Top mass and width from CMS and ATLAS

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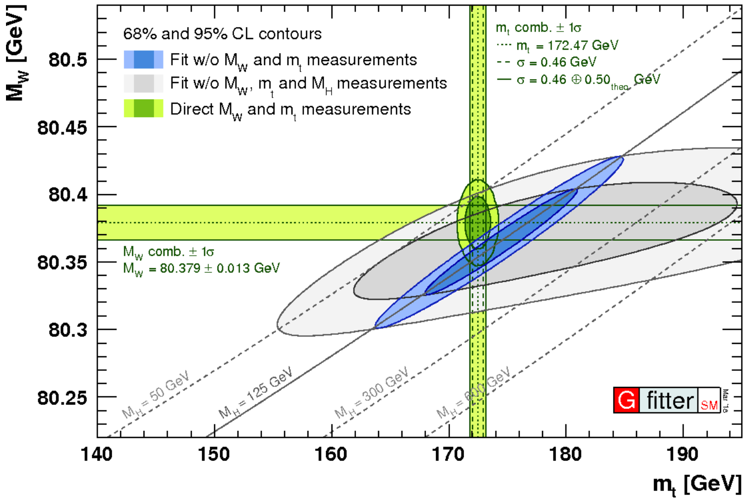
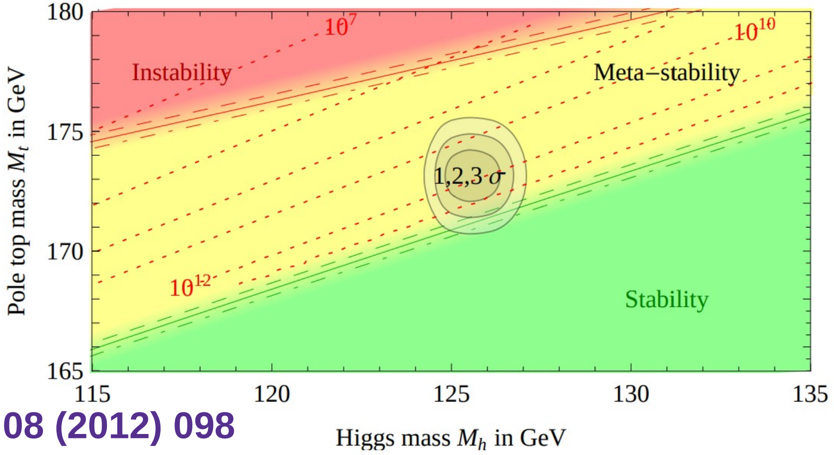
Top quark mass

- 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.
- Uncertainty of single measurements at the sub-GeV level, combinations ~half-GeV.



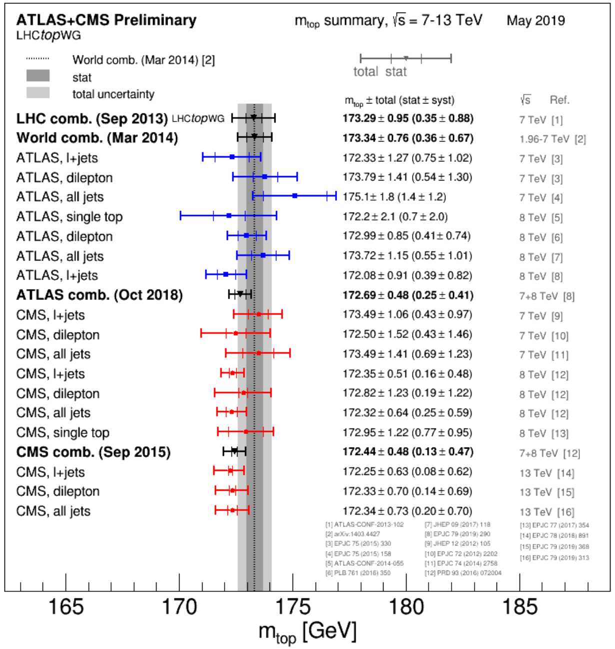


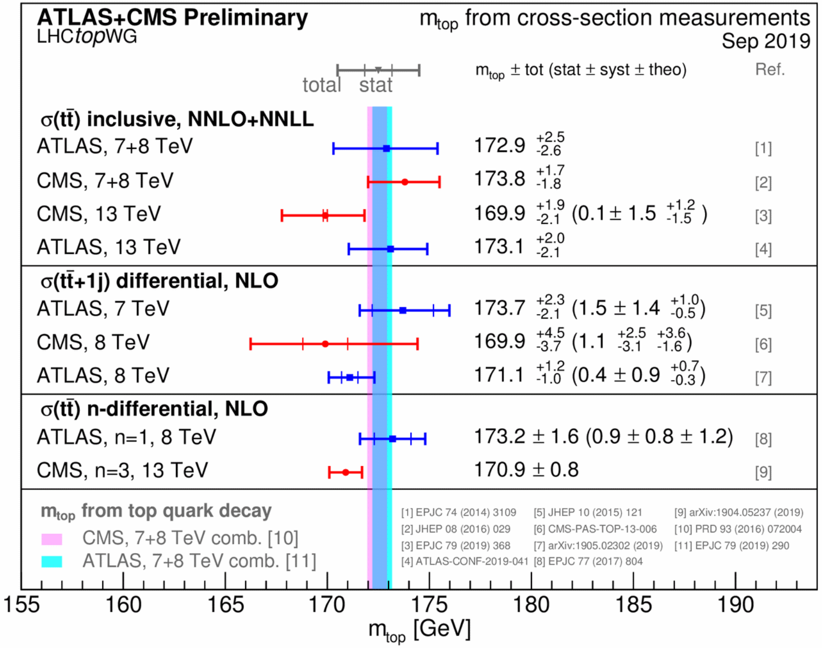
JHEP 08 (2012) 098

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)

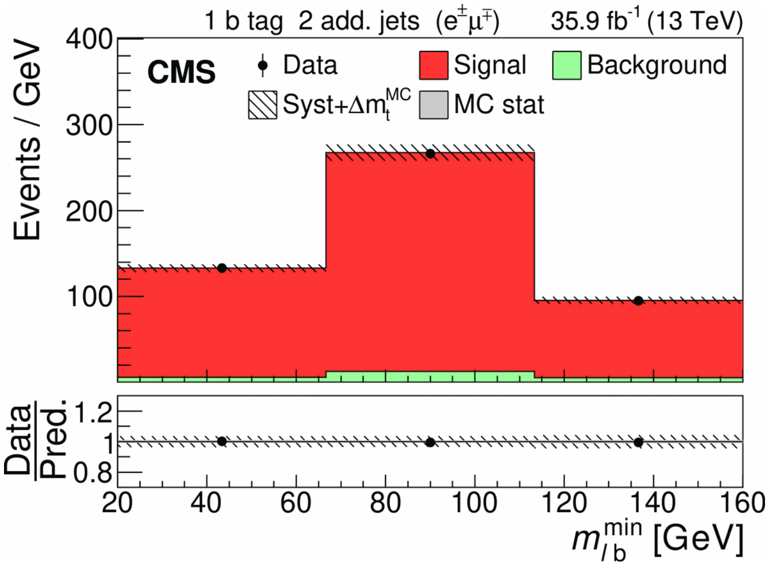




Measurement of $\sigma_{t\bar{t}}$ and m_t^{MC}

13 TeV - 35.9 fb^{-1} - Eur. Phys. J. C 79 (2019) 368

- Dilepton final state
- 12 event categories defined in terms of N_{jets}, $N_{b\text{-}jets}$
- Profile likelihood method that includes nuisance parameters corresponding to all systematic uncertainties.
  Use m_t^{MC} as free parameter → measure $\sigma_{t\bar{t}}$ and m_t^{MC} simultaneously
- Enhanced sensitivity to m_t^{MC} obtained including m_{lb}^{min} (min mass of lepton-b pair in the event) among the fitted observables



$$m_t^{MC} = 172.33 \pm 0.14\,(\text{stat})\,^{+0.66}_{-0.72}\,(\text{syst})\,\text{GeV}$$

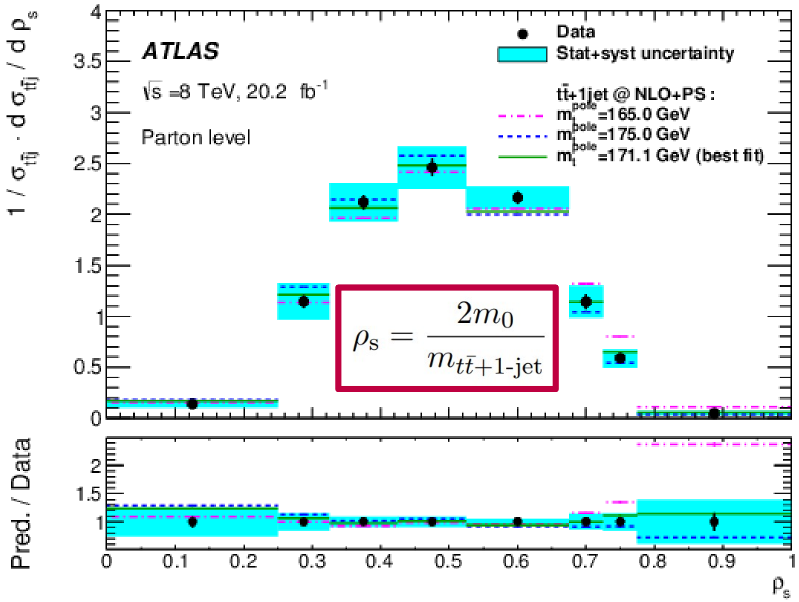
Total uncertainty: 0.7 GeV (0.4%)

- Also extracted m_t^{POLE} and $m_t^{\overline{MS}}$
  Values depending on the PDF set

PDF set	$m_t(m_t)$ (GeV)	m_t^{pole} (GeV)
ABMP16	$161.6 \pm 1.6\,(\text{fit} + \text{PDF} + \alpha_S)\,^{+0.1}_{-1.0}\,(\text{scale})$	$169.9 \pm 1.8\,(\text{fit} + \text{PDF} + \alpha_S)\,^{+0.8}_{-1.2}\,(\text{scale})$
NNPDF3.1	$164.5 \pm 1.6\,(\text{fit} + \text{PDF} + \alpha_S)\,^{+0.1}_{-1.0}\,(\text{scale})$	$173.2 \pm 1.9\,(\text{fit} + \text{PDF} + \alpha_S)\,^{+0.9}_{-1.3}\,(\text{scale})$
CT14	$165.0 \pm 1.8\,(\text{fit} + \text{PDF} + \alpha_S)\,^{+0.1}_{-1.0}\,(\text{scale})$	$173.7 \pm 2.0\,(\text{fit} + \text{PDF} + \alpha_S)\,^{+0.9}_{-1.4}\,(\text{scale})$
MMHT14	$164.9 \pm 1.8\,(\text{fit} + \text{PDF} + \alpha_S)\,^{+0.1}_{-1.1}\,(\text{scale})$	$173.6 \pm 1.9\,(\text{fit} + \text{PDF} + \alpha_S)\,^{+0.9}_{-1.4}\,(\text{scale})$

Pole mass with $t\bar{t}$+1jet

8 TeV - 20.2 fb^{-1} - JHEP 11 (2019) 150



Determination of pole and running mass in the $\overline{\text{MS}}$ scheme:

$$m_t^{\text{pole}} = 171.1 \pm 0.4\ (\text{stat}) \pm 0.9\ (\text{syst})\ ^{+0.7}_{-0.3}\ (\text{theo})\ \text{GeV}$$

$$m_t(m_t) = 162.9 \pm 0.5(\text{stat}) \pm 1.0(\text{syst})\ ^{+2.1}_{-1.2}\ (\text{theo})\ \text{GeV}$$

Total uncertainty: 1.2 GeV (0.7%) (POLE), 2.3 (1.4%) ($\overline{\text{MS}}$)

Mass scheme	m_t^{pole} [GeV]	$m_t(m_t)$ [GeV]
Value	**171.1**	**162.9**
Statistical uncertainty	**0.4**	**0.5**
Simulation uncertainties		
Shower and hadronisation	0.4	0.3
Colour reconnection	0.4	0.4
Underlying event	0.3	0.2
Signal Monte Carlo generator	0.2	0.2
Proton PDF	0.2	0.2
Initial- and final-state radiation	0.2	0.2
Monte Carlo statistics	0.2	0.2
Background	<0.1	<0.1
Detector response uncertainties		
Jet energy scale (including *b*-jets)	0.4	0.4
Jet energy resolution	0.2	0.2
Missing transverse momentum	0.1	0.1
b-tagging efficiency and mistag	0.1	0.1
Jet reconstruction efficiency	<0.1	<0.1
Lepton	<0.1	<0.1
Method uncertainties		
Unfolding modelling	0.2	0.2
Fit parameterisation	0.2	0.2
Total experimental systematic	**0.9**	**1.0**
Scale variations	(+0.6, −0.2)	(+2.1, −1.2)
Theory PDF⊕α_s	0.2	0.4
Total theory uncertainty	**(+0.7, −0.3)**	**(+2.1, −1.2)**
Total uncertainty	**(+1.2, −1.1)**	**(+2.3, −1.6)**

Modeling (Shower and hadronisation, Colour reconnection)

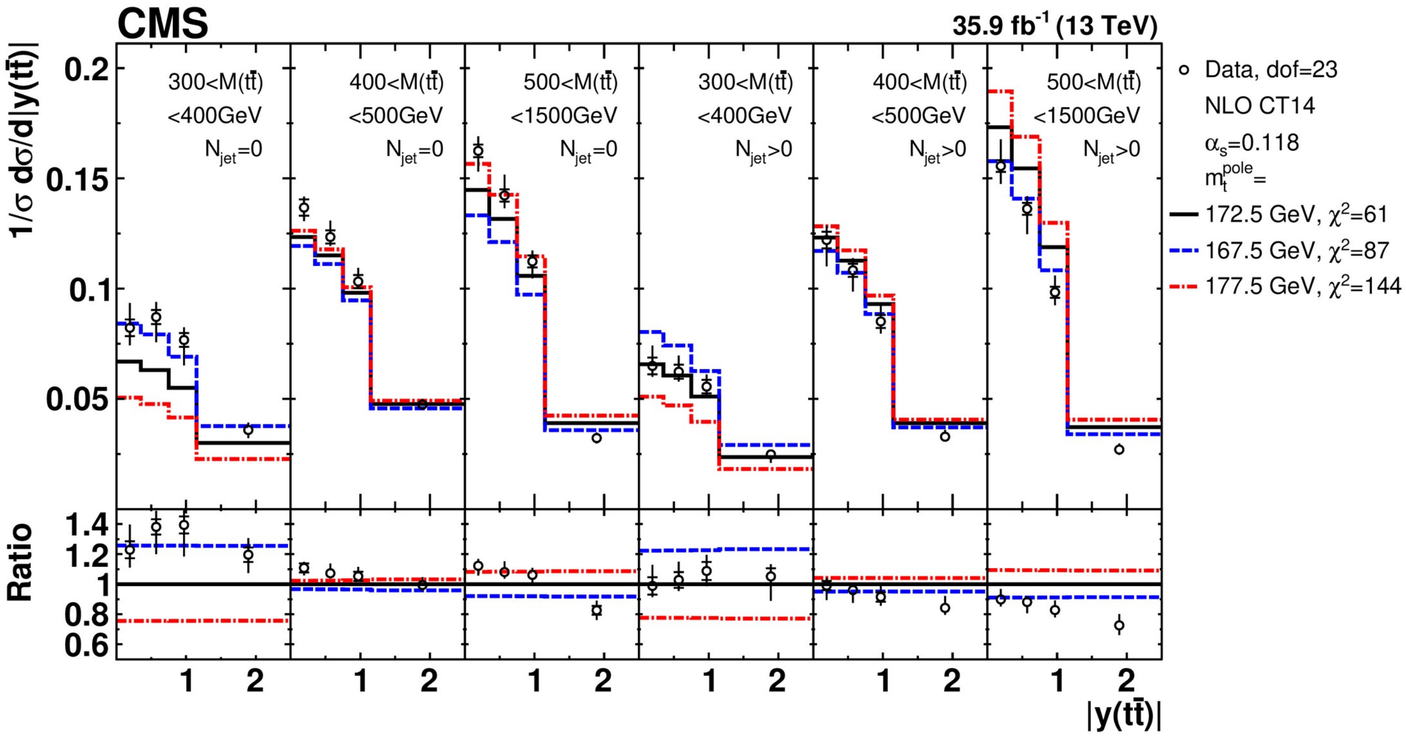
Calibration (Jet energy scale)

Theory (Scale variations)

Pole mass from multi-differential

13 TeV - 35.9 fb^{-1} - arXiv:1904.05237

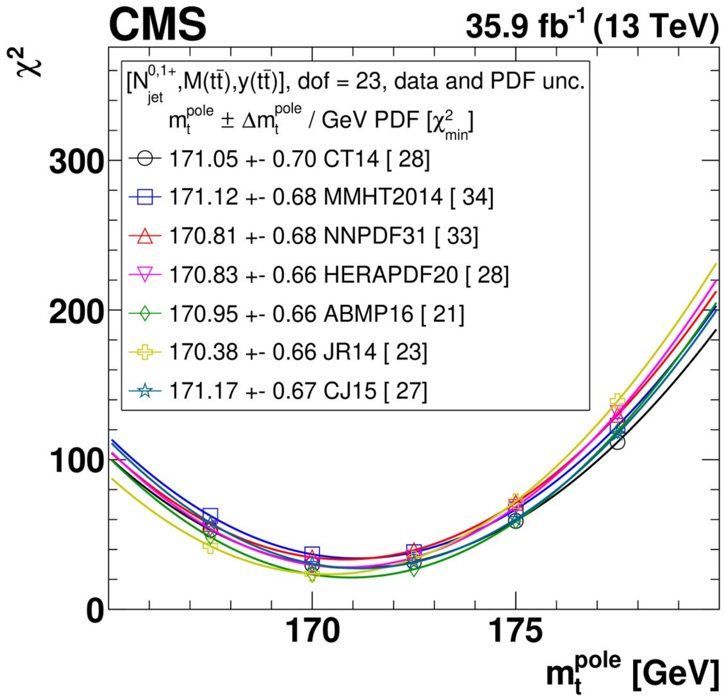
- Use dilepton events
- Triple-differential cross-section: N_{jet}, $m_{t\bar{t}}$, $y_{t\bar{t}}$ unfolded at parton-level
- Dominant uncertainties: JES and signal modeling

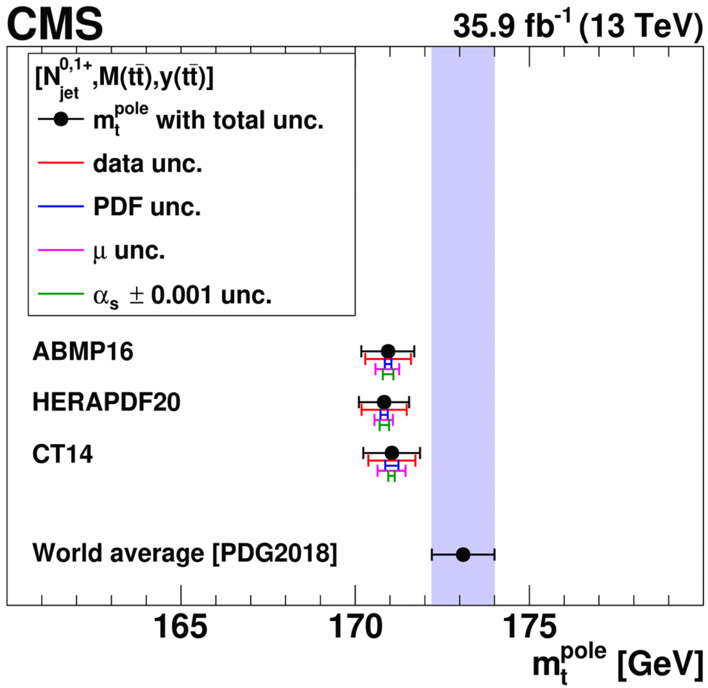


Pole mass from multi-differential

13 TeV - 35.9 fb^{-1} - arXiv:1904.05237

Measurements compared with NLO predictions obtained using aMC@NLO (fixed order mode) for the simultaneous extraction of m_t^{POLE}, α_s and PDFs.





$$m_t^{pole} = 170.5 \pm 0.7(\text{fit}) \pm 0.1(\text{model})^{+0.0}_{-0.1}(\text{param}) \pm 0.3(\text{scale})\ \text{GeV}$$

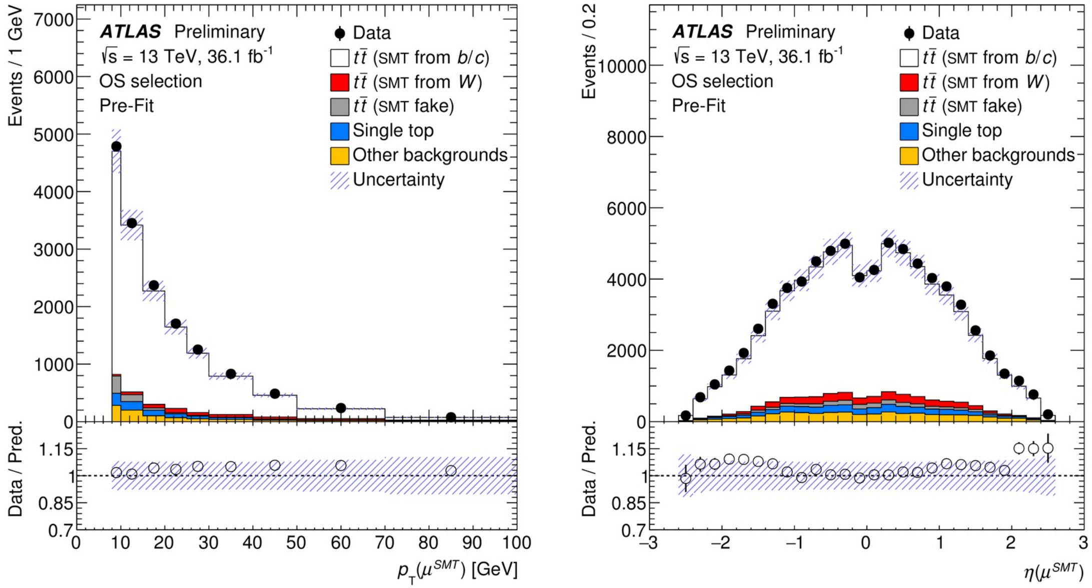
Total uncertainty: 0.8 GeV (0.47%)

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)

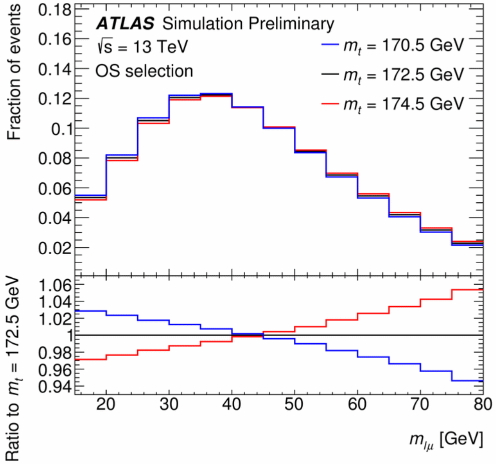
Soft Muon Tagging for b-jets: presence of a muon candidate within a distance ΔR <0.4 of a selected jet candidate

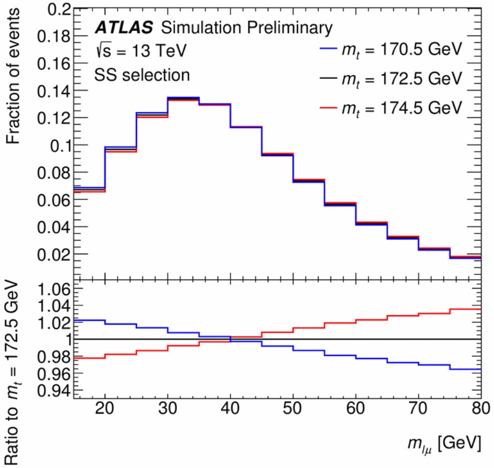


Soft muon kinematics

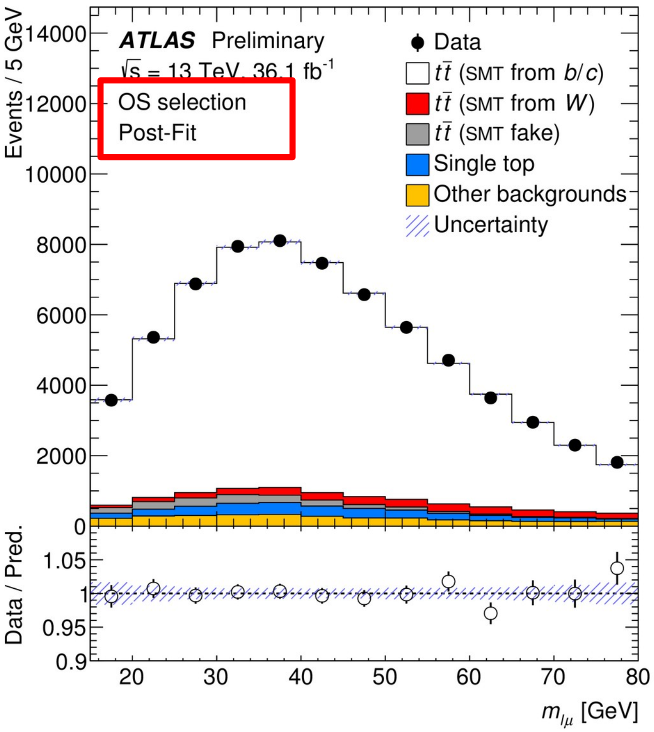
Top quark mass with Soft Muons

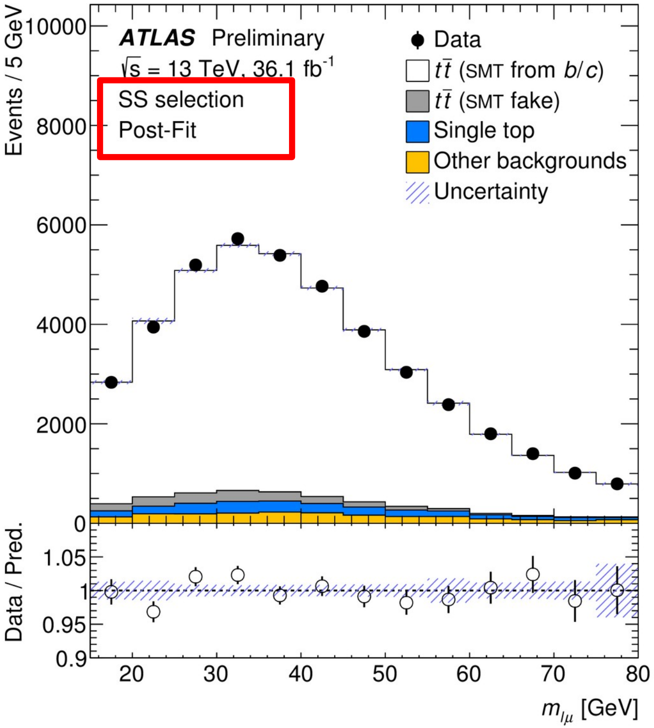
13 TeV - 36.1 fb^{-1} - ATLAS-CONF-2019-046





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





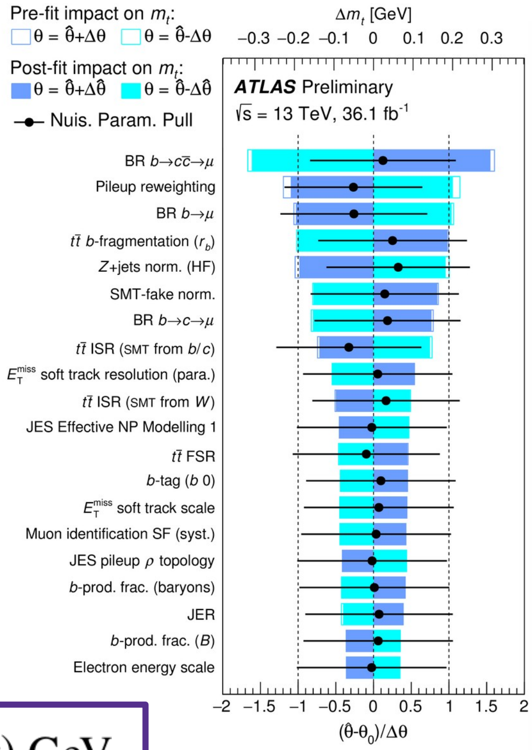
Top quark mass with Soft Muons

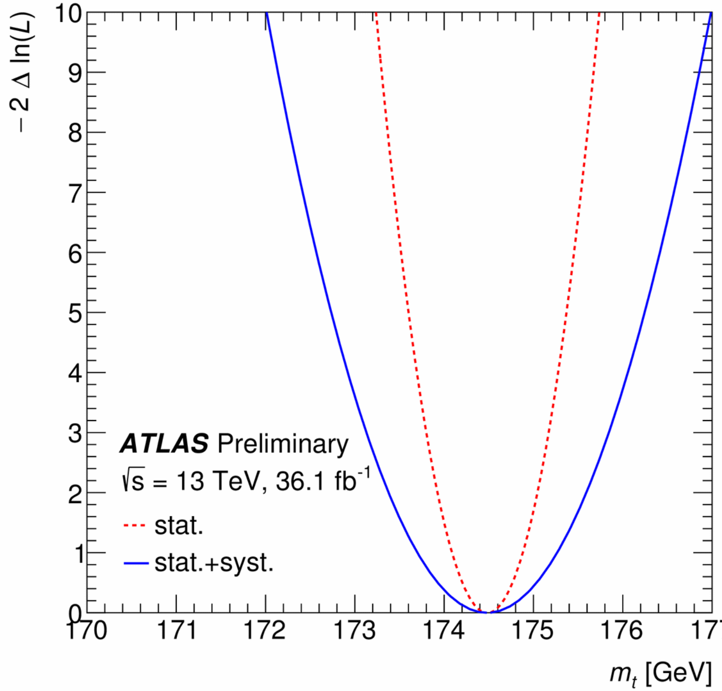
13 TeV - 36.1 fb^{-1} - ATLAS-CONF-2019-046

$m_{l\mu}$ 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 ones: b fragmentation and decay, $t\bar{t}$ production.





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

Total uncertainty: 0.78 GeV (0.45%)

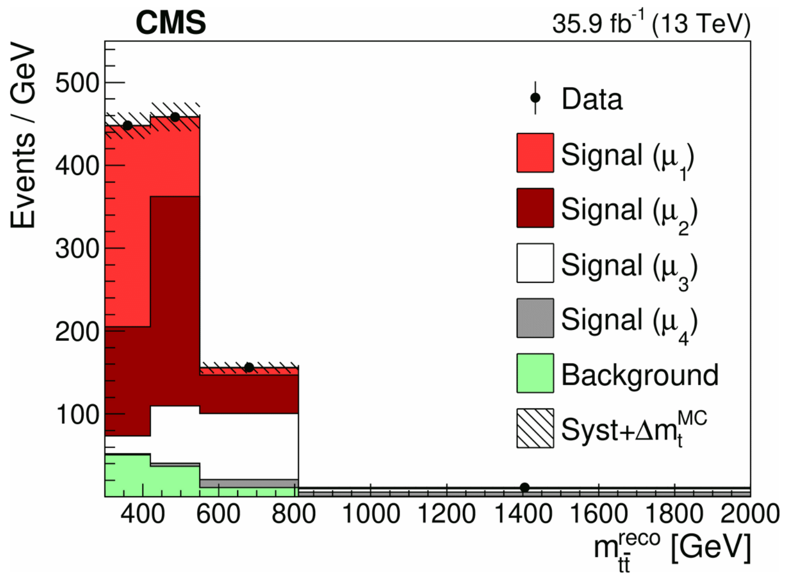
Running top quark mass

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}

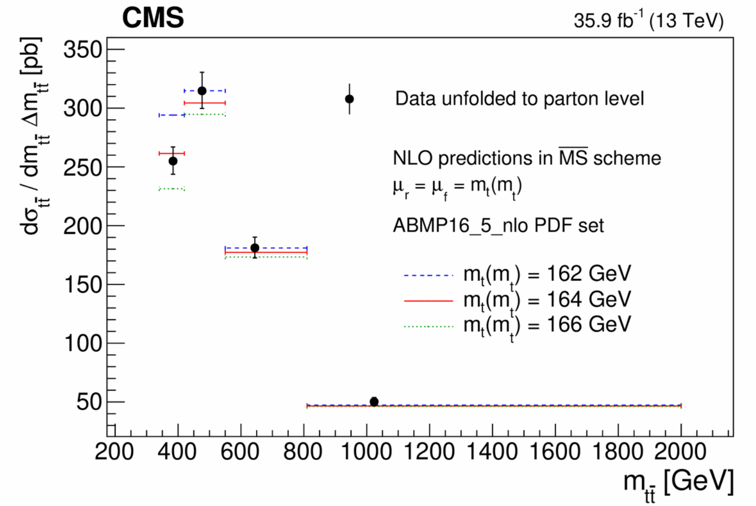
m_{lb}^{min}: min mass of lb pair

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 $m_t(m_t)$

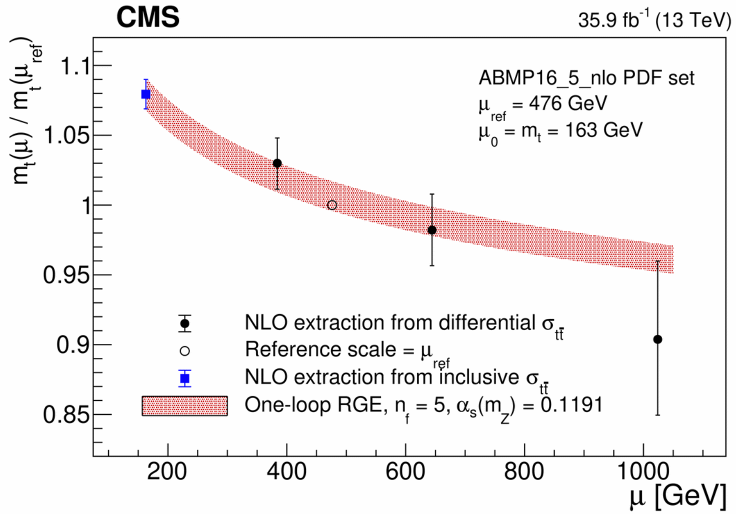
The value of $m_t(m_t)$ is determined independently in each m_{tt} bin

$m_t(m_t) \rightarrow m_t(\mu_k)$ 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

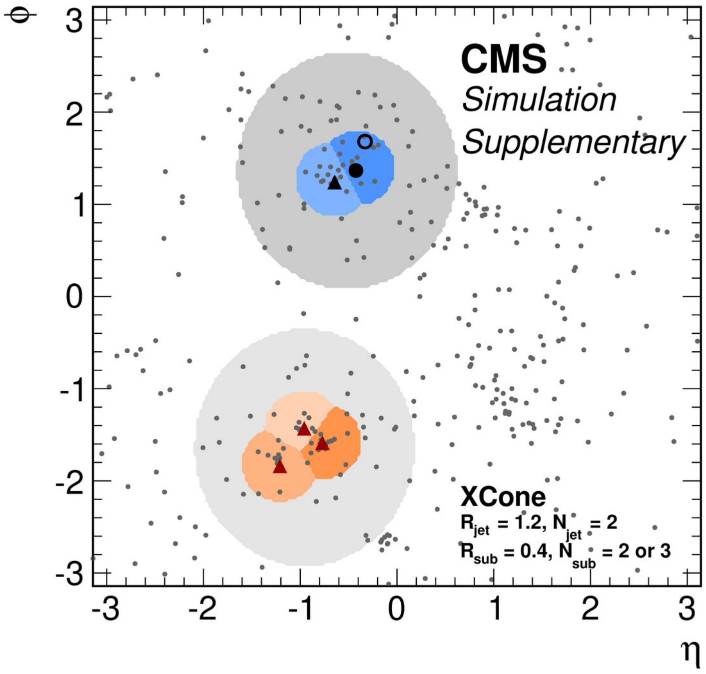


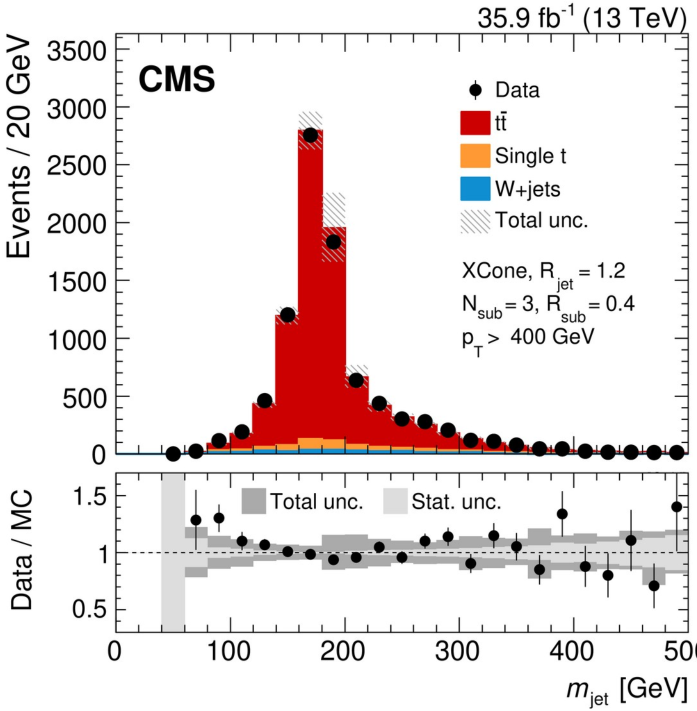
Ratios with respect to a reference scale, to exploit cancellations in the uncertainty

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

13 TeV - 35.9 fb^{-1} - arXiv:1911.03800

- 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





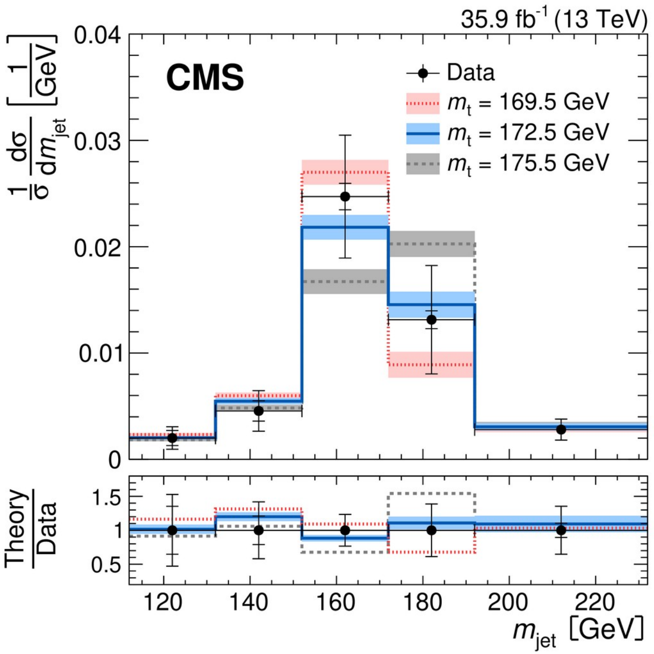
Top quark mass in boosted $t\bar{t}$ events

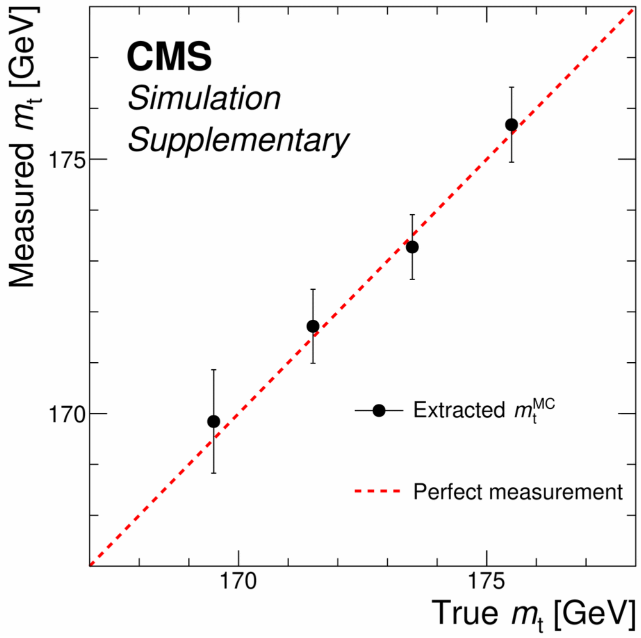
13 TeV - 35.9 fb^{-1} - arXiv:1911.03800

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.





Top quark width: overview of techniques

- Recent calculation at NNLO: Γ_t=1.322 GeV, for m_t=172.5 GeV (Phys. Rev. Lett. 110 (2013) 042001)
- Deviations from the SM could indicate non-SM decays or non-SM couplings of the top quark

- "Indirect" methods → extract Γ_t from B(t→ bW) measurements, assuming the SM

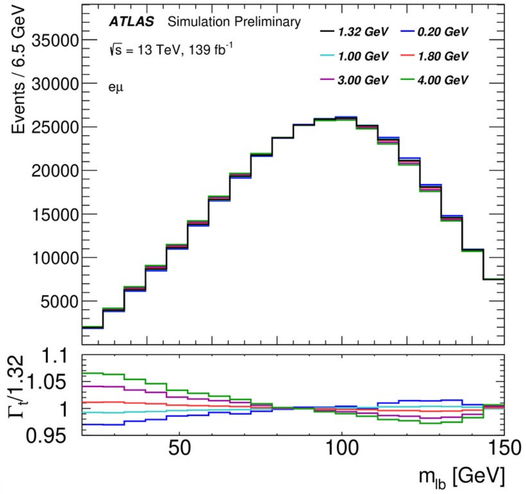
  Most precise indirect measurement by CMS:
  $\Gamma_t = 1.36 \pm 0.02(\text{stat})^{+0.14}_{-0.11}(\text{syst})$ GeV (Phys. Lett. B 736 (2014) 33)
- "Direct" methods → extraction from distributions sensitive to Γ_t. Larger uncertainty limited by the experimental resolutions

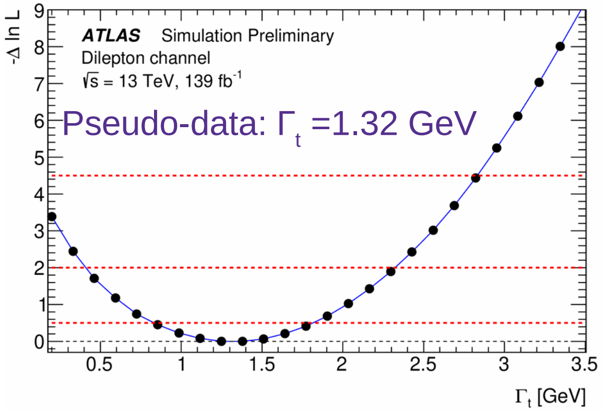
  Previous measurements:
  - CDF: based on the reconstructed m_{top} distribution:
    $1.10 < \Gamma_t < 4.05$ GeV (68% CL) (Phys. Rev. Lett. 111 (2013) 202001)
  - ATLAS $\sqrt{s}$=8 TeV, 20fb^{-1}: using l-jets, based on m_{lb} and $\Delta R_{min}(j_b,j_l)$:
    $\Gamma_t = 1.76 \pm 0.33(\text{stat})^{+0.79}_{-0.68}(\text{syst})$ GeV (Eur. Phys. J. C 78 (2018) 129)
  - Herwig, Jezo, Nachman: reinterpretation of ATLAS measurement using non-resonant production:
    $\Gamma_t = 1.28 \pm 0.30$ GeV (Phys. Rev. Lett. 122 (2019) 231803)

Direct measurement of top quark width

13 TeV - 139 fb^{-1} - ATLAS-CONF-2019-038

- New analysis: dilepton channel
- Choice of distribution sensitive to Γ_t : m_{lb} (invariant mass of the lepton and b-jet of leptonic top).
  - m_{lb} > 150 GeV sensitive to NLO effects in top decay, so not considered in the analysis
- Strategy:
  - create templates of m_{lb} for different Γ_t values
  - profile likelihood fit on data
  - fit validation using pseudo-experiments at different Γ_t (closure obtained within 0.01 GeV)



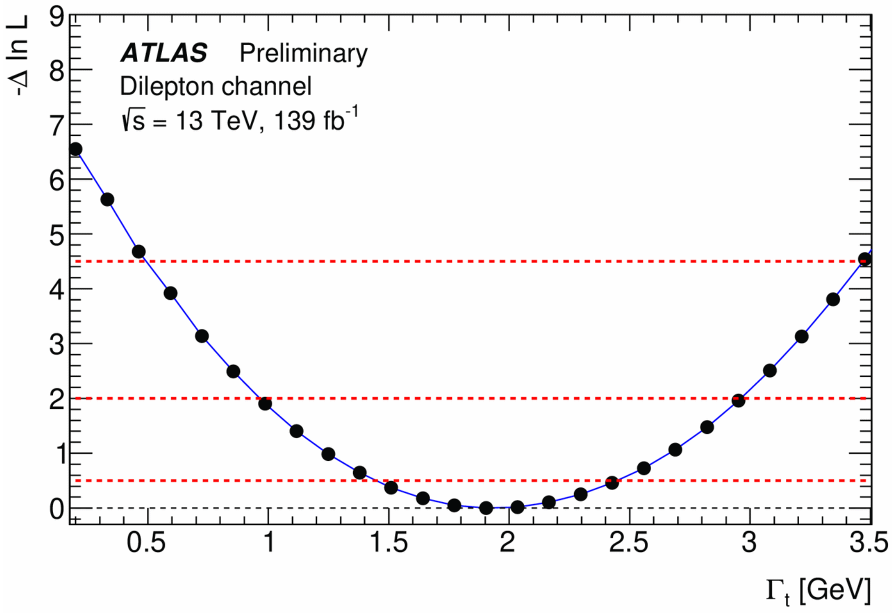


Direct measurement of top quark width

13 TeV - 139 fb^{-1} - ATLAS-CONF-2019-038

Measured top quark width:

$\Gamma_t = 1.94^{+0.52}_{-0.49}$ GeV
Total uncertainty: 26%



Statistical uncertainty: 0.21 GeV

Contributions to the systematic uncertainty

Source	Impact on Γ_t [GeV]
Jet reconstruction	±0.24
Signal and bkg. modelling	±0.19
MC statistics	±0.14
Flavour tagging	±0.13
E_T^{miss} reconstruction	±0.09
Pile-up and luminosity	±0.09
Electron reconstruction	±0.07
PDF	±0.04
$t\bar{t}$ normalisation	±0.03
Muon reconstruction	±0.02
Fake-lepton modelling	±0.01

Dominated by jet calibration, bkg model, MC statistics, b-tagging

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
- Improving on current uncertainty at few hundreds MeV poses 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
- Direct measurements of Γ_t consistent with SM expectation but affected by larger uncertainties than indirect ones