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ATLAS EXPERIMENT

# Highlights of top quark cross-section measurements at ATLAS

Lake Louise Winter Institute — 2018

erc

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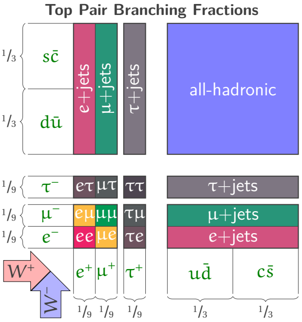
on behalf of the ATLAS collaboration

# Introduction




## Why study top-quark physics?

- most massive (known) elementary particle
- decays before hadronisation
- production through strong & EWK, rich space of decays

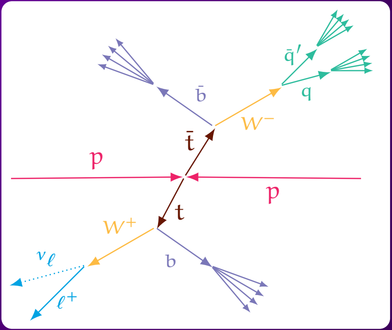
## What's new?

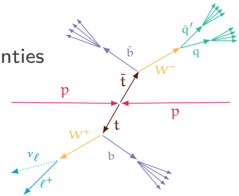
- LHC Run II dataset has grown $\rightarrow \int \mathcal{L} dt = 36\,\text{fb}^{-1}$
- new analyses with $\sqrt{s} = 8$ TeV data, more analyses at $\sqrt{s} = 13$ TeV
- new results made public since LLWI2017:

| top cross section | | | | | | |
|---|---|---|---|---|---|---|
| single top | | top pair production | | | $t/t\bar{t} + X$ | |
| t-channel | $Wt$ | | | | $t + Z$ | $t\bar{t} + \gamma$ |
| l+jets | dilepton | dilepton | l+jets | all-hadronic | trilepton | l+jets |
| 8 TeV total fiducial differential | **13 TeV differential** | 8 TeV $e\mu$ events differential | **8 TeV inclusive**<br>8 TeV $l = \tau$ inclusive<br>13 TeV differential<br>13 TeV excl. $N_{\text{Jets}}$ differential | **13 TeV fiducial differential** | **13 TeV inclusive** | 8 TeV fiducial differential |

# At the precision frontier

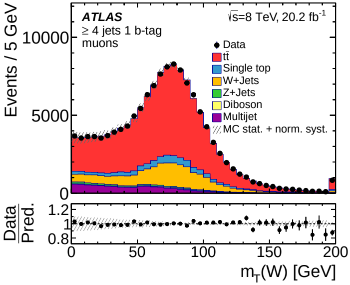
$\sqrt{s} = 8$ TeV, $t\bar{t} \rightarrow$ l+jets
▷ arXiv:1712.06857






- previous best: $\delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}} \sim 3.2\%$ (dilepton $e\mu$, 8 TeV)
- l+jets has larger backgrounds than dilepton, suffers from jet uncertainties $\longrightarrow$ new approach

**Select** $1l(e/\mu)$, $\geq 4$ jets, $\geq 1$b-tag, missing transverse momentum




$\longrightarrow$ $\sim 336$k events @ $\sim 79\%\, t\bar{t}$

## Backgrounds

**Data-driven:**

- $W$+jets: shape from clean $Z$+jets "converted" to $W$+jets
- "Fake" leptons: shape from enhanced control regions, normalised by fit to $E_T^{\text{miss}}/m_T^W$ $(e/\mu)$

**Simulation**

- Single top, $Z$+jets, diboson

- need to constrain jet and b-tag uncertainties
- increase sensitivity to signal contribution to dataset

define 3 exclusive signal regions

**4 jets, 2 b-tags** | **$\geq$ 4 jets, 1 b-tag** | **$\geq$ 4 jets, $\geq$ 2 b-tag**

▷ arXiv:1712.06857

define 3 exclusive signal regions

**4 jets, 2 b-tags** | **≥ 4 jets, 1 b-tag** | **≥ 4 jets, ≥ 2 b-tag**

**Unambiguous $t\bar{t}$ reconstruction**

- \+ unambiguous jet assignment
- \+ low background contamination
- ▶ $m(jj)$ **provides sensitivity to JES & radiation**

**Simple $t\bar{t}$ reconstruction algorithm**

- ▶ Select 4 highest $p_T$ jets
- ▶ $l + E_T^{miss} \rightarrow W_{Lep}$
- ▶ **lep top:** $W_{Lep}$ + jet closest to $l$
- ▶ **had top:** other 3 jets

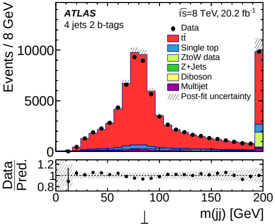
(≥ 4 jets, 1 b-tag)

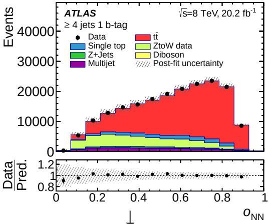
- \+ high statistics; more than half of all selected data
- − high background contamination
- ▶ **large** $W$**+jets contamination** $\sim 16\%$

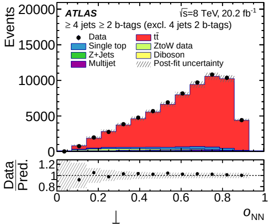
(≥ 4 jets, ≥ 2 b-tag)

- \+ high signal purity
- ▶ **sensitivity to extra HF radiation and** $c$**-as-**$b$ **mistags**

build neural net (object combination masses & orientation, aplanarity)
$\rightarrow$ discriminate $t\bar{t}$ from ($W$+jets) background




**simultaneous signal yield extraction fit**

▷ arXiv:1712.06857

define 3 exclusive signal regions

- **4 jets, 2 b-tags**
- **≥ 4 jets, 1 b-tag**
- **≥ 4 jets, ≥ 2 b-tag**

→ simultaneous signal yield extraction fit

- **binned maximum-likelihood fit** to discriminating distributions
  - **simultaneous** in three signal regions
  - signal yield $N_{t\bar{t}}$ and $W$+jets normalisation floating
  - nuisance parameters introduce b-**tagging efficiency** and **jet energy scale** correction

$\longrightarrow$ use $N_{t\bar{t}}$ to extract inclusive and fiducial cross section

**Measured** $\sigma_{\text{fid}}(t\bar{t}) = 48.8 \pm 0.1\,(\text{stat.}) \pm 2.0\,(\text{syst.}) \pm 0.9\,(\text{lumi.})\,\text{pb}$ — $\delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$: 4.5 %

$\sigma_{\text{inc}}(t\bar{t}) = 248.3 \pm 0.7\,(\text{stat.}) \pm 13.4\,(\text{syst.}) \pm 4.7\,(\text{lumi.})\,\text{pb}$ — $\delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$: 5.7 %

**Predicted** $\sigma_{\text{SM}}(t\bar{t}) = 253\,^{+13}_{-15}\,\text{pb}$

**Dominant Syst.**

| | |
|---|---|
| Lumi. | 1.9 % |
| Lep. ID | 1.4 % |
| Lep. Trig. | 1.3 % |
| PDF | 3.0 % |
| Scales | 2.2 % |
| Lumi. | 1.9 % |

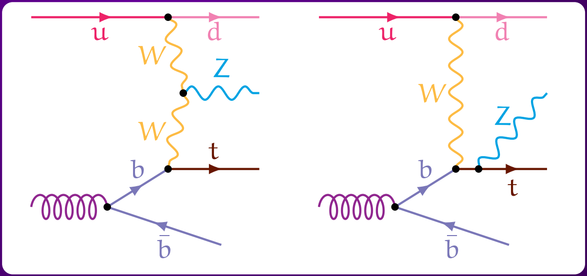
**compare to dilepton**

| inclusive | fiducial |
|---|---|
| 4.4 % | 3.9 % |

▷ arXiv:1712.06857

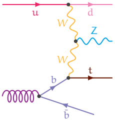
# At the rarity frontier

$\sqrt{s} = 13$ TeV, tZ → trilepton
▷ arXiv:1710.03659

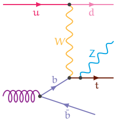


## Motivation

- production sensitive to $V_{tb}$ $\longrightarrow$ probing fundamental SM structure
- sensitivity to $tZ$ coupling and $WWZ$ triboson coupling
- no observation of $tZ$ yet




$WWZ$ **coupling**

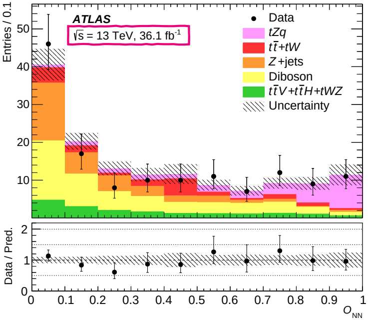



$tZ$ **coupling**

## Event Selection

- trilepton w/ opp. sign same-flavour pair $l^+l^-l$
- one b-tagged jet, one additional untagged jet
- $|m_{ll} - m_Z| < 10$ GeV, $m_T^W > 20$ GeV

$$\left.\begin{array}{ll} l^+l^- & \longrightarrow Z \\ l + E_T^{miss} & \longrightarrow W \\ W + b & \longrightarrow t \end{array}\right.$$




## Analysis Strategy

- construct Neural Network (NN) to discriminate signal from backgrounds
- extract signal yield $N_{tZq}$ with profile likelihood fit of NN output in signal region

## Backgrounds

- **Diboson:** (**dominant**) from simulation, normalisation from CR

Fake/non-prompt lepton:

- $t\bar{t}$: simulation + normalisation from $\frac{\text{data}}{\text{MC}}$ in CR
- $Z$+**jets:** fake factor method from fake enhanced CR

- $tW, t\bar{t} + V/H, tWZ$: from simulation

**Measured:**
$$\mu = 0.75 \pm 0.21\,(\text{stat.}) \pm 0.17\,(\text{syst.}) \pm 0.05(\text{theo.})$$
$$\sigma_{tZq} = 600 \pm 170\,(\text{stat.}) \pm 140\,(\text{syst.})\,\text{fb}$$

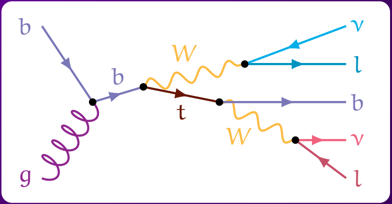
**Predicted:** $\sigma_{SM}^{NLO} = 800\,\text{fb}\,^{+6.1}_{-7.1}\,\%$

- **significance:** $4.2\sigma$ (observed), $5.4\sigma$ (expected)
- precision statistically limited!
  $\longrightarrow$ expect more to come with 2017 dataset

▷ arXiv:1710.03659

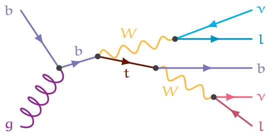
# At the rarity frontier

$\sqrt{s} = 13$ TeV, $Wt \rightarrow$ dilepton
▷ arXiv:1712.01602



## Motivation

- production and decay sensitive to $V_{tb}$
  $\longrightarrow$ probe fundamental SM structure
- sensitivity to new physics affecting $Wtb$ coupling

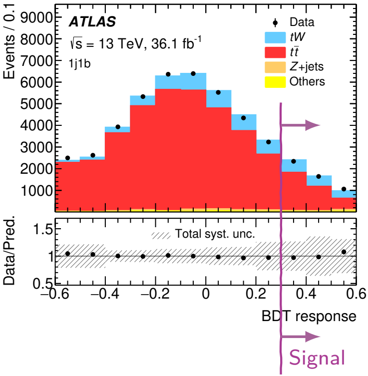



## Event selection

- exactly two leptons $l^+l^-$
- exactly one jet, must have b-tag
- lepton flavour dependent kinematic cuts in $(m_{ll}, E_T^{miss})$ to reduce Z+jets contamination

## Analysis strategy

- train BDT to discriminate $t\bar{t}$ from $tW$
- apply cut on BDT output: $tW$ purity $\sim 17\% \nearrow 35\%$
  $\longrightarrow$ also reduces impact of systematics (from $t\bar{t}$ bgr.)
- **measure** energies / masses of final state objects & combinations
- correct for detector effects & acceptance ("unfolding")
  - $\longrightarrow$ **unfold distributions** to particle level
  - $\longrightarrow$ normalise to fiducial cross section
  - $\longrightarrow$ compare to predictions from MC, assess agreement as $\chi^2$




## Backgrounds

- taken from simulation: $t\bar{t}$ (**dominant**), Z+jets, diboson

▷ arXiv:1712.01602

# Variables

$E(\mathrm{b})$

probe:
**top quark production**

- traceable to top quark

$m(\mathrm{l}_1\mathrm{b})$
$m(\mathrm{l}_2\mathrm{b})$

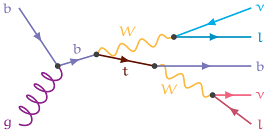
probe:
**top quark decay**

- sensitive to spin correlations

$E(\mathrm{llb})$
$m_\mathrm{T}(\mathrm{ll}\nu\nu\mathrm{b})$
$m(\mathrm{llb})$

probe:
$\mathrm{t}W$ **system**

- combined system

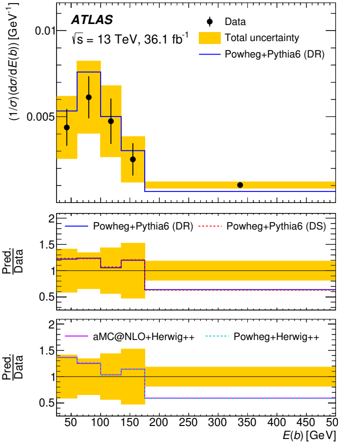



$\rightarrow$ all observables selected w/ minimal bias from BDT & low correlation to BDT output

- both stat. & syst. uncertainties sizeable
- measurements consistent with predictions
- comparison w/ alternative treatment of $\mathrm{t}\bar{\mathrm{t}}/\mathrm{t}W$ interference gives similar results

**alternative treatment of** $\mathrm{t}\bar{\mathrm{t}}/\mathrm{t}W$ **interference** →

**alternative ME generator** →

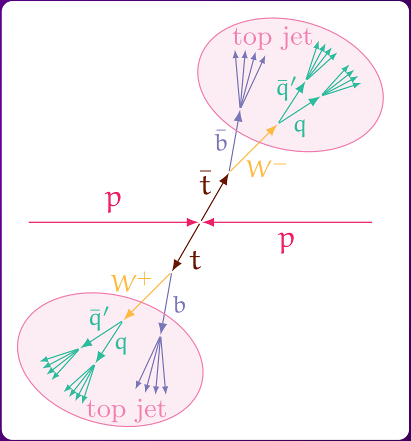



▷ arXiv:1712.01602

# At the kinematic frontier

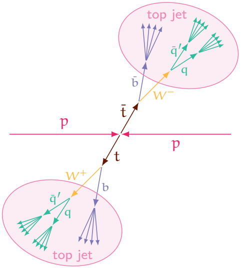
$\sqrt{s} = 13$ TeV, $t\bar{t} \rightarrow$ all-hadronic

▷ arXiv:1801.02052



## Motivation

- full $t\bar{t}$ event kinematic reconstruction
- measurement at kinematic frontier: very high top $p_T$




## Event selection

- 2 b-tagged small-$R = 0.4$ jets w/ $p_T > 25$ GeV
- 2 large-$R = 1.0$ jets w/ $p_T > 500/350$ GeV
  - large-$R$ jets must be **top-tagged**
  - large-$R$ jets must have $\Delta R(j,b) < 1$

$\sim 3500$ events
$\sim 75\%$ **pure** $t\bar{t}$

## Backgrounds

- **QCD multijets:** (**dominant**) estimated from data (ABCD method)
- **non-allhadronic $t\bar{t}$, single top, $t\bar{t} + H/V$:** from simulation

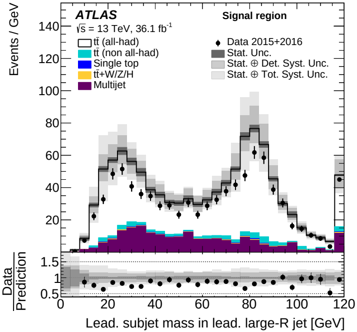
## Analysis strategy

- measure top-jet and $t\bar{t}$ observables
- unfold to **stable particle level** and **parton level**

→ stable, "detector-like" particles
0 l, 2 small-$R$ jets, 2 large-$R$ jets
top- and b-tag large-$R$-jets

→ $t\bar{t}$ event with $p_T$ cuts
$p_T^t > 500/300$ GeV

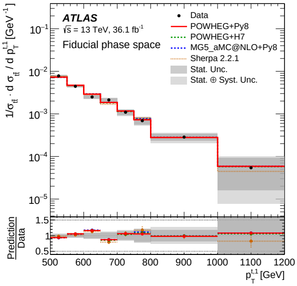
- compare unfolded results to NLO predictions
- assess compatibility using $\chi^2/p$-value



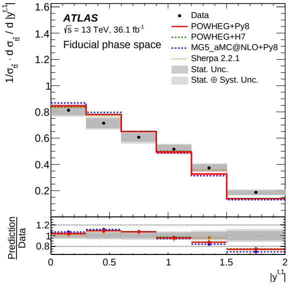

▷ arXiv:1801.02052

# Results

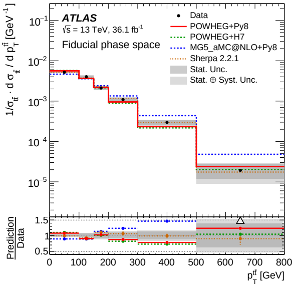
- predicted total particle-level cross-section exceeds the observed value
  large systematic uncertainties $\rightarrow$ effect is not statistically significant
- reasonable agreement between normalised measured differential cross-sections and predictions




**leading top-jet $p_{\mathrm{T}}$**




**leading top-jet $|y|$**




**top-pair $p_{\mathrm{T}}$**

- top-jet transverse momentum modelled very well by simulation
- leading top rapidity shows small slope, more central tops predicted, sub-leading top not affected
- largest discrepancy from `aMC@NLO+Py8` e.g. modelling di-top $p_{\mathrm{T}}$

▷ arXiv:1801.02052

# Summary

- the LHC has proven itself as **top factory** enabling access to more elusive phase-space regions
- inclusive measurements of $\sigma_{t\bar{t}}$ reach $4-5\%$ **precision**, consistent with SM
- measurements of rare production $(tZ/t\bar{t}+\gamma)$ compatible with SM prediction
- MC predictions agree broadly with differential measurements across a variety of final states and kinematic regimes
- no top quark measurements with 2017 dataset public yet, expect $36\,\mathrm{fb}^{-1} \nearrow \sim 80\,\mathrm{fb}^{-1}$
  - opens up access to rarer and rarer processes
  - potential for reduced stat. uncertainties on 3 of 4 measurements presented here
  - potential to extend differential measurements to more dimensions, additional final states

| Measurement | $\sqrt{s}$ [TeV] | $\int \mathcal{L}\mathrm{d}t$ [fb$^{-1}$] | ATLAS code | Link |
|---|---|---|---|---|
| single top: $tW$, differential | 13 | 36 | ▷ TOPQ-2016-12 | ▷ arXiv:1712.01602 |
| single-top: $t$-channel, differential | 8 | 20 | ▷ TOPQ-2015-05 | ▷ arXiv:1702.02859<br>▷ Eur. Phys. J. C 77 (2017) 531 |
| $t\bar{t}$: l+jets, $+N$ jets, differential | 13 | 3.2 | ▷ TOPQ-2017-01 | |
| $t\bar{t}$: all-had, differential | 13 | 36 | ▷ TOPQ-2016-09 | ▷ arXiv:1801.02052 |
| $t\bar{t}$: l+jets, inclusive | 8 | 20.3 | ▷ TOPQ-2016-08 | ▷ arXiv:1712.06857 |
| $t\bar{t}$: $e\mu$, differential | 8 | 20 | ▷ TOPQ-2015-02 | ▷ arXiv:1709.09407<br>▷ Eur. Phys. J. C 77 (2017) 804 |
| $t\bar{t}$: l+jets, differential | 13 | 3.2 | ▷ TOPQ-2016-01 | ▷ arXiv:1708.00727<br>▷ JHEP 11 (2017) 191 |
| $t\bar{t}$: $\tau$+jets, inclusive | 8 | 20 | ▷ TOPQ-2015-18 | ▷ arXiv:1702.08839<br>▷ Rev. D 95 (2017) 072003 |
| tZ: trilepton, inclusive | 13 | 36 | ▷ TOPQ-2016-14 | ▷ arXiv:1710.03659 |
| $t\bar{t}\gamma$: l+jet, differential | 8 | 20.2 | ▷ TOPQ-2015-21 | ▷ arXiv:1706.03046<br>▷ JHEP 11 (2017) 086 |

# Backup

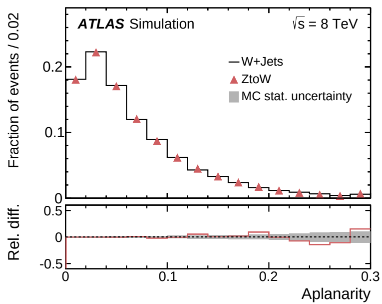
# $Z$ to $W$ conversion

- novel technique to model shape of $W$+jets contribution from data
- exploits similarity of production and decay of $Z$ boson to $W$ boson in $V$+jets events

## Procedure

1. Select almost background-free $Z$+jets sample
   - exactly two oppositely charged same-flavour leptons
   - dilepton invariant mass is consistent with $Z$ boson mass: $80 < m_{ll} < 102\,\text{GeV}$
2. *"Convert"* events to have a $W$ boson mother
   - boost leptons to $Z$ boson rest frame
   - scale lepton momenta according to boson mass ratio: $\vec{p}^{\star}_{l} \mapsto \frac{m_W}{m_Z} \times \vec{p}^{\star}_{l}$
   - boost leptons back into lab-frame
   - randomly select one of the leptons to be dropped, recalculate $E_{\text{T}}^{\text{miss}}$
3. Apply event selection requirements

- Detailed studies are performed in simulation as well as validation region to ensure proper modelling
- Residual shape differences are accounted for as systematic uncertainties
- Expected $W$+jets yield taken from simulation, also used as pre-fit yield




▹ arXiv:1712.06857

# Reconstruction

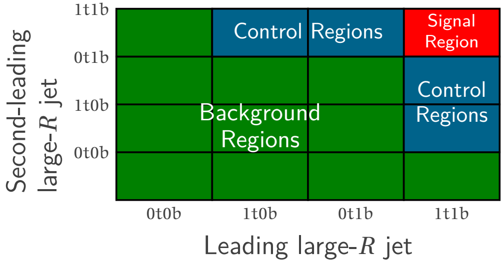
- 2 Anti-$k_T$ $R = 0.4$ (*"small-R"*) jets with $p_T > 25$ GeV and $|\eta| < 2.5$
  - both must be b-tagged using BDT-based tagger @ 70 % nominal efficiency
- no isolated electrons or muons with $p_T > 25$ GeV and $|\eta| < 2.5$
- 2 Anti-$k_T$ $R = 1.0$ (*"Large-R"*) jets with $|\eta| < 2.0$
  - jets are trimmed with $R_{\text{sub}} = 0.2$ and $f_{\text{cut}} = 0.05$
  - jet mass within 50 GeV of top-quark mass
  - transverse momentum: $p_T > 500/350$ GeV
  - both large-$R$ jets must have small-$R$ jet within $\Delta R < 1.0$ ("b-*matched*")
  - both large-$R$ jets must be **top-tagged**
    - cut on $N$-subjettiness $\tau_{32}$ and jet mass
    - cut value dynamic with $p_T$ to achieve flat 50 % efficiency

# QCD Multijet Background Estimate

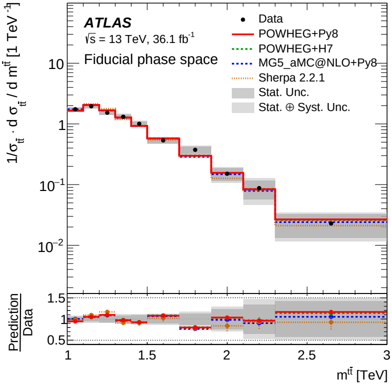
- ABCD method performed using pre-selected (data) events
- events are divided into 16 categories based on top-tagging and b-matching of both large-$R$ jets
- Subtract signal and backgrounds estimated with MC simulation
- Estimate signal and control region distributions from ratios of distributions in background regions, e.g.

$$N_{\text{Signal}} = \frac{N^{0t0b}_{1t1b} \times N^{1t1b}_{0t0b}}{N^{0t0b}_{0t0b}}$$

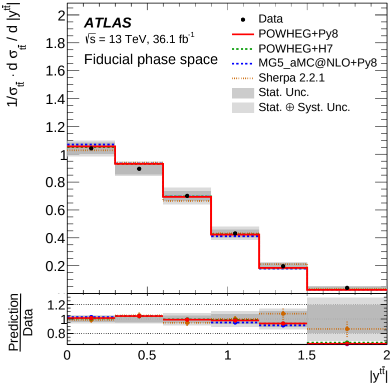
  where $N^{Y}_{X}$ is event count with tag $X$ ($Y$) for leading (sub-leading) large-$R$ jet
- measure correlations between tags using additional background regions



# $t\bar{t}$ system




**mass of top-quark pair**




**top-pair $|y|$**

▷ arXiv:1801.02052