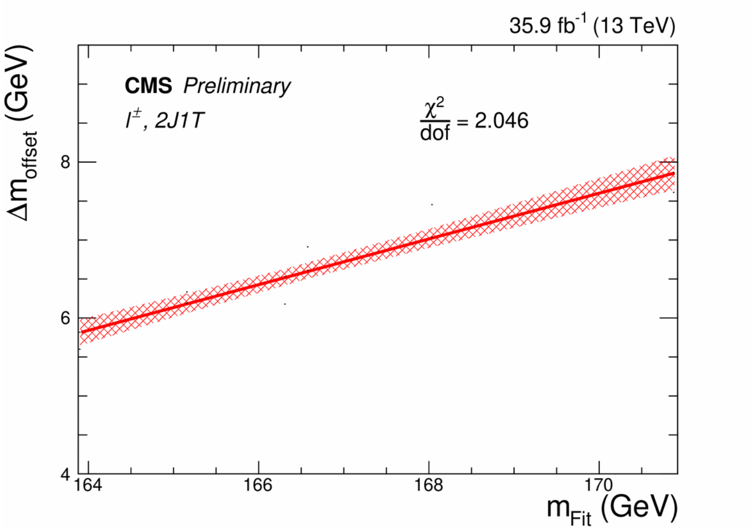


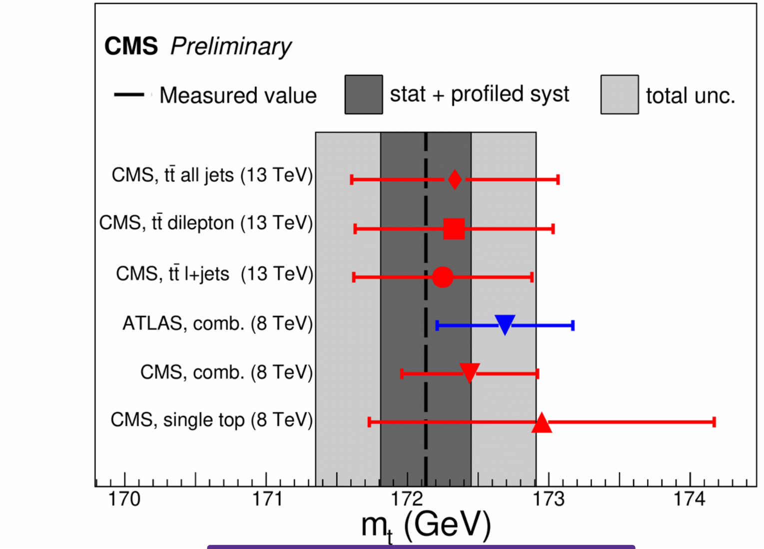
Top quark mass from single top events NEW!

13 TeV - 35.9 fb^{-1} - CMS-PAS-TOP-19-009

- Offset correction: $m_{t,Fit}$ calibrated on true $m_{t,True}$ using signal and $t\bar{t}$ samples with varied m_t
- Mismatch caused mainly by incorrect determination of $p_{z,\nu}$ in signal reconstruction

$$\Delta m_{offset} = m_{t,True} - m_{t,Fit}$$





$$m_t = 172.13^{+0.76}_{-0.77}\, GeV$$

Uncertainty competitive with $t\bar{t}$ measurements (0.45%)
Dominated by signal and $t\bar{t}$ modeling

$$\frac{m_{\bar{t}}}{m_t} = 0.995^{+0.005}_{-0.006} \qquad m_t - m_{\bar{t}} = 0.83^{+0.77}_{-1.01}\, GeV$$

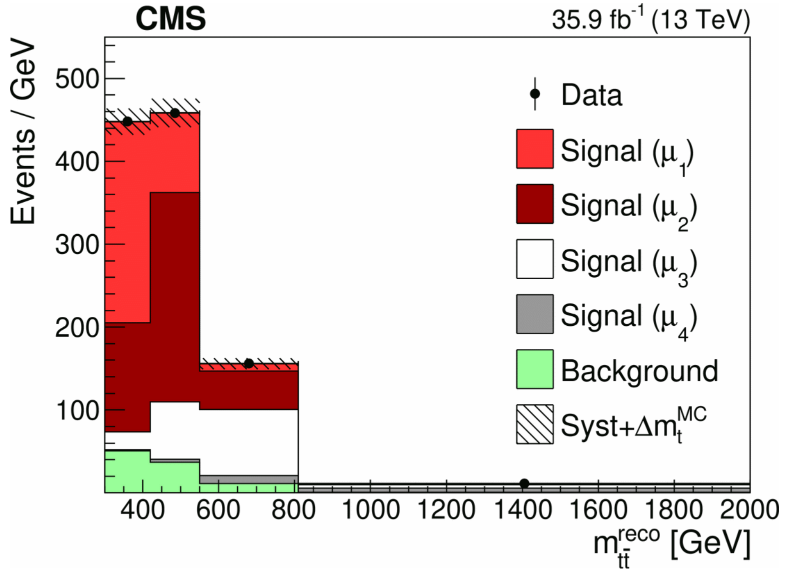
Running top quark mass

13 TeV - 35.9 fb^{-1} - Phys. Lett. B 803 (2020) 135263

- Use $t\bar{t}$ event in the eμ channel
- The simulated sample is divided in 4 sub-samples, corresponding to $m_{t\bar{t}}$ intervals at parton-level, treated as an independent signal process of $t\bar{t}$ production at the scale μ_k (mean $m_{t\bar{t}}$ in the bin)
- Maximum likelihood unfolding: the number of events in each bin ν_i is the sum of signal s_i^k and background b_i and depends on the cross-section in each bin $\sigma_{t\bar{t}}^{(\mu)}$ and on m_t^{MC} and nuisance parameters λ

$$\nu_i = \sum_{k=1}^{4} s_i^k(\sigma_{t\bar{t}}^{(\mu_k)}, m_t^{MC}, \vec{\lambda}) + \sum_j b_i^j(m_t^{MC}, \vec{\lambda})$$

- Sub-categories in each $m_{t\bar{t}}$ bin are defined based on the number of b-jets



Input distributions to the fit in all event categories:

	$N_b = 1$	$N_b = 2$	Other N_b
$N_{jets} < 2$	N_{events}	n.a.	N_{events}
$m_{t\bar{t}}^{reco}$ 1	$m_{\ell b}^{min}$	jet p_T^{min}	N_{events}
$m_{t\bar{t}}^{reco}$ 2	$m_{\ell b}^{min}$	jet p_T^{min}	N_{events}
$m_{t\bar{t}}^{reco}$ 3	$m_{\ell b}^{min}$	jet p_T^{min}	N_{events}
$m_{t\bar{t}}^{reco}$ 4	N_{events}	N_{events}	N_{events}

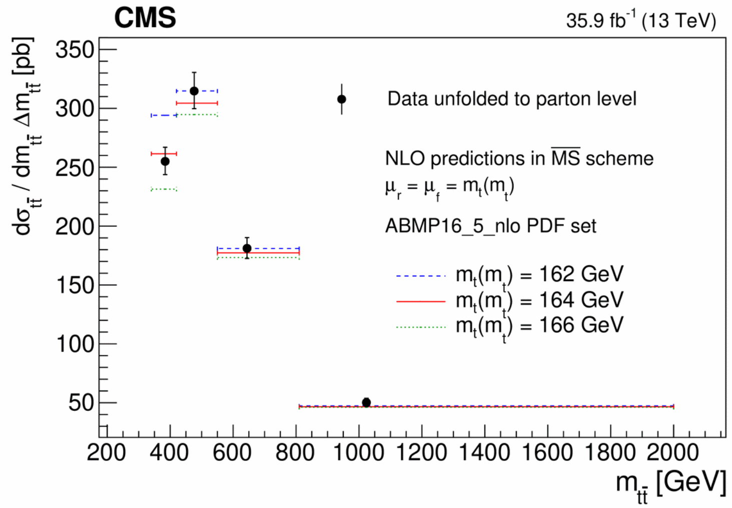
m_{lb}^{min}: min mass of lb pair

jet p_T^{min}: p_T of softest jet

Running top quark mass

13 TeV - 35.9 fb^{-1} - Phys. Lett. B 803 (2020) 135263

- Theoretical predictions in the $\overline{MS}$ scheme at NLO implemented in MCFM v6.8
- Using ABMP16_5_nlo PDF set, in which m_t is treated in the $\overline{MS}$ scheme



The plot shows the measured values of $\sigma_{t\bar{t}}^{(\mu)}$ compared to NLO calculations at in the $\overline{MS}$ scheme for different $m_t(m_t)$

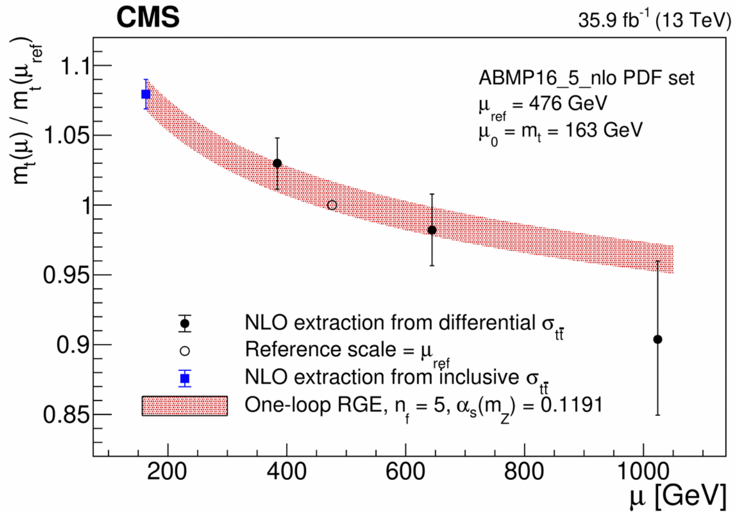
The value of $m_t(m_t)$ is determined independently in each m_{tt} bin

$m_t(m_t) \rightarrow m_t(\mu_k)$ at one loop precision using CRunDec_v3.0

Measured running mass compared with the evolution from $m_t(m_t) = 162.9 \pm 1.6$ (fit+extr+PDF+αs) $^{+2.5}_{-3.0}$ (scales) GeV

→ Total uncertainty: 3.4 GeV (2.1%)

obtained from the inclusive cross-section



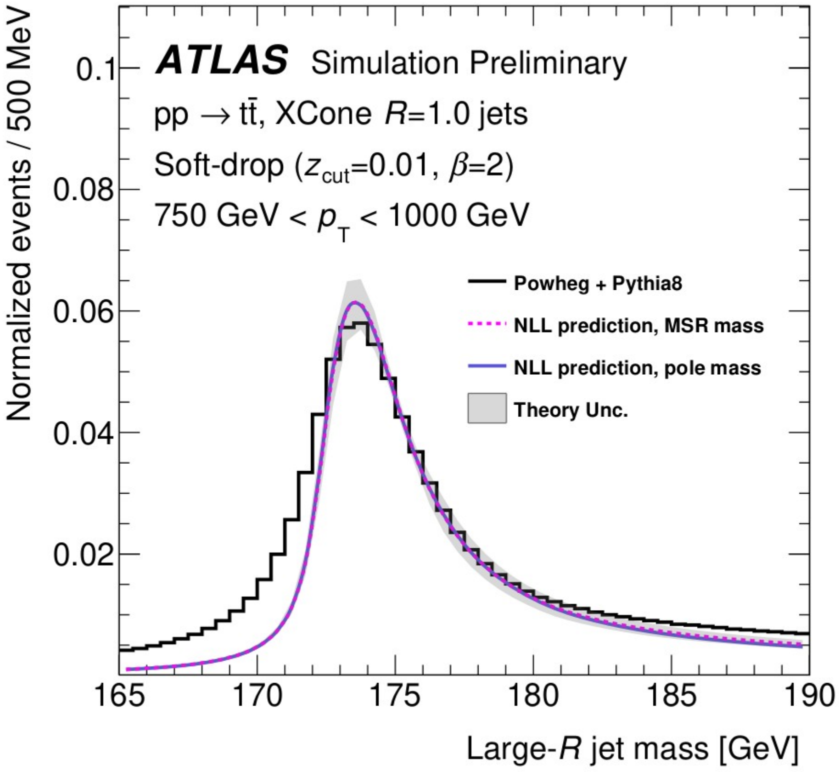
Ratios with respect to a reference scale, to exploit cancellations in the uncertainty

Interpretation of m_t in MC

NEW!

ATL-PHYS-PUB-2021-034

- Differences between m_t^{MC} and m_t^{pole} expected of the order of 0.5 GeV, due to non-perturbative QCD effects that affect the top mass determination
- Interpretation of m_t^{MC} obtained by comparing MC distributions with calculations within well-defined theoretical framework → pole mass or MSR mass schemes
  - MSR mass, similar to the $\overline{MS}$ mass, depends on a scale [1] → Setting the scale to 1 GeV: **$m_t^{MSR}(1\ GeV) \approx m_t^{pole}$**
- Hadronically decaying top quarks fully reconstructed as lightly groomed large-R jets in boosted kinematic regime
  - Large-R jet with R=1 using XCone algorithm
  - Soft-drop with parameters β=0,1,2 and z_{cut}=0.01,0.05
- Jet substructure distributions calculable in perturbative QCD beyond leading log resummation



[1] A. Hoang et al, Phys.Rev.Lett.101, 151602 (2008)

Interpretation of m_t in MC

NEW!

ATL-PHYS-PUB-2021-034

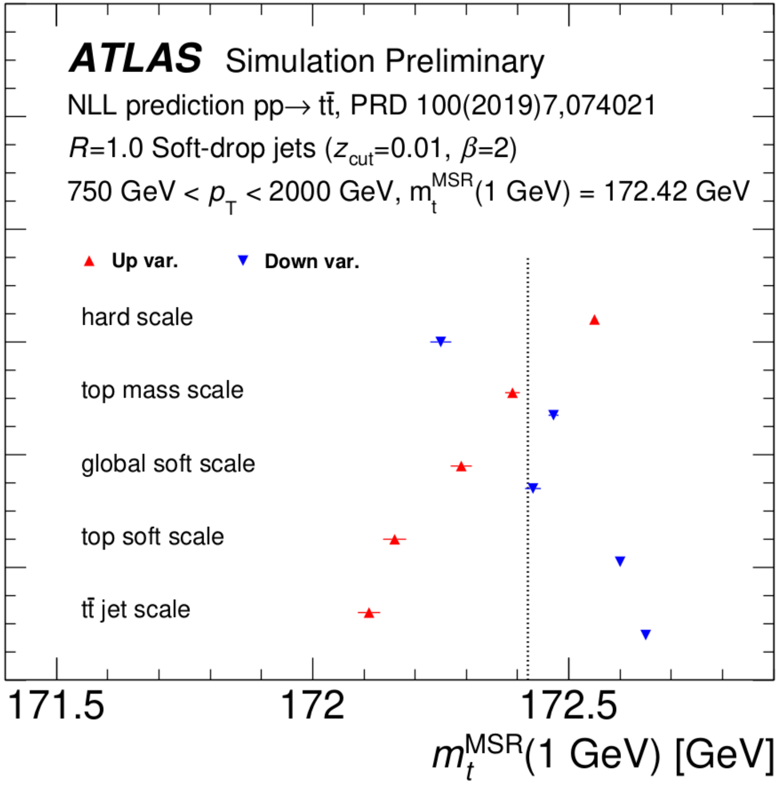
- Theoretical uncertainties: 5 scales varied up/down → +230/-310 MeV
- Method uncertainties: fit range and kinematic range → ±190 MeV
- UE modeling → ±155 MeV
- Powheg+Pythia8 MC variations (ME and PS models, ISR/FSR, recoil to colored objects on/off, B and D hadron decays) have minimal impact on m_t^{MSR}

$$m_t^{MC} = m_t^{MSR}(1\,GeV) + \Delta m^{MSR}$$

$$\Delta m^{MSR} = 80^{+350}_{-400}\,MeV$$

m_t^{MC} very close to m_t^{MSR}(1 GeV)

Uncertainties dominated by theoretical ones

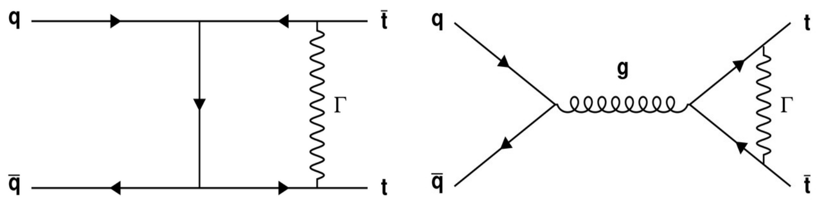


Top Yukawa coupling using $t\bar{t}$ events

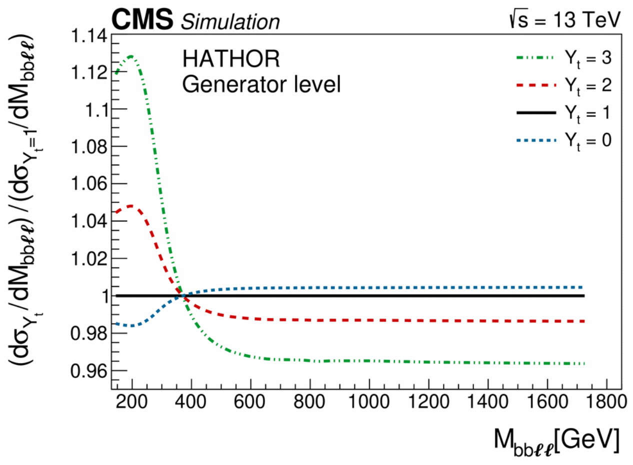
NEW!

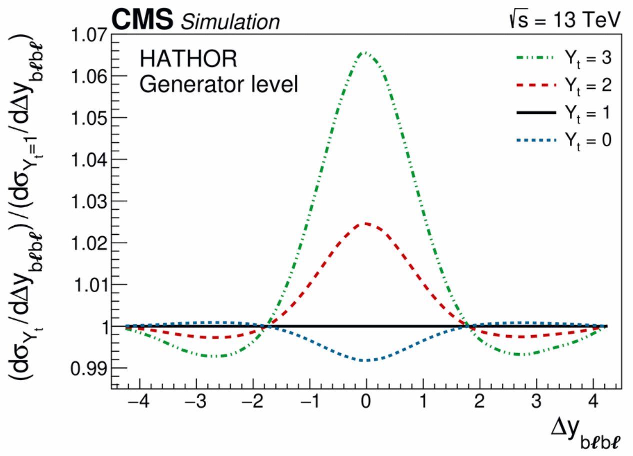
13 TeV - 137 fb^{-1} - Phys. Rev. D 102 (2020) 092013

- Top Yukawa coupling $g_t^{SM} \sim 1 \rightarrow Y_t = g_t/g_t^{SM} \sim 1$
- The coupling strength affects the kinematic distributions of $t\bar{t}$ events through loop corrections
  - $M_{t\bar{t}}$ and $\Delta y_{t\bar{t}} = y_t - y_{\bar{t}}$ significantly affected
  - Using M_{bbll} and Δy_{blbl} in dileptonic events to minimize the impact of top mis-reconstruction



- Loop corrections from QCD+EW evaluated using HATHOR to compute double-differential cross-sections as a function of $M_{t\bar{t}}$ and $\Delta y_{t\bar{t}}$ depending on Y_t
  → Implement EW corrections as multiplicative weight correction for MC





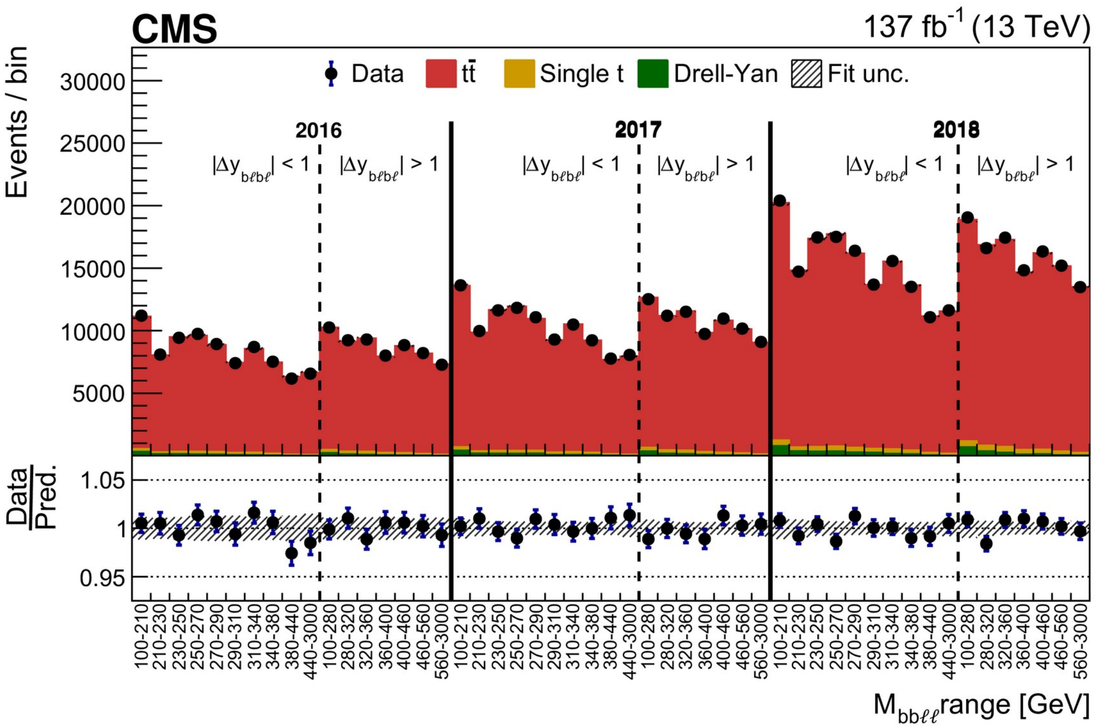
Top Yukawa coupling using $t\bar{t}$ events

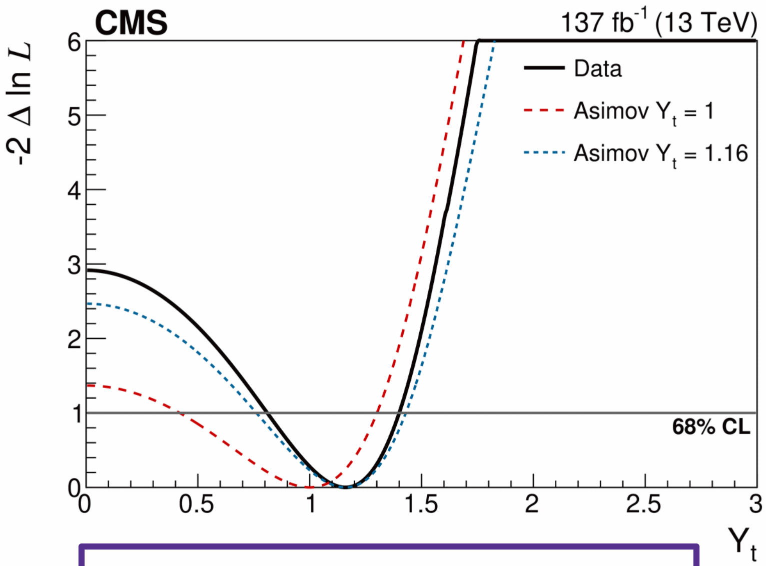
NEW!

13 TeV - 137 fb^{-1} - Phys. Rev. D 102 (2020) 092013

Y_t extracted with profile likelihood scan

Data/MC comparison at maximum likelihood Y_t=1.16





$$Y_t = 1.16^{+0.07}_{-0.08}(stat)^{+0.23}_{-0.34}(syst)$$

Dominant contributions to the uncertainty:
- EW corrections (8%)
- ISR/FSR modeling in $t\bar{t}$ (8%)
- $t\bar{t}$ scale uncertainty (7%)
- JES (7%)

Summary

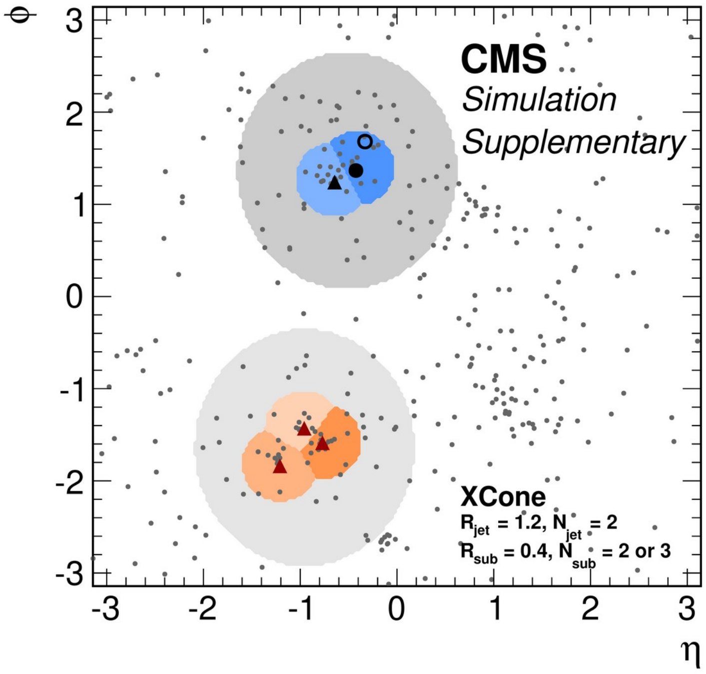
- m_t is a fundamental parameter of the SM that allows precision tests of the SM and provides insights on the fate of the universe
- Current m_t measurements with uncertainty below the GeV (~300 MeV in combinations) pose experimental and theoretical challenges
- The ultimate m_t determination is not a single measurement but a physics program, that includes:
  - techniques with uncertainties coming from different sources
  - different theoretical interpretations
- Measurements of the top Yukawa coupling may be sensitive to new physics effects.
  - At the moment good agreement with the SM: $Y_t = 1.16^{+0.07}_{-0.08}(stat)^{+0.23}_{-0.34}(syst)$

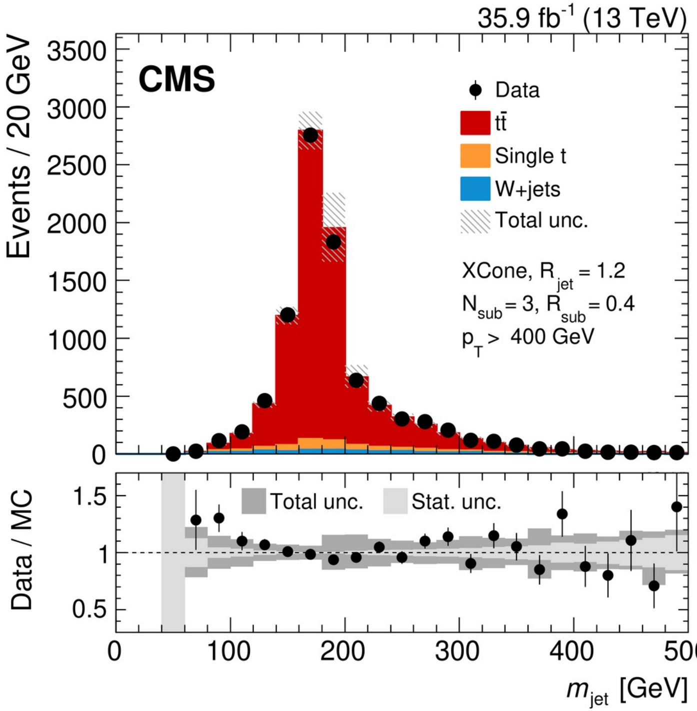
BONUS

Top quark mass in boosted $t\bar{t}$ events

13 TeV - 35.9 fb^{-1} - Phys. Rev. Lett. 124 (2020) 202001

- Boosted l+jets topology
- Exclusive XCone algorithm in 2 steps:
  1) 2 jets R=1.2
  2) 2 (lept) or 3 (hadr) sub-jets R=0.4
- $p_{T,jet}$>400 GeV, m_{jet}=mass of the 3 sub-jets of hadronic candidate





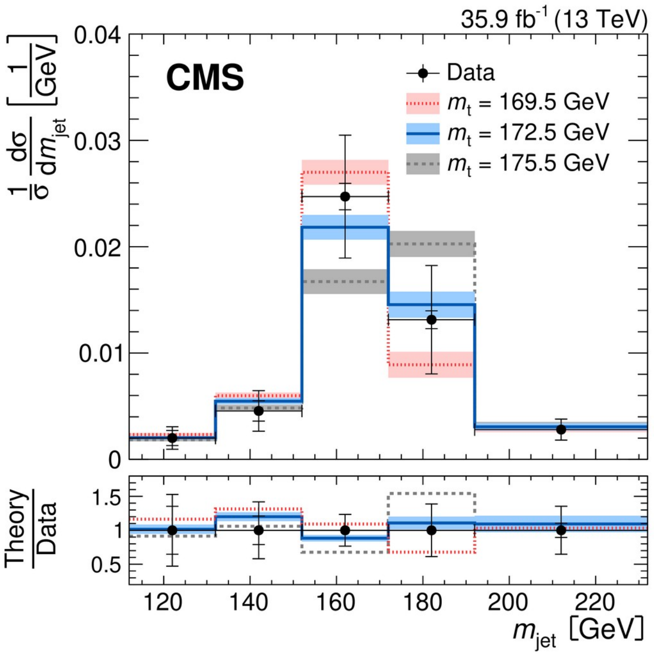
Top quark mass in boosted $t\bar{t}$ events

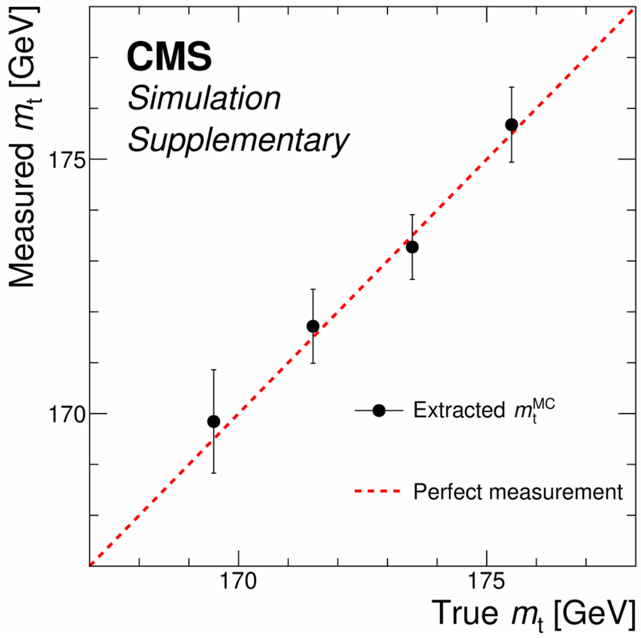
13 TeV - 35.9 fb^{-1} - Phys. Rev. Lett. 124 (2020) 202001

m_t = 172.6 ± 0.4 (stat) ± 1.6 (syst) ± 1.5 (model) ± 1.0 (theo) GeV
Total uncertainty: 2.5 GeV (1.4%)

Measurement of m_t^{MC} using m_{jet}, unfolded at particle level.

Impressive improvement on m_t from boosted tops with respect to 8 TeV result (9.0 GeV total uncertainty), mainly due to larger sample size and XCone jet reconstruction.





Running top quark mass: distributions

Examples of distributions used in the running top quark mass measurements

1^{st} $m_{t\bar{t}}^{RECO}$ bin

2^{nd} $m_{t\bar{t}}^{RECO}$ bin