Top quark pair production in ATLAS

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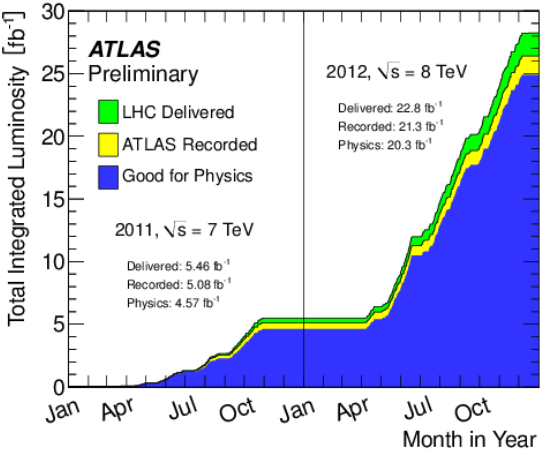
Outline

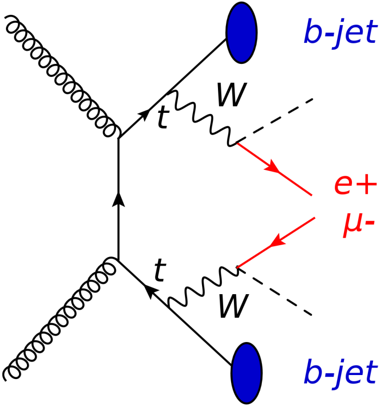
- inclusive cross-section in dilepton channel [arXiv:1406.5375]
- differential cross-sections in l+jets channel [arXiv:1407.0371 and ATL-PHYS-PUB-2013-008]
- production cross-section as a function of jet multiplicity and jet transverse momentum [arXiv:1407.0891]
- measurement of $t\bar{t}$ production with a veto on additional central jet activity [Eur. Phys. J. C **72** (2012) 2043 and ATL-PHYS-PUB-2014-005]
- charge asymmetry [JHEP **02** (2014) 107, ATLAS-CONF-2012-057 and ATLAS-CONF-2014-012]

ATLAS dataset

Integrated luminosity of good quality data recorded by ATLAS:

- 2011: $\mathcal{L}_{\rm int} = 4.6\ \ {\rm fb}^{-1}$, $\sigma_{t\bar{t}} = 177.3^{+10.1}_{-10.8}$ pb, $N_{t\bar{t}} \sim 0.8$ M
- 2012: $\mathcal{L}_{\rm int} = 20.3\ \ {\rm fb}^{-1}$, $\sigma_{t\bar{t}} = 252.9^{+13.3}_{-14.5}$ pb, $N_{t\bar{t}} \sim 5$ M





Signal events:

- opposite-sign $e\mu$ pair with $\mathrm{p_T} > 25\ \mathrm{GeV}$, $|\eta| < 2.5$
- at least one b-tagged jet

Simultaneously determine:

- $\sigma_{t\bar{t}}$: cross-section
- ϵ_b : efficiency to reconstruct and tag b-jet

Count events with exactly two (N_2) and one (N_1) b-jets:

$$N_2 = \mathcal{L}_{\mathrm{int}}\sigma_{t\bar{t}}\ \epsilon_{e\mu} C_b {\epsilon_b}^2 + N_2^{\mathrm{bkg}}$$

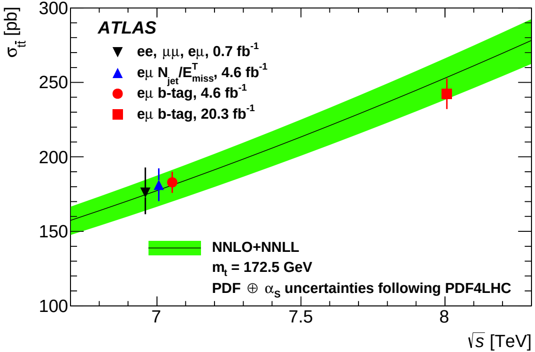
$$N_1 = \mathcal{L}_{\mathrm{int}}\sigma_{t\bar{t}}\ \epsilon_{e\mu} 2\epsilon_b(1 - C_b\epsilon_b) + N_1^{\mathrm{bkg}}$$

where

- $\epsilon_{e\mu}$: efficiency to pass the opposite-sign $e\mu$ preselection
- C_b :tagging correlation coefficient

$$\sigma_{t\bar{t}} = 182.9 \pm 3.1 \pm 4.2 \pm 3.6 \pm 3.3\,\text{pb}\ (\sqrt{s} = 7\ \text{TeV})$$
$$\sigma_{t\bar{t}} = 242.4 \pm 1.7 \pm 5.5 \pm 7.5 \pm 4.2\,\text{pb}\ (\sqrt{s} = 8\ \text{TeV})$$

with stat., experimental and theory syst., luminosity and beam energy uncertainty.



- total measurement unc.: $3.9\%(\sqrt{s} = 7\ \text{TeV})$ and $4.3\%(\sqrt{s} = 8\ \text{TeV})$
- NNLO+NNLL theo. unc.: $5.7\%(\sqrt{s} = 7\ \text{TeV})$ and $5.3\%(\sqrt{s} = 8\ \text{TeV})$

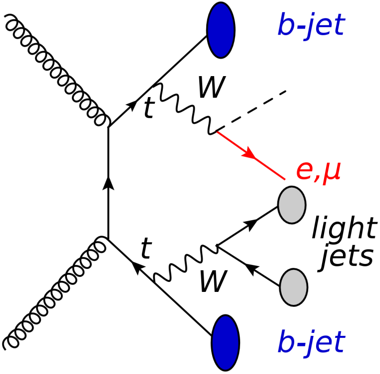
Inclusive cross-section: modelling uncertainties

Modelling uncertainties not dominant for inclusive $\sigma_{t\bar{t}}$, but notably reduced in fiducial measurement

- $\epsilon_{e\mu}$=acceptance · reconstruction efficiency
- acceptance: fraction of events with e, μ: $\mathrm{p_T} > 25\ \mathrm{GeV}$, $|\eta| < 2.5$
- $\sigma_{t\bar{t}}$=acceptance · $\sigma_{t\bar{t}}^{\mathrm{fid}}$ ⇒ dependence on PDF significantly reduced

$\sqrt{s}$	7 TeV		8 TeV	
	$\Delta\epsilon_{e\mu}/\epsilon_{e\mu}$ (%)	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)	$\Delta\epsilon_{e\mu}/\epsilon_{e\mu}$ (%)	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)
	Uncertainty (inclusive $\sigma_{t\bar{t}}$)			
$t\bar{t}$ modelling	0.71	1.43	0.65	1.22
Parton distribution functions	1.03	1.04	1.12	1.13
Total uncertainty ($\sigma_{t\bar{t}}$)	1.56	3.89	1.66	4.27
	Uncertainty (fiducial $\sigma_{t\bar{t}}^{\mathrm{fid}}$)			
$t\bar{t}$ modelling	0.84	1.56	0.74	1.31
Parton distribution functions	0.35	0.38	0.23	0.28
Total uncertainty ($\sigma_{t\bar{t}}^{\mathrm{fid}}$)	1.27	3.81	1.27	4.14

Performed in single lepton channel, at $\sqrt{s} = 7$ TeV

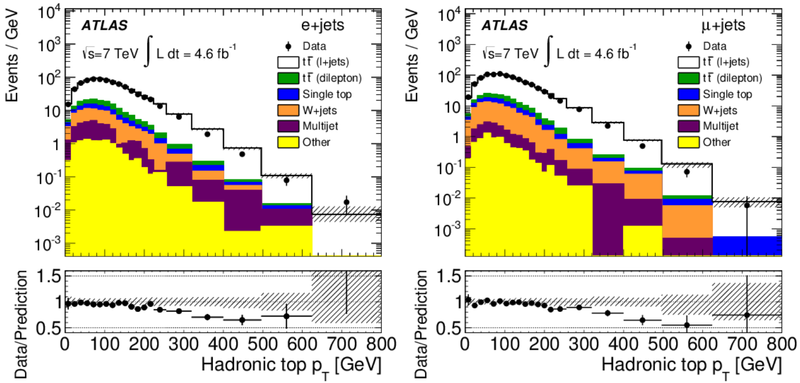


Signal events:

- exactly one e or μ with p_T >25 GeV, $|\eta| < 2.5$
- $\geq$ 4 jets with p_T >25 GeV, $|\eta| < 2.5$
- $\geq$ 1 b-tagged jet @ 70%
- $E\!\!\!/_T > 30$ GeV
- $m_T^W > 35$ GeV
  $m_T^W = \sqrt{2 p_T^\ell p_T^\nu (1 - \cos(\phi^\ell - \phi^\nu))}$
- + cut on quality of $t\bar{t}$ system reconstruction: $\log(L) > -50$

Hadronically decaying top p_T

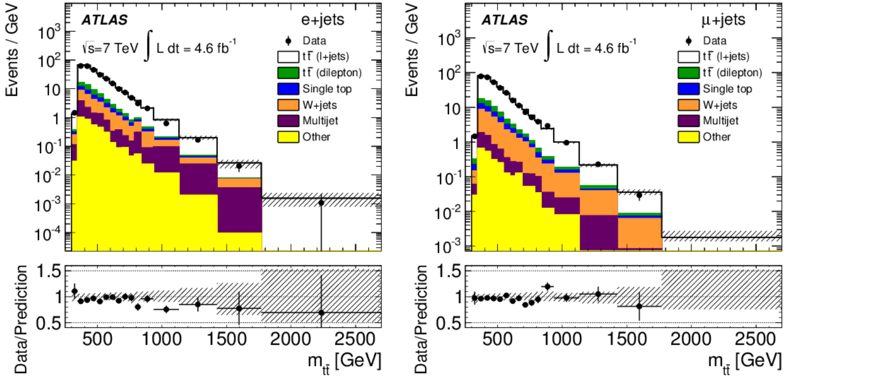
- pass MC predictions through detector simulation
- pass data and simulation through (the same) reconstruction and analysis
- figures: data vs simulation for hadronically decaying top p_T. Left: *e*-channel, right: μ-channel



For MC prediction: Alpgen +Herwig:
simulation prediction overshoots the data for high p_T(p_T>200 GeV).

Invariant mass of the $t\bar{t}$ system

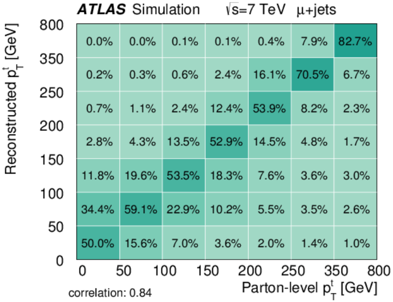
- pass MC predictions through detector simulation
- pass data and simulation through (same) reconstruction and analysis
- figures: data vs simulation for invariant mass of the $t\bar{t}$ system $\mathrm{m}_{t\bar{t}}$. Left: e-channel, right: μ-channel

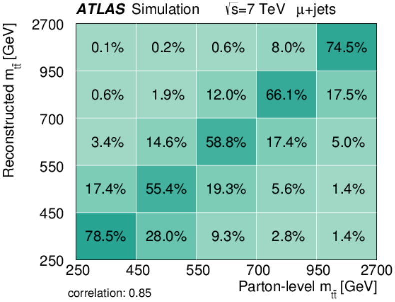


For MC prediction: ALPGEN +HERWIG:
agreement of data and simulation predictions (within uncertainties).

Unfolding

- background-subtracted measurements are corrected for detector effects
- regularized matrix inversion (Singular Value Decomposition method) used
- left: migration matrix for hadronically decaying top $\mathrm{p_T}$(μ-chan.)
- right: migration matrix for $\mathrm{m}_{t\bar{t}}$(μ-chan.)

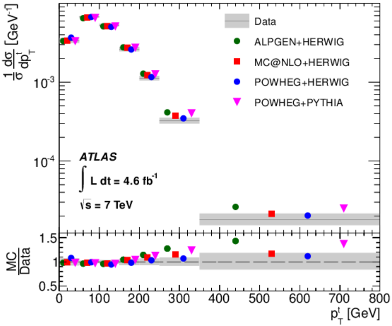


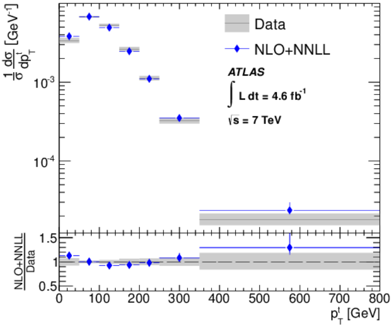


e and μ channel combination is performed using BLUE (best linear unbiased estimator) method.

After unfolding and channel combination:

- left: data vs various MC generator predictions
- right: top p_T compared to NLO+NNLL prediction, Phys. Rev. D **82** (2010) 114030. Uncertainties: MSTW2008NNLO PDF + error sets, μ_r, μ_f varied by factor of 1/2 and 2, scale choices: $\mu = m_{t\bar{t}}$ and $\mu = \sqrt{m_t^2 + {p_T}_t^2}$.



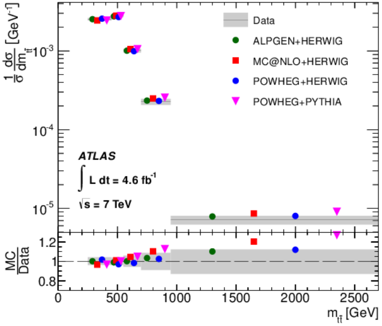


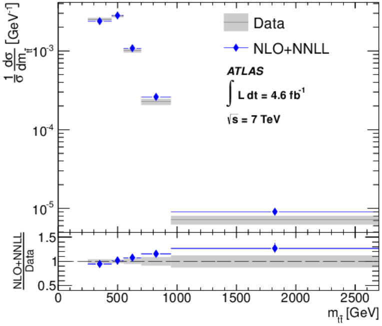
p-values: ALPGEN: 0.00, MC@NLO: 0.24, POWHEG-hvq +HERWIG: 0.57, POWHEG-hvq +PYTHIA: 0.00, NLO+NNLL: 0.27

Invariant mass of the $t\bar{t}$ system

After unfolding and channel combination:

- left: data vs various MC generator predictions
- right: $\mathrm{m}_{t\bar{t}}$ compared to NLO+NNLL prediction, JHEP **09** (2010) 097. Uncertainties: MSTW2008NNLO PDF + error sets, μ_r, μ_f varied by factor of 1/2 and 2, scale choices: $\mu = \mathrm{m}_{t\bar{t}}$ and $\mu = \sqrt{m_t^2 + \mathrm{p_T}_t{}^2}$.





p-values: ALPGEN: 0.63, MC@NLO: 0.14, POWHEG-hvq +HERWIG: 0.24, POWHEG-hvq +PYTHIA: 0.01, NLO+NNLL: 0.20

MC generator *p*-values affected by several steerable modelling aspects:

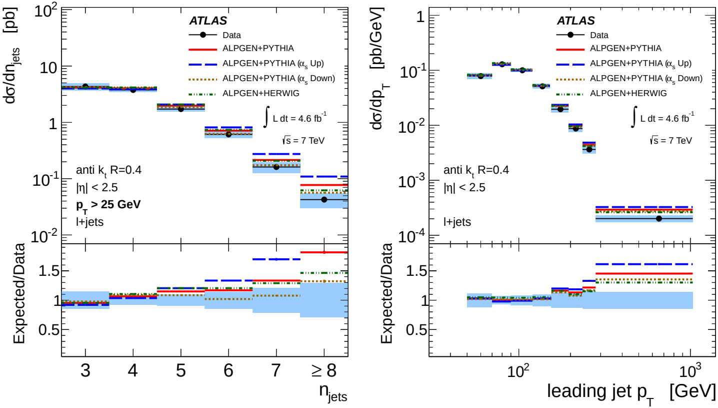
- **Parton Distribution Functions:** PDF choice can increase/decrease data-simulation agreement. Top pair production differential distributions should thus soon be relevant for constraining PDF models (e.g. *g* PDF at high *x* values).
- **Parton shower and hadronization details:** e.g. *p*-values of POWHEG-hvq +HERWIG differ notably from POWHEG-hvq +PYTHIA ones. (Partly) explained by momentum rescaling during parton shower. See e.g. P. Nason's talk @ May 2014 TOPLHCWG mtg.
- **Renormalization and Factorization scale choice**
- **Generator-specific parameters/assumptions:** e.g. details of hardest emission in NLO generators. See e.g. K. Hamilton's talk @ Top2012.
- ...

Data-simulation agreement and understanding can be improved by generator tuning and extension of models taken into account.

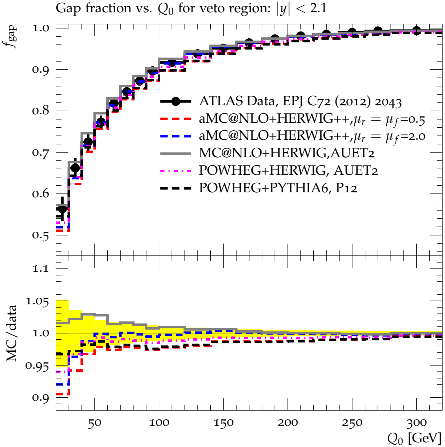
Jet multiplicity and p_T

Differential cross-section as a function of jet multiplicity and jet transverse momentum:

- 7TeV, single lepton channel
- jet multiplicity: using a number of p_T threshold cuts: 25, 40, 60, 80 GeV
- transverse momentum: up to including the fifth jet
- measurements corrected for detector effects using Bayesian Iterative unfolding



- Measure fraction of events with no *extra* jet in a central rapidity region of the detector (f_{gap}).
- 7 TeV, dileptonic events with 2 *b*-tagged jets (enables flagging *extra* jets not from $t\bar{t}$ decay)



- measurement done as a function of p_T-threshold (Q_0) and scalar sum of *extra* jet activity (Q_{sum})
- both jet multiplicity and p_T(prev. slide) and gap fraction measured in fiducial phase-space and (being) implemented in Rivet framework; valuable information for improving the description of extra jet activity in $t\bar{t}$ events

Data vs theory for Njet and $f_{gap}(Q_0)$, $f_{gap}(Q_{sum})$

General trend:
if a model prediction of $f(Q_0)$ too low,
then Njet too high. Consistent with expectations.

NLO generators:

- in general yield satisfactory agreement with the data for $f_{gap}(Q_0)$
- the observable has some sensitivity also to parton shower activity, defficiencies or bugs in which can spoil the data-MC agreement (e.g. dead regions in fortran HERWIG, buggy MPI activity in old versions of HERWIG++ $\leq$ 2.6.1)
- not expected to do well for Njet (out of the box) and mostly don't

LO Multi-leg generators:

- both of $f_{gap}(Q_0)$, $f_{gap}(Q_{sum})$ and Njet proove to be challenging to describe within current experimental uncertainties
- measurements useful (and used) for generator tuning (fiducial, Rivet)
- sensitive parameters: factorization scale, renormalization scale, parameters controlling initial and final state radiation

$t\bar{t}$ production via qg or $q\bar{q}$: t emitted in direction of q, $\bar{t}$ in direction of $\bar{q}$

Tevatron :

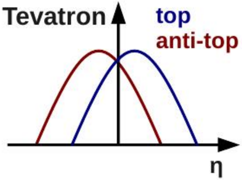
$$A_{FB} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

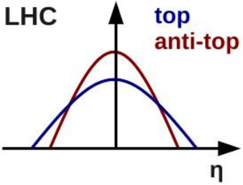
$$\Delta y = y_t - y_{\bar{t}}$$

LHC:

$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

$t\bar{t}$ asymmetry: $\Delta|y| = |y_t| - |y_{\bar{t}}|$
(lepton asymmetry: $\Delta|\eta| = |\eta_{l^+}| - |\eta_{l^-}|$)



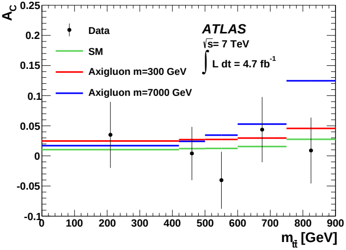


- $t\bar{t}$-based A_{FB}: $\sim$ **8.8% in SM***
- $t\bar{t}$-based A_C: $\sim$ **1.2% in SM***

*SM reference values: NLO QCD+EW corrections, Phys. Rev. D **86**, 034026

Measure top quark based asymmetry

- use kinematic fit based on a likelihood approach to reconstruct t and $\bar{t}$ 4-momenta
- correct for detector effects using Fully Bayesian unfolding

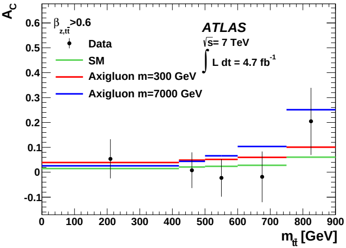


Inclusive result:

$A_c^{t\bar{t}} = 0.006 \pm 0.010($ stat. $+$ syst.$)$,
SM: $A_c^{t\bar{t}} = 0.0123 \pm 0.0005$

Differential measurements:

- $m(t\bar{t}), \mathrm{p_T}(t\bar{t}), y(t\bar{t})$
- z-component of $t\bar{t}$ velocity: β;
- measure differential asymmetries at $\beta > 0.6$



ATLAS + CMS combination:

$A_c^{t\bar{t}} = 0.005 \pm 0.007$ stat. $\pm\, 0.006$ syst.

All measurements consistent with SM.

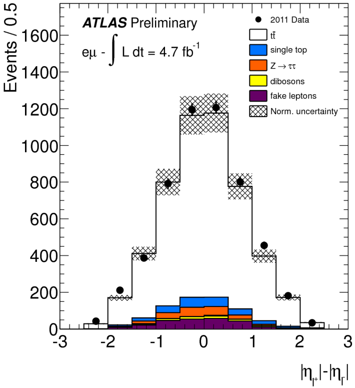
Measure lepton and top quark based asymmetry

- A_C^{ll}: no reconstruction needed
- $A_C^{t\bar{t}}$: use ME method to reconstruct t and $\bar{t}$ 4-momenta
- correct for detector effects using calibration

Inclusive asymmetry results:

- $A_c^{ll} = 0.023 \pm 0.012$ stat. ± 0.008 syst.
  SM : $A_c^{ll} = 0.0049 \pm 0.0001$
- $A_c^{t\bar{t}} = 0.057 \pm 0.024$ stat. ± 0.015 syst.
  SM : $A_c^{t\bar{t}} = 0.0123 \pm 0.0005$

- **for both single lepton and dilepton results: stat. > syst.**



Conclusions

- inclusive and differential $t\bar{t}$ cross-section measurements are precise enough to challenge state-of-the-art theory predictions
- differential measurements effective in highlighting a number of observables sensitive to details of MC generator modelling/theory assumptions:
  - top $\mathrm{p_T}$
  - invariant mass and $\mathrm{p_T}$ of the $t\bar{t}$ system
  - differential cross-section as a function of jet multiplicity
  - ...
- a number of recent Run I measurements done in fiducial region. This reduces dependence on assumptions made for the simulated predictions.
- Together with implementation in Rivet framework, fiducial measurements also ease comparisons to theory predictions.
- A recently particularly interesting and debated $t\bar{t}$ observable, charge asymmetry, is so far found to be consistent with the SM in inclusive and differential ATLAS measurements.
- A number of other measurements done/in progress with Run I data; `https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults` .