Measurement of charge and CP asymmetries in b-hadron decays using top quark events collected by the ATLAS detector in pp collisions at $\sqrt{s} = 8$ TeV

Top2016

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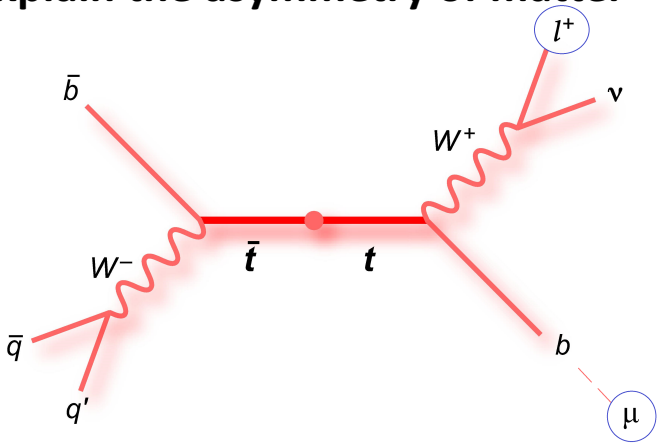
ATLAS EXPERIMENT

Motivation

At present, observed CP violation (CPV) is not sufficient to explain the asymmetry of matter-antimatter in the universe.

CPV expected in b- and c-quark decays

Top decays offer an alternate b-production to resonant $b\bar{b}$ pairs for CPV measurements.
Abundance of top quarks at LHC allows for exploitation of this technique for the first time.



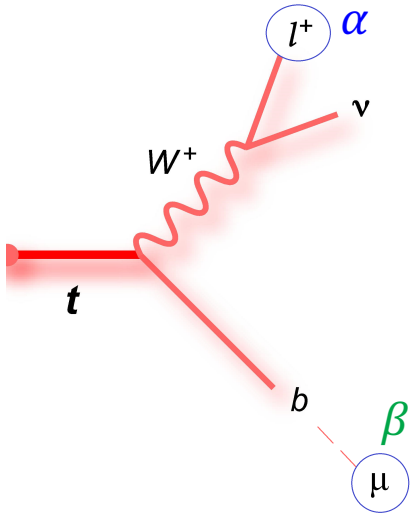
The charge of the b-quarks may be determined at both production and decay in a way unique to this analysis, using an associated W-lepton and a semi-leptonic decay to a soft muon [Phys.Rev.Lett. 110 (2013) 232002]

- In addition, a sizeable inclusive like-sign dimuon charge asymmetry has been reported by the $D0$ experiment:
  - Tension with the SM ($\sim 3\sigma$).
  - Tension with (but not excluded by) LHCb and BaBar.

[PRD **89**, (2014) 012002]
[PRL **114** (2015) 041601]
[PRL **117** (2016) 061803]
[PRL **114** (2015) 081801]

Analysis technique

- Use inclusive l+jets $t\bar{t}$ events in which a b-hadron decays to a muon
- Consider number of SMT muons, $N^{\alpha\beta}$, where:
  - α = charge of W-lepton (tags b-quark charge at production)
  - β = charge of SMT Muon (tags b-quark charge at decay)



- Same Sign (SS)
- $t \to l^+\nu\left(b \to \bar{b}\right) \to l^+l^+X$
- $t \to l^+\nu\,(b \to c) \to l^+l^+X$
- $t \to l^+\nu\left(b \to \bar{b} \to c\bar{c}\right) \to l^+l^+X$

- Opposite Sign (OS)
- $t \to l^+\nu\, b \to l^+l^-X$
- $t \to l^+\nu\,(b \to \bar{b} \to \bar{c}) \to l^+l^-X$
- $t \to l^+\nu\,(b \to c\bar{c}) \to l^+l^-X$

CPV Direct:: $P(b \to l^+X) \neq P(\bar{b} \to l^-X)$ Mixing:: $P\left(b \to \bar{b} \to l^+X\right) \neq P\left(\bar{b} \to b \to l^-X\right)$

$$A^{ss} = \frac{P(b \to l^+) - P\left(\bar{b} \to l^-\right)}{P(b \to l^+) + P\left(\bar{b} \to l^-\right)} = \frac{\left(\frac{N^{++}}{N^+}\right) - \left(\frac{N^{--}}{N^-}\right)}{\left(\frac{N^{++}}{N^+}\right) + \left(\frac{N^{--}}{N^-}\right)}$$

$$A^{os} = \frac{P(b \to l^-) - P\left(\bar{b} \to l^+\right)}{P(b \to l^-) + P\left(\bar{b} \to l^+\right)} = \frac{\left(\frac{N^{+-}}{N^+}\right) - \left(\frac{N^{-+}}{N^-}\right)}{\left(\frac{N^{+-}}{N^+}\right) + \left(\frac{N^{-+}}{N^-}\right)}$$

Probability formulation: Insensitive to charge asymmetric effects from reconstruction of W-boson leptons and $t\bar{t}$ charge asymmetry

Analysis outline

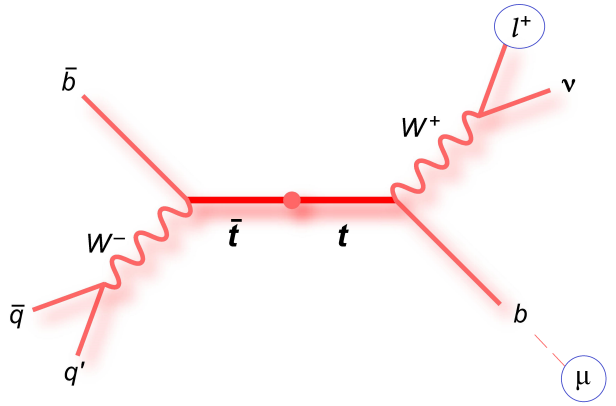
1. Perform a ‘standard’ $t\bar{t}$ l+jets event selection
2. Double tag jets with MV1@85% and SMT algorithm
3. Fully reconstruct $t\bar{t}$ events with KLFitter
   - Tells us if an SMT muon is same- or different-top (next slide)
4. Unfold data to a fiducial volume
5. Measure Charge asymmetries
6. Extract CP asymmetries

Kinematic Likelihood Fitter

- KLFitter is designed to provide **kinematic fitting using a likelihood approach** (arXiv:1312.5595)
- Used to fully reconstruct the $t\bar{t}$ event topology

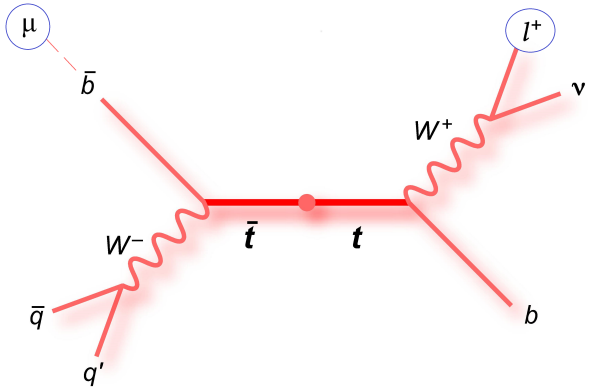
- Allows for determination of the initial charge of the b
  - For same-top SMT muons : $W^{\pm} \Rightarrow b^{\mp}$
  - For different-top SMT muons : $W^{\pm} \Rightarrow b^{\pm}$

Same Top Events



- Calculates a likelihood (event probability,) for the four reconstructed jets to produce each possible permutation – maximum likelihood permutation is taken as correct jet topology
- **KLFitter performs with around 80% purity after extensive optimisation**

Different Top Events



Lepton charge pairs

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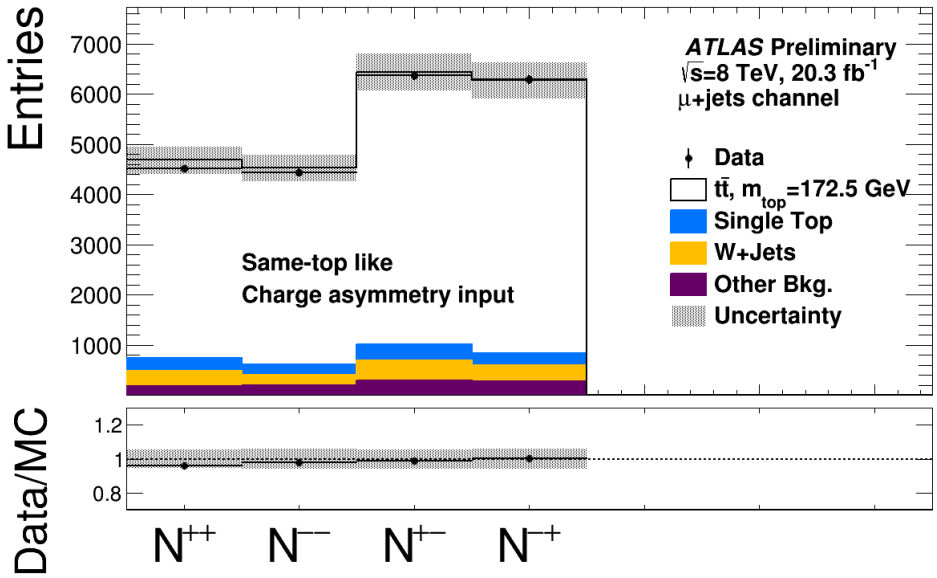
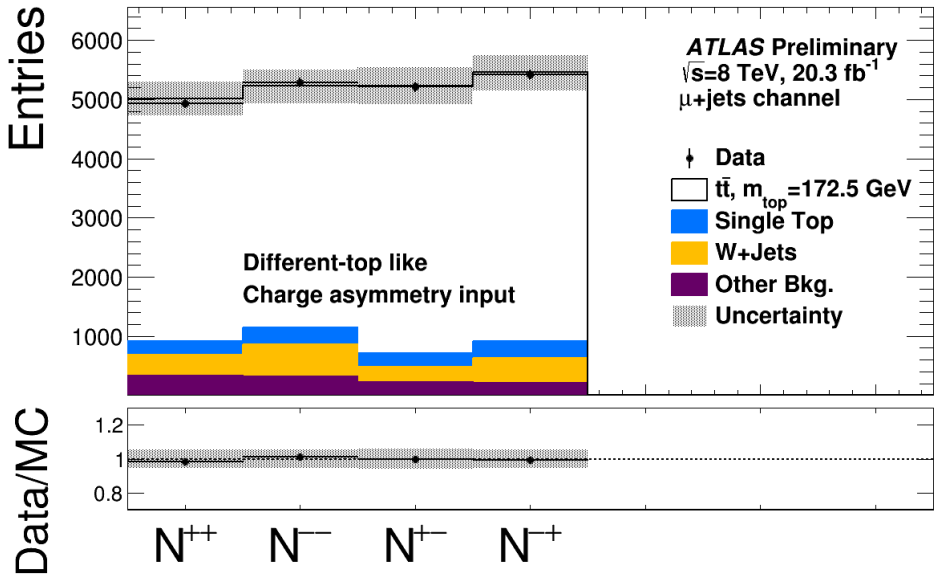


Same-Top KLFitter Decision



Different-Top KLFitter Decision

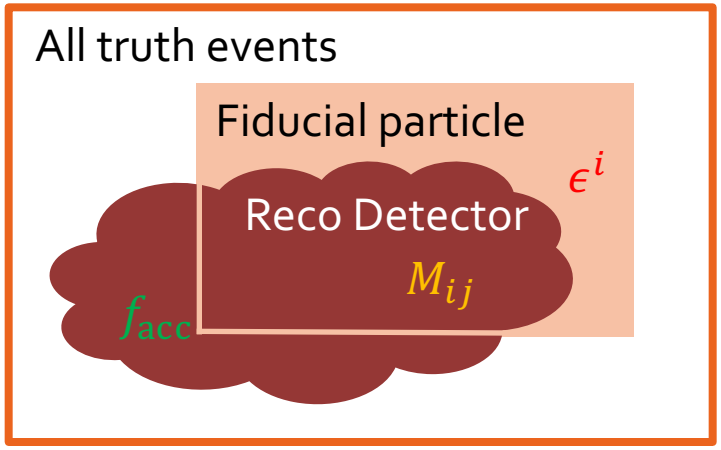
Lepton charge pairing distributions showing the data in solid circles, the $t\bar{t}$ simulation in white, the single-top in blue, the W+jets in yellow and all other backgrounds in purple. The hashed area represents all experimental systematic uncertainties as well as the b-hadron production and hadron-to-muon branching ratio uncertainties.

Unfolding

$$N^i_{\text{fid}} = \frac{1}{\epsilon^i} \cdot \sum_j M^{-1}_{ij} \cdot f^j_{\text{acc}} \left(N^j_{\text{data}} - N^j_{\text{bkg}} \right)$$

$$f^j_{\text{acc}} \equiv \left(\frac{N_{\text{reco}\wedge\text{part}}}{N_{\text{reco}}} \right)^j \qquad \epsilon^i \equiv \left(\frac{N_{\text{reco}\wedge\text{part}}}{N_{\text{part}}} \right)^j$$

- f^i_{acc}= Applied bin-by-bin to correct for SMT muons that are present at the reconstruction level, but not at the fiducial level.
- M_{ij}= Discrete 4x4 Response Matrix. Corrects for migrations between 4 CA bins, these are caused by mistakes in ST/DT identification due to KLF performance or due to charge mis-ID on the triggered leptons (extremely small effect)
- $\frac{1}{\epsilon^i}$ = Applied bin-by-bin to the unfolded data to correct for SMT muons that are present at the particle-level, but not at the reconstruction level.



	$N^{++}{}_j$	$N^{--}{}_j$	$N^{+-}{}_j$	$N^{-+}{}_j$
$N^{++}{}_i$	0.79	0.00	0.00	0.21
$N^{--}{}_i$	0.00	0.79	0.21	0.00
$N^{+-}{}_i$	0.00	0.21	0.79	0.00
$N^{-+}{}_i$	0.21	0.00	0.00	0.79

Charge asymmetry results

$$A^{ss} = -0.007 \pm 0.006\ (\text{stat.})\ ^{+0.002}_{-0.002}\ (\text{expt.}) \pm 0.005\ (\text{model})$$

$$A^{os} = 0.0041 \pm 0.0035\ (\text{stat.})\ ^{+0.0013}_{-0.0011}\ (\text{expt.}) \pm 0.0027\ (\text{model})$$

SM Expectations
[PRL **110**, 232002]

$$A^{ss} < 10^{-4}$$

$$A^{os} < 10^{-4}$$

Charge asymmetries are consistent with SM

Systematics:

- Most should be negligible – those which scale all entries up or down uniformly will not affect asymmetries.
- Systematics which are charge dependent are largely cancelled by the ratio formulation of the asymmetries
- Additionally, IFSR has a non-negligible effect on KLFitter performance, leading to largest modelling systematic.

CP asymmetry extraction

- CP asymmetries can be extracted from A^{ss}, A^{os}

$$A^{ss} = r_b A^{bl}_{\text{mix}} + r_{c\bar{c}} A^{bc}_{\text{mix}} + r_c A^{bc}_{\text{dir}} - (r_c + r_{c\bar{c}}) A^{cl}_{\text{dir}}$$

$$A^{os} = \tilde{r}_c A^{bc}_{\text{mix}} + \tilde{r}_b A^{bl}_{\text{dir}} + (\tilde{r}_c + \tilde{r}_{c\bar{c}}) A^{cl}_{\text{dir}}$$

$$A^{bl}_{\text{mix}} = \frac{\Gamma(b\to\bar{b}\to l^+X) - \Gamma(\bar{b}\to b\to l^-X)}{\Gamma(b\to\bar{b}\to l^+X) + \Gamma(\bar{b}\to\bar{b}\to l^-X)}$$

$$A^{bc}_{\text{mix}} = \frac{\Gamma(b\to\bar{b}\to\bar{c}X) - \Gamma(\bar{b}\to b\to cX)}{\Gamma(b\to\bar{b}\to cX) + \Gamma(\bar{b}\to\bar{b}\to cX)}$$

$$A^{bl}_{\text{dir}} = \frac{\Gamma(b\to l^-X) - \Gamma(\bar{b}\to l^+X)}{\Gamma(b\to l^-X) + \Gamma(\bar{b}\to l^+X)}$$

$$A^{cl}_{\text{dir}} = \frac{\Gamma(\bar{c}\to l^-X_L) - \Gamma(c\to l^+X_L)}{\Gamma(\bar{c}\to l^-X_L) + \Gamma(c\to l^+X_L)}$$

$$A^{bc}_{\text{dir}} = \frac{\Gamma(b\to cX_L) - \Gamma(\bar{b}\to\bar{c}X_L)}{\Gamma(b\to cX_L) + \Gamma(\bar{b}\to\bar{c}X_L)}$$

Decay chain fractions, r_i, represent proportional contributions from each decay

CP asymmetry results

$$A^{b}_{\mathrm{mix}} = \frac{A^{\mathrm{SS}}}{r_b + r_{c\bar{c}}} = -0.025 \pm 0.021\,(\mathrm{stat.}) \pm 0.008\,(\mathrm{expt.}) \pm 0.017\,(\mathrm{model})$$

$$A^{b\ell}_{\mathrm{dir}} = \frac{A^{\mathrm{OS}}}{\widetilde{r}_b} = 0.005 \pm 0.004\,(\mathrm{stat.}) \pm 0.001\,(\mathrm{expt.}) \pm 0.003\,(\mathrm{model})$$

$$A^{c\ell}_{\mathrm{dir}} = \frac{-A^{\mathrm{SS}}}{r_c + r_{c\bar{c}}} = 0.009 \pm 0.007\,(\mathrm{stat.}) \pm 0.003\,(\mathrm{expt.}) \pm 0.006\,(\mathrm{model})$$

$$A^{bc}_{\mathrm{dir}} = \frac{A^{\mathrm{SS}}}{r_c} = -0.010 \pm 0.008\,(\mathrm{stat.}) \pm 0.003\,(\mathrm{expt.}) \pm 0.007\,(\mathrm{model})$$

SM Expectations

$A^{b}_{\mathrm{mix}} < 10^{-5}$ [arXiv: 1511.09466v1, arXiv: 1412.7515v1 (HFAG)]

$A^{bl}_{\mathrm{dir}} < 10^{-7}$ [PRL **110**, 232002]

$A^{cl}_{\mathrm{dir}} < 10^{-11}$

$A^{bc}_{\mathrm{dir}} < 10^{-9}$ [PLB **694** (2011)]

CP asymmetries are consistent with SM

CP asymmetries

- **Current limits** are extrapolated from exclusive measurements and branching ratios, which at 2σ are: (No limits set on A_{dir}^{bc})
  - $\boldsymbol{A_{dir}^{bl}(\mathrm{extrap.}) \leq 0.012}$
  - $\boldsymbol{A_{dir}^{cl}(\mathrm{extrap.}) \leq 0.060}$

  [PRD **87**, 074036]

At 2σ the constraints made by this paper are stronger than the existing limit on A_{dir}^{cl} This the first direct experimental constraint on A_{dir}^{bc}.

- The anomalous $D0$ like-sign dimuon asymmetry may be interpreted in terms of both mixing and direct CP asymmetry separately, both of which would be at odds with the SM.
- In the direct case, to satisfy the $D0$ result it is required that either:
  - $A_{\mathrm{dir}}^{bl} \approx (0.003 \pm 0.001)$
  - $A_{\mathrm{dir}}^{cl} \approx (0.009 \pm 0.003)$

  [PRD **87**, 074036]
- **The results of this paper are consistent with both SM and the $D0$ results within 1σ.**

Conclusion

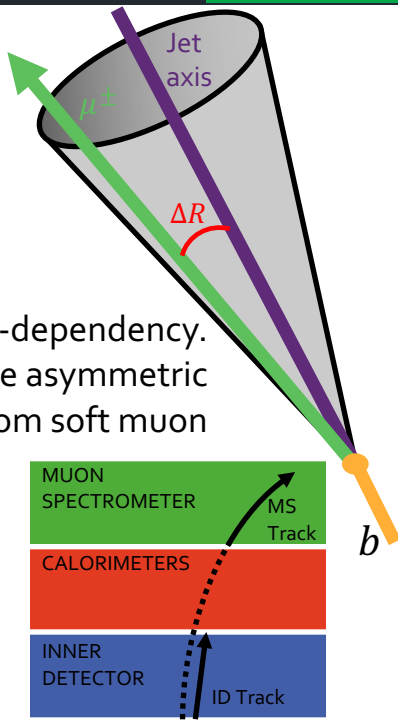
- The **first analysis to use this technique** to measure CPV in b- and c-quark decays
- The charge asymmetries and CP asymmetries presented are **consistent with the Standard Model** expectations.
- Results provide the first experimental constraint of A_{dir}^{bc}, strengthen the existing 2σ constraint on A_{dir}^{cl} and provides an equivalent constraint on A_{dir}^{bl}
- The largest uncertainty on all asymmetry measurements reported is statistical.

BACKUP

Soft Muon Tagger (MI)

- SMT Muon is STACO
- SMT Muon Requirements:
  - Standard MCP cuts (Pixel hits, holes….)
  - ΔR (jet, μ) < 0.5
  - $|d_0|$ < 3 mm
  - p_T > 4 GeV, $|z_0 \sin\theta|$ < 3 mm, $|\eta|$ < 2.5
  - Is Combined
  - N(tracks in tagged jet) > 3 OR Jet EM Frac < 0.8
- Momentum Imbalance $MI = \frac{p^{ID} - p^{ME}}{p^{ID}} < 0.1$
  - Significance of difference between track momentum measurements, from the ID and extrapolated Muon Spectrometer (ME).
- μ+jets channel only, veto on invariant mass of W-boson μ and SMT μ
  - $8 < M_{\mu\mu} < 11$ GeV : Veto $\Upsilon \rightarrow \mu\mu$
  - $80 < M_{\mu\mu} < 100$ GeV : Veto Z $\rightarrow \mu\mu$

Calibrated with charge-dependency. Accounts for charge asymmetric effects from soft muon



Probability formulations

$$\mathrm{P}\left(\bar{b} \to l^{-}\right) = \frac{N\left(\bar{b} \to l^{-}\right)}{N\left(\bar{b} \to l^{-}\right) + N\left(\bar{b} \to l^{+}\right)} = \frac{N^{--}}{N^{--} + N^{-+}} = \frac{N^{--}}{N^{-}}$$

$$\mathrm{P}(b \to l^{+}) = \frac{N(b \to l^{+})}{N(b \to l^{-}) + N(b \to l^{+})} = \frac{N^{++}}{N^{+-} + N^{++}} = \frac{N^{++}}{N^{+}}$$

$$\mathrm{P}(b \to l^{-}) = \frac{N(b \to l^{-})}{N(b \to l^{-}) + N(b \to l^{+})} = \frac{N^{+-}}{N^{+-} + N^{++}} = \frac{N^{+-}}{N^{+}}$$

$$\mathrm{P}\left(\bar{b} \to l^{+}\right) = \frac{N\left(\bar{b} \to l^{+}\right)}{N\left(\bar{b} \to l^{-}\right) + N\left(\bar{b} \to l^{+}\right)} = \frac{N^{-+}}{N^{--} + N^{-+}} = \frac{N^{-+}}{N^{-}}$$

Decay chain fractions

- The decay chain fractions are determined in the fiducial volume
- If N_i are the number of weighted MC events in the categories:

$$
\begin{aligned}
N_{r_b} &= N\left[t \to \ell^+\nu\left(b \to \overline{b}\right) \to \ell^+\ell^+X\right], \\
N_{r_c} &= N\left[t \to \ell^+\nu\left(b \to c\right) \to \ell^+\ell^+X\right], \\
N_{r_{c\overline{c}}} &= N\left[t \to \ell^+\nu\left(b \to \overline{b} \to c\overline{c}\right) \to \ell^+\ell^+X\right],
\end{aligned}
$$

$$
\begin{aligned}
r_b &= \frac{N_{r_b}}{N_{r_b} + N_{r_c} + N_{r_{c\overline{c}}}}, \\
r_c &= \frac{N_{r_c}}{N_{r_b} + N_{r_c} + N_{r_{c\overline{c}}}}, \\
r_{c\overline{c}} &= \frac{N_{r_{c\overline{c}}}}{N_{r_b} + N_{r_c} + N_{r_{c\overline{c}}}},
\end{aligned}
$$

$$
\begin{aligned}
N_{\widetilde{r}_b} &= N\left[t \to \ell^+\nu b \to \ell^+\ell^-X\right], \\
N_{\widetilde{r}_c} &= N\left[t \to \ell^+\nu\left(b \to \overline{b} \to \overline{c}\right) \to \ell^+\ell^-X\right], \\
N_{\widetilde{r}_{c\overline{c}}} &= N\left[t \to \ell^+\nu\left(b \to c\overline{c}\right) \to \ell^+\ell^-X\right].
\end{aligned}
$$

$$
\begin{aligned}
\widetilde{r}_b &= \frac{\widetilde{N}_{r_b}}{\widetilde{N}_{r_b} + \widetilde{N}_{r_c} + \widetilde{N}_{r_{c\overline{c}}}}, \\
\widetilde{r}_c &= \frac{\widetilde{N}_{r_c}}{\widetilde{N}_{r_b} + \widetilde{N}_{r_c} + \widetilde{N}_{r_{c\overline{c}}}}, \\
\widetilde{r}_{c\overline{c}} &= \frac{\widetilde{N}_{r_{c\overline{c}}}}{\widetilde{N}_{r_b} + \widetilde{N}_{r_c} + \widetilde{N}_{r_{c\overline{c}}}}.
\end{aligned}
$$

Cross-section measurement

- Good agreement with theory and other measurements
  - Only published papers are listed in the comparison table

$$\boldsymbol{\sigma_{t\bar{t}} = 250 \pm 1(\text{Stat.})^{+24}_{-23}(\text{Syst.}) \pm 5(\text{Lumi.}) \pm 4(\text{Beam})\ \text{pb}}$$

Theory prediction	$\sigma_{t\bar{t}} = 252.0 \pm 11.7^{+6.4}_{-8.6}$ pb	[PRL 110 (2013) 252004]
ATLAS $e\mu$	$\sigma_{t\bar{t}} = 242.4 \pm 1.7(\text{Stat.}) \pm 5.5(\text{Syst.}) \pm 7.5(\text{Lumi.}) \pm 4.2(\text{Beam})$ pb	[EPJC 74 (2014) 3109]
ATLAS l + jets	$\sigma_{t\bar{t}} = 260 \pm 1(\text{Stat.})^{+22}_{-23}(\text{Syst.}) \pm 8(\text{Lumi.}) \pm 4(\text{Beam})$ pb	[PRD 91 (2015), 112013]
CMS $ee, \mu\mu, e\mu$	$\sigma_{t\bar{t}} = 244.9 \pm 1.4(\text{Stat.})^{+6.3}_{-5.5}(\text{Syst.}) \pm 6.4(\text{Lumi.})$ pb	[JHEP 08 (2016) 029]
CMS $e\tau, \mu\tau$	$\sigma_{t\bar{t}} = 257 \pm 3(\text{Stat.}) \pm 24(\text{Syst.}) \pm 7(\text{Lumi.})$ pb	[PLB 739 (2014) 23]
CMS all hadronic	$\sigma_{t\bar{t}} = 275.6 \pm 6.1(\text{Stat.}) \pm 37.8(\text{Syst.}) \pm 7.2(\text{Lumi.})$ pb	[EPJC 76 (2016) 128]

Systematics

- Many systematics affect the scale of events uniformly and therefore largely cancel when measuring ratios for the charge asymmetries.
- Larger systematics tend to come from the effect on the KLFitter performance

- A selection of uncertainties in order of magnitude are:
  - Statistical
  - IFSR (Modelling)
  - PDF (Modelling)
  - JES (Experimental)
  - Jet Vertex Fraction (Experimental)

b-tagged jet multiplicity

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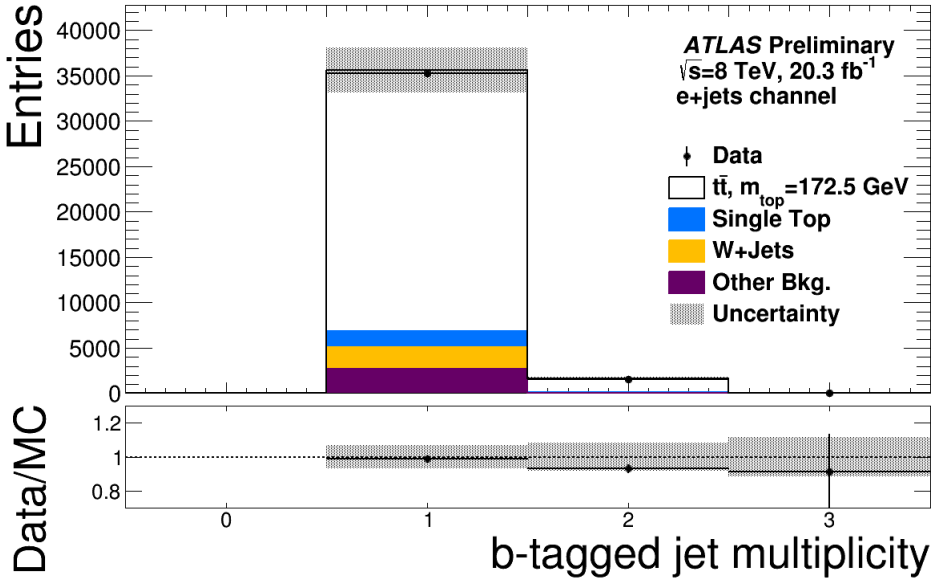
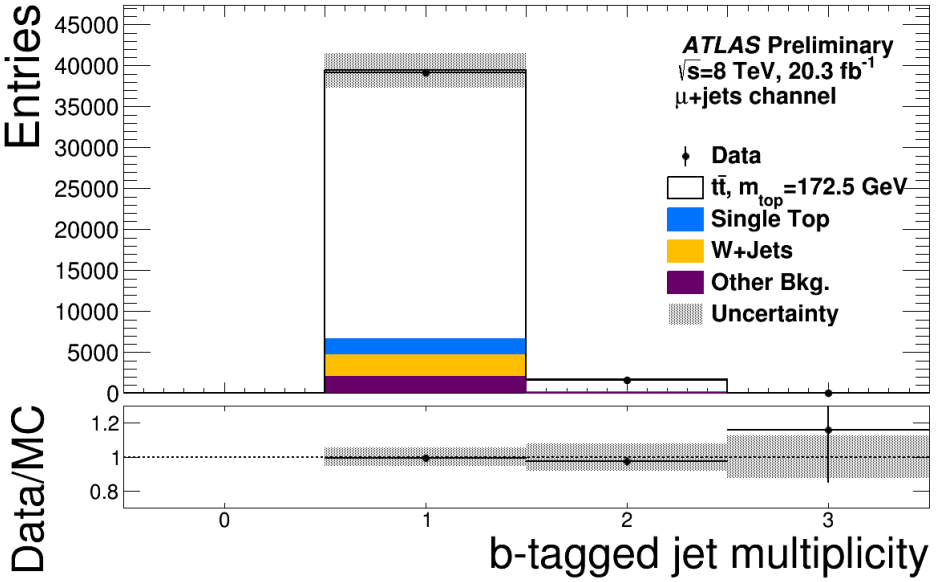


(a)



(b)

Distributions showing the data in solid circles, the $t\bar{t}$ simulation in white, the single-top in blue, the W+jets in yellow and all other backgrounds in purple. The hashed area represents all experimental systematic uncertainties as well as the b-hadron production and hadron-to-muon branching ratio uncertainties. The distributions on the left hand side show the e+jets channel while the distributions on the right hand side show the μ+jets channel. (a) and (b) show the b-tagged jet multiplicity.

b-tagged jet p_T

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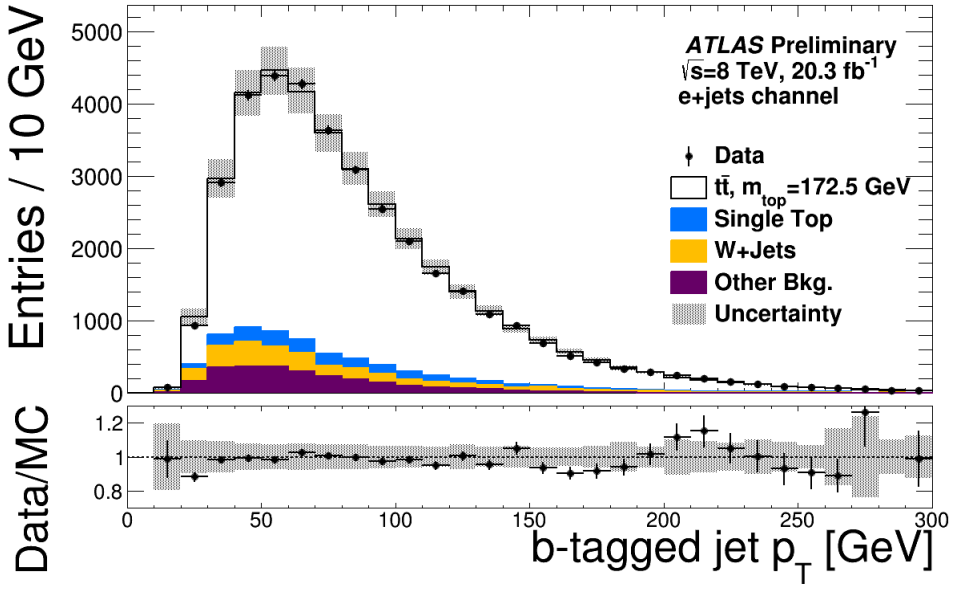
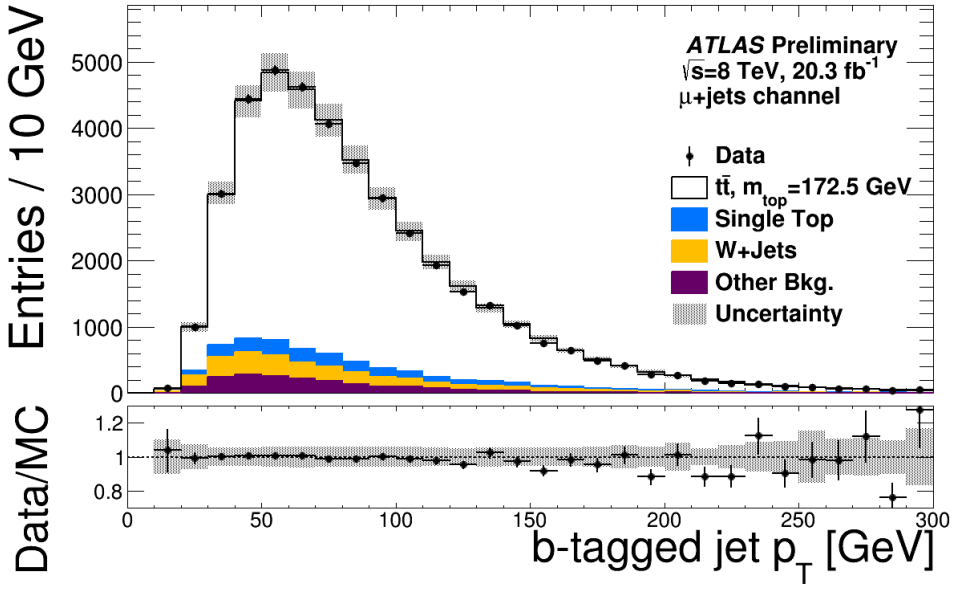


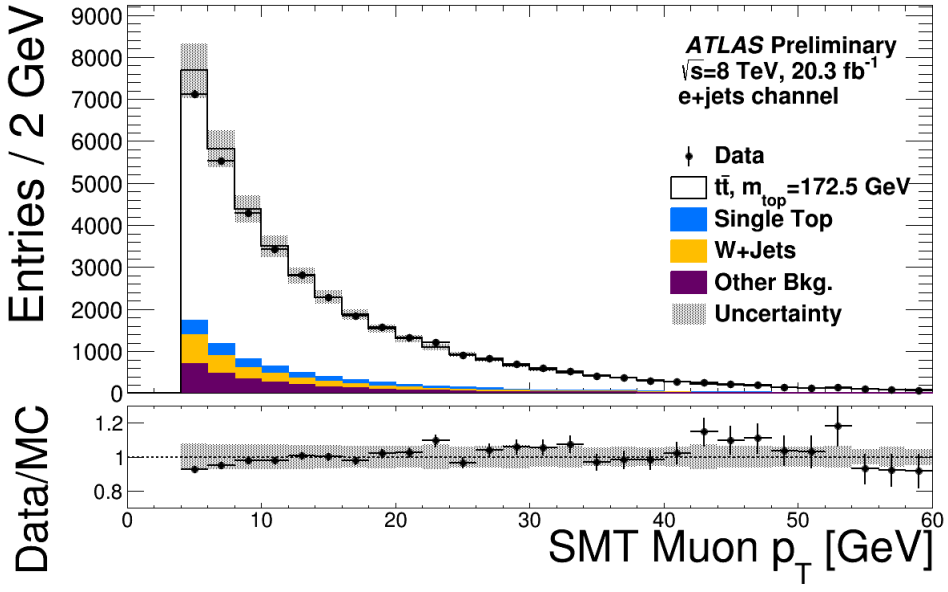
(c)



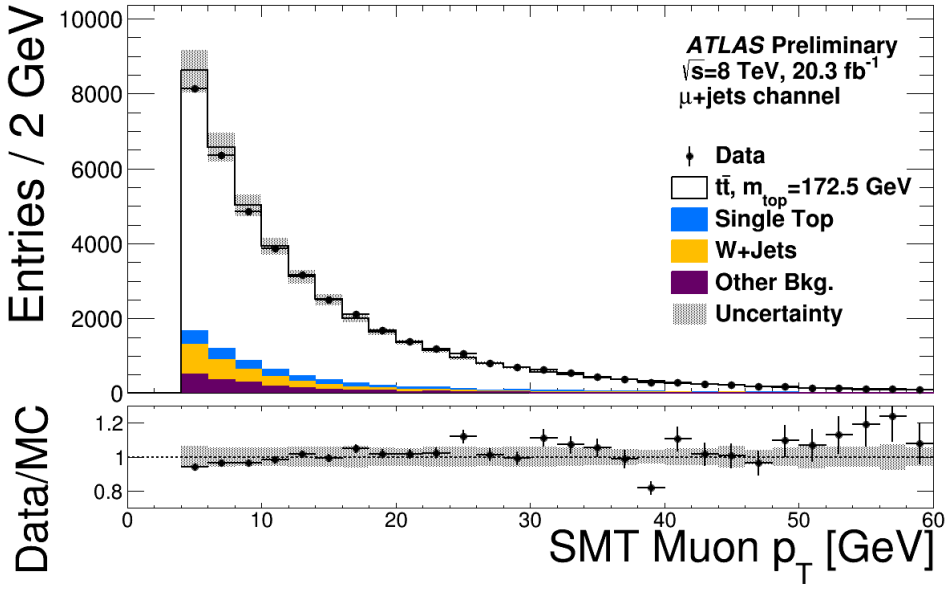
(d)

Distributions showing the data in solid circles, the $t\bar{t}$ simulation in white, the single-top in blue, the W+jets in yellow and all other backgrounds in purple. The hashed area represents all experimental systematic uncertainties as well as the b-hadron production and hadron-to-muon branching ratio uncertainties. The distributions on the left hand side show the e+jets channel while the distributions on the right hand side show the μ+jets channel. (c) and (d) show the b-tagged jet p_T.

SMT μ p_T



(e)



(f)

Distributions showing the data in solid circles, the $t\bar{t}$ simulation in white, the single-top in blue, the W+jets in yellow and all other backgrounds in purple. The hashed area represents all experimental systematic uncertainties as well as the b-hadron production and hadron-to-muon branching ratio uncertainties. The distributions on the left hand side show the e+jets channel while the distributions on the right hand side show the μ+jets channel. (e) and (f) show the SMT muon μ.

Same Top-like lepton charge pairs

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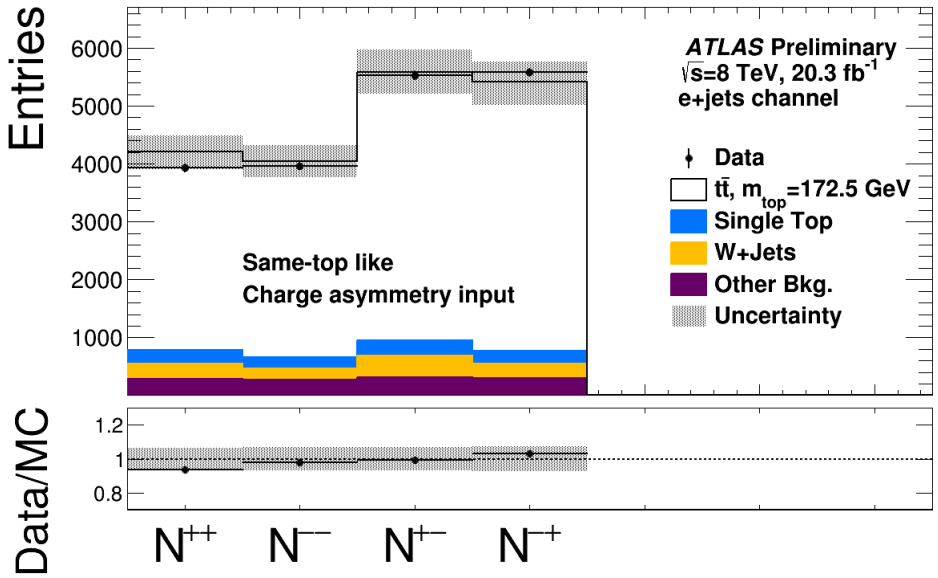
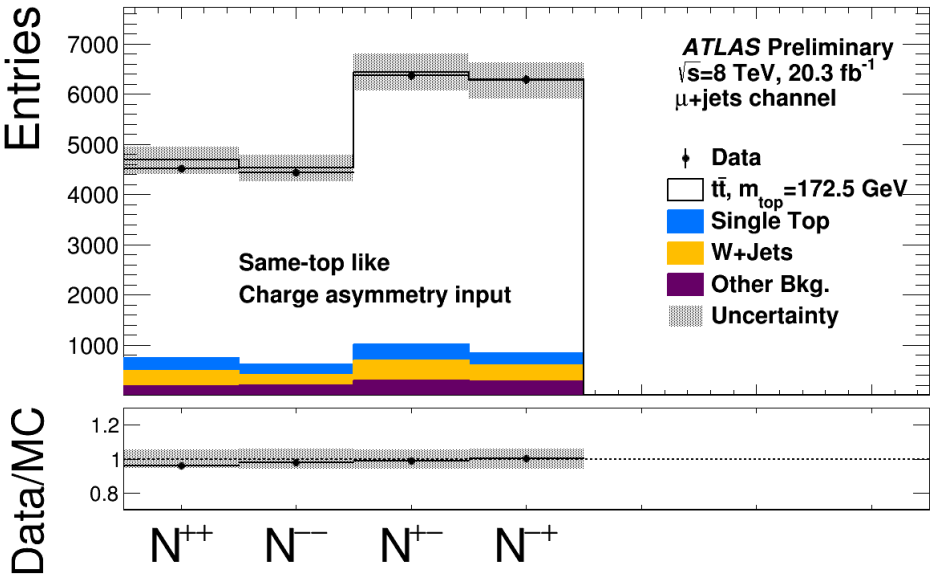


(a)

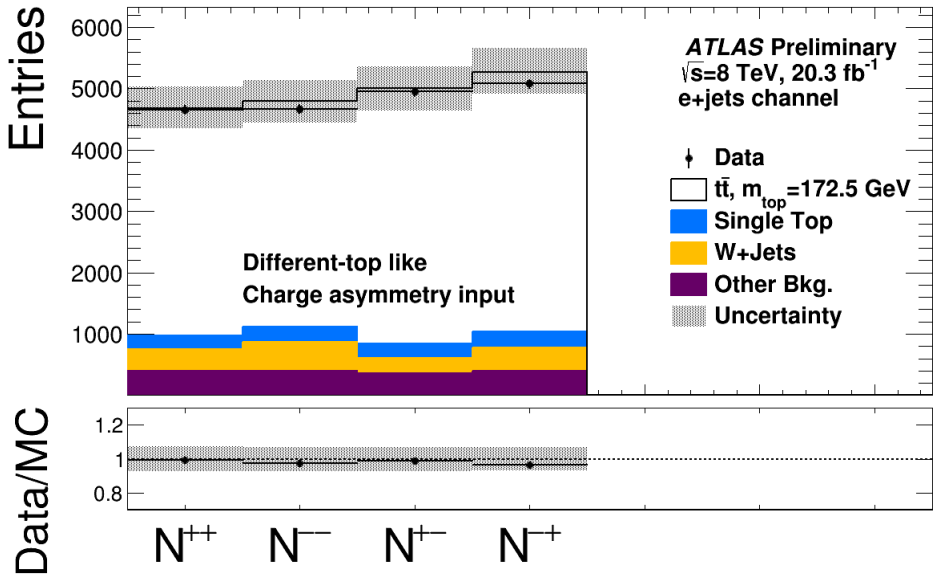


(b)

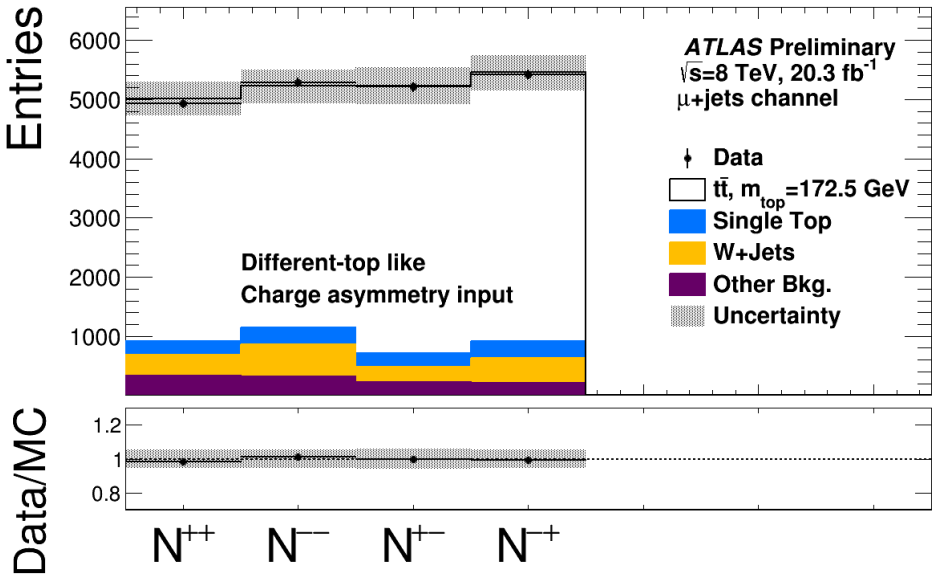
Same-top like charge pairings distributions showing the data in solid circles, the $t\bar{t}$ simulation in white, the single-top in blue, the W+jets in yellow and all other backgrounds in purple. The hashed area represents all experimental systematic uncertainties as well as the b-hadron production and hadron-to-muon branching ratio uncertainties. (a) shows the e+jets channel while (b) shows the μ+jets channel.

Different Top-like lepton charge pairs

Physics Department



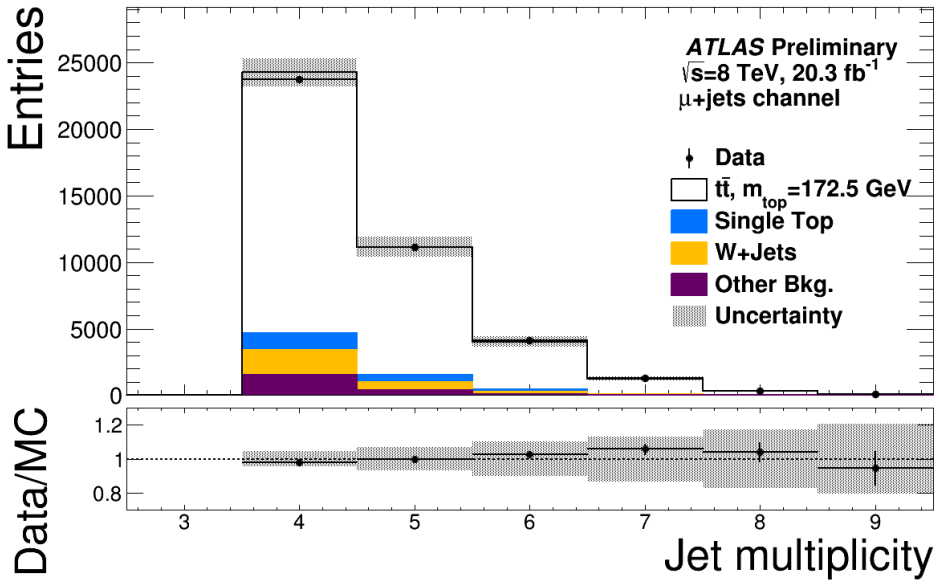
(a)



(b)

Different-top like charge pairings distributions showing the data in solid circles, the $t\bar{t}$ simulation in white, the single-top in blue, the W+jets in yellow and all other backgrounds in purple. The hashed area represents all experimental systematic uncertainties as well as the b-hadron production and hadron-to-muon branching ratio uncertainties. (a) shows the e+jets channel while (b) shows the μ+jets channel.

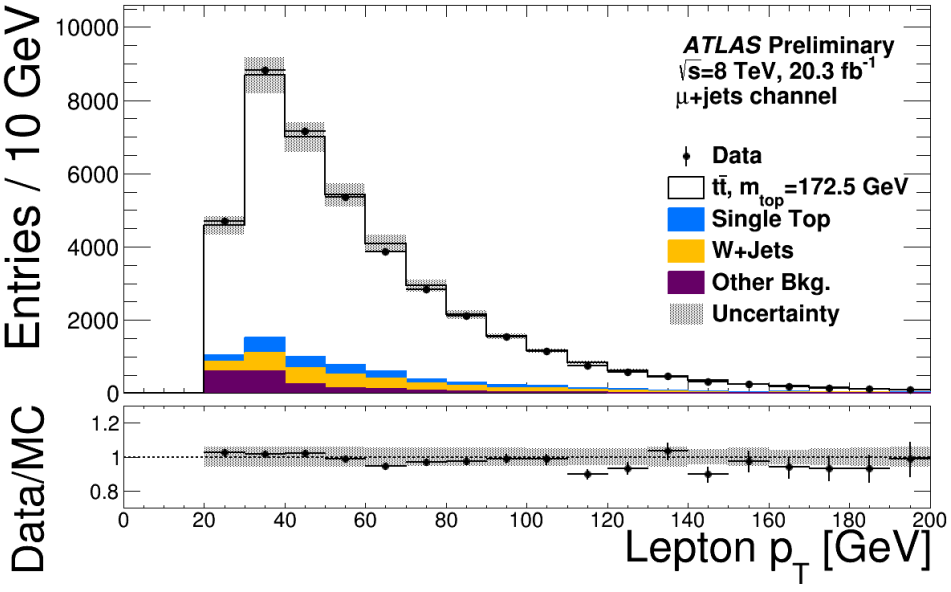
Jet multiplicity



(b)

Jet multiplicity distributions showing the data in solid circles, the $t\bar{t}$ simulation in white, the single-top in blue, the W+jets in yellow and all other backgrounds in purple. The hashed area represents all experimental systematic uncertainties as well as the b-hadron production and hadron-to-muon branching ratio uncertainties. (b) shows the μ+ jets channel.

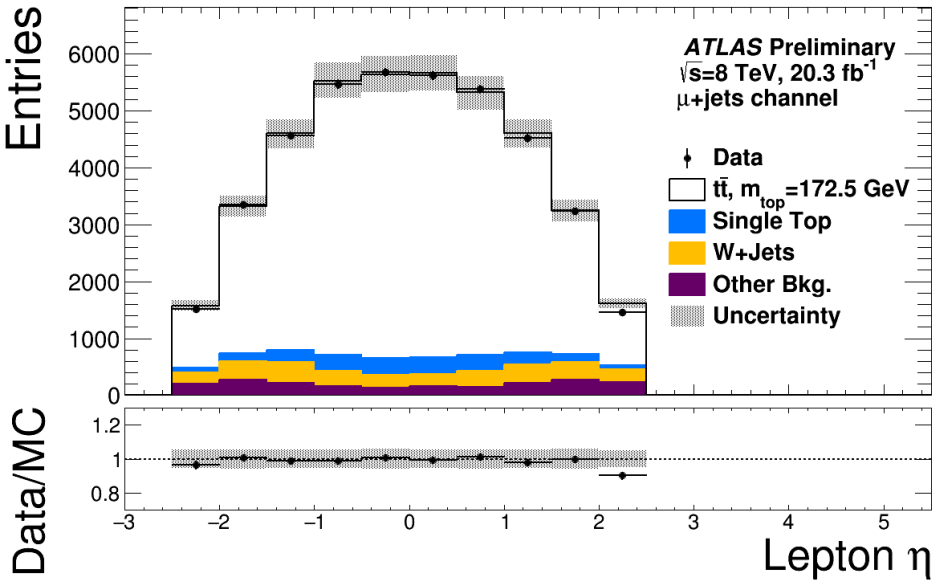
Lepton p_T



(b)

Lepton p_T distributions showing the data in solid circles, the $t\bar{t}$ simulation in white, the single-top in blue, the W+jets in yellow and all other backgrounds in purple. The hashed area represents all experimental systematic uncertainties as well as the b-hadron production and hadron-to-muon branching ratio uncertainties. (b) shows the μ+ jets channel.

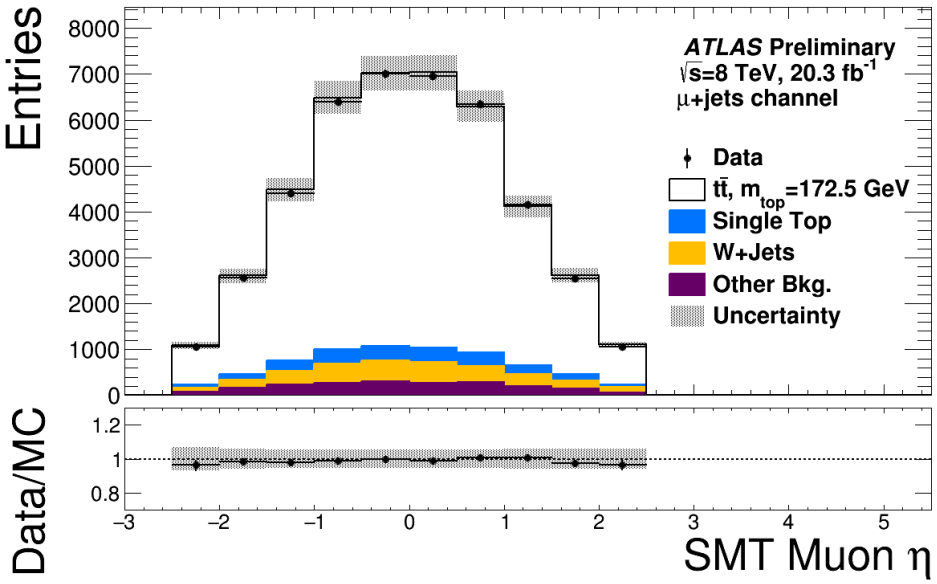
Lepton η



(b)

Lepton η distributions showing the data in solid circles, the $t\bar{t}$ simulation in white, the single-top in blue, the W+jets in yellow and all other backgrounds in purple. The hashed area represents all experimental systematic uncertainties as well as the b-hadron production and hadron-to-muon branching ratio uncertainties. (b) shows the μ+ jets channel.

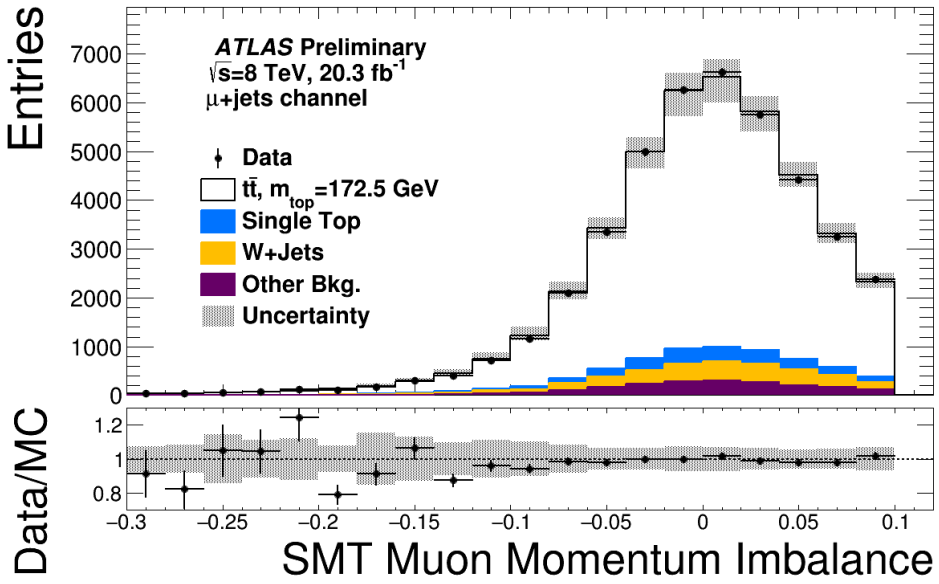
SMT μ η



(b)

SMT muon p_T distributions showing the data in solid circles, the $t\bar{t}$ simulation in white, the single-top in blue, the W+jets in yellow and all other backgrounds in purple. The hashed area represents all experimental systematic uncertainties as well as the b-hadron production and hadron-to-muon branching ratio uncertainties. (b) shows the μ+ jets channel.

SMT μ Momentum Imbalance



(b)

SMT muon momentum imbalance showing the data in solid circles, the $t\bar{t}$ simulation in white, the single-top in blue, the W+jets in yellow and all other backgrounds in purple. The hashed area represents all experimental systematic uncertainties as well as the b-hadron production and hadron-to-muon branching ratio uncertainties. (b) shows the μ+ jets channel.