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Direct Top-Quark Decay Width Measurement in the $t\bar{t}$ Lepton+Jets Channel at 8 TeV

Helmholtz Alliance Meeting

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Bundesministerium
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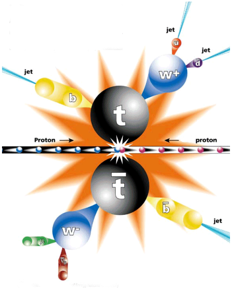
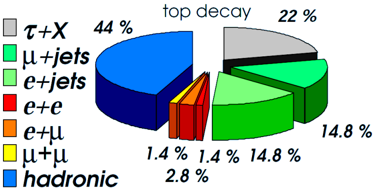
FSP 103
ATLAS

Top Quark

- Discovered in 1995 at Tevatron
- Produced abundantly at LHC → precision measurements by ATLAS and CMS
- Heaviest known elementary particle ($m_t \approx 173$ GeV)
- Extremely short mean lifetime ($\approx 10^{-25}$ s)
  - Decays before hadronization



Top quark decays



- $t \to W + b$ almost 100%
- Lepton+jets channel:
  Lepton $= e, \mu(\tau \to e, \mu)$
- Signature: 4 jets (with 2 b jets),
  $t\bar{t} \to WbWb \to bbqq\ell\nu$

Top Quark Decay Width

Introduction

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- Top quark decay width has not been measured directly at ATLAS
- Indirect measurements
  - Indirect CMS measurement Phys. Lett. B 736 (2014) 33
  - Using cross-section from single top events $\sigma_{t-\text{ch}}$ and branching ratio from $t\bar{t}$ dileptonic events $\mathcal{B}(t \to Wb)$
  - **Model dependent!**
  - Result: $\Gamma_t = 1.36^{+0.14}_{-0.11}$ GeV ($\sqrt{s} = 8$ TeV, $\mathcal{L}_{\text{int}} = 19.7$ fb^{-1})
- Direct measurements - **model independent**, can probe wider classes of BSM physics
  - CDF measurement Phys. Rev. Lett 111 (2013) 202001
    - Template fit, ℓ+jets $t\bar{t}$ events ($\sqrt{s} = 1.96$ TeV, $\mathcal{L}_{\text{int}} = 8.7$ fb^{-1})
    - In-situ calibration with m_W^{reco}
    - Result: $1.10 < \Gamma_t < 4.05$ GeV at 68% C.L.
  - CMS measurement CMS PAS TOP-16-019
    - Dileptonic events, $\sqrt{s} = 13$ TeV, $\mathcal{L}_{\text{int}} = 12.9$ fb^{-1}
    - Profile-likelihood fit using $m_{\ell b}$
    - Result: $0.6 < \Gamma_t < 2.4$ GeV at 95% C.L.

- ATLAS ℓ+jets $t\bar{t}$ events at $\sqrt{s} = 8$ TeV

Event selection: Cuts

- Trigger cuts & trigger matching
- ≥ 4 good jets ($p_{\mathrm{T}} > 25$ GeV, $|\eta| < 2.5$)
- Exactly one good e/μ, no good μ/e ($p_{\mathrm{T}} > 25$ GeV and η cuts)
- $E_{\mathrm{T}}^{\mathrm{miss}} > 40$ GeV (0 b-tag events), $E_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV (1 b-tag events)
- $E_{\mathrm{T}}^{\mathrm{miss}} + m_W^{\mathrm{T}} > 60$ GeV (0+1 b-tag)
- b-Tagging: MV1-tagger 70 % eff.

Considered background

W+jets
W+jets normalisation: categorised by heavy flavour content (W+light, $W+c$, $W+bb/cc$) with data-driven calibration factors applied

Z+jets

Diboson

Single top

Fake leptons
Using data-driven matrix method

Data

- Events with 4 jets (incl.), $\sqrt{s} = 8$ TeV with $\mathcal{L}_{\mathrm{int}} = 20.2\ \mathrm{fb}^{-1}$
- Events split by lepton type (e, μ) and by b-tag multiplicity: 1excl., 2incl

Event Reconstruction
Algorithms and Options

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Challenge

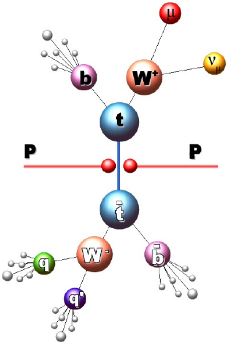
- Identify second *b*-jet and associate jets to their corresponding partons

KLFitter: → **NIM A 748 (2014) 18**

⇒ **Likelihood-based reconstruction method** with extensions: *b*-tagging information, fixed top quark mass $m_t = 172.5$ GeV

KLFitter options for ℓ+jets channel

- 4 or 5 jets in reconstruction (jets considered in permutations)
- Additional cut on LogLikelihood to improve fraction of correctly reconstructed events
- Additional cut on reconstructed m_W^{reco} to further improve fraction of correctly reconstructed events

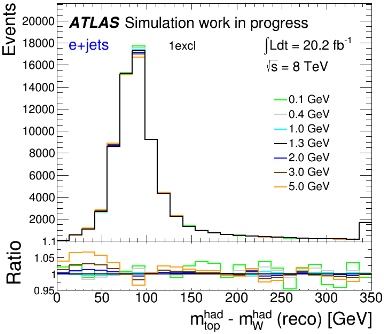


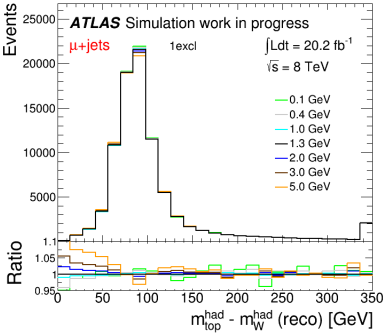
Analysis Strategy

Basic Idea

Templates

- Find observable sensitive to top quark decay width
- Create templates with different top widths: $\Gamma_t = 0.1 - 15$ GeV ($\Delta\Gamma_t \approx 0.1$ GeV)
- Reweight signal distributions of observables based on Breit-Wigner function ($m_{\text{top}} = 172.5$ GeV)





Template Fit

One Observable Fit

- Combination of el. and muon channel and 1excl. + 2incl. *b*-tag bins
- Each signal/background contribution included in the fit
- Background normalization constrained by Gaussian priors (with width equal to expected uncertainty)
- Likelihood: $\mathcal{L}(< obs. > |\Gamma_t) = (\sum_{\mathrm{S+B}} P_t(< obs. > |\Gamma_t)) \cdot \prod_{\mathrm{B}} P_{\mathrm{pr}}(\mathrm{Gauss})$

Two Observables Fit

- Fit two observables simultaneously
- One observable from hadronic branch and one from leptonic branch - uncorrelated
- Reduce statistical and/or systematic uncertainty

Further Improvements

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Jet Related Uncertainties

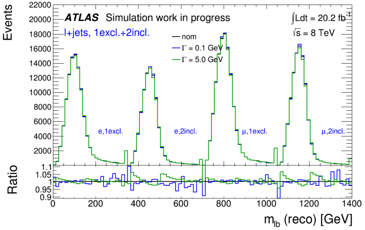
- JES and JER are expected to be dominant systematic uncertainties
- Ways to reduce JES/JER
  - Choose observables with low sensitivity to JES/JER
  - Focus on phase space regions with better detector resolution

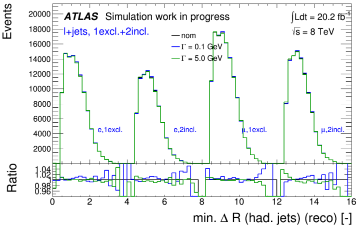
Decisions, decisions

- Different observables:
  - **"Direct"** - mass related observables: m_t^{had}, $m_{\ell b}$
  - **Ratios** - R32; ratio of top mass divided by the peak mass in the sample, ...
  - ΔR related observables
- Different phase space regions (better detector resolution, lower pile-up)
  - **Split** events by jet $|\eta|$ ($|\eta| = 0.8, 1, 1.2$ tested)
  - **Split** events by jet energy ($E_b = 100$ GeV & $E_{\mathrm{light}} = 50$ GeV)
  - Fit different regions simultaneously

Choice of the Observables

- All mass observables from hadronic branch suffer from large ISR/FSR uncertainty
- Many observables sensitive to JES uncertainty
- Need to compromise between large systematic uncertainties and width sensitivity
- $m_{\ell b}$ shows good results: sensitive to width and low uncertainties
- Use $m_{\ell b}$ with combination of hadronic observable
    - Decided to use ΔR related observables: low jet energy related systematics, but smaller width sensitivity





Fit validation

Linearity Tests

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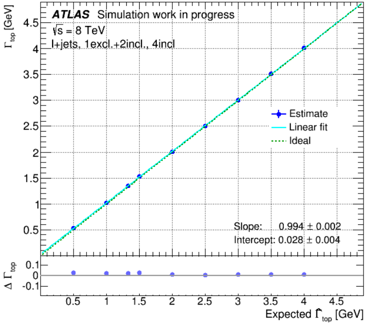
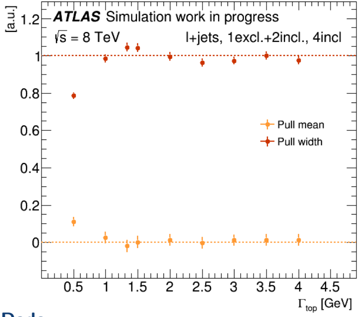
- Generate 1000 Pseudo-experiments for different widths: 0.5 GeV $\geq \Gamma_t \leq$ 5.0 GeV
- PE: Poisson fluctuations in each bin + Gaussian fluctuations for bkg. normalization
- Fit each distribution using all templates (signal + bkg.)
- Interpolation with three values around minimum to estimate top decay width
- Linearity tests to check for problems/biases

$\Rightarrow$ Sharpe edge at $\Gamma_t = 0$ leads to shift at low reco. Γ_t





Summary

and Outlook

Conclusions

- Direct top quark width measurement is important test of SM and it can probe of BSM physics
- Top width has not been measured directly at ATLAS
- Tested different reconstruction settings and observables

Outlook

- Need to rerun full software chain for the final settings
- Need to run a lot of pseudoexperiments (very CPU intensive)

Backup

Comparison with CDF

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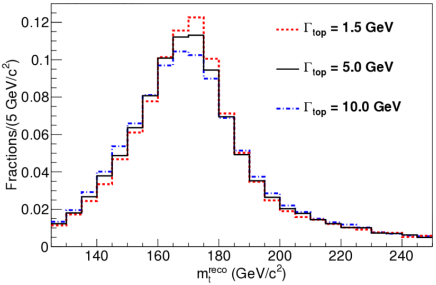
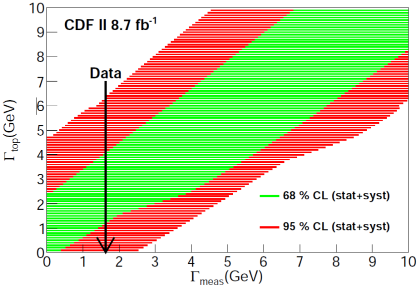
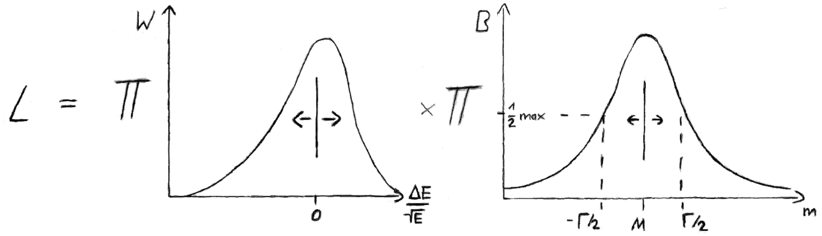
CDF measurement (Phys. Rev. Lett 111 (2013) 202001)

- CDF observed the same behaviour of PE distributions for small width values
- Gaussian shape "deformed" due to edge at $\Gamma_t = 0$ GeV
  since negative width values not allowed in our measurement





⇒ Maximisation of a likelihood for all permutations in the ℓ+jets channel:



$$L = B(m_{q_1 q_2 q_3}|m_t, \Gamma_t) \cdot B(m_{q_1 q_2}|m_W \Gamma_W) \cdot B(m_{q_4 \ell \nu}|m_t, \Gamma_t) \cdot B(m_{\ell\nu}|m_W \Gamma_W)$$
$$\cdot \prod_{i=1}^{4} W_{\text{jet}}(E_i^{\text{mess}}|E_i) \cdot W_\ell(E_\ell^{\text{mess}}|E_\ell) \cdot W_{\text{miss}}(E_x^{\text{miss}}|p_x^\nu) \cdot W_{\text{miss}}(E_y^{\text{miss}}|p_y^\nu)$$

- Free parameters: m_t, E_i, E_ℓ, p_j^ν
- Breit-Wigner functions B; transfer functions W with Double-Gaussian resolution

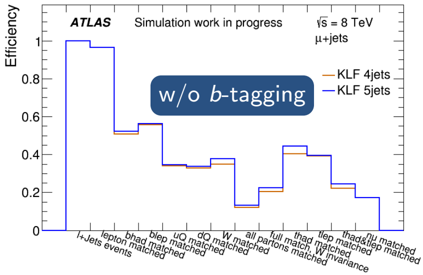
⇒ Permutation with largest L chosen as estimate for jet-to-particle association

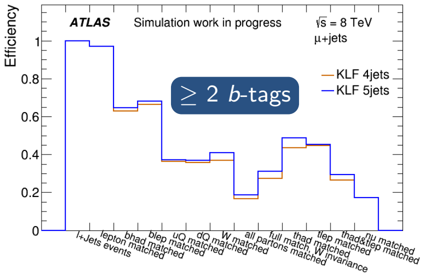
Comparison: KLFitter with 4 or 5 jets used for reconstruction

- Compare reco. efficiencies of individual particles for both KLFitter jet options based on full sim. Powheg+Pythia $t\bar{t}$ signal sample in different b-tag bins

⇒ KLFitter with 5 jets used for reconstruction performs better

- Studies ongoing: Systematic effects are sensitive to KLFitter option





Template Fit

Settings

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Setting up a 1D fit

- 1D fit with combination of el. and muon channel and 1excl. + 2 incl. *b*-tag bins
- Fit parameters for signal and all background contributions
- Background normalisations constrained by Gaussian priors

⇒ Likelihood: $\mathcal{L}(<obs.>|\Gamma_t) = (\sum_{\mathrm{S+B}} P_t(<obs.>|\Gamma_t)) \cdot \prod_{\mathrm{B}} P_{\mathrm{pr}}(\mathrm{Gauss})$

- Code based on RooFit using RooHistPdfs to build likelihood

Background treatment

- Fit parameters: $n_{W+\mathrm{light}}$, $n_{W+bb/cc}$, n_{W+c}, n_{QCD}, $n_{\mathrm{singletop}}$, n_{diboson}, $n_{Z+\mathrm{jets}}$
- ...each constrained by Gaussian with width of expected uncertainty:

- W+light: 4%
- $W+bb/cc$: 11%
- $W+c$: 27%
- QCD: 30%
- Single Top: 3.2%
- Diboson: 48%
- Z+jets: 48%

ISR/FSR effect on mass distributions