Final state measurements in $t\bar{t}$ events and comparison to MC generators

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Discuss ATLAS and CMS Run1 final state measurements in $t\bar{t}$ events for the following observables:

- jet veto,
- jet multiplicities and p_{T}-spectra,
- $t\bar{t}$+heavy flavour production.

Comment also on the MC generator modelling of these quantities;

- $t\bar{t}$ MCs need to provide simulated samples suitable for:
  - precision $t\bar{t}$ measurements,
  - measurements where $t\bar{t}$ is an important background ($t\bar{t}H$, SUSY & other NP searches).
- $\Rightarrow$ good modelling of hard-process and additional jets related observables is required (frequently with the same sample).
- Stress NLO+PS generators and newer generators (e.g. C++ showers) expected to take over from the legacy ones during Run 2.
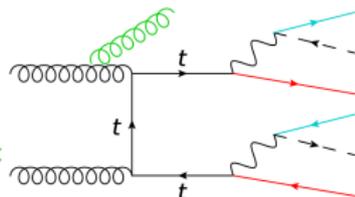
- $t\bar{t}$ dilepton events with 2 b-jets
- additional jets ($\sim$ not from Born-level ME)
- measure fraction of events with no additional jets with $p_T > Q_0$

$$f_{\text{gap}}(Q_0) = n_{\text{gap}}(Q_0)/N_{t\bar{t}}$$

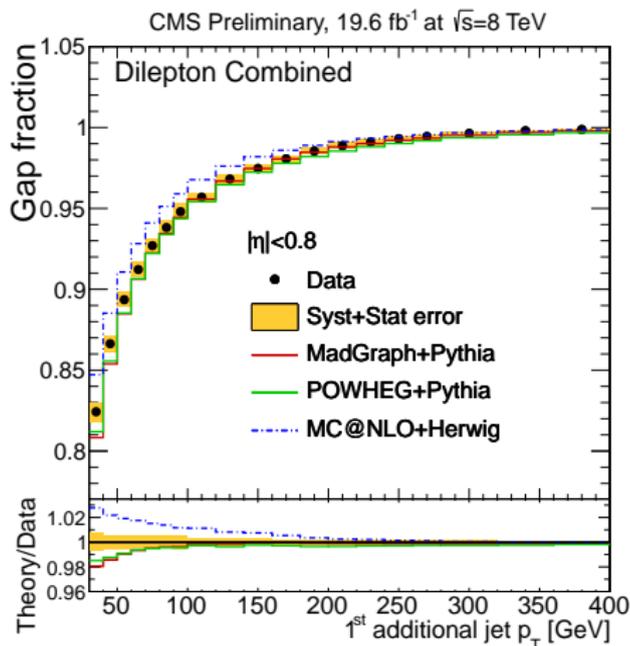- High precision: many uncertainties cancel in the ratio.
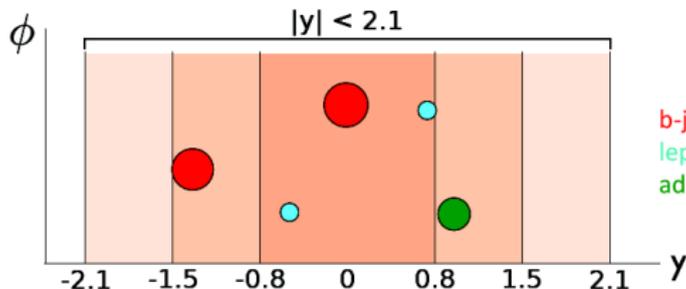
- Probes the modelling of the additional jets; too large f_{gap} = too little activity.

ATLAS: EPJ C72 (2012) 2043, CMS: EPJ C74 (2014) 3014, CMS-PAS-TOP-12-041.

Jet Veto: NLO+PS modelling

CMS-PAS-TOP-12-041

- NLO+PS modelling ok figure: $|\eta| < 0.8$ region that shows some data-MC difference (agreement better for inclusive $|\eta|$)

- CMS uncertainties small enough for data to prefer some NLO setups over other?

- Beware of low Q_0 regions ($Q_0 \ll m_t$). Soft interactions (e.g. hard parton-beam remnant interactions) can be of $\sim O(5\%)$ (Phys Rev D 86 114038).

Trends observed to be correlated with other observables (n(jets), jet spectra, H_T).

- Rivet implementation of ATLAS: EPJ C72 (2012) 2043
- Rivet = Robust Independent Validation of Experiment and Theory
  http://rivet.hepforge.org/
- ATL-PHYS-PUB-2015-002, ATL-PHYS-PUB-2014-005, ATL-PHYS-PUB-2015-007: new generator commissioning and tuning.
- With judicious choice of setups: data-MC agreement.
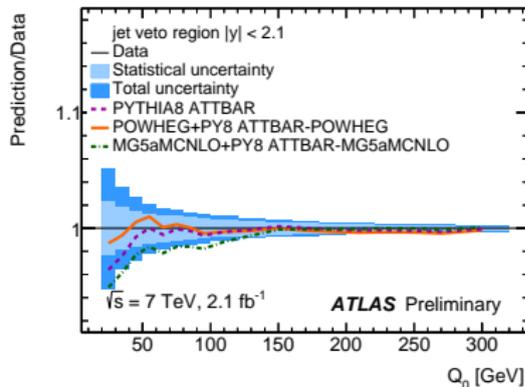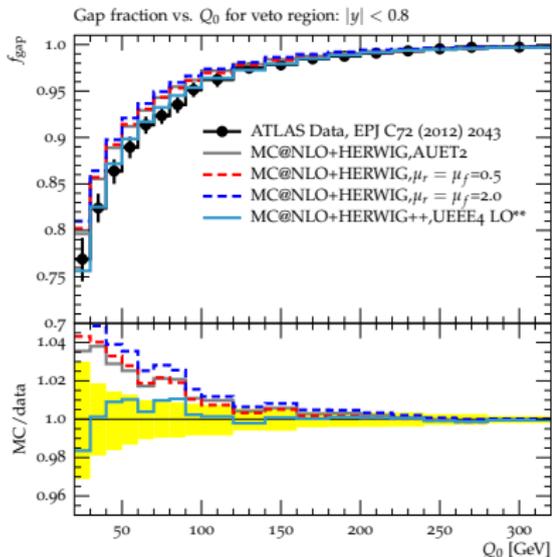
Measure n(jets) distributions in $t\bar{t}$ events, CMS: CMS-PAS-TOP-12-041, EPJ C74 (2014) 3014, ATLAS: JHEP 01 (2015) 020.
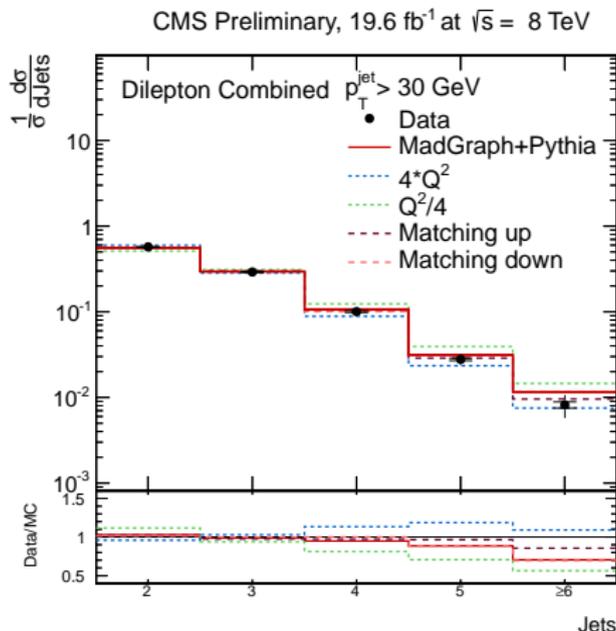
Several theoretical approaches:

- NLO+PS, (N)LO multi-leg+PS, LO+PS.
- best to use in Run1? Depends on use-case, e.g.: -inclusive $\sigma_{t\bar{t}}$: sensitive to n(jets) when using e.g. H_T or light jet b-tagging fake rates, -SUSY search in final state with high n(jets), where $t\bar{t}$ is a large background, -high-p_T NP signal simulation: which generator parameters to use?

Large n(jets): multi-leg best suited, NLO+PS not expected to work out of the box.

Example use-case: inclusive $\sigma_{t\bar{t}}$: sensitive to n(jets) when using e.g. H_{T} or light jet b-tagging fake rates. High n(jets): NLO+PS MCs not expected to yield precise predictions with default setups. (CMS-PAS-TOP-12-041, ATL-PHYS-PUB-2015-002)
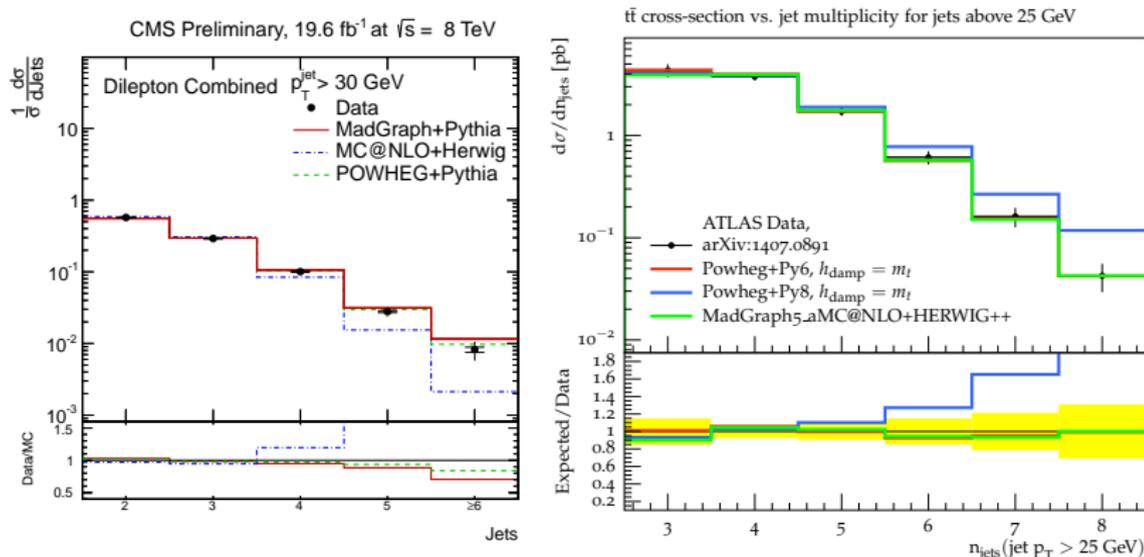
- MC@NLO+fortran HERWIG trend consistent with f_{gap}.
- With judicious choice of MC setups: data-MC agreement can be achieved, also for newer generators (multi-leg NLO+PS provide improved predictions).

Jet Spectra

Measure jet p_T, η, jet-jet ΔR distributions in $t\bar{t}$ events, CMS-PAS-TOP-12-041, ATLAS: JHEP01 (2015) 020.
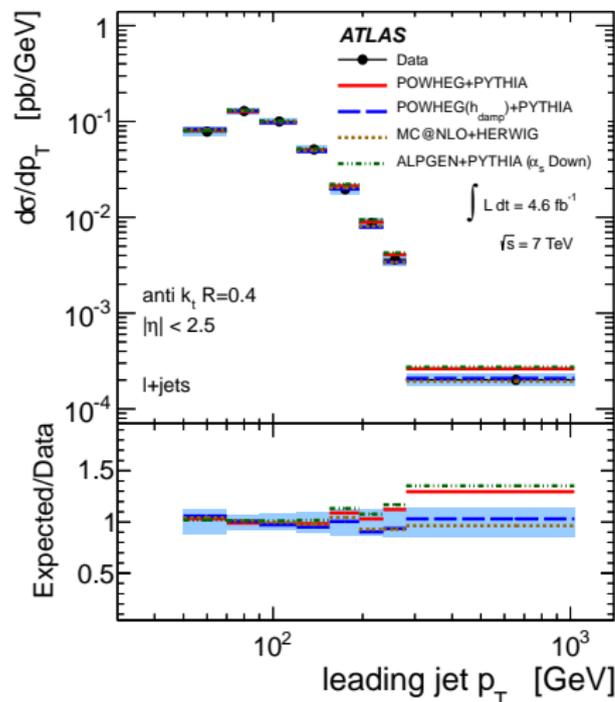
ATLAS:

- single lepton decay channel, ≥ 1 b-jet + extra p_T-cuts on the two leading jets,
- 1st-4th jet $\sim$ proxy for hard process modelling (top, $t\bar{t}$ p_T),
- 5th jet $\sim$ proxy for additional jet modelling,
- Rivet implementation available.

CMS:

- additional jets kinematics in dilepton decay channel events with ≥ 2 b-jets,
- probing additional jets modelling in the same phase-space as jet veto, but using different observables.

Jet Spectra: 1st additional jet p_T

universität**bonn**

- ATLAS: JHEP01 (2015) 020, 7 TeV, l+jets channel
- CMS: CMS-PAS-TOP-12-041, 8 TeV, dilepton channel
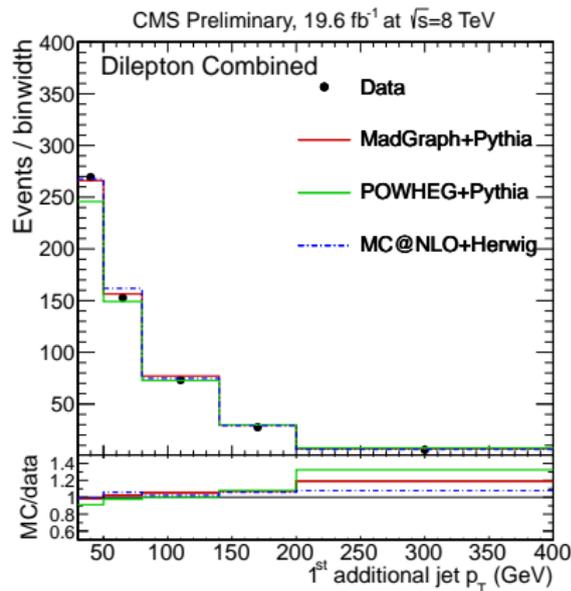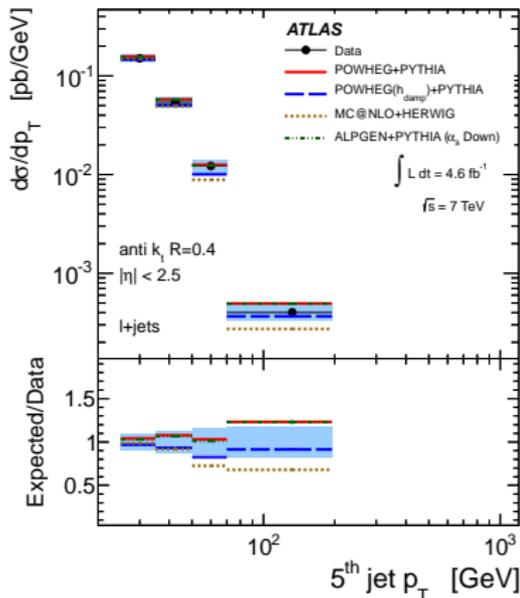
- ATLAS: MC@NLO+fortran HERWIG trend consistent with f_{gap}.
- With judicious choice of MC setups: data-MC agreement can be achieved, also for newer generators.

$t\bar{t}+b\bar{b}$ **production:**

- presence of two very different scales: m_t and jet p_{T}.
- Thus large ren./fac. scale uncertainties from theory.
- Irreducible background to $t\bar{t}H(H \to b\bar{b})$.
- Measurements: test theory prediction and reduce $t\bar{t}H$ measurement uncertainties.

$t\bar{t} + jj$ **and** $t\bar{t} + c\bar{c}$: **source of reducible background due to** b-**jet mis-tagging.**

Experimental measurements:

- so far in $t\bar{t}$ dilepton decay channel
- ATLAS: Phys. Rev. D 89, 072012 (2014):
  $\sigma(t\bar{t}+\text{HF jet})/\sigma(t\bar{t}+\text{light jet})$, where HF$=b, c$
- CMS: CMS-PAS-TOP-12-024 (7 TeV), arXiv:1411.5621 (8 TeV):
  - ratio: $\sigma(t\bar{t}+b\bar{b})/\sigma(t\bar{t}+jj)$,
 - as well as $\sigma(t\bar{t}+b\bar{b})$, $\sigma(t\bar{t}+jj)$ values.

$\sigma(t\bar{t}+b\bar{b})/\sigma(t\bar{t}+jj)$

CMS-PAS-TOP-12-024 (7 TeV), arXiv:1411.5621 (8 TeV)

Results reported in two different regions of the phase space:

- Visible (aka fiducial) phase space:
  - leptons, jets from $t\bar{t}+b\bar{b}$: required to be within experimentally accessible region;
  - $p_T > 20$ GeV, $|\eta| < 2.4$ (2.5 for jets).
- Full phase space:
  - purpose: comparison to parton-level theoretical calculations.
  - (Though NLO+PS predictions now also available.)
  - Perform jet reconstruction on partons (gluons, quarks lighter than top) and $\tau \rightarrow$ hadrons.
  - extra jet $p_T > 20$ GeV and $p_T > 40$ GeV results provided.

Measurement strategy:

- combined secondary vertex (CSV) b-tagging algorithm:
  - (SV+lifetime info of tracks) $\rightarrow$ $b-$tagging discriminator
- data fit of CSV discriminator of 3rd and 4th highest CSV jets to obtain $\sigma(t\bar{t}+b\bar{b})/\sigma(t\bar{t}+jj)$ and the absolute normalization.
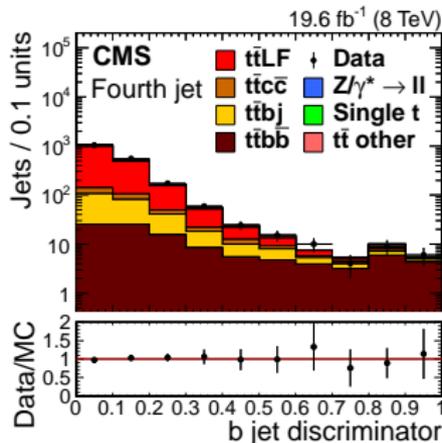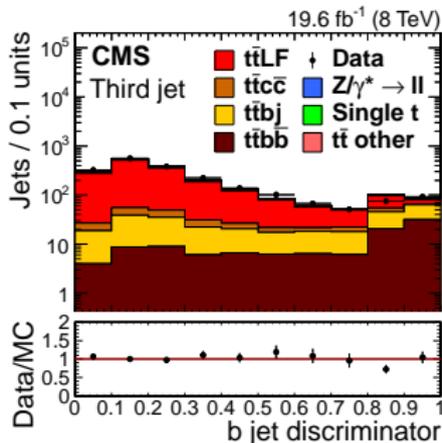
Phase Space (PS)	$\sigma_{t\bar{t}b\bar{b}}$ [pb]	$\sigma_{t\bar{t}jj}$ [pb]	$\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj}$
Visible PS (particle)			
Jet $p_T > 20\,\text{GeV}/c$	$0.029 \pm 0.003 \pm 0.008$	$1.28 \pm 0.03 \pm 0.15$	$0.022 \pm 0.003 \pm 0.005$
Full PS (parton)			
Jet $p_T > 20\,\text{GeV}/c$	$1.11 \pm 0.11 \pm 0.31$	$52.1 \pm 1.0 \pm 6.8$	$0.021 \pm 0.003 \pm 0.005$
Jet $p_T > 40\,\text{GeV}/c$	$0.36 \pm 0.08 \pm 0.10$	$16.1 \pm 0.7 \pm 2.1$	$0.022 \pm 0.004 \pm 0.005$
NLO calculation			
Jet $p_T > 40\,\text{GeV}/c$	0.23 ± 0.05	21.0 ± 2.9	0.011 ± 0.003

Dominant uncertainties: *b*-tagging efficiency and MC modelling.

ATLAS and CMS have performed a number of final state measurements in $t\bar{t}$ events during Run1.

- These offer tests of pQCD modelling (and beyond, e.g. jet veto),
- and enable us to improve the performance of the MC generators.
- Rivet implementation of many measurements available and used for tuning and Run 2 generators commissioning.
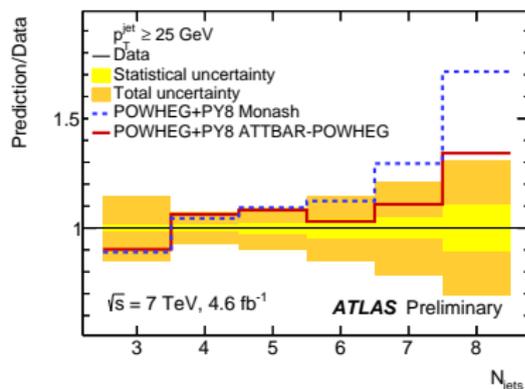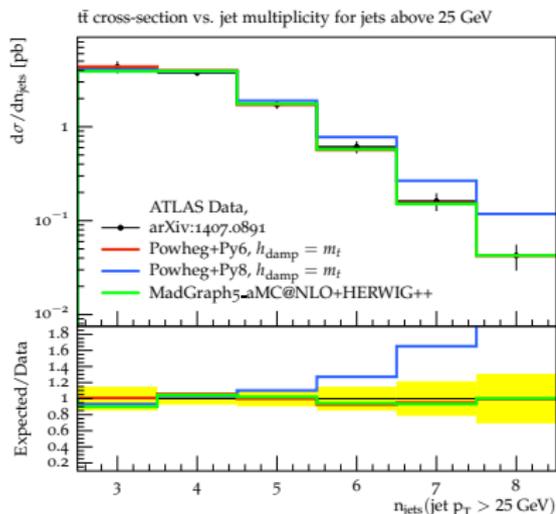
MC Modelling:

- good modelling in MC-s: jet veto, jet multiplicities and p_T-spectra;
  - achieved with measurements and subsequent tuning of the sensitive parameters.
- For some distributions (e.g. top p_T) modelling issues more tricky;
  - in L. Scodellaro's talk.
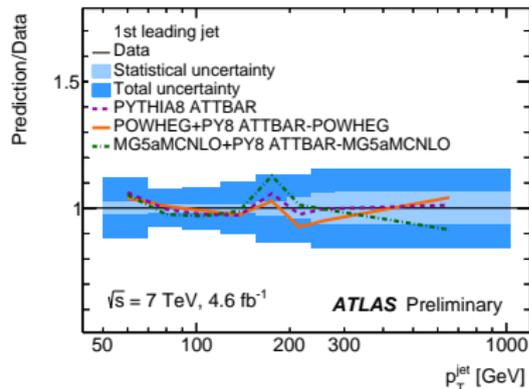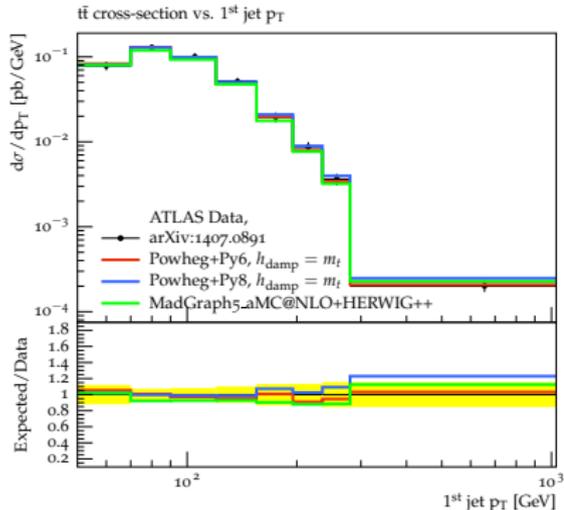
$t\bar{t}$+HF measurements: test state-of-the-art theory.

- In the future we will hopefully be able to reduce measurement uncertainties (currently $\sim 30\%$),
- and provide Rivet implementation of the fiducial measurements.

Extra

- **Rivet implementation** of ATLAS: JHEP 01 (2015) 020
- **ATL-PHYS-PUB-2015-002**, **ATL-PHYS-PUB-2015-007**: new generator commissioning and tuning
- Using ME and PS handles: can reach data-MC agreement in *newer generators*.

$t\bar{t}$ cross-section vs. jet multiplicity for jets above 25 GeV

ATLAS Data,
arXiv:1407.0891
Powheg+Py6, $h_{damp} = m_t$
Powheg+Py6, $h_{damp} = m_t$
MadGraph5_aMC@NLO+HERWIG++

$d\sigma/dn_{jets}$ [pb]

Expected/Data

n_{jets}(jet $p_T > 25$ GeV)

$p_T^{jet} \geq 25$ GeV
Data
Statistical uncertainty
Total uncertainty
POWHEG+PY8 Monash
POWHEG+PY8 ATTBAR-POWHEG

Prediction/Data

$\sqrt{s} = 7$ TeV, 4.6 fb^{-1} *ATLAS* Preliminary

N_{jets}

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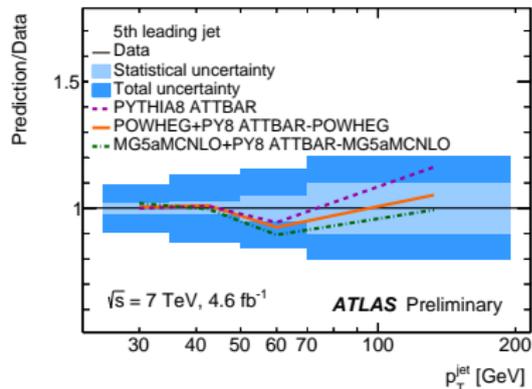- Using ME and PS handles: can reach data-MC agreement in *newer generators*.
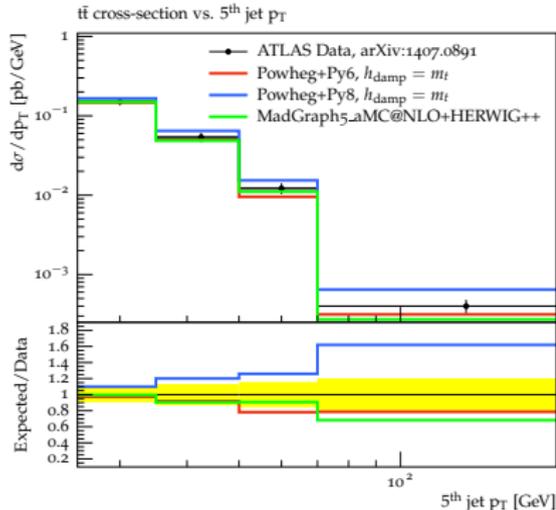
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arXiv:1411.5621

truth-level objects (fiducial measurement):

- leptons: pt>20, eta<2.4 .From W from top decays. tau $\rightarrow$ e,mu = included
- jets: pt>20, eta<2.5, dR(j,j)>0.5, remove jet if dR(j,l)<0.5. From all final state particles, excluding ν, antikt, 0.5.
- truth b-jet: B-hadron = one of the constituents. c-jets: similar with lower priority

ttbb,cc,LF definition:

- ttbb(cc): 2 extra jets contain B(C)-hadron in the constituents
- ttbj: only 1 extra jets contains B-hadron in the constituents
- c-tagging done only if b-tagging fails
- ttLF: both jets from light flavour or light+c
- tt+other: the background contributions from single top production and from tt events that fail the visible phase-space cuts.

Fiducial phase-space: all charged particles (but not ν) from ttjj in the fiducial region defined above.

arXiv:1411.5621

measurement phase-space:

- leptons: pt>20, eta<2.4 (same as truth-level)
- leptons: relative isolation (not at truth-level)
- jets: pt>30, eta<2.5 (truth-level: pt>20)
- b-tagging: CSV algorithm, $\epsilon_b \sim$45% $\epsilon_{light} \sim$0.1%
- extra event-level cuts (not at truth-level): os leptons, mll>12 GeV
 ee,emu:$|mll - mZ| <$15 GeV, ee,mumu: MET>30 GeV

arXiv:1411.5621

full phase-space measurement:

- jet reconstruction is performed on the partons (gluons, as well as quarks lighter than top) before hadronization + $\tau \to$ hadrons

- showering done with Pythia6; thus parton 4-vectors are after all boosts and rotations from PS and hadronization

- jet reconstruction algorithm: same as for the fiducial measurement

- b jets: dR=0.5 truth-matching of parton-jets to b-quarks

- results are quoted for two different jet p_{T} thresholds of $p_{\mathrm{T}} > 20$ and > 40 GeV for extra jets (not from top).

$t\bar{t}$+HF

arXiv:1411.5621

Normalized distribution of the b jet discriminator:
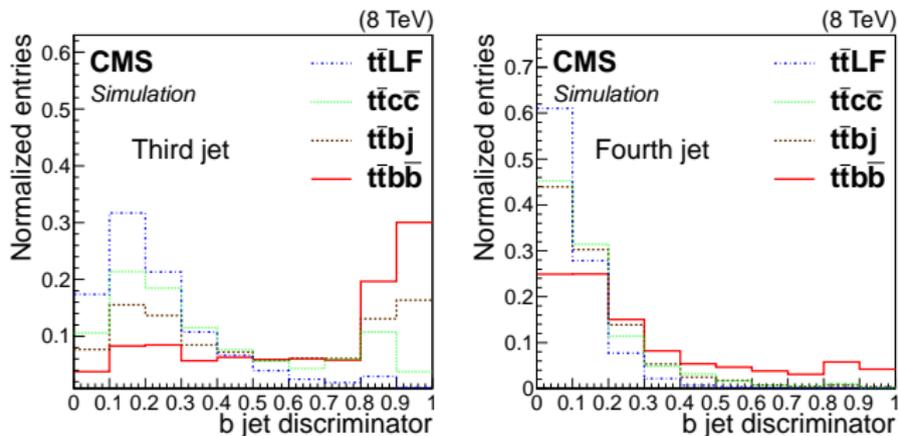
fit:

- simultaneously to ttbb and ttjj CSV discriminator distribution
- contains two free parameters, an overall normalization and the ratio of the number of ttbb events to ttjj events.
- ttcc and ttLF contributions are combined, and the ratio of the ttbb to ttbj contributions is constrained using the predictions from the MC simulation.

arXiv:1411.5621

Source	$\sigma_{t\bar{t}b\bar{b}}$ (%)	$\sigma_{t\bar{t}jj}$ (%)	$\frac{\sigma_{t\bar{t}b\bar{b}}}{\sigma_{t\bar{t}jj}}$ (%)
Pileup	1.0	1.0	1.0
JES & JER	11	8.0	5.0
b tag (b quark flavour)	15	<0.1	15
b tag (c quark flavour)	4.0	<0.1	4.0
b tag (light flavour)	7.0	<0.1	7.0
Ratio of $t\bar{t}b\bar{b}$ and $t\bar{t}bj$	9.0	<0.1	9.0
Bkgnd modelling	1.0	1.0	1.0
$t\bar{t}c\bar{c}$ fraction in the fit	4.2	0.2	4.0
Lepton identification	4.0	4.0	—
MC generator	3.0	3.0	3.0
Q^2 scale	8.0	3.0	6.0
PS matching	12	5.0	3.0
PDF	4.0	4.0	<0.1
Eff. ($t\bar{t}c\bar{c}$ fraction)	—	1.6	1.6
Luminosity	2.6	2.6	—
Total uncertainty	28	12	22