Top-Quark Pair Cross-Section Results at LHC in Final States with Tau or no Leptons

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on behalf of ATLAS and CMS

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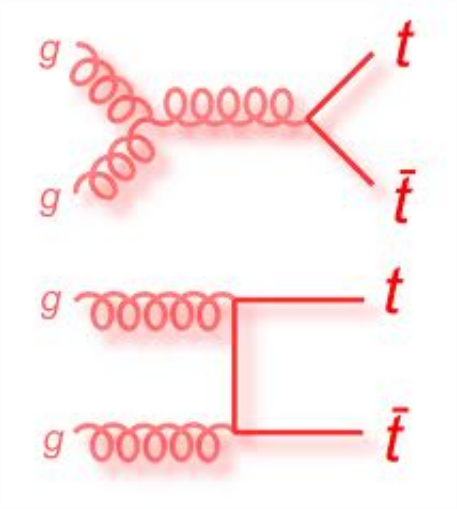
Outline

- Top-quark pair production
- Final states with τ or no leptons
- Results at LHC
- Summary

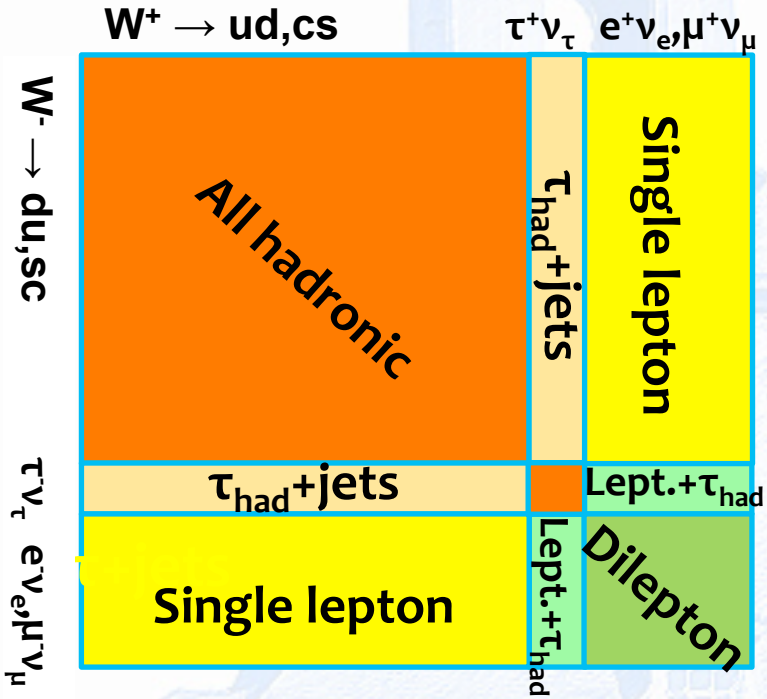
Top-Quark Pair Production

- Top-quark pairs are produced via the gluon-gluon and quark-anti-quark strong interaction
  - $\sigma^{\text{theory}} \cong 167^{+17}_{-18}$ pb (approx. NNLO, m_{top}=172.5 GeV) at 7 TeV c.m. energy of *pp* collisions **by HATHOR, Comput. Phys. Commun., 182 (2011) 1034**



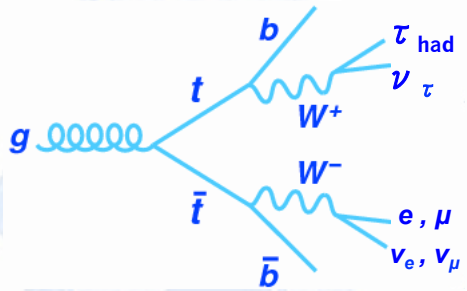
≈80%

≈20%

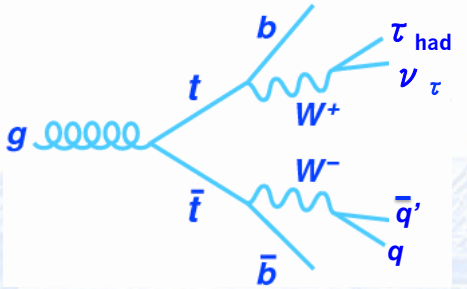


Final States Included in this Presentation

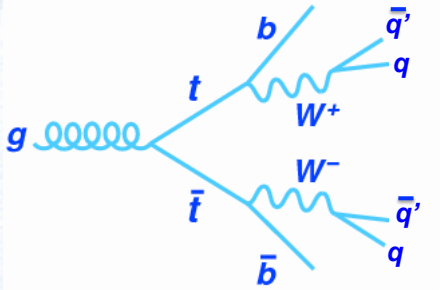
- Dilepton final state with one τ lepton and an electron or a muon



- Lepton+jets final state with a τ lepton and hadronic jets
  - Only hadronically decaying τ leptons can be reconstructed
    - ✧ BR($\tau \rightarrow$ hadrons) ≈ 65%



  - Enhanced branching fraction of a τ final state can be an indication of new physics
    - ✧ e.g., t → bH$^{\pm}$(→ τ ν_{τ})



- Fully hadronic final state – each W boson decays into a quark-pair

MC Event Generators

- MC@NLO + Herwig
  - $t\bar{t}$
  - Single top

- Alpgen + Herwig
  - W+jets
  - Z+jets
  - QCD multi-jets

- Herwig
  - Diboson

- Tauola for τ decays

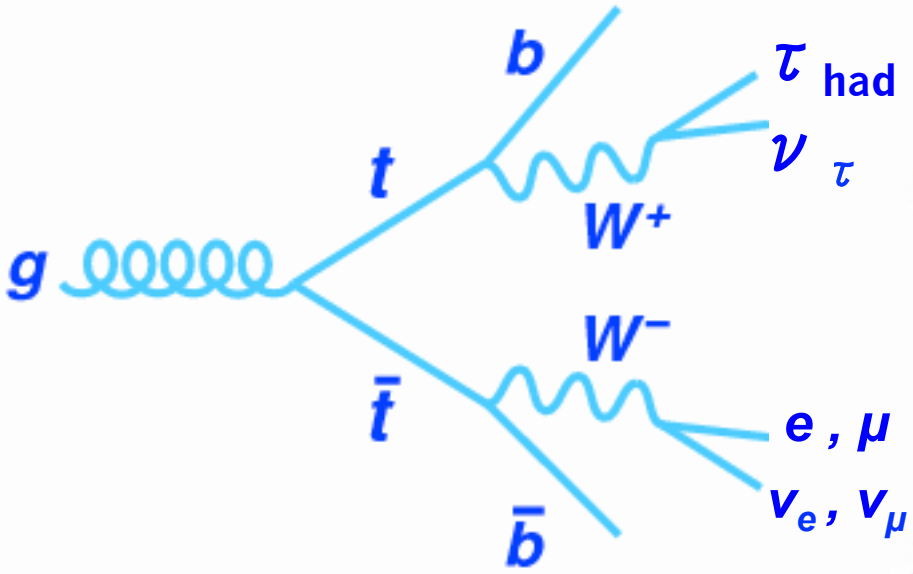
- MadGraph + Pythia
  - $t\bar{t}$
  - W+jets
  - Z+jets

- Pythia
  - Diboson
  - QCD multi-jets

- Powheg + Pythia
  - Single top

- Tauola for τ decays

Hadronic τ + Lepton Final State



- BR($t\bar{t}$ → *hadronic* τ + *lepton*) ≅ 3.7%

- Main backgrounds
  - Top-quark pair, other lepton+jets final states
  - W+jets
  - Z+jets

Trigger & Event Selection

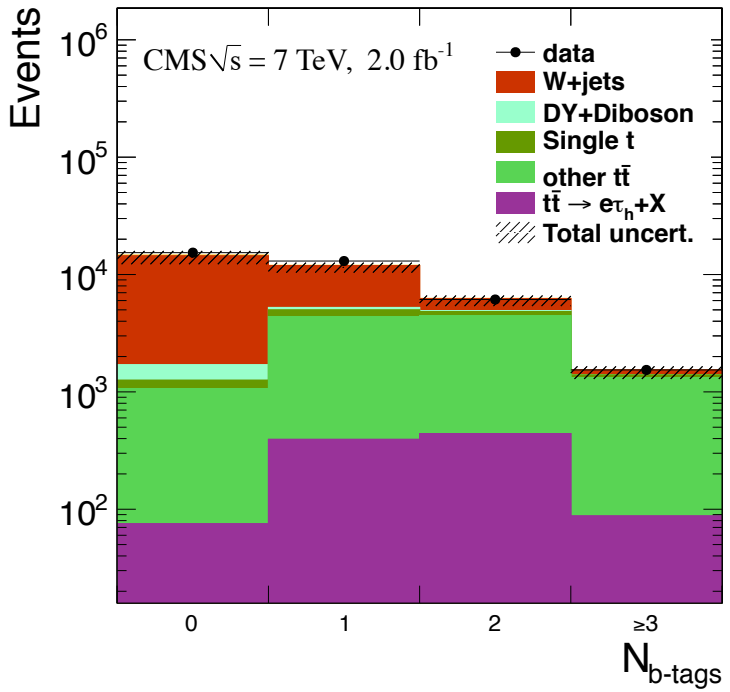
- **e (μ) + dijets + H_T^{miss}**
  - $p_{T,e}$ > 17 ÷ 27 GeV
  - $p_{T,\mu}$ > 17 ÷ 24 GeV
  - H_T^{miss} > 15 ÷ 20 GeV
  - $p_{T,j1}$ > 30 GeV
  - $p_{T,j2}$ > 25 GeV
- **1 isolated electron (muon)**
  - p_T > 35 (30) GeV
  - $|\eta|$ < 2.5 (2.1)
- **≥2 jets**
  - p_T > 35 (30) GeV
  - $|\eta|$ < 2.4
  - ≥1 b-jet
- **E_T^{miss} > 45 (40) GeV**
- **1 τ_{had}, OS to the lepton**
  - p_T>20 GeV & $|\eta|$<2.4

Thresholds were varied during the data taking period

Values in brackets are for the muon channel

Phys. Rev. D 85, 112007 (2012)
arXiv:1203.6810

$t\bar{t} \rightarrow \tau_{had} + \mu + X$: **L=2.2 fb^{-1}**
$t\bar{t} \rightarrow \tau_{had} + e + X$: **L=2 fb^{-1}**



Object Selection Details

Phys. Rev. D 85, 112007 (2012)
τ_{had}+lepton arXiv:1203.6810

- b-tagging, Jet Probability tagger
  - Calculates probability for a jet to be initiated from the primary vertex
  - Uses a signed significance of a track impact parameter, **IP/σ(IP)**

b-jet tagging eff. ≈ 76%
Light jet misTag. ≈ 13%

- Hadron-Plus-Strip (HPS) algorithm for τ_{had} reconstruction
  - Able to identify single particles in charged and neutral hadrons and photons
    - ✧ Allows to reconstruct hadronically decaying τ leptons
  - Charge of τ is calculated as a sum of the charges of associated hadrons

- τ_{had} isolation in a cone $\Delta R \leq 0.5$
  - No photon with $E_T > 1.5$ GeV
  - No charged hadron with $p_T > 1$ GeV

τ Id. eff. ≈ 37%
jet misId. ≈ 0.5%

Background Measurement

Phys. Rev. D 85, 112007 (2012)
τ_{had}+lepton arXiv:1203.6810

- Misidentified τ_{had} background
  - Mainly the W($l\nu$)+jets and top-quark pair lepton+jets events, where one jet is wrongly identified as τ_{had}
    - Has an electron or a muon and ≥3 jets
  - Data driven method, which exploits a probability for each jet to be misidentified as τ_{had} is used
    - The misidentification probability depends on p_T, η and a width (in $\eta \times \varphi$) of jets and is measured in data
      - Using an enriched QCD multi-jets sample

- MC simulation for the rest of the background
  - Z+jets
  - Single top
  - Diboson
  - Top-quark pair
    - (not included in the misidentified τ_{had} measurement)

Cross-Section Measurement

Source	N_{events} ($\pm$ stat. $\pm$ syst.)	
	$e\tau_h$	$\mu\tau_h$
$t\bar{t} \to WbWb \to \ell\nu b\, \tau\nu b$	$99.9 \pm 3.0 \pm 10.1$	$162.0 \pm 4.0 \pm 16.7$
misidentified τ	$54.3 \pm 6.4 \pm 8.1$	$88.5 \pm 8.9 \pm 10.8$
$Z/\gamma^* \to \tau\tau$	$16.6 \pm 3.3 \pm 2.9$	$25.8 \pm 4.3 \pm 6.1$
$t\bar{t} \to WbWb \to \ell\nu b\, \ell\nu b$	$9.0 \pm 0.9 \pm 1.7$	$13.3 \pm 1.2 \pm 2.5$
$Z/\gamma^* \to ee, \mu\mu$	$4.8 \pm 1.8 \pm 1.3$	$0.7 \pm 0.7 \pm 0.7$
Single top	$7.9 \pm 0.4 \pm 1.1$	$13.5 \pm 0.5 \pm 1.9$
VV	$1.3 \pm 0.1 \pm 0.2$	$2.0 \pm 0.2 \pm 0.3$
Total expected	$193.9 \pm 4.9 \pm 18.0$	$306.1 \pm 6.1 \pm 27.9$
Data	176	288

Phys. Rev. D 85, 112007 (2012)
τ_{had}+lepton arXiv:1203.6810

$$\sigma = \sigma^{theory} * (N_{obs} - B) / S$$

$$\sigma_{t\bar{t}}(\tau\, e) = 136 \pm 23(stat.) \pm 23(syst.) \pm 3(lumi.)\ pb$$

$$\sigma_{t\bar{t}}(\tau\, \mu) = 147 \pm 18(stat.) \pm 22(syst.) \pm 3(lumi.)\ pb$$

- The Best Linear Unbiased Estimator (BLUE) method is used for combination

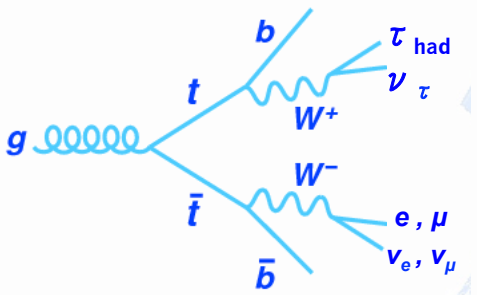
$$\sigma_{t\bar{t}} = 143 \pm 14(stat.) \pm 22(syst.) \pm 3(lumi.)\ pb$$

Trigger & Event Selection

- **Single electron or muon**
  - $p_{T,e} > 20 \div 22$ GeV
  - $p_{T,\mu} > 18$ GeV

Threshold was increased
In the second part of
the data taking period

arXiv:1205.2067



- **1 isolated electron or muon**
  - $E_{T,e} > 25$ GeV & $|\eta| < 2.47$
    - Excluding $1.37 < |\eta| < 1.52$
  - $p_{T,\mu} > 20$ GeV & $|\eta| < 2.5$
- **1 τ_{had}**
  - $20 \text{ GeV} < E_T < 100$ GeV
  - $|\eta| < 2.3$
- **≥2 jets (≥1 b-jet)**
  - $p_T > 25$ GeV & $|\eta| < 2.5$
  - $\Delta R(\text{jet}, \tau_{had}) > 0.4$
- **$E_T^{miss} > 30$ GeV**
- **$E_T^{miss} + \Sigma |p_{T,obj.=lep.,jet}| > 200$ GeV**

L = 2.05 fb^{-1}

Pile-up: ~6.3 events

- 8 selections:
  - "1 prong" and "3 prong" τ_{had}
  - OS and SS τ_{had} and lepton
  - 0 b-jet and ≥1 b-jet

τ_{had} Selection Details

arXiv:1205.2067

τ_{had}+lepton

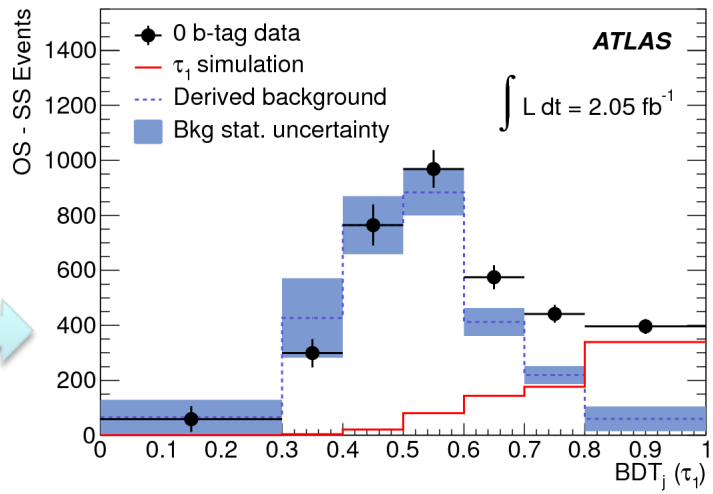
- Jet is identified as τ_{had} if the following criteria are met
  - The jet has 1, 2 or 3 associated tracks
    - Tracks are counted inside $\Delta R<0.4$ from the jet axis
    - $p_T > 4$ GeV for the leading track
    - $p_T>1$ GeV for additional tracks
- τ_{had} overlapping with a muon or an electron is removed
  - $\Delta R<0.4$
- Electrons misidentifed as τ_{had} are removed on the base of a Boosted Decision Trees (BDT_e) discriminator
  - τ_{had} selection efficiency: 85%
  - Electron rejection factor : 60
- Another BDT_j discriminator is used to separate τ_{had} and jets
  - Separate discriminators for “1 prong” and “3 prong” τ_{had}

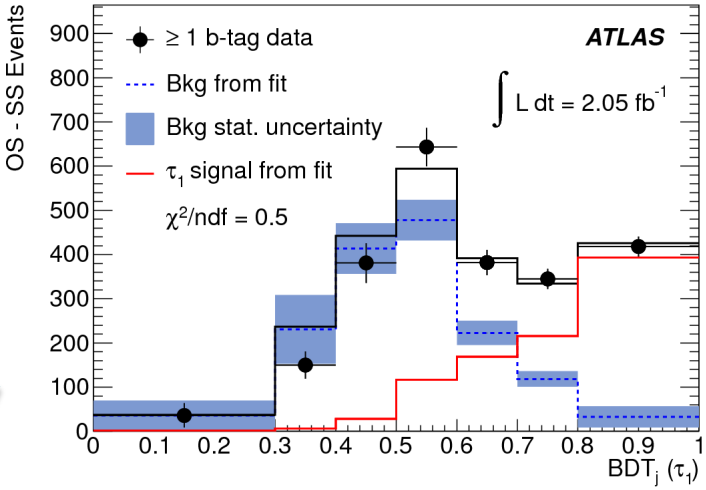
Template Fit of BDT_j Discriminator

arXiv:1205.2067

τ_{had}+lepton

- Signal and background BDT_j templates from OS-SS distributions are obtained
  - Cancels gluon and b-anti-b jets contribution
- 0 b-jet selection is used to obtain fake τ_{had} templates of the BDT discriminator
  - Derived separately for 1 and 3 prong candidates
  - Contribution of the true τ_{had} events is subtracted using MC
    - Mainly $Z \rightarrow \tau\ \tau$
  - Corrections applied for 0 b-jet to ≥1 b-jet extrapolation using MC
- Template fit in the signal region (≥1 b-jet)



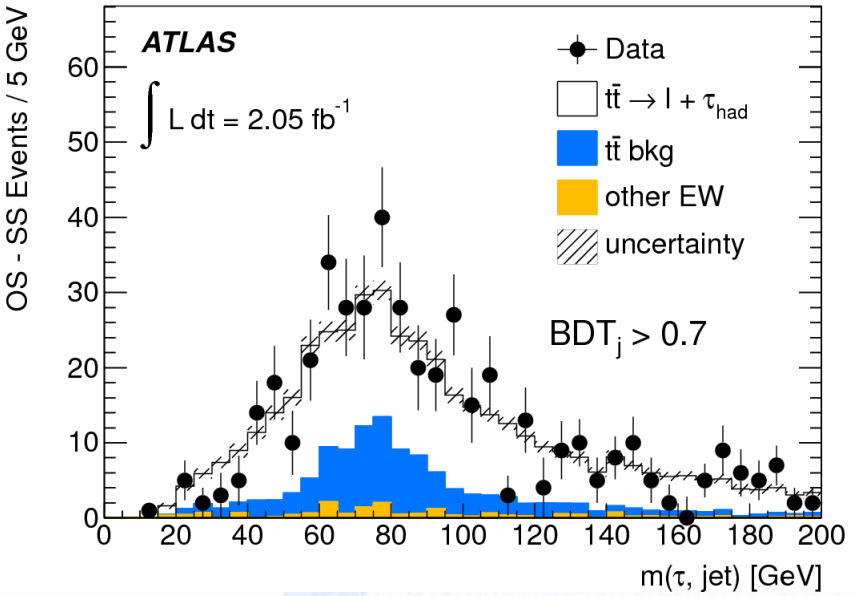


Cross-Section Measurement

arXiv:1205.2067

τ_{had}+lepton

- Measurement using fitted number of signal and background events
  - Cut on BDT output at 0.7



$\sigma_{t\bar{t}}(\tau\, e) = 186 \pm 15(stat.) \pm 20(syst.) \pm 7(lumi.)$ pb

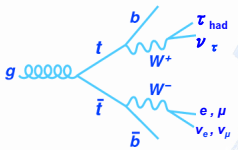
$\sigma_{t\bar{t}}(\tau\, \mu) = 187 \pm 18(stat.) \pm 20(syst.) \pm 7(lumi.)$ pb

- Combined result (BLUE):

$$\sigma_{t\bar{t}} = 186 \pm 13(stat.) \pm 20(syst.) \pm 7(lumi.)\ pb$$

Cross-Section Systematic Uncertainties

Phys. Rev. D 85, 112007 (2012)
arXiv:1203.6810



arXiv:1205.2067

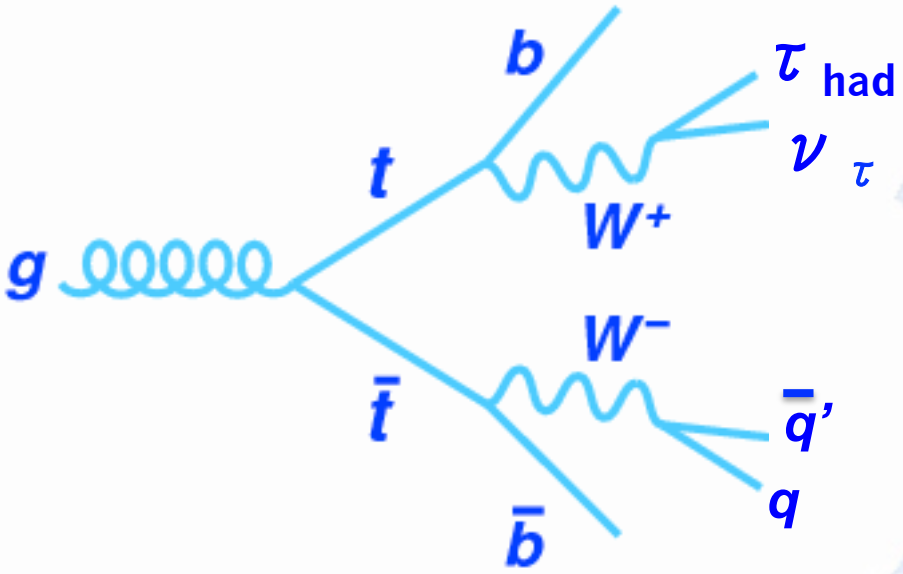
CMS

$\sigma_{t\bar{t}}$ = 143 ± 14(stat.) 10%
± 22(syst.) 15%
± 3(lumi.) 2%
pb

$\sigma_{t\bar{t}}$ = 186 ± 13(stat.) 7%
± 20(syst.) 11%
± 7(lumi.) 4%
pb

- Misidentified τ background
  - ≈13% , e+ τ_{had}
  - ≈10% , $\mu + \tau_{had}$
- τ_{had} identification
  - ≈6%
- JES/JER/E_T^{miss}
  - ≈6%
- b-jet tagging and light jet mistagging
  - ≈5%
- b-tagging
  - ≈8-9%
- ISR/FSR
  - ≈4-5%
- τ_{had} identification
  - ≈3%
- JES/JER
  - ≈2-3%

Hadronic τ + Jets Final State



- BR($t\bar{t}$ → *hadronic* τ + *jets*) ≅ 9.8%

- Main background
  - QCD multi-jets
  - Top-quark pair, other final states
  - Combinatorics
    - Top-quark pair signal but wrongly reconstructed τ_{had}

Trigger & Event Selection

ATLAS-CONF-2012-032

τ_{had}+jets

L = 1.67 fb^{-1}

- **≥ 4 jets (Level - 1)**
  - E_T > 10 GeV
  - $|\eta|$ < 3.2
  - 2 b-jets
    - High Level Trigger algorithm for b-tagging
      - ≈70% b-tagging efficiency wrt offline b-tagging
- **≥ 5 jets**
  - p_T > 20 GeV
  - $|\eta|$ < 2.5
  - ≥ 2 b-jets
  - 1 τ_{had} candidate jet
- **Veto on electron & muon**
- **E_T^{miss} significance > 8**

Object Selection Details

ATLAS-CONF-2012-032

τ_{had}+jets

- E_T^{miss} significance: $E_T^{miss}/(0.5 \cdot \sqrt{\Sigma E_T})$
  - ΣE_T - scalar sum of the transverse energy of all objects contributing in E_T^{miss}

- b-tagging
  - 60% efficiency in MC top-quark pair sample
  - 340 rejection factor for light jets
  - 5% chance of tau misidentification in MC top-quark pair sample

- τ_{had} selection
  - Exclude those 3 jets, whose vector sum gives the highest p_T
    - b-jet with the highest b-tag probability must be one of these 3 jets
    - b-jet with the second highest b-tag probability has not be included – it is also excluded

≈70% eff.

  - Select the remaining highest p_T jet as τ_{had}
    - At least 1 such a jet remains after the event selection

≈50% eff.

Fit Observable

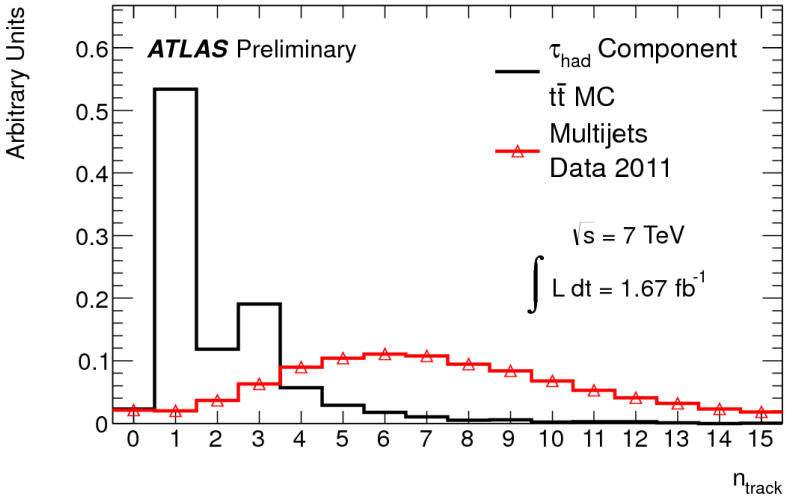
ATLAS-CONF-2012-032

τ_{had}+jets

- Number of tracks – $\mathbf{n_{track} = n_1 + n_2}$
  - $\mathbf{n_1}$ – number of (inner) tracks in $\Delta R<0.2$ with $p_T>1$ GeV
  - $\mathbf{n_2}$ – number of (outer) tracks in $0.2<\Delta R<0.6$
    - ✧ Counts only those tracks, which are not softer than the inner tracks based on $p_T/\Delta R$ metric

ΔR is calculated from a τ_{had} axis

- Signal template from a top-quark pair MC simulation
  - Significant contribution from electrons misidentified as τ_{had}
    - ✧ τ_{had} + electron template



- Good separation between signal and data driven background
  - Multi-jets
  - Combinatorics

Combinatorial background has larger fraction of quark jets than Multi-jets background, which is dominated by gluon jets

Binned Likelihood Fit of n_{track} Templates

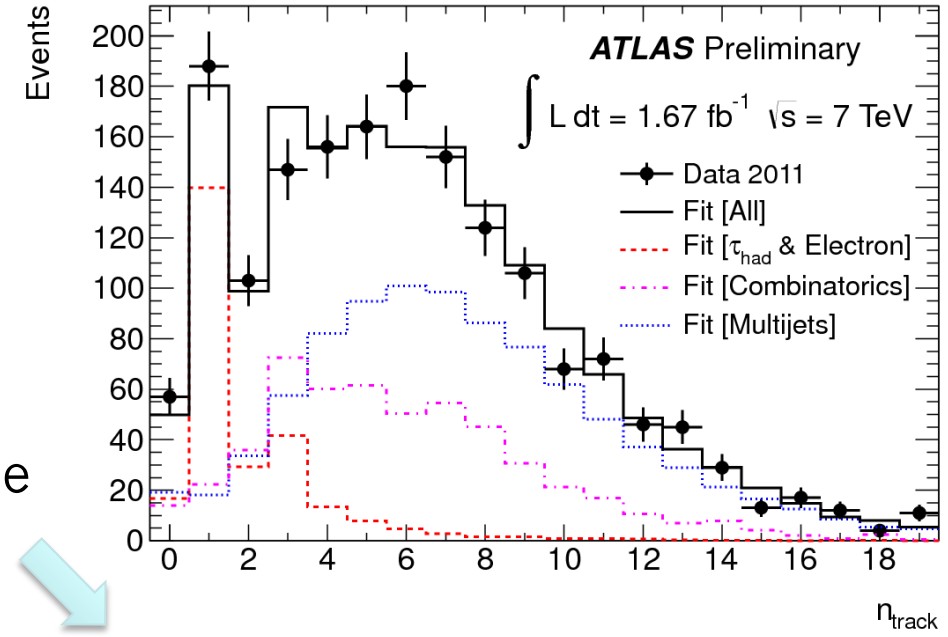
ATLAS-CONF-2012-032

τ_{had}+jets

- Number of combinatorial background events is constrained to the number of signal (τ_{had} + electron) events
  - They come from the same top-quark pair production
  - Assuming that the relative production rates of the two are known

- Fit likelihood function is used to obtain statistical uncertainties

- Pseudo-experiments for all systematic variations of templates ➔ distribution of the estimate of τ_{had}+electron
  - Mean and RMS as measured number of events and its systematic uncertainty



$N_{\tau+e} = 268 \pm 24(stat.) \pm 17(syst.)$

Cross Section Measurement

ATLAS-CONF-2012-032

τ_{had}+jets

- Calculate the number of τ_{had} events from the fit result, $N_{\tau+e}$
  - Subtract single top and W+jets contributions as predicted by MC
    - 12±3 , single top events
    - 13±14 , Wbb events
  - Apply the τ_{had} events fraction (©MC) to the result
    - $N_\tau/(N_\tau+N_e) = 0.77 \pm 0.03(\text{stat.}) \pm 0.03(\text{syst.})$

$$N_\tau = 188 \pm 22(\text{stat.}) \pm 15(\text{syst.})$$

- Calculate the cross-section:

$$\sigma_{t\bar{t}} = 200 \pm 19(\text{stat.}) \pm 43(\text{syst.+lumi.})\ \text{pb}$$

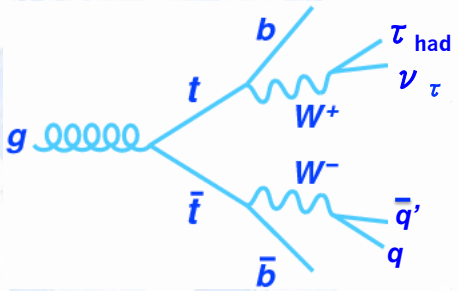
Trigger & Event Selection

CMS-PAS-TOP-11-004

- **≥4 jets**
  - $p_T > 40 \div 45$ GeV
  - $|\eta| < 2.5$

Threshold was increased
In the second part of
the data taking period

- **1 jet matches to a τ_{had} candidate (offline)**
  - Leading track $p_T > 5$ GeV



- **≥3 jets**
  - $p_T > 45$ GeV & $|\eta| < 2.4$
  - 1 b-jet
  - 4^{th} jet with $p_T > 20$ GeV
- **1 τ_{had}**
  - $p_T > 45$ GeV & $|\eta| < 2.3$
- **Veto on electron & muon**
- **$E_T^{miss} > 20$ GeV**

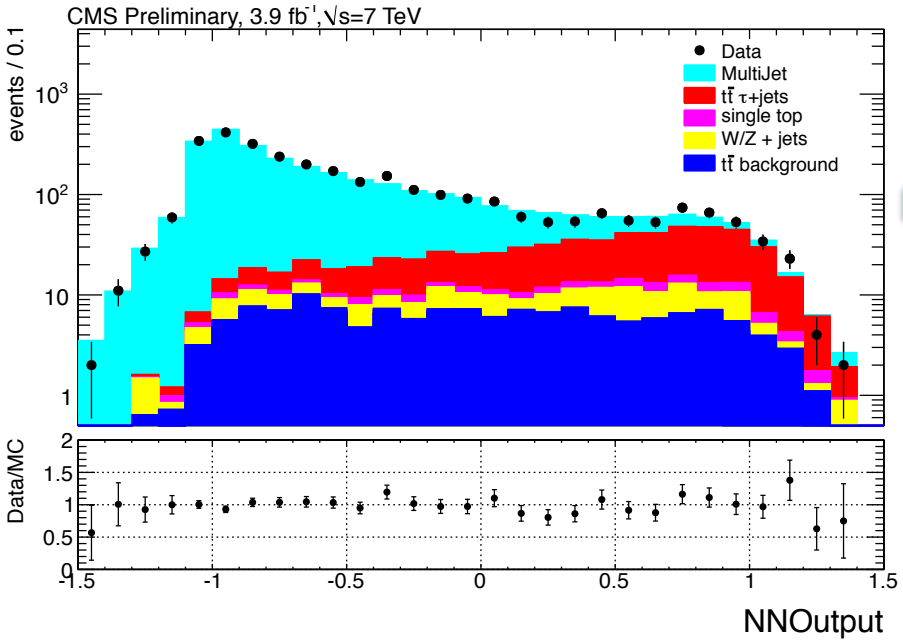
L = 3.9 fb^{-1}

Neural Network for Signal Estimation

CMS-PAS-TOP-11-004

τ_{had}+jets

- MultiLayerPercepton (MLP) algorithm in TMVA
  - Trained using simulated signal and data driven multi-jets templates
    - Multi-jets template is obtained with the same signal selection but with reversed b-jet requirement
      - Jet kinematics corrections are applied



Source	Events (± stat.)
Signal $t\bar{t} \to \tau_h$+jets	387 ± 29
Other $t\bar{t}$	148 ± 4
W+jets	61 ± 8
Z+jets	20 ± 5
Single top	40 ± 1
Multijet	2394 ± 29
Total backgrounds	2663 ± 31
Data	3050

Expected signal in MC: 409 ± 7

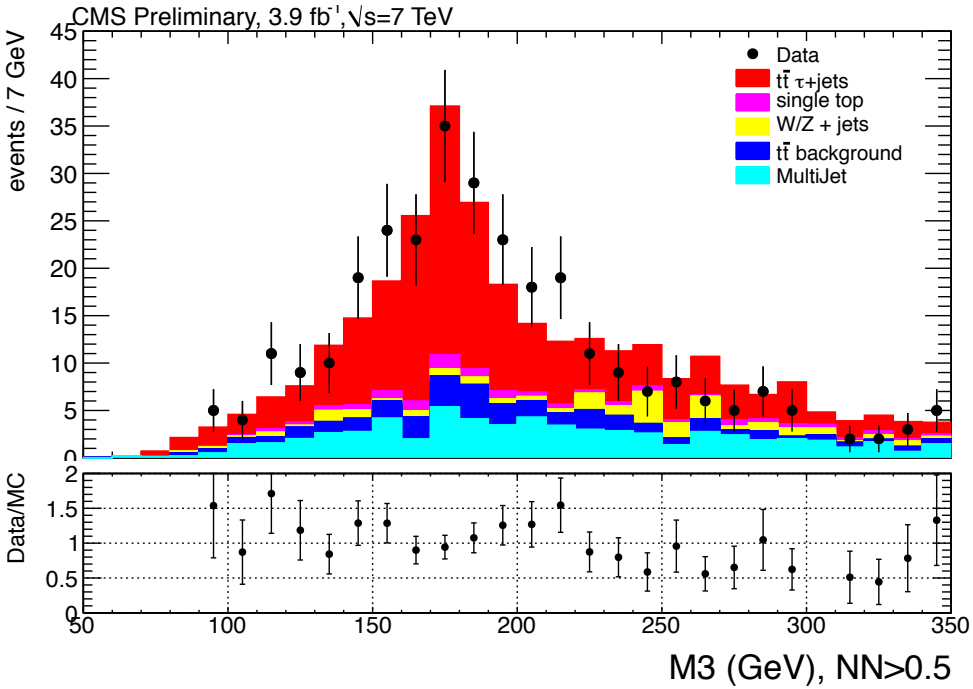
- All backgrounds except of multi-jets are estimated from MC

Cross-Section Measurement

- Final selection of events is done by imposing a cut on the MLP output to be greater than 0.5
  - Invariant mass of the three-jets system with the highest transverse momentum after the events final selection

CMS-PAS-TOP-11-004

τ_{had}+jets

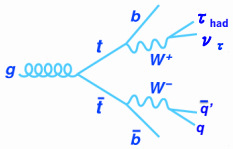


- Cross-selection is calculated based on the final selection of events

$$\sigma_{t\bar{t}} = 156 \pm 12(\text{stat.}) \pm 33(\text{syst.}) \pm 3(\text{lumi.})\ \text{pb}$$

Cross-Section Systematic Uncertainties

CMS-PAS-TOP-11-004



ATLAS-CONF-2012-032

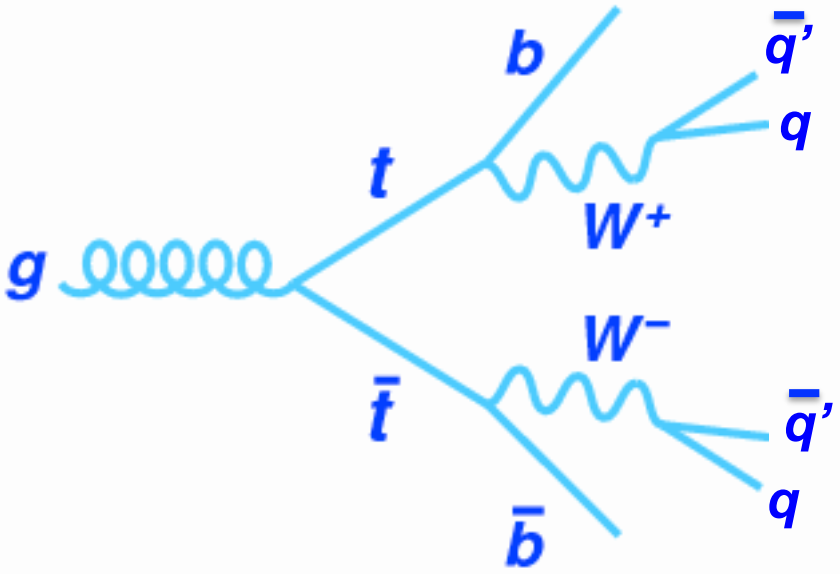
$\sigma_{t\bar{t}}$ = 156 ± 12(stat.) 8%
± 33(syst.) 21%
± 3(lumi.) 2%
pb

$\sigma_{t\bar{t}}$ = 200 ± 19(stat.) 10%
± 43(syst.+lumi.) 22%
pb

- Jet energy correction
  - ≈11%
- τ_{had} identification
  - ≈9%
- τ_{had} trigger
  - ≈7%
- τ_{had} energy correction
  - ≈7%
- MLP output fit & MC stat.
  - ≈8%

- ISR/FSR
  - ≈12%
- b-tagging
  - ≈10%
- MC Generator/Hadronization model
  - ≈7%
- Likelihood fit
  - ≈7%
- JES
  - ≈6%

Fully Hadronic Final State



- BR($t\bar{t}$ → *jets*) ≅ 46%
- Main background
  - QCD multi-jets

Trigger & Event Selection

CMS-PAS-TOP-11-007

fully hadronic

- **≥4 jets**
  - p_T > 50 GeV
  - 5th jet with p_T > 40 GeV
  - 6th jet with p > 30 GeV
    - ✧ Only second period of data taking

L = 1.09 fb^{-1}

Pile-up: ~5.6 events

- **≥6 jets**
  - ≥4 jets (≥2), p_T > 60 GeV
  - 5th jet, p_T > 50 GeV
  - 6th jet, p_T > 40 GeV
  - $|\eta_{jets}| < 2.4$
  - ≥2 b-jets
  - Additional jets with p_T > 30 GeV are considered in a measurement

Kinematic Fit

CMS-PAS-TOP-11-007
fully hadronic

- Reconstruct a top-quark pair system from jets and fit with the least square method
  - Reconstruct both W bosons assuming $m_W = 80.4$ GeV
  - Assumes $m_{t1}^{rec} = m_{t2}^{rec}$ and both are free parameters of the fit
  - Allow all distinguishable permutations of jets
    - Only b-jets are taken as b-quark candidates
      - E.g., if there are exactly 2 b-jets and 4 light jets ➔ 6 permutations

- Take the permutation with the smallest χ^2

- Accept events with $P(\chi^2)>0.01$

MC: correct match ≈ 42%

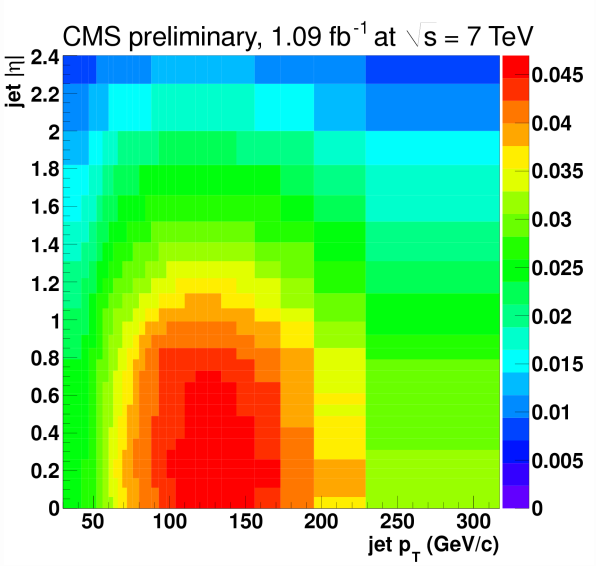
- Derive fitted top mass templates from the selected events after the kinematic fit
  - Templates are inputs for likelihood fit for signal cross-section extraction

Background Template

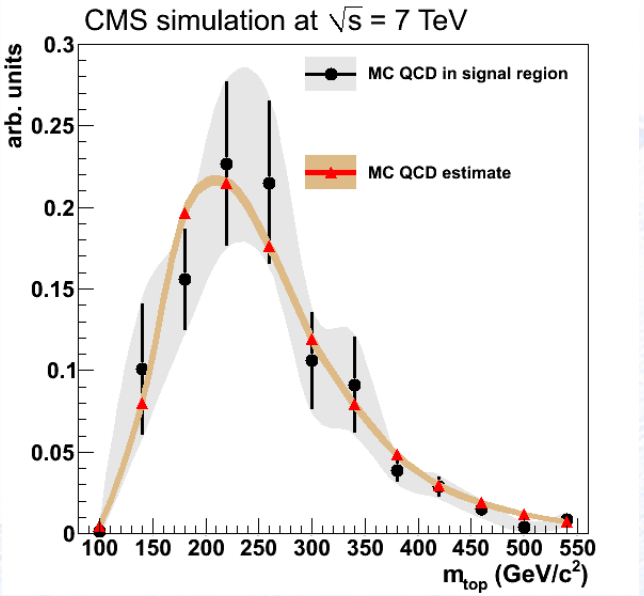
CMS-PAS-TOP-11-007
fully hadronic

- Derive multi-jets template from data
  - Events with ≥6 jets and 0 b-tagged (d_B<2)
  - Needs to be corrected with ≥2 b-jets kinematics
  - Derive b-tagging weights map for light jets from all data events
    - ✧ Negligible fraction of real b-jets

$$R(p_T, |\eta|) = \frac{N(p_T, |\eta|, d_B > 2.0)}{N(p_T, |\eta|, d_B \leq 2.0)}$$



The method shows good agreement with MC simulation



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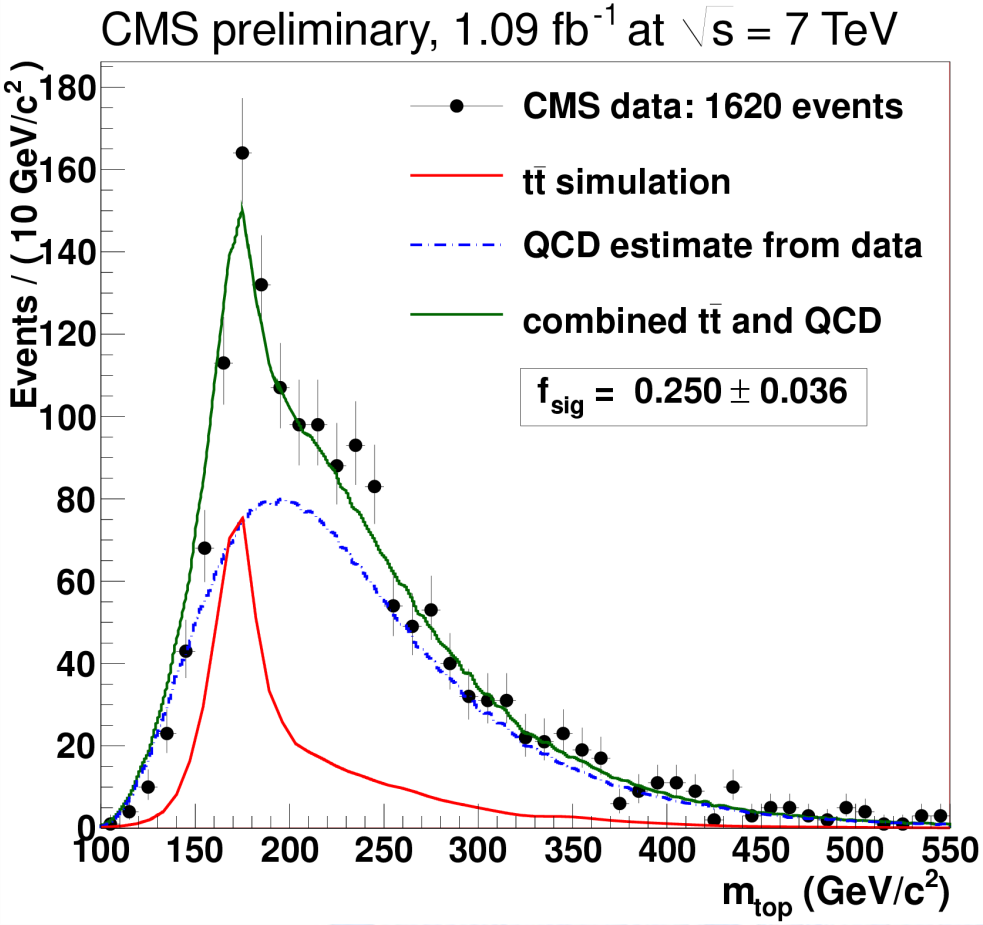
Cross-Section Measurement

CMS-PAS-TOP-11-007

fully hadronic

- Likelihood fit of data with the top-quark pair and multi-jets templates of the top mass obtained in events after the kinematic fit selection
- The signal fraction in the selected data sample is a fit free parameter
  - Is converted into the cross-section of the top-quark pair inclusive cross-section

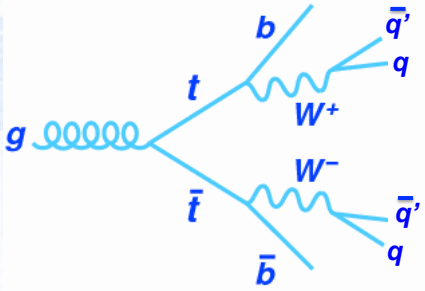


$$\sigma_{t\bar{t}} = 136 \pm 20(\text{stat.}) \pm 40(\text{syst.}) \pm 8(\text{lumi.})\ \text{pb}$$

Trigger & Event Selection

ATLAS-CONF-2012-031

- **≥5 jets (HLT)**
  - E_T > 30 GeV
  - $|\eta|$ < 3.2



- **≥6 jets**
  - ≥5 jets (≥2 b-jets)
    - p_T > 55 GeV & $|\eta|$ < 2.5
  - 6th jet
    - p_T > 30 GeV & $|\eta|$ < 2.5
- **$\Delta R(b_{jet}1, b_{jet}2) > 1.2$**
- **$\Delta R(jet_i, jet_k) > 0.6$**
- **$S_t < 6$**
- **Veto on isolated leptons**

L = 4.7 fb^{-1}

$$S_t = E_{\mathrm{T}}^{\mathrm{miss}} / \left(0.5\sqrt{\mathrm{GeV}} \times \sqrt{H_{\mathrm{T}}}\right)$$

H_T – scalar sum of transverse momenta of all jets

Likelihood Based Kinematic Fit

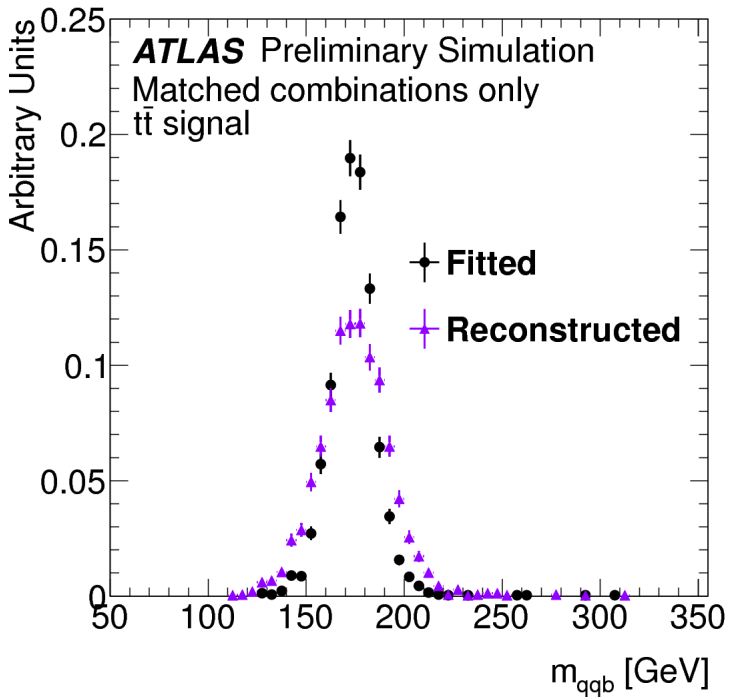
ATLAS-CONF-2012-031
fully hadronic

- Minimize the likelihood function wrt 7 free parameters: m_t^{reco} and 6 jet energies, $E_{b \text{ and }} E_q$

$$
\begin{aligned}
L_{kin} \;=\; & \mathrm{BW}\left(m_{q_1q_2} \mid m_W, \Gamma_W\right) \cdot \mathrm{BW}\left(m_{q_3q_4} \mid m_W, \Gamma_W\right) \cdot \\
& \mathrm{BW}\left(m_{q_1q_2b_1} \mid m_{\mathrm{top}}^{\mathrm{reco}}, \Gamma_{\mathrm{top}}\right) \cdot \mathrm{BW}\left(m_{q_3q_4b_2} \mid m_{\mathrm{top}}^{\mathrm{reco}}, \Gamma_{\mathrm{top}}\right) \cdot \\
& \mathrm{W}\left(\hat{E}_{\mathrm{jet}_1} \mid E_{b_1}\right) \cdot \mathrm{W}\left(\hat{E}_{\mathrm{jet}_2} \mid E_{b_2}\right) \cdot \mathrm{W}\left(\hat{E}_{\mathrm{jet}_3} \mid E_{q_1}\right) \cdot \mathrm{W}\left(\hat{E}_{\mathrm{jet}_4} \mid E_{q_2}\right) \cdot \\
& \mathrm{W}\left(\hat{E}_{\mathrm{jet}_5} \mid E_{q_3}\right) \cdot \mathrm{W}\left(\hat{E}_{\mathrm{jet}_6} \mid E_{q_4}\right) \cdot \\
& \prod_{i=1}^{2} \left\{ \begin{array}{c} \epsilon; b_i \; b-\text{tagged} \\ (1-\epsilon); b_i \text{ not } b-\text{tagged} \end{array} \right\} \cdot \prod_{i=1}^{4} \left\{ \begin{array}{c} \frac{1}{R}; q_i \; b-\text{tagged} \\ (1-\frac{1}{R}); q_i \text{ not } b-\text{tagged} \end{array} \right\}
\end{aligned}
$$

  - W boson mass and width are fixed to their measured values
  - Assumes $m_{t1}^{reco} = m_{t2}^{reco}$ and both are free parameters of the fit
    - Γ_t depends on m_t^{reco} and varies accordingly
  - All permutations of jets are considered
    - $6 \leq N_{jets} \leq 10$
  - Breit-Wigner (BW) shape is assumed for the reconstructed top mass
  - $W(E_{jet} | E_q)$ – transfer functions are obtained from MC

Final Event Selection



ATLAS-CONF-2012-031

fully hadronic

- The permutation with the minimal $-\ln(L_k)$ is selected
- Kinematic fit improves the top mass resolution
  - In fully matched MC events
- Cut on the event fit likelihood
  - $L_k^{max} / \Sigma L_k > 0.8$
- Cut on the χ^2 discriminant built out of the kinematic fit result
  - $\chi^2 < 30$

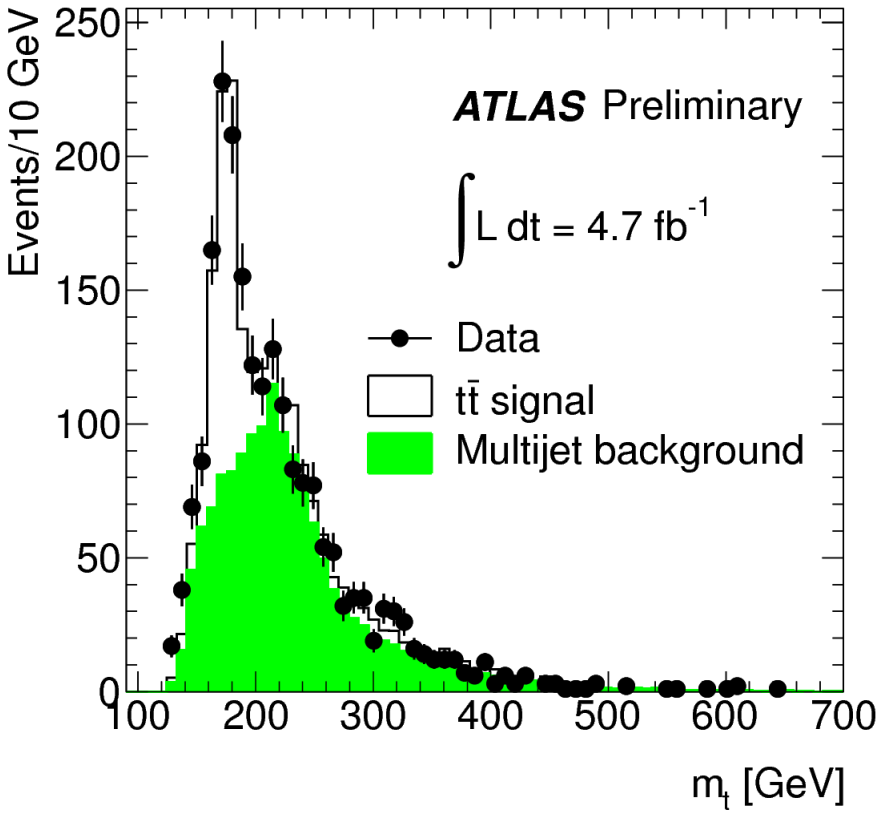
$$\chi^2 = \frac{\left(m_{j_1,j_2} - m_W\right)^2}{\sigma_W^2} + \frac{\left(m_{j_1,j_2,b_1} - m_t\right)^2}{\sigma_t^2} + \frac{\left(m_{j_3,j_4} - m_W\right)^2}{\sigma_W^2} + \frac{\left(m_{j_3,j_4,b_2} - m_t\right)^2}{\sigma_t^2}$$

Cross-Section Extraction

ATLAS-CONF-2012-031

fully hadronic

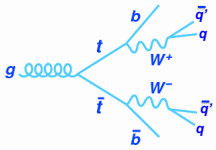
- Multi-jets template is obtained from data
  - Same selection as the signal sample but no b-jets
  - Differences in kinematics and heavy flavor contents are considered as systematic uncertainties
    - MC simulation of multi-jets is used
- Signal fraction in data is estimated with a likelihood fit



$\sigma_{t\bar{t}}$ = 168 ± 12(stat.) +60/-57(syst.) ± 7(lumi.) pb

Cross-Section Systematic Uncertainties

CMS-PAS-TOP-11-007



ATLAS-CONF-2012-031

$\sigma_{t\bar{t}}$ = 136 ± 20(stat.) 15%
± 40(syst.) 30%
± 8(lumi.) 6%
pb

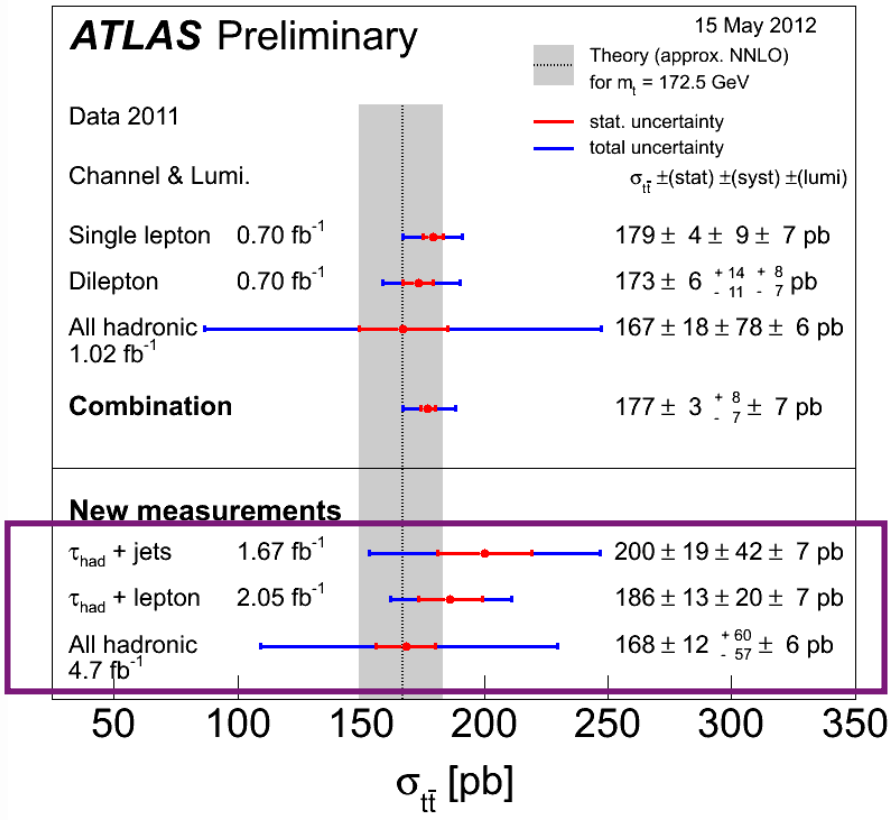
$\sigma_{t\bar{t}}$ = 168 ± 12(stat.) 7%
+60/-57(syst.) 35%
±7(lumi.) 4%
pb

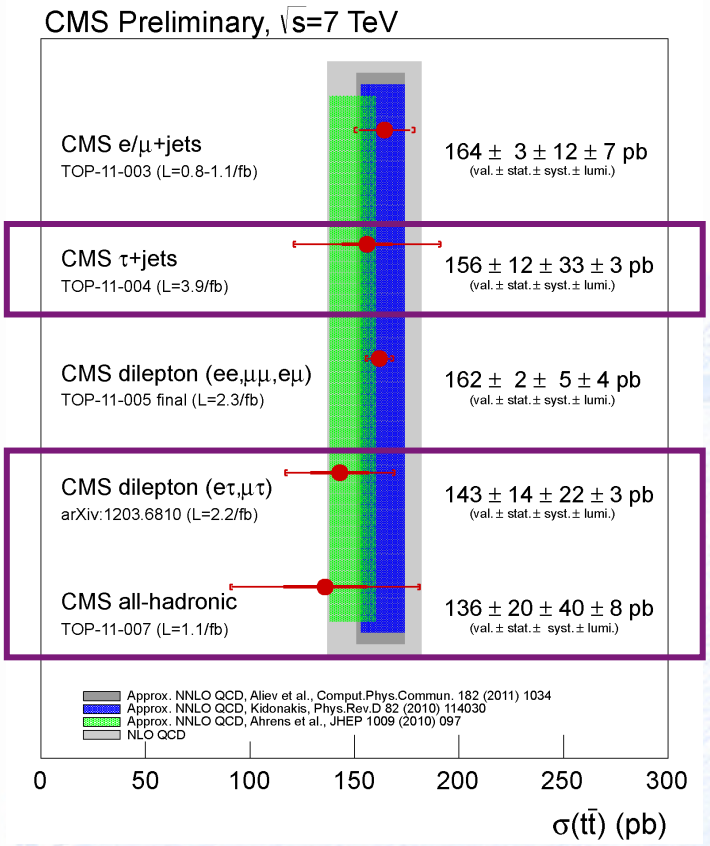
- b-tagging
  - ≈16%
- JES
  - ≈14%
- Background
  - ≈12%
- Choice of Q^2
  - ≈9%
- MC tune
  - ≈8%

- JES
  - +20/-11%
- b-tagging
  - ≈17%
- ISR/FSR
  - ≈17%
- Showering/Hadronization model
  - ≈13%
- Multi-jet trigger
  - ≈10%

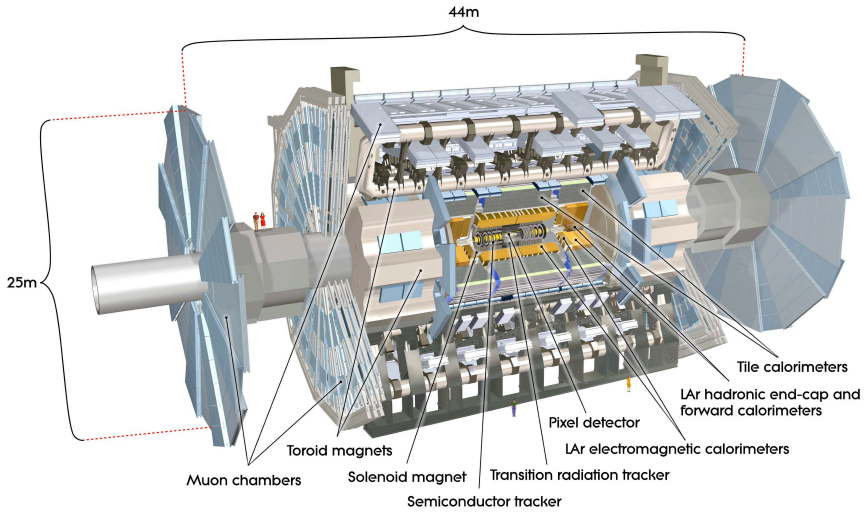
Summary

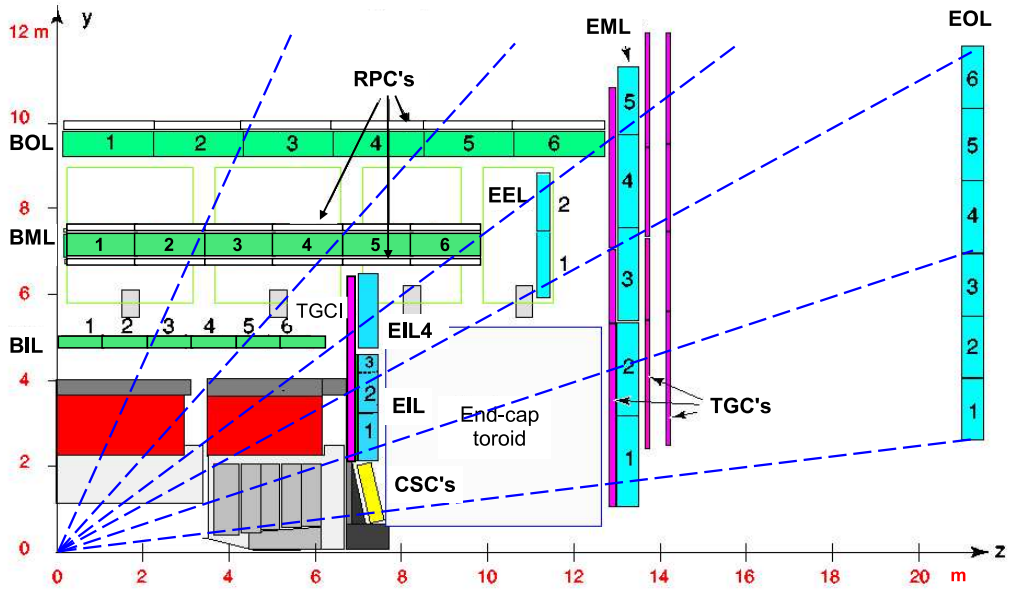
- ATLAS and CMS have measured top-quark pair production cross-section also in final states with τ-lepton and fully hadronic
- Results are consistent with the SM prediction within uncertainties





Back-up Slides





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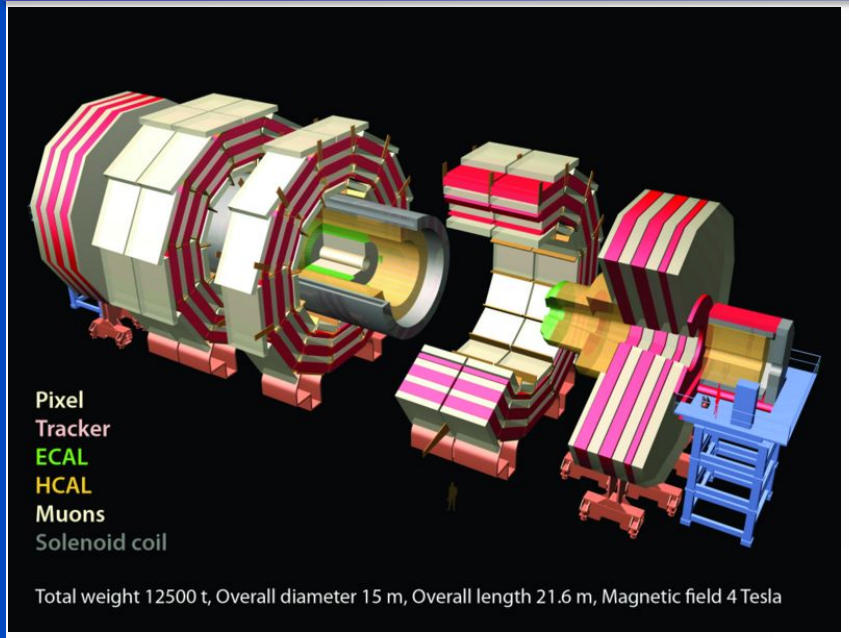

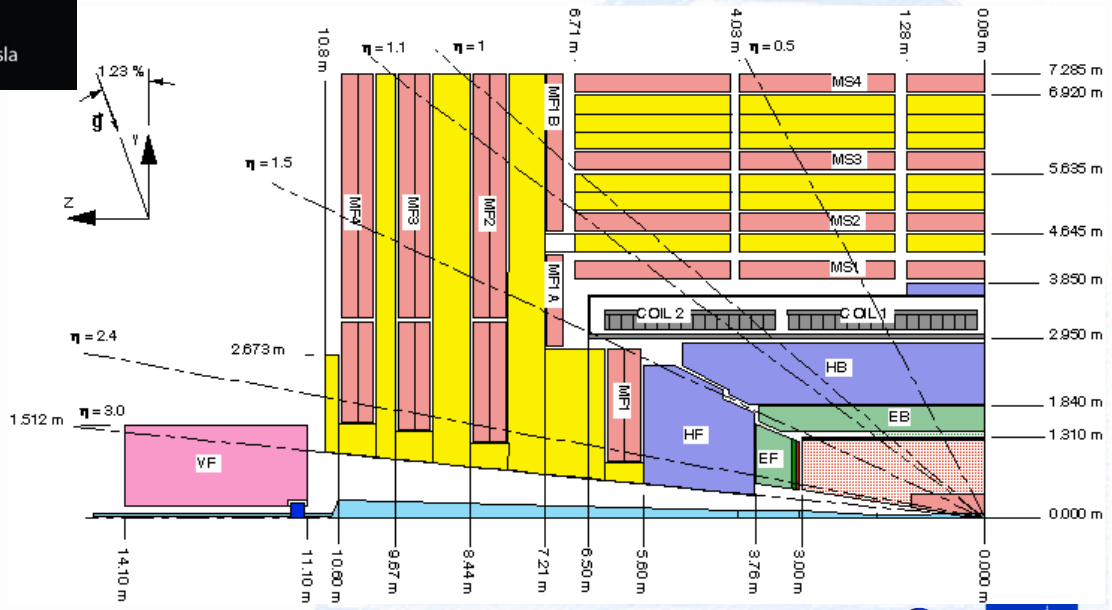

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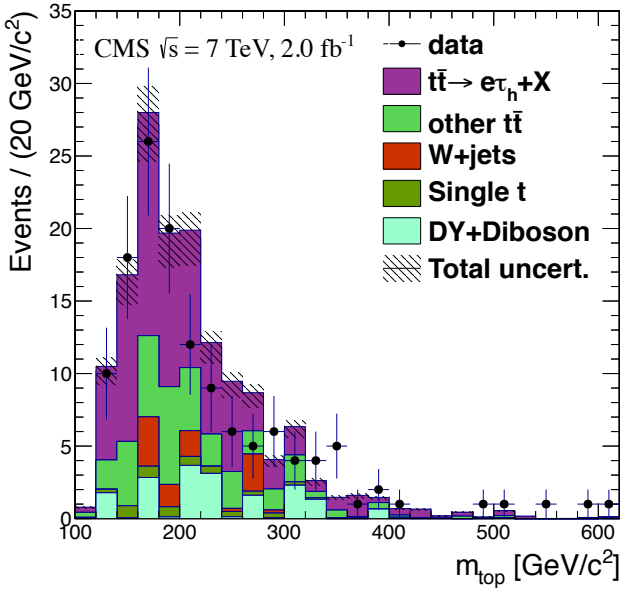
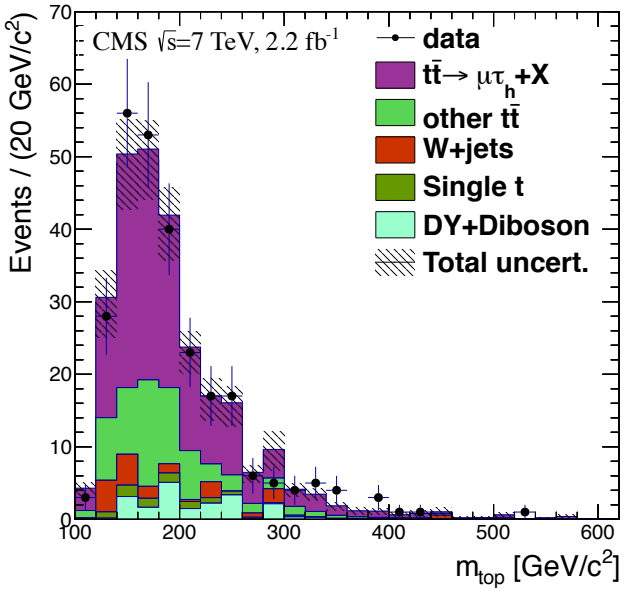
Reconstructed Top Mass

Phys. Rev. D 85, 112007 (2012)
τ_{had}+lepton arXiv:1203.6810

- Event based numerical solution for the top-quark pair system kinematics with two leptons
  - Independent variation of jets E_T , E_T^{miss} direction, $p_{||}$ of top-quark pair system within their measured resolution
  - Accept the solution with the lowest invariant mass of top-quark pair system if the difference between the reconstructed masses of top and anti-top quarks is less than 3 GeV





Systematic Uncertainties

Phys. Rev. D 85, 112007 (2012)
τ_{had}+lepton arXiv:1203.6810

Source	Uncertainty [%]		Combination [%]
	$e\tau_h$	$\mu\tau_h$	
τ misidentification background	12.6	9.8	10.8
τ jet identification	6.4	6.3	6.3
b-jet tagging, misidentification	5.3	5.3	5.3
jet energy scale, jet energy resolution, E_T^{miss}	5.1	6.2	5.8
theoretical uncertainty on signal efficiency	4.0	4.0	4.0
pile-up modelling	2.3	2.3	2.3
electron selection	3.1	0	1.1
muon selection	0	2.0	1.3
cross section of MC backgrounds	1.6	1.4	1.5
luminosity	2.2	2.2	2.2
weight	0.38	0.62	$\chi^2/N_{dof} = 2.381/1$ (p-value = 0.198)

Variables for Building BDT Discriminator

arXiv:1205.2067

τ_{had}+lepton

- BDT_e - for removal of misidentified electrons
  - Uses 7 variables
  - The most discriminative ones are:
    - E/p
    - E_{EM}/E_{tot}
      - E_{EM} is the energy of the candidate jet in the electromagnetic calorimeter
    - Cluster based shower width

- BDT_j – for discriminating against jets
  - Uses 8 (10) variables for "1 prong" ("3 prong") τ_{had} identification
  - The most discriminative variables are:
    - Calorimeter and track isolation
    - Cluster based jet mass
    - Energy fraction within $\Delta R<0.1$ around the jet axis
  - Fake background is higher for "3 prong" candidates

Event Yields

arXiv:1205.206 τ_{had}+lepton

$\mu + \tau$	τ_1				τ_3			
	0 b-tag		≥ 1 b-tag		0 b-tag		≥ 1 b-tag	
	OS	SS	OS	SS	OS	SS	OS	SS
$t\bar{t}(\mu + \tau)$	60 ± 2	< 1	390 ± 4	2 ± 1	17 ± 1	1 ± 1	118 ± 3	2 ± 1
$t\bar{t}(\mu + e)$	3 ± 1	< 1	12 ± 1	1 ± 1	1 ± 1	< 1	3 ± 1	< 1
$t\bar{t}(\mu$+jets)	308 ± 4	163 ± 3	1528 ± 9	660 ± 6	685 ± 6	443 ± 5	3484 ± 13	2000 ± 10
μ+jets	5010 ± 70	3020 ± 60	496 ± 17	297 ± 13	12230 ± 120	8670 ± 90	1293 ± 28	928 ± 24
Multi−jets	470 ± 140	540 ± 160	117 ± 35	150 ± 40	990 ± 300	1120 ± 340	460 ± 140	400 ± 120
$Wt(\mu + \tau)$	7 ± 1	< 1	18 ± 1	1 ± 1	2 ± 1	< 1	5 ± 1	< 1
$Z \to \tau\tau$	301 ± 13	2 ± 1	16 ± 3	< 1	75 ± 7	1 ± 1	3 ± 2	< 1
Total	6160 ± 160	3730 ± 170	2580 ± 40	1110 ± 40	14000 ± 320	10230 ± 350	5370 ± 140	3330 ± 120
Data	5450	3700	2472	1332	13322	10193	5703	3683

$e + \tau$	τ_1				τ_3			
	0 b-tag		≥ 1 b-tag		0 b-tag		≥ 1 b-tag	
	OS	SS	OS	SS	OS	SS	OS	SS
$t\bar{t}(e + \tau)$	54 ± 7	1 ± 1	342 ± 19	3 ± 2	15 ± 4	< 1	103 ± 10	2 ± 1
$t\bar{t}(e + e)$	2 ± 1	< 1	11 ± 3	1± 1	< 1	< 1	2 ± 1	< 1
$t\bar{t}(e$+jets)	273 ± 17	146 ± 12	1340 ± 40	599 ± 25	633 ± 25	399 ± 20	3090 ± 60	1780 ± 40
e+jets	3950 ± 60	2590 ± 50	380 ± 20	256 ± 16	10140 ± 100	7530 ± 90	1120 ± 33	841 ± 29
Multi−jets	600 ± 180	620 ± 190	170 ± 50	140 ± 40	2000 ± 600	2000 ±600	690 ± 210	610 ± 180
Z $\to ee$	92 ± 10	3 ± 2	9 ± 3	< 1	11 ± 3	2 ± 1	< 1	< 1
$Wt(e + \tau)$	7 ± 3	< 1	17 ± 4	< 1	1 ± 1	< 1	5 ± 2	< 1
$Z \to \tau\tau$	217 ± 15	2 ± 1	15 ± 4	< 1	60 ± 7	1 ± 1	3 ± 2	< 1
Total	5190 ± 190	3360 ± 200	2280 ± 70	990 ± 50	12900 ± 600	9900 ± 600	5020 ± 220	3230 ± 180
Data	5111	3462	2277	1107	12102	9635	5033	3192

Systematic Uncertainties

arXiv:1205.2067

τ_{had}+lepton

Source	$\mu + \tau$	$e + \tau$
μ (ID/Trigger)	-1.1 /$+1.5$	–
e (ID/Trigger)	–	± 2.9
JES	$-2.0/+2.2$	-1.9 /$+2.8$
JER	± 1.0	± 1.2
ISR/FSR	± 4.8	± 3.5
Generator	± 0.7	± 0.7
PDF	± 2.0	± 2.1
b-tag	$-7.7/+9.0$	$-7.5/+8.9$
τ_1 ID	$-3.0/+3.2$	$-2.7/+3.0$
τ_3 ID	$-3.1/+3.4$	$-2.9/+3.2$

Event Selection Yields

ATLAS-CONF-2012-032

τ_{had}+jets

Events have true τ_{had}

p_T>15 GeV & $|\eta|$<2.5

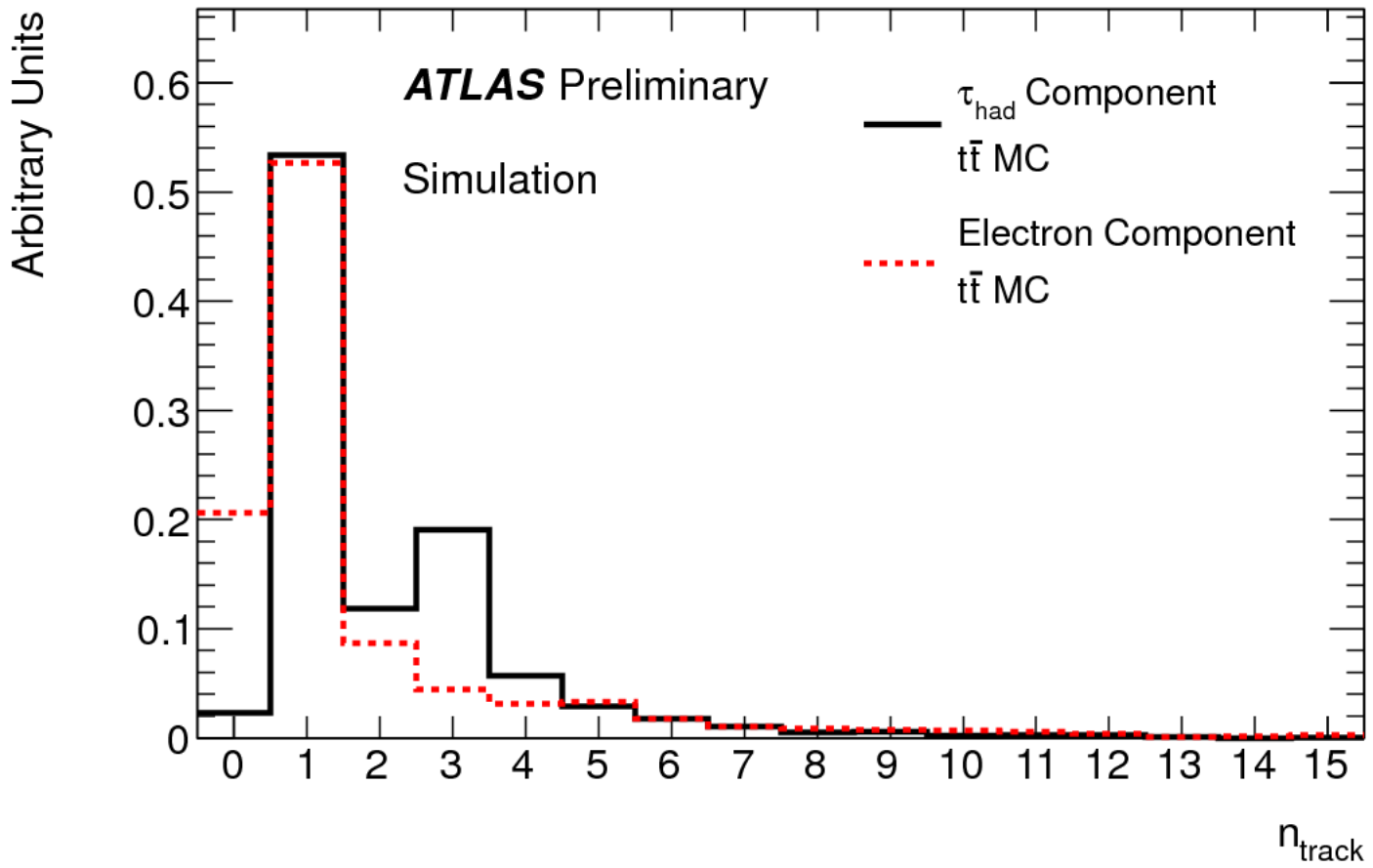
	Multijets	$b\bar{b}$	W+jets	$Wb\bar{b}$	Single t	All $t\bar{t}$	$t\bar{t}$ with τ_{had}
Selected events	293	757	4	41	36	691	299
True τ_{had}	0	0	1	10	10	150	149
True e	0	0	0	3	2	44	3

Reconstructed τ_{had} is

τ_{had} + Electron Template

ATLAS-CONF-2012-032

τ_{had}+jets



Combinatorics Template of n_{track}

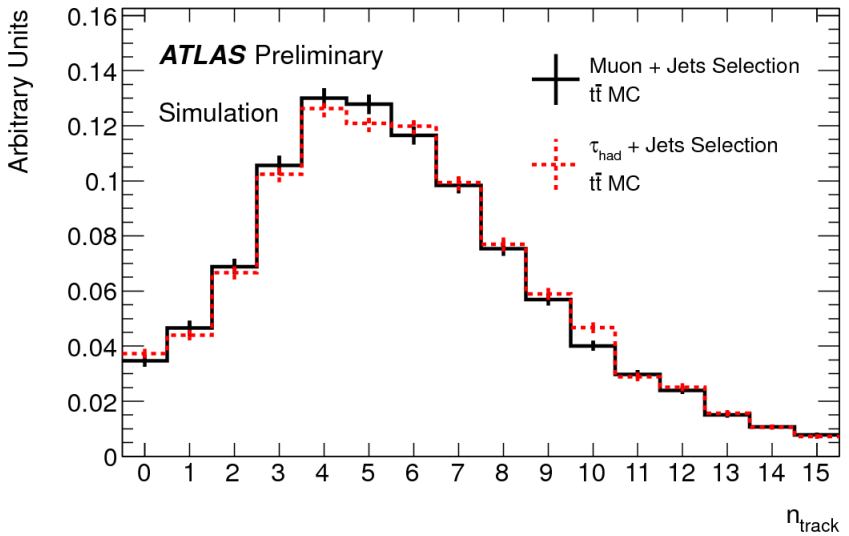
ATLAS-CONF-2012-032

τ_{had}+jets

- Use $t\bar{t} \rightarrow \mu$ +jets selection in data
  - Same signal selection but τ is replaced with muon
    - Minimal number of jets is released from 5 to 4
    - Non top-quark pair background is reduced at ~5% level (©MC)
  - Consider both 2 highest p_T non-tagged jets as τ_{had} candidates
    - n_{track} distribution is corrected for the small dependence on p_T
  - Remove small contribution from dileptons: $t\bar{t} \rightarrow \mu + \tau_{had}$+X and $t\bar{t} \rightarrow \mu$ +e+X with real τ_{had} using their MC samples

- Test procedure using MC simulation of $t\bar{t} \rightarrow \mu$ + jets and $t\bar{t} \rightarrow \tau_{had}$+jets

- Take a difference as systematics



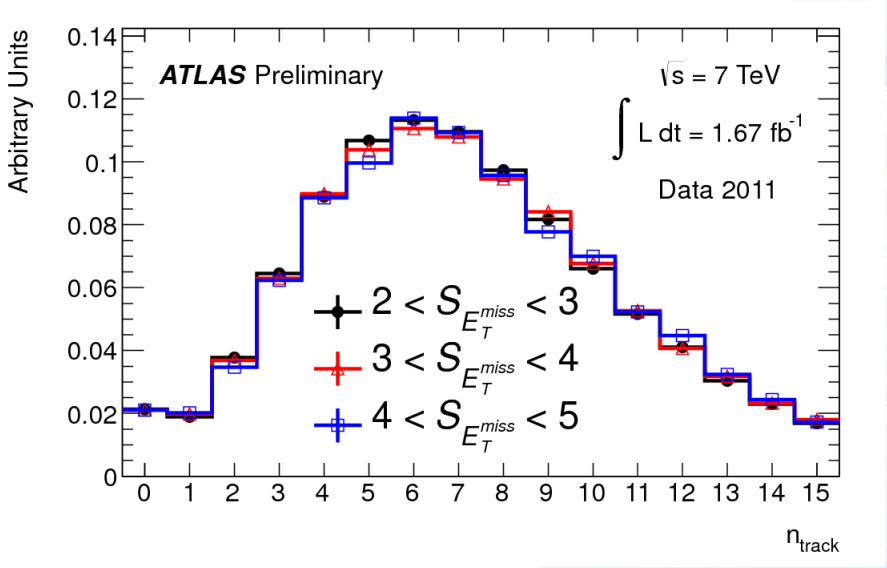
QCD Multi-jets Template of n_{track}

ATLAS-CONF-2012-032

τ_{had}+jets

- Use E_T^{miss} significance for definition of a control region for the QCD multi-jets
  - Derive multi-jets template for n_{track} in the control region
  - Control region: $3 < \text{significance}(E_T^{miss}) < 4$
    - < 1% contribution from other processes

- n_{track} distribution for multi-jets doesn't depend on the E_T^{miss} significance



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Systematic Uncertainties

ATLAS-CONF-2012-032

τ_{had}+jets

Fit uncertainties

Source of uncertainty	$\Delta n_{tau\&electron}$ (relative)
tau & electron template	
τ_{had}/e ratio	< 1%
Statistical uncertainty	1%
Jet energy scale	< 1%
Pile-up	1%
ISR/FSR	5%
Track reconstruction	< 1%
combinatorics template	
Closure in simulation	2%
Dilepton subtraction	1%
Statistical uncertainties (data)	4%
Statistical uncertainties (Monte Carlo)	1%
p_T reweighting	< 1%
multijets template	
Closure to $2 < S_{E_T^{miss}} < 3$ sideband	1%
Closure to $4 < S_{E_T^{miss}} < 5$ sideband	< 1%
Statistical uncertainties ($2 < S_{E_T^{miss}} < 3$)	< 1%
Statistical uncertainties ($3 < S_{E_T^{miss}} < 4$)	< 1%
Statistical uncertainties ($4 < S_{E_T^{miss}} < 5$)	1%
Total fit uncertainty	7%

Selection efficiency uncertainties

Source of uncertainty	Relative uncertainty
ISR/FSR	12%
Choice of hadronization model	7%
Choice of event generator	2%
PDFs	2%
E_T^{miss} significance mismodeling	5%
Jet energy scale	6%
Jet reconstruction efficiency	< 1%
Jet energy resolution	2%
b-jet tagging efficiency	10%
b-jet trigger efficiency	3%
Light jet mistag rate	< 1%
Electron veto	< 1%
Muon veto	< 1%
Pile-up	1%
Luminosity	4%
Total ε uncertainty	19%

Object Selection Details

CMS-PAS-TOP-11-004

τ_{had}+jets

- b-tagging, Jet Probability tagger
- HPS algorithm for τ_{had} reconstruction
- τ_{had} isolatation
  - $\Sigma E_T < 1$ GeV for additional particles in $\Delta R \leq 0.5$

τ Id. eff. ≈ 44%

Jet misId. ≈ 0.5%

- Additional discrimination against electrons & muons using Boosted Decision Trees

Systematic Uncertainties

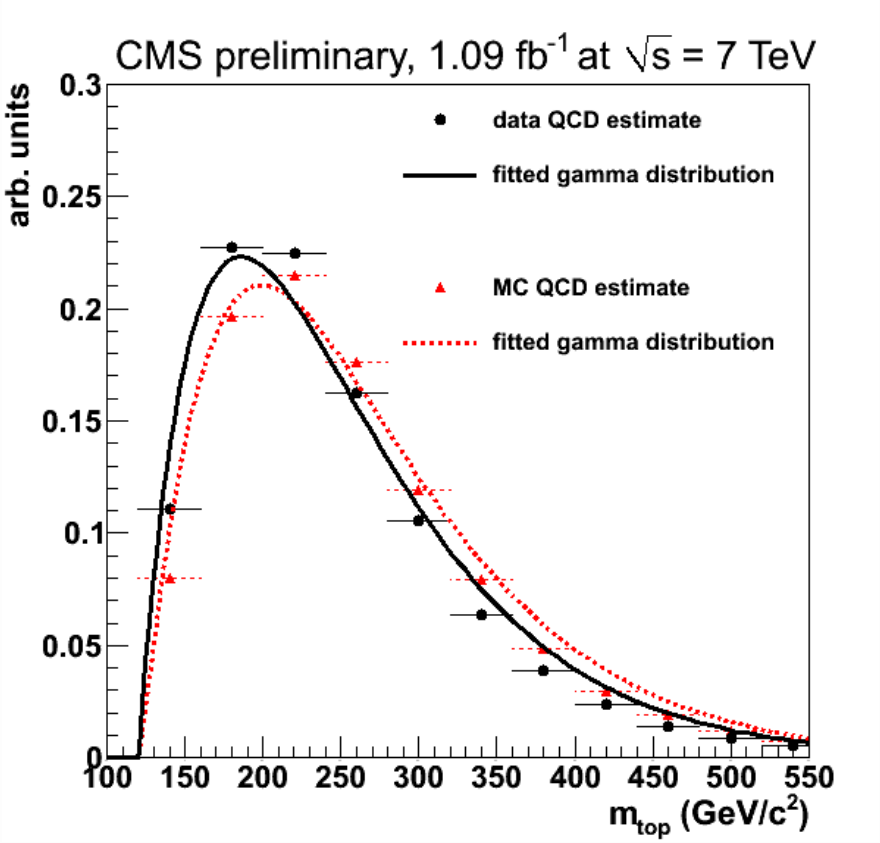
CMS-PAS-TOP-11-004

τ_{had}+jets

Relative uncertainty [%]	
Theoretical cross section	± 3
Top quark mass	±3
Q^2 scale	±2
Parton matching	±3
PDF	± 5
Tau trigger leg	± 7
Pileup	+5 -1
Tau energy correction	± 7
Tau identification	± 9
Jet energy correction	± 11
Jet energy resolution	± 2
Unclustered $E_{\mathrm{T}}^{\mathrm{miss}}$	± 7
B-tagging	± 3
Multijet b-mistagging reweighting	± 5
Systematic	± 21
Statistical from fit and MC	±8
Statistical from trigger	±1
Total statistical	± 8

Background Template Uncertainty

CMS-PAS-TOP-11-007
fully hadronic



$$f(x) = \frac{\left(\frac{x-\mu}{\beta}\right)^{\gamma-1} \exp\left(-\frac{x-\mu}{\beta}\right)}{\beta\Gamma(\gamma)}$$

$$\Gamma(a) = \int_0^\infty t^{a-1} e^{-t}\, dt$$

Systematic Uncertainties

CMS-PAS-TOP-11-007
fully hadronic

Source	Relative Uncertainty (%)
B-Tagging	15.7
Jet Energy Scale	13.5
Background	12.2
Q^2 Scale	8.7
Tune	8.1
ISR/FSR	5.6
Top Quark Mass	5.3
Parton Shower Matching	5.2
Jet Energy Resolution	4.8
Trigger	4.5
Pile-Up	0.6
Systematic	29.1
Statistical	14.3
Luminosity	6.0
Total Uncertainty	33.0

Systematic Uncertainties

ATLAS-CONF-2012-031
fully hadronic

Source of uncertainty	Contribution (%)
Jet energy scale (JES)	+20/−11
b-tagging	± 17
ISR, FSR	± 17
Parton shower and Hadronisation	± 13
Multi-jet trigger	± 10
Generator	± 7
PDF	+7/−4
Pile-up	+5/−7
Background model	± 4
Luminosity	± 4
Jet energy resolution	± 3
Jet reconstruction efficiency	< 1
Total	+36/−34