MANCHESTER 1824
The University of Manchester

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Measurements of the top quark pair production rate in pp collisions at 13 TeV with the ATLAS detector

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Introduction

Motivation

- Inclusive cross-section measurement is first physics effort of Top WG in Run II
- First glance at physics at exciting new energy frontier
- Excellent opportunity for testing:
  - new Run II analysis software framework
  - new prescriptions for systematics, objects, etc. for Run II
  - new Monte Carlo

Data Set and Analysis Information

- Analysis uses $85\,\mathrm{pb}^{-1}$ of data
  $\rightarrow$ taken during July 2015 @ 50 ns bunch spacing
- Has been presented at *Top 2015*: ATLAS-CONF-2015-049

Object Selection

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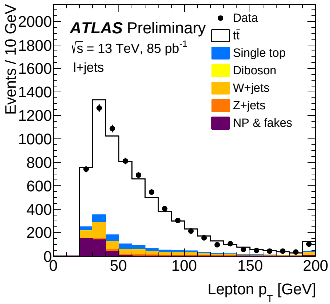
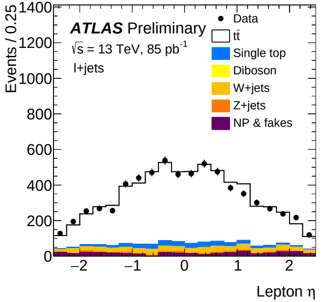
Electrons Likelihood-based identification
@ $p_T > 25$ GeV, $|\eta| < 2.47$,
exclude $1.37 < |\eta| < 1.52$

Muons Track-matching-based identification
@ $p_T > 25$ GeV, $|\eta| < 2.5$
remove μ at $\Delta R < 0.4$ w.r.t. jets





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Jets `AntiKt` $R = 0.4$ using topological calorimeter clusters
@ $p_T > 25$ GeV, $|\eta| < 2.5$
remove jets at $\Delta R < 0.2$ w.r.t. electron

b-Tag Multivariate discriminant
@ $70\,\%$ efficiency WP $\rightarrow$ purity $\approx 95\,\%$

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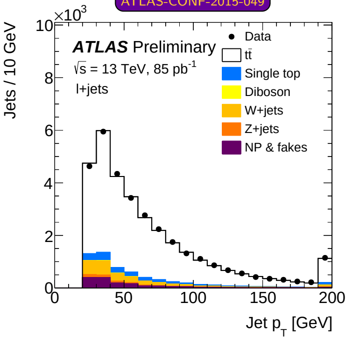

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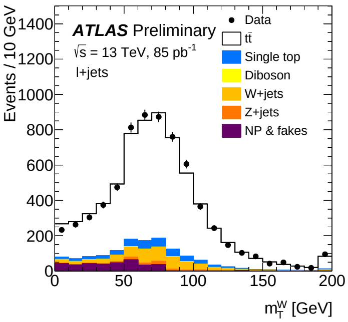

b-Tag Multivariate discriminant
@ $70\,\%$ efficiency WP → purity $\approx 95\,\%$

E_t^{Miss} negative global vector sum p_T of all selected physics objects plus *soft terms* accounting for unclassified momenta / energy

Isolation for electrons and muons
→ cut on extra calo cluster and track energy within certain ΔR

additional MC corrections such as lepton efficiencies / scale factors, etc. are applied

Event Selection

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ℓ+Jets

Require exactly one lepton: either e or μ

Require low-p_T isolated lepton trigger **OR** high-p_T lepton trigger

Require at least four jets and at least one b-tag

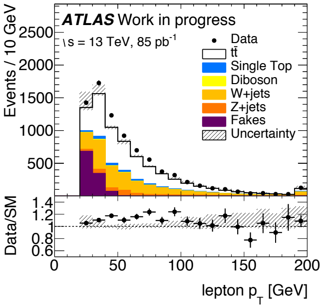
Require

e+Jets **OR** $E_T^{\text{Miss}} > 40$, $M_T^W > 50$

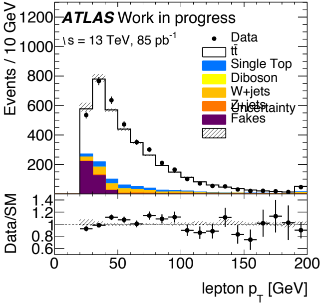
μ+Jets $E_T^{\text{Miss}} + M_T^W > 60$ GeV

$\rightarrow$ reduces fake background

Single Muon ≥ 4 Jets



Single Muon Signal Cuts



Event Selection

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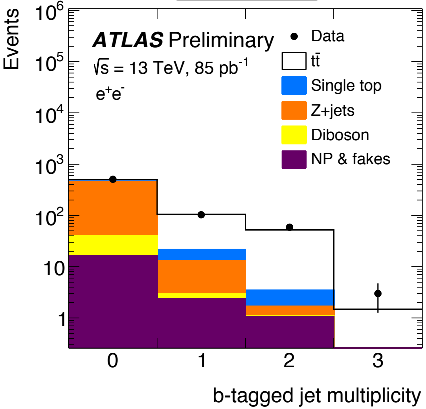

$\ell\ell$ Dilepton

Require exactly two electrons or muons of opposite charge

Require m_{ll} not in Z mass window $81 < m_{ll} < 101$ GeV

Require $E_T^{\text{Miss}} > 30$ GeV

Require $m_{ll} > 60$ GeV to reject low mass resonances

Classify based on heavy flavour tag:

- exactly one b-Tag
- exactly two b-Tags

Extraction of Cross-Section — ℓ+Jets

Single Formula

$$\sigma_{t\bar{t}}^{\ell j} := \frac{N_{\text{Obs}}^{\ell j} - N_{\text{Bgr}}^{\ell j}}{\varepsilon_{\ell j} \cdot \mathcal{L}_{\text{Int}}}$$

- $N_{\text{Obs}}^{\ell j}$ and $N_{\text{Bgr}}^{\ell j}$ are the number of observed respectively expected background events in the ℓ+Jets channel
- $\mathcal{L}_{\text{Int}}$ is the integrated luminosity
- $\varepsilon_{\ell j}$ is the (total) selection efficiency in the ℓ+Jets channel

Extraction of Cross-Section — ℓ+Jets

$$\sigma_{t\bar{t}}^{\ell j} := \frac{N_{\text{Obs}}^{\ell j} - N_{\text{Bgr}}^{\ell j}}{\varepsilon_{\ell j} \cdot \mathcal{L}_{\text{Int}}}$$

$N_{\text{Obs}}^{\ell j}$ $N_{\text{Bgr}}^{\ell j}$ $\varepsilon_{\ell j}$ $\mathcal{L}_{\text{Int}}$

- number of signal events is obtained directly from data

Extraction of Cross-Section — ℓ+Jets

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$N_{\text{Obs}}^{\ell j}$ $N_{\text{Bgr}}^{\ell j}$ $\varepsilon_{\ell j}$ $\mathcal{L}_{\text{Int}}$

- number of signal events is obtained directly from data
- number of background events is estimated using a combination of MC-based and data-driven methods

Single Top, **Diboson**, Z+**Jets**: taken directly from MC

W+**Jets**: normalisation extracted by exploiting charge asymmetry in W events; shapes of distributions taken from MC

Fakes: estimated using matrix method; real and fake efficiencies are measured using **loose** leptons in real/fake dominated control regions

Extraction of Cross-Section — ℓ+Jets

$$\sigma_{t\bar{t}}^{\ell j} := \frac{N_{\text{Obs}}^{\ell j} - N_{\text{Bgr}}^{\ell j}}{\varepsilon_{\ell j} \cdot \mathcal{L}_{\text{Int}}}$$

$N_{\text{Obs}}^{\ell j}$ $N_{\text{Bgr}}^{\ell j}$ $\varepsilon_{\ell j}$ $\mathcal{L}_{\text{Int}}$

- number of signal events is obtained directly from data
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- extracted from signal MC, various replicas for systematic variations

Extraction of Cross-Section — ℓ+Jets

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$N_{\text{Obs}}^{\ell j}$ $N_{\text{Bgr}}^{\ell j}$ $\varepsilon_{\ell j}$ $\mathcal{L}_{\text{Int}}$

- number of signal events is obtained directly from data
- number of background events is estimated using a combination of MC-based and data-driven methods
- extracted from signal MC, various replicas for systematic variations
- luminosity given by GRL as $\mathcal{L}_{\text{Int}} = 85\,\text{pb}^{-1}$
- affected by a single uncertainty
  luminosity (up/down) for $9\,\% \; (\equiv 7.65\,\text{pb}^{-1})$

Extraction of Cross-Section — ℓ+Jets

$$\sigma_{t\bar{t}}^{\ell j} := \frac{N_{\text{Obs}}^{\ell j} - N_{\text{Bgr}}^{\ell j}}{\varepsilon_{\ell j} \cdot \mathcal{L}_{\text{Int}}}$$

Event Yields

Sample	e+Jets	μ+Jets
$t\bar{t}$	2800 ± 400	2620 ± 340
W+Jets	340 ± 100	230 ± 60
Single Top	190 ± 34	180 ± 30
Z+Jets	71 ± 35	45 ± 22
Diboson	10 ± 5	10 ± 5
Fakes	200 ± 60	$140 \, ^{+60}_{-40}$
Total Expected	3600 ± 500	3220 ± 350
Observed	3439	3314

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Extraction of Cross-Section — $\ell\ell$

Coupled equations

$$\text{Exactly one } b\text{-tag:} \quad N_1^{\ell\ell} = \mathcal{L}_{\text{Int}} \sigma_{t\bar{t}}\, \epsilon_{\text{Presel}}^{\ell\ell} 2\epsilon_b^{\ell\ell} \left(1 - C_b^{\ell\ell}\epsilon_b^{\ell\ell}\right) + N_1^{\text{Bkg},\ell\ell}$$

$$\text{Exactly two } b\text{-tags:} \quad N_2^{\ell\ell} = \mathcal{L}_{\text{Int}} \sigma_{t\bar{t}}\, \epsilon_{\text{Presel}}^{\ell\ell} C_b^{\ell\ell}\epsilon_b^{\ell\ell}\epsilon_b^{\ell\ell} + N_2^{\text{Bkg},\ell\ell}$$

- evaluation is performed separately for $\ell\ell = \{ee,\, \mu\mu\}$
- $\epsilon_{\text{Presel}}^{\ell\ell}$ is the selection efficiency for the $\ell\ell$ preselection requirements
- $\epsilon_b^{\ell\ell}$ is probability of quark q from decay $t \to W^+ q$ (charge conjugates implied) to
  - fall within detector acceptance, **AND**
  - be reconstructed as jet passing object selection, **AND**
  - be tagged as b-Jet
- $C_b^{\ell\ell}$ accounts for correlations in double-b-tagging

  in practice probability of double-b-tag is not the naïve $\epsilon_b^{\ell\ell} \cdot \epsilon_b^{\ell\ell}$

  $\rightarrow$ $C_b^{\ell\ell} := \epsilon_{bb}^{\ell\ell} / \left(\epsilon_b^{\ell\ell}\right)^2$
- $N_1^{\text{Bkg},\ell\ell}$ and $N_2^{\text{Bkg},\ell\ell}$ are the background contributions

Extraction of Cross-Section — $\ell\ell$

$N_i^{\mathrm{Bkg},\ell\ell}$ $\epsilon_{\mathrm{Presel}}^{\ell\ell}$ $C_b^{\ell\ell}$

- obtained using a mixture of simulation and data-driven methods

Diboson
$Z(\to \tau\tau \to \ell\ell\nu^4)$+**Jets**
NP & Fakes
} taken directly from MC

Wt **Single Top** normalisation is taken from an approximate NNLO calculation

$Z(\to \ell\ell)$+**Jets** normalisation

- initial normalisation is NNLO prediction
- scaled using correction factor obtained from Z control region (inversion of mass window) in data
- correction is parametrised in number of b-tags

shapes of distributions taken from MC

Extraction of Cross-Section — $\ell\ell$

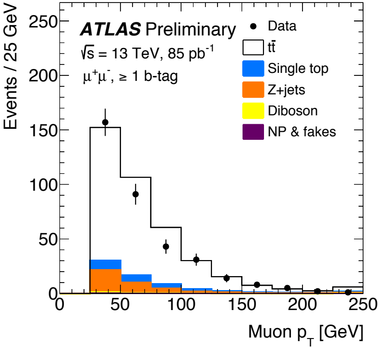
$N_i^{\mathrm{Bkg},\ell\ell}$ $\epsilon^{\ell\ell}_{\mathrm{Presel}}$ $C_b^{\ell\ell}$

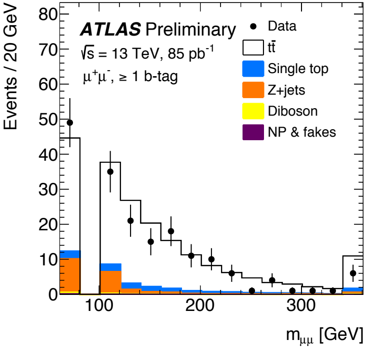
- obtained using a mixture of simulation and data-driven methods
- both are obtained from $t\bar{t}$ Monte Carlo samples
- sensitive to systematics affecting E_T^{Miss} (e.g. JES) due to event selection cuts
- uncertainties on these quantities directly translate to uncertainties on $\sigma_{t\bar{t}}$

Extraction of Cross-Section — $\ell\ell$

Target quantities

- Cross-section $\sigma_{t\bar{t}}$ is extracted by solving the coupled equations (using maximum likelihood fit)
- b-tagging efficiencies $\epsilon_b^{\ell\ell}$ for $\ell\ell = \{ee, \mu\mu\}$ are extracted alongside





$\mu\mu$-Channel — Signal Region

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Extraction of Cross-Section — $\ell\ell$

Event Yields

Sample	Electron Channel 1 Tag	Electron Channel 2 Tags	Muon Channel 1 Tag	Muon Channel 2 Tags
$t\bar{t}$	84 ± 12	49 ± 18	100 ± 13	58 ± 21
$Z(\rightarrow \ell\ell)+$ Jets	9.9 ± 2.3	0.6 ± 0.7	18 ± 6	2.5 ± 2.0
$Z(\rightarrow \tau\tau \rightarrow \ell\ell\nu^4)$+Jets	0.14 ± 0.11	< 0.01	0.11 ± 0.12	0.02 ± 0.05
Diboson	0.5 ± 0.4	0.02 ± 0.06	0.8 ± 0.6	0.07 ± 0.08
NP & Fakes	2.4 ± 0.5	1.1 ± 0.4	0.27 ± 0.23	0.08 ± 0.16
Single Top	8.7 ± 1.6	1.8 ± 0.9	10.3 ± 1.6	2.0 ± 0.9
Total Background	21.6 ± 2.8	3.4 ± 1.8	29.4 ± 3.0	4.6 ± 1.8
Total Expected	105 ± 12	52 ± 18	129 ± 14	62 ± 21
Observed	103	59	108	65

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Calculation of Systematic Uncertainties

Systematics

- systematic variations result in modified parameter values
- varied parameter extracted using
  - alternative Monte Carlo
  - systematic variation of nominal Monte Carlo
- simultaneous variation of all parameters for a given systematic ensures that systematic correlations are taken into account

Procedure

Variations of input to formula are directly propagated onto $\sigma_{t\bar{t}}$ by repeating the extraction procedure, e.g.:

$$\ell\text{+Jets};\quad \textbf{JES:}\qquad \sigma_{t\bar{t}}^{\ell j}\,(\text{JES}) = \frac{N_{\text{Obs}}^{\ell j} - N_{\text{Bgr}}^{\ell j}\,(\text{JES})}{\varepsilon_{\ell j}\,(\text{JES}) \cdot \mathcal{L}_{\text{Int}}}$$

Systematic Uncertainties — ℓ+Jets

Summary of Uncertainties

Overall uncertainty $\sim 15\,\%$

- Dominating uncertainties:
  JES and Luminosity
- Subdominant uncertainties:
  b-tagging and hadronisation

Uncertainty	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ [%]
Data statistics	± 1.5
$t\bar{t}$ NLO modelling	± 0.6
$t\bar{t}$ hadronisation	± 4.1
Initial/final state radiation	± 1.9
PDF	± 0.7
Single top cross-section	± 0.3
Diboson cross-sections	± 0.2
Z+jets cross-section	± 1.0
W+jets method stats.	± 1.7
W+jets modelling	± 0.4
Electron energy scale/resolution	± 0.1
Electron identification	± 2.1
Electron isolation	± 0.4
Electron trigger	± 2.8
Muon momentum scale/resolution	± 0.1
Muon identification	± 0.2
Muon isolation	± 0.3
Muon trigger	± 1.2
E_T^{Miss} scale/resolution	± 0.4
Jet energy scale	$^{+10.0}_{-7.6}$
Jet energy resolution	± 0.6
b-tagging	± 4.1
Misidentified leptons	$^{+1.3}_{-1.6}$
Analysis systematics	$^{+12.6}_{-10.8}$
Integrated luminosity	$^{+10.8}_{-9.0}$
Total uncertainty	$^{+16.6}_{-14.1}$

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Systematic Uncertainties — $\ell\ell$

Summary of Uncertainties

Overall uncertainty $\sim 16\,\%$

- Dominating uncertainties:
  Data stats, $t\bar{t}$ modelling, and Luminosity
- Subdominant uncertainties:
  electron ID and PDF uncertainties

Uncertainty	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ [%]
Data statistics	± 7.6
$t\bar{t}$ NLO modelling	± 2.6
$t\bar{t}$ hadronisation	± 7.9
Initial/final state radiation	± 1.5
PDF	± 3.7
Single top Wt cross-section	± 0.6
Single top interference	< 0.05
Diboson cross-sections	± 0.4
Z+Jets $\rightarrow \ell\ell$ modelling	± 1.5
Z+Jets $\rightarrow \tau\tau$ modelling	± 0.1
Electron energy scale	± 0.3
Electron energy resolution	± 0.2
Electron identification	± 3.6
Electron isolation	± 1.0
Electron trigger	± 0.2
Muon momentum scale	± 0.1
Muon momentum resolution	± 1.1
Muon identification	± 0.8
Muon isolation	± 1.0
Muon trigger	± 0.6
Jet energy scale	± 1.2
Jet energy resolution	± 0.2
b-tagging efficiency	± 0.8
Missing transverse momentum	± 0.3
NP & Fakes	± 1.5
Analysis systematics	± 11
Integrated luminosity	10
Total uncertainty	16

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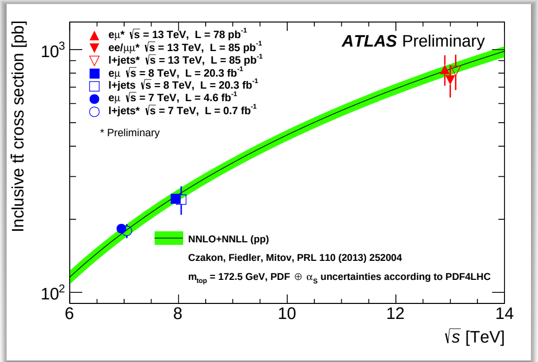
Summary

- The very first $t\bar{t}$ cross-section measurement in ℓ+Jets and same-flavour dilepton events was presented
- The extracted cross-section values are consistent with the SM prediction

$$\sigma_{t\bar{t}}^{\ell+\text{Jets}} = 817 \pm 13\,(\text{stat.}) \pm 103\,(\text{syst.}) \pm 88\,(\text{lumi.})\,\text{pb}$$
$$\sigma_{t\bar{t}}^{\ell\ell} = 749 \pm 57\,(\text{stat.}) \pm 91\,(\text{syst.}) \pm 82\,(\text{lumi.})\,\text{pb}$$

- Improvements in luminosity, modelling, and resolutions expected to provide significant increase in precision for future measurement
- Differential cross-section measurement ongoing (with Manchester contributions)



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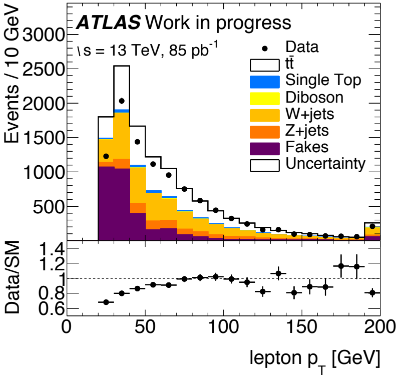
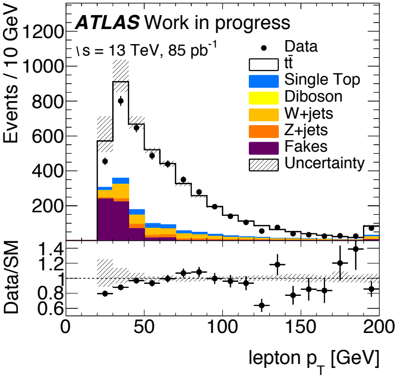
Backup

ℓ+Jets: Kinematics Plots for ee-Channel





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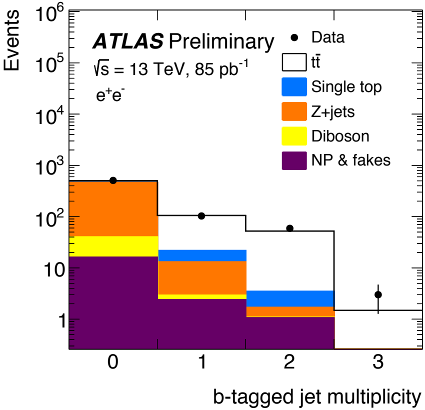
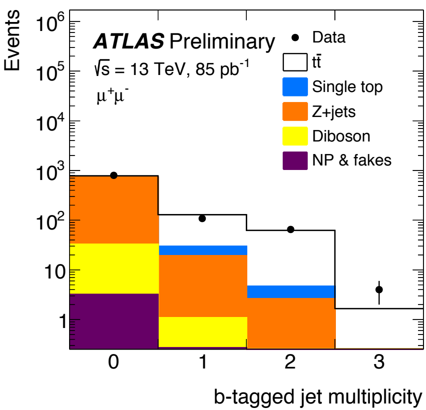
Dilepton: b-Tag Multiplicity



ee-Channel



$\mu\mu$-Channel

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Dilepton: Z+Jets Normalisation

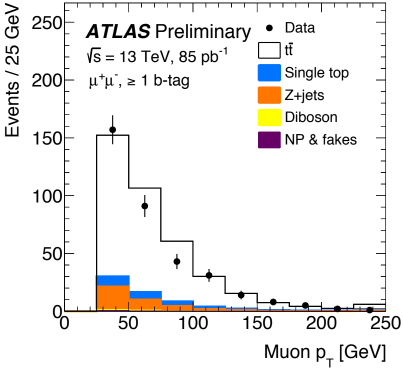
1. Initial normalisation: NNLO prediction
2. Control region: $|m_{ll} - m_Z| < 10\,\text{GeV}$
3. This yields Z+Jets estimate, which is corrected by f^i, where

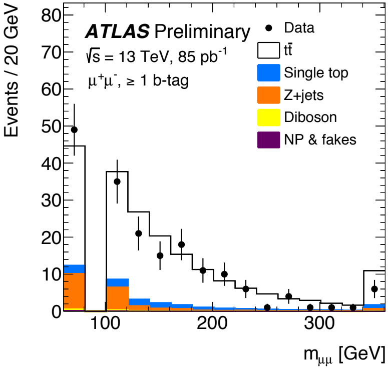
$$f^i := \frac{N^i_{\text{Data}} - N^i_{\text{Bkg}}}{N^i_{Z\,\text{MC}}},$$

where

- N^i_{Data} is the number of data events in the control region with i b-tagged jets
- N^i_{Bkg} is the number of event from other processes expected in the control region with i b-tagged jets (mainly $t\bar{t}$, Wt and diboson events), and $N^i_{Z\,\text{MC}}$ is the number of events predicted by the Z Monte Carlo sample in the control region with i b-tagged jets

Dilepton: Kinematics Plots for ee-Channel





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Calculation of Systematic Uncertainties — Details

Systematics

Systematic variations result in modified parameter values

- many are obtained using standard CP group recommendations
  e.g. leptons, jets, b-tagging, ...
- signal modelling evaluated using a suite of comparison Monte-Carlo
- PDF uncertainties evaluated using recent PDF sets
  i.e. `CT14`, `MMHT 2014`, `NNPDF 3.0`
- additional, analysis specific background uncertainties, e.g.
  - charge asymmetry modelling and
  - Z+Jets modelling
  - alternative fake/real efficiency parameterisation
- simultaneous variation of all parameters for a given systematic ensures that systematic correlations are taken into account

Procedure

Variations of input to formula are directly propagated onto $\sigma_{t\bar{t}}$ by repeating the extraction procedure, e.g.:

$$\ell\text{+Jets;} \quad \textbf{JES:} \qquad \sigma_{t\bar{t}}^{\ell j}(\text{JES}) = \frac{N_{\text{Obs}}^{\ell j} - N_{\text{Bgr}}^{\ell j}(\text{JES})}{\varepsilon_{\ell j}(\text{JES}) \cdot \mathcal{L}_{\text{Int}}}$$