Direct top-quark decay width measurement at $\sqrt{s} = 13$ TeV with the ATLAS experiment

Tomas Dado
On behalf of the ATLAS Collaboration

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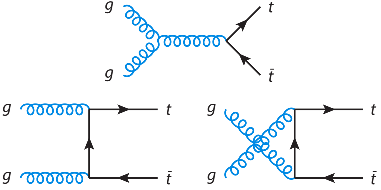
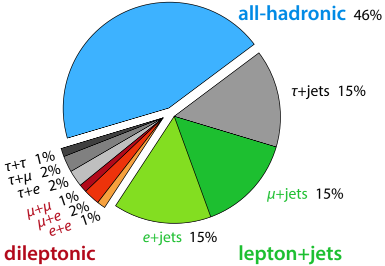
- Heaviest known elementary particle ($m_t \approx 173$ GeV)
- Extremely short mean lifetime ($\approx 10^{-25}$ s)
- Top quark decays before hadronisation
- Produced abundantly at the LHC $\rightarrow$ precision measurements by ATLAS and CMS



$t\bar{t}$ decays



- Mostly produced in pairs
- At the LHC: dominated by gluon-gluon fusion ($\approx$ 90% at $\sqrt{s} = 13$ TeV)
- In the SM top quark decays almost exclusively to W and b
- Focusing on dilepton decays (ee,$\mu\mu$,$e\mu$)

Basics

- Decay width, Γ_t, is trivially related to mean lifetime
- Depends on the top-quark mass, $\Gamma_t \sim m_t^3$
- Best theoretical prediction: NNLO (QCD): $\Gamma_t = 1.322$ GeV for $m_t = 172.5$ GeV
  Phys. Rev. Lett. 110 (2013) 042001

Motivation

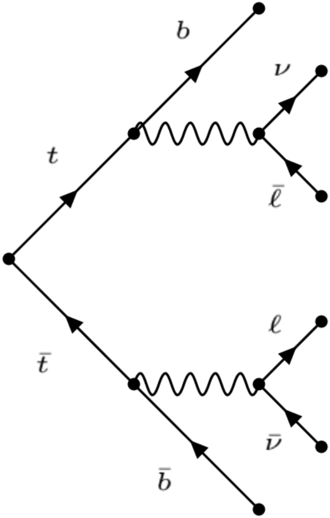
- Some BSM scenarios predict different Γ_t for the same m_t
  - Two Higgs doublet models (2HDM), SUSY - new particles and/or radiative corrections
  - Flavour changing neutral currents (FCNC) - new decay channels
  - CKM V_{tb} modifications - Γ_t depends quadratically on $|V_{tb}|$
- “Orthogonal" to top mass measurement - sensitive to different effects
- Direct measurements - less model dependent than indirect measurements

Event selection

- Full Run 2 pp dataset - 139 fb^{-1}
- Three orthogonal channels ee, $\mu\mu$, $e\mu$

Selection

- Single lepton triggers (e or μ)
- ≥ 2 jets (anti-k_T, $R = 0.4$), $p_T > 25$ GeV
- 2 charged leptons with opposite sign, $p_T > 25(27)$ GeV
- ≥ 2 b-tagged jets (60 % efficiency)
- $m_{\ell\ell} > 15$ GeV
- $E_T^{\text{miss}} > 60$ GeV, for ee and $\mu\mu$
- $80 < m_{\ell\ell} < 100$ veto, for ee and $\mu\mu$



- Very pure selection, backgrounds smaller than 5%

Analysis

Basic strategy

- Identify observable sensitive to decay width with small systematic uncertainties
- Create templates for the observable for various Γ_t
- Use additional observable insensitive to Γ_t but sensitive to systematic uncertainties - control region
- Use profile likelihood fit to extract the width from data

Event reconstruction

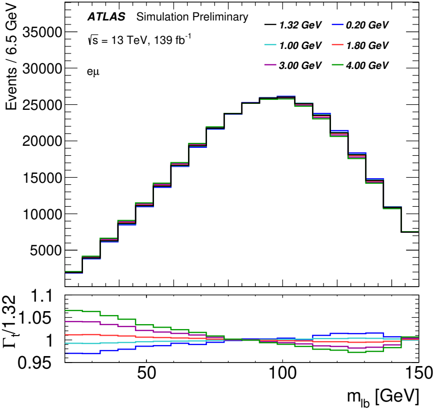
- No attempt to reconstruct neutrinos
  - Large uncertainties from reconstruction, E_T^{miss}
- Need to pair charged leptons and the b-jets from $t\bar{t}$ decay
- Using smallest ΔR between lepton and b-jet
  - Leads to around 63% correct pairings

Task

- Generate distributions for alternative decay widths
- Not possible with dedicated MC - too much CPU needed

Reweighting

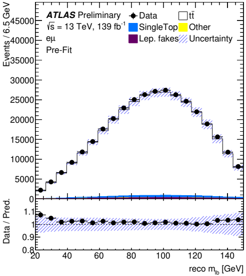
- Using Breit-Wigner distribution to reweight nominal samples
  - $m_{\ell b}$ distribution, $m_{\ell b} < 150$ GeV to reduce NLO effects in decay
  - Using MC truth record about per-event top-quark mass
- Cross-checked with two generated samples ($\Gamma_t = 0.7$ and 3.0 GeV)
- Shapes agree well, normalisation difference observed
  - $t\bar{t}$ normalisation free-floating

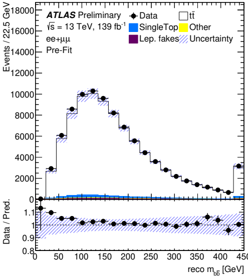


- Templates for $m_{\ell b}$ using $e\mu$
- Control region: $m_{b\bar{b}}$ using combined ee and $\mu\mu$

Fit challenge

- Standard implementations allow only 3 templates in profile likelihood
- Need to use multiple templates from $\Gamma_t = 0.2$ GeV to 4.0 GeV
- Transform the template fitting into normalisation fit
  - Add weight for each template
  - Piece-wise linear interpolation
  - Make the weight depend on Γ_t
  - Fitting normalisation of the templates = fitting the width





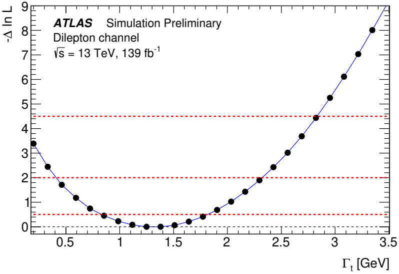
- Non-standard profile likelihood fit - requires validation

Pseudoexperiments

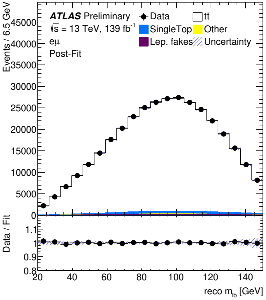
- Fits neglecting systematic uncertainties ("stat-only") on MC prediction
- Vary distributions withing expected statistical uncertainties
- Repeat for different input Γ_t
- Good agreement for the fitted mean value and the uncertainty

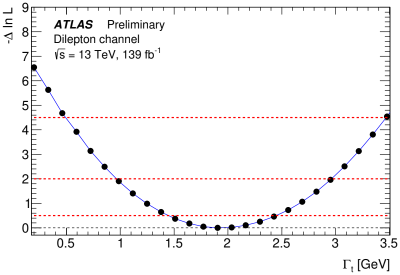
Asimov fits

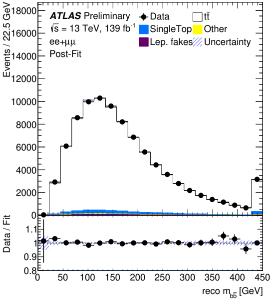
- Using full fit model and fitting MC prediction for different input Γ_t
- Non-closure of the order of 0.01 GeV - negligible



- Simultaneous fit of both regions
- Assuming $m_t = 172.5$ GeV
- Full syst. model: $\Gamma_t = 1.9 \pm 0.5$ GeV
- Stat-only fit: $\Gamma_t = 1.90 \pm 0.21$ GeV
- $t\bar{t}$ norm. consistent with prediction







- Dominant systematic uncertainties:
  - Jet uncertainties
  - $t\bar{t}$ modelling
  - MC statistics
  - b-tagging
- Top mass not included as a systematic uncertainty
- Measuring width as a function of mass

Source	Impact on Γ_t [GeV]
Jet reconstruction	± 0.24
Signal and bkg. modelling	± 0.19
MC statistics	± 0.14
Flavour tagging	± 0.13
$E_{\mathrm{T}}^{\mathrm{miss}}$ 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

	$m_t = 172$		$m_t = 172.5$ GeV		$m_t = 173$ GeV	
	Mean [GeV]	Unc. [GeV]	Mean [GeV]	Unc. [GeV]	Mean [GeV]	Unc. [GeV]
Measured	2.01	$+0.53$ -0.50	1.94	$+0.52$ -0.49	1.90	$+0.52$ -0.48
Theory	1.306	$< 1\%$	1.322	$< 1\%$	1.333	$< 1\%$

Summary

- Direct measurement of the top-quark decay width using full Run 2
- Using dilepton $t\bar{t}$ events
- Using profile-likelihood with multiple templates
- $\Gamma_t = 1.9 \pm 0.5$ GeV
- Significantly improves 8 TeV result (lepton+jets)
  - $\Gamma_t = 1.76 \pm 0.33\,(\text{stat.})^{+0.79}_{-0.68}\,(\text{syst.})$ Eur. Phys. J. C 78 (2018) 129

Outlook

- Plan to use lepton+jets events
  - Modelling more challenging
  - Combinatorial background
- Combination of both channels

Backup

Yields

	Event Yields		
	ee	$\mu\mu$	$e\mu$
$t\bar{t}$	34000±1700	49100±2500	176000±9000
Single top	1150± 60	1570± 80	5300± 260
$Z+VV+t\bar{t}X$	230± 120	390± 200	380± 190
Fake leptons	800± 400	41± 20	2100±1100
Total prediction	37000±1800	51100±2500	184000±9000
Data	37926	52166	186951