Top quark production cross-section at LHC in ATLAS.

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Outline

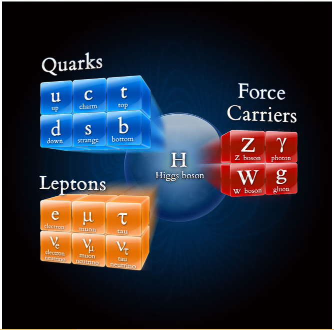
- Introduction
  - Top quark within Standard Model
  - The Tevatron legacy
  - Why top is interesting?
  - How to measure it in ATLAS?
- Top-pair production
  - Single and di-lepton channel
  - Differential $t\bar{t}$ cross section
- Single top production
  - t-channel
  - Wt-channel
- Summary & prospects

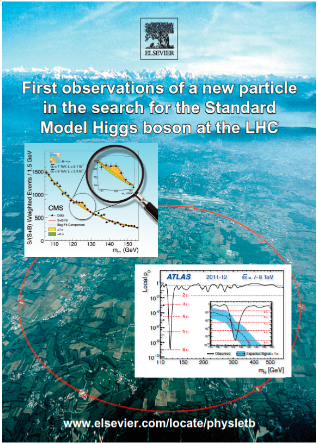
Setting the scene: Top in the Standard Model

The SM top quark:

- Spin $1/2$ fermion, charge $+2/3$.
- Weak-isospin partner of the bottom quark
- Most massive constituent of matter

  $m_t = 173.29 \pm 0.23(stat.) \pm 0.92(syst.)\,\mathrm{GeV/c^2}$ (CONF-2013-102)
  - $\sim$ 40 times heavier than bottom quark
- Short lifetime: $\tau \sim 4 \times 10^{-25}$ s
  - Decays faster than hadronisation
  - Spin information passed to decay products
- Large Yukawa coupling in SM: $Y_t > 0.9$.





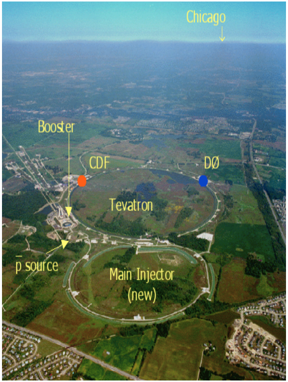
The Higgs boson:

- The last piece for the Standard Model puzzle was discovered at the LHC (CERN) on July 2012.
- $m_{higgs} \sim 126$ GeV

Top discovery

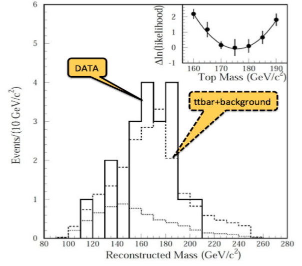
The top quark was discovered in 1995 by the CDF and D0 collaborations at the Tevatron proton-antiproton collider at Fermilab.

TEVATRON



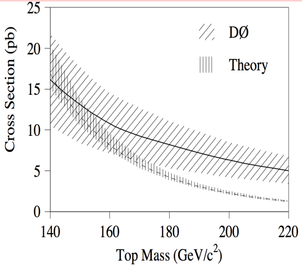
Centre of mass energy: 1.96 TeV

CDF, PRL 74 2626 (1995)



- $\rightarrow$ 19 selected events
- $\rightarrow$ exp. background 6.9 events
- $\rightarrow$ 4.8 s.d. significance
- $\rightarrow$ $m_{top} = 176 \pm 8(stat.) \pm 10(syst.)\ \mathrm{GeV/c^2}$
- $\rightarrow$ $\sigma_{t\bar{t}} = 6.8^{+3.6}_{-2.4}$ pb

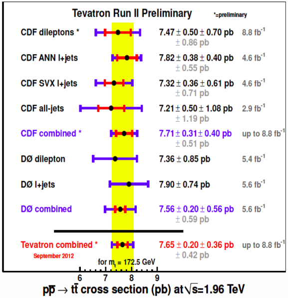
D0, PRL 74 2632 (1995)



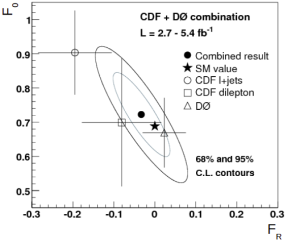
- $\rightarrow$ 17 selected events
- $\rightarrow$ exp. background 3.8 events
- $\rightarrow$ 4.6 s.d. significance
- $\rightarrow$ $m_{top} = 199^{+19}_{-21}(stat.) \pm 22(syst.)\ \mathrm{GeV/c^2}$
- $\rightarrow$ $\sigma_{t\bar{t}} = 6.4 \pm 2.2$ pb

The top physics legacy of the Tevatron (1)

- Top quark is mainly produced in top-antitop ($t\bar{t}$) pairs

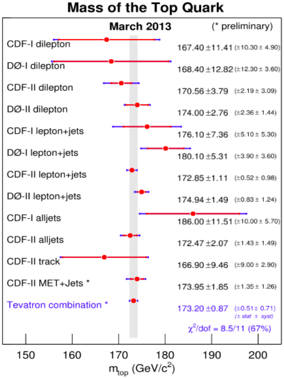


Phys. Rev. D 85 (2012) 071106



SM predictions: $F_0 \sim 69\%$; $F_R \sim 0\%$; $F_L \sim 31\%$

Top pair cross section ($\sigma_{t\bar{t}} = 7.50 \pm 0.48$ pb(6%)) and top mass ($m_t = 172.9 \pm 0.9$ GeV (0.5%)) have been determined in all possible channels at Tevatron

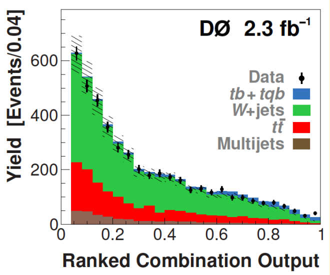


- With thousands of $t\bar{t}$ collected by D0 and CDF, many properties of the top have been studied (spin correlation, charge asymmetry, charge, width, W helicity in top decay).
  - Almost all measurements consistent with Standard Model expectations within uncertainties
  - The measurement of forward-backward asymmetry show more than 3σ deviation from the SM

The top physics legacy of the Tevatron (2)

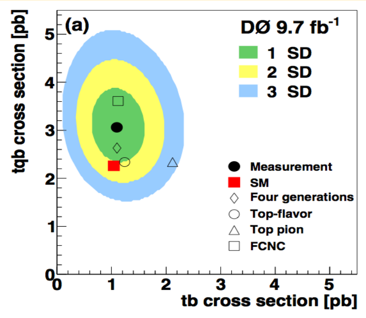
- Single top quarks can be produced by electroweak interaction via three channels: *t*-channel, *s*-channel and *Wt*-channel.

D0 and CDF made first observation in 2009



Expected 223 single top events from 4519 *b*-tagged selected events

Sensitivity to some models of BSM physics that will change the $s-$ or $t-$ channel cross section

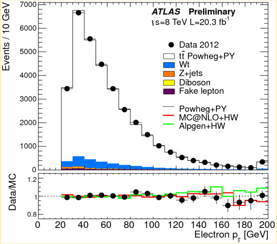


- Since they are looking for a small signal in a very large background ($S/B \sim 0.05$), these analyses introduced the use of Multivariate Techniques: Neural Network (NN), Boosted Decision Trees (BDT).
- The first evidence of the s-channel single top production at D0 was published in 2013

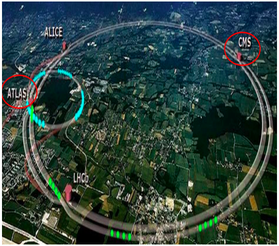
Top quark physics at the LHC

- LHC have opened a new era for high precision measurements top quarks.

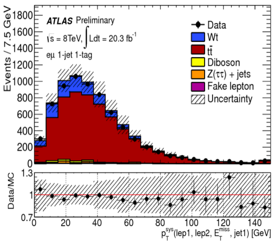
Top pair production:



21559 events observed, 2640 expected to be background ($S/B \sim 7$)



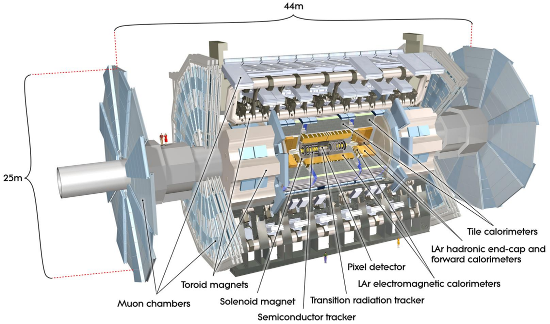
Single top production:



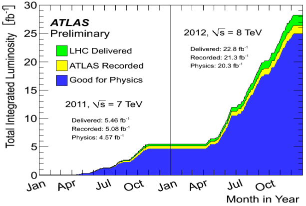
13159 events observed, 1140 expected to be *Wt* ($S/B \sim 0.1$)

- LHC top physic program complementary to Tevatron:
  - Same production mechanism but at different rates
  - Higher centre-of-mass energy
  - Large top quark samples available at 7 (2011) and 8 TeV (2012):
    - More than $10\times$ top quarks produced than at Tevatron with $\sim 5\ \mathrm{fb}^{-1}$ (2011)

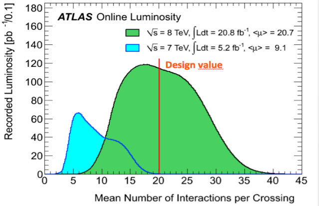
The ATLAS detector



Results presented based on:
4.7 fb^{-1}(2011) to 20.3 fb^{-1}(2012)



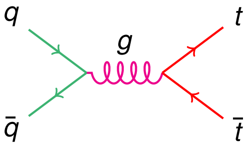
- High detector operation and data quality efficiency:
  - Detectors, trigger & DAQ systems working very well.
  - Average fraction of operational channels close to 100% for all subsystems.
- Pileup challenge:
  - Reach higher values of pile-up without degrading performance.
  - Twice more pileup in 2012 than in 2011.



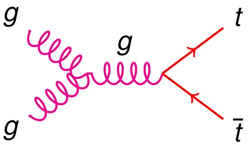
Top quark production at LHC

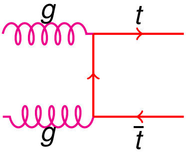
Top-pair production via strong interaction

15% $q - \bar{q}$ **annihilation**



Main mode (85%): **gluon fusion**



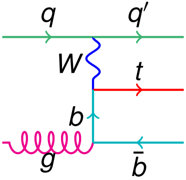


Calculations available up to NNLO + NNLL accuracy
with $m_t = 172.5$ GeV

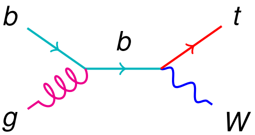
$\sigma(7 \text{ TeV}) = 177.3^{+10.1}_{-10.8}$ pb
$\sigma(8 \text{ TeV}) = 252.9^{+13.3.2}_{-14.5}$ pb

Single top production via electroweak interaction

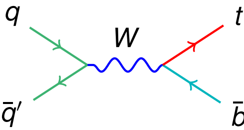
***t*-channel**



***Wt* channel**



***s*-channel**



Approx NNLO
$m_t = 172.5$ GeV

$\sigma(7 \text{ TeV}) = 64.6 \pm 2.4$ pb
$\sigma(8 \text{ TeV}) = 87.8 \pm 3.4$ pb

$\sigma(7 \text{ TeV}) = 15.7 \pm 1.1$ pb
$\sigma(8 \text{ TeV}) = 22.4 \pm 1.5$ pb

$\sigma(7 \text{ TeV}) = 4.6 \pm 0.2$ pb
$\sigma(8 \text{ TeV}) = 5.6 \pm 0.2$ pb

Why is the top quark so interesting?

Top physics is one of the main pillars of the physics program at the LHC:

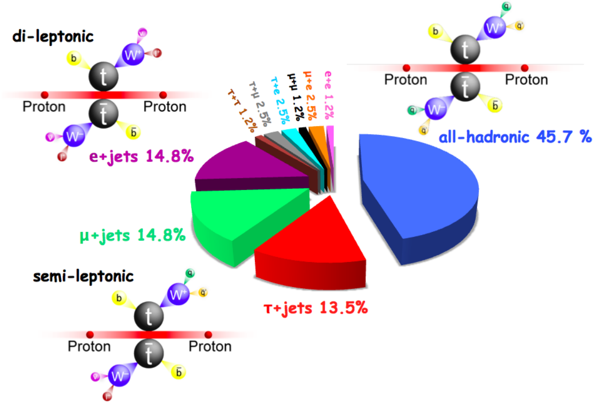
- Direct probe of the Standard Model:
  - Measurements of the top-pair production cross-section provide:
    - Test of perturbative Quantum Chromodynamics (QCD) calculations
    - Test of the SM description of the top quark decay
  - Measurements of the single top production provide a test of SM predictions:
    - Production cross-section and direct determination of the quark mixing matrix element $|V_{tb}| \rightarrow$ Test of unitarity of the CKM matrix
    - Probe of the b-quark structure function
- Any observed deviation from the SM predictions would give hints to different models of new physics
  - Several scenarios with direct/indirect coupling to new physics
    - Excited quarks, charged Higgs, charged W-like bosons, composite models
- Top is an important background in searches to Higgs and several expected beyond the SM (BSM) processes

Top quark decay in SM

In the SM, top quarks decay nearly 100% into a *W* and a *b* quark

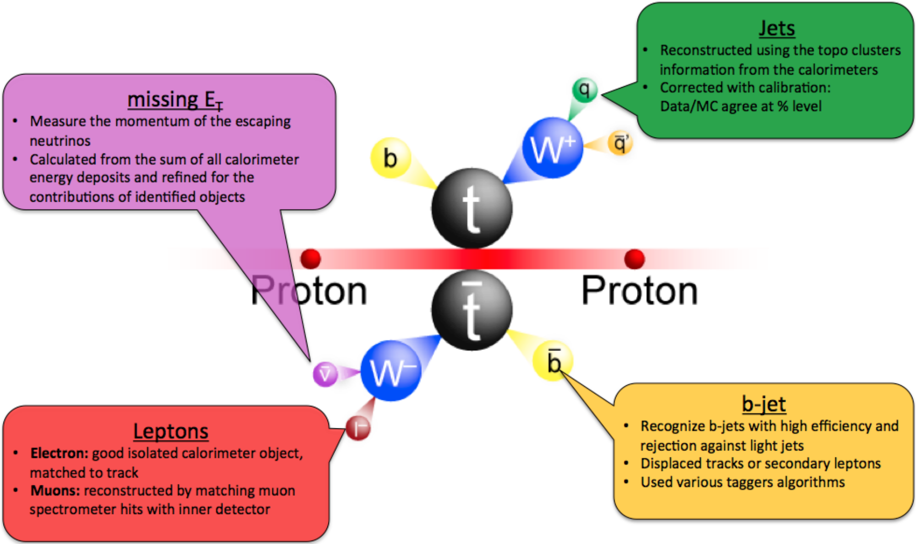
- W decays either to quarks or leptons
- Classified according to W boson decay

Top-pair Branching Ratios



Ingredients for top quark physics

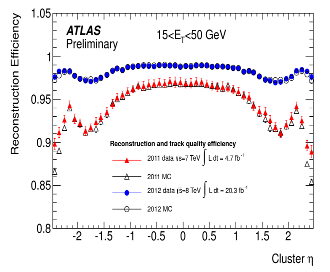
Top physics analysis involve a broad range of signatures: leptons (e, μ, τ), jets, E_T^{miss}.



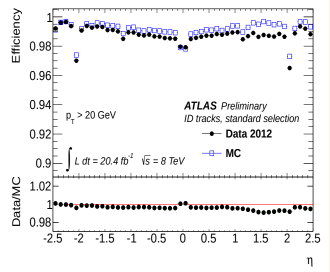
Leptons

- **Electrons** reconstructed combined the information of tracker and calorimeter.
  - Electron reco. efficiency closed to 98% in 2012
  - Good description of data by MC
- **Muons** reconstructed combined the information from silicon tracking and muon systems
  - Muon ID reco. efficiency $\sim$ 99% in 2012
- **Taus** identified through the reconstruction of their hadronic decay products.
  - Challenge: Used multivariate techniques like BDT to remove jets and electron faking tau candidates
- Most of the lepton systematic uncertainties related to:
  - Reco., ID and trigger efficiencies.
  - Momemtum, energy scale and lepton resolution.
- Lepton uncertainties affect cross-section measurements up to 6%.

Electron reconstruction efficiency

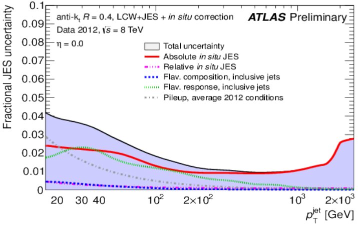


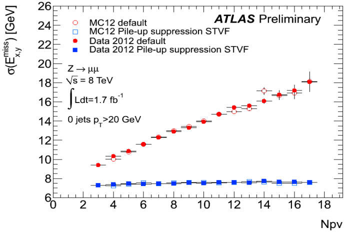
Muon identification reconstruction efficiency



Jets, *b*-jets & Missing Transverse Energy

- **Jets** reconstructed with the anti-k_t algorithm from topological clusters of energy depositions with a distance parameter of 0.4
  - Several corrections applied to account for pile-up, vertex position, η & p_T effects (based on simulation).
  - Residual corrections for in-situ techniques.
- Jet Energy Scale uncertainties at the level of $1-2\%$



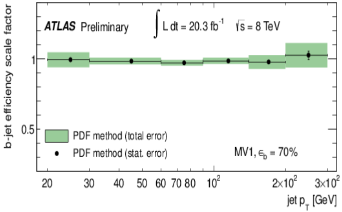


- **Missing transverse energy** calculated as the negative of the vectorial sum of all objects in the event

$$E_T^{miss} = E_T^{miss}(e) + E_T^{miss}(\gamma) + E_T^{miss}(jets) + E_T^{miss}(SoftTerm) + E_T^{miss}(\mu)$$

- Jet and soft terms are the most affected by pileup
  - Pileup suppression improves E_{miss}^{T} resolution, but worsen the scale by over-correcting the soft terms

- To recognise *b*-jets with high efficiency:
  - several algorithms based on his characteristics. e.g. long lifetime and large mass to identify the secondary decay vertex.
- *b*-tag efficiency systematics up to 8% and the mistagging of jets also considered as systematics



Backgrounds estimate

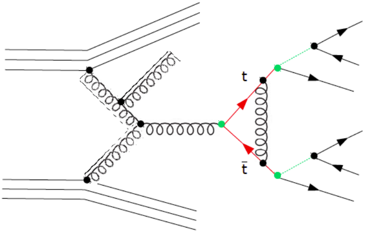
- Backgrounds are events that pass the same requirements as signal because of:
  - same final state & kinematics
  - detection imperfection
- There are several methods to estimate the background sources:
  - By Monte-Carlo (MC) simulation (see next slide)
  - By data-driven methods;
    W+jets and multijet backgrounds are difficult to model in simulation
    - Multijet; Matrix method:
      Using real/fake efficiencies in loose/tight selections
    - $W + jets$; Charge Asymmetry Method
      The number of *W*+jets events (N_{W+jets}) is estimated by measuring the difference between the number of events selected with an antilepton (N^{ℓ^+}) and with a lepton (N^{ℓ^-}):

$$N_{W+jets} = R(W)x(N_{tot}^{\ell^+} - N_{tot}^{\ell^-})$$

with $N_{tot}^{\ell^+}$ and $N_{tot}^{\ell^-}$ measured in data. The factor R is the inverse of the W charge asymmetry and it is also extracted from data

Montecarlo & predictions

- Monte Carlo simulation consist of several steps:
  - Matrix element included:
    - Leading-Order (LO) or Next-to-Leading-Order (NLO) calculations
    - Top quark decays
    - Parton Density Functions (PDF)
    - Other effects: Spin correlation, V-A structure, Top and *b* masses
  - Non-perturbative part of the event generation:
    - Showering including Initial and Final State Radiation (IFSR)
    - Hadronization and Factorization
    - Color reconnections, underlying event, pileup



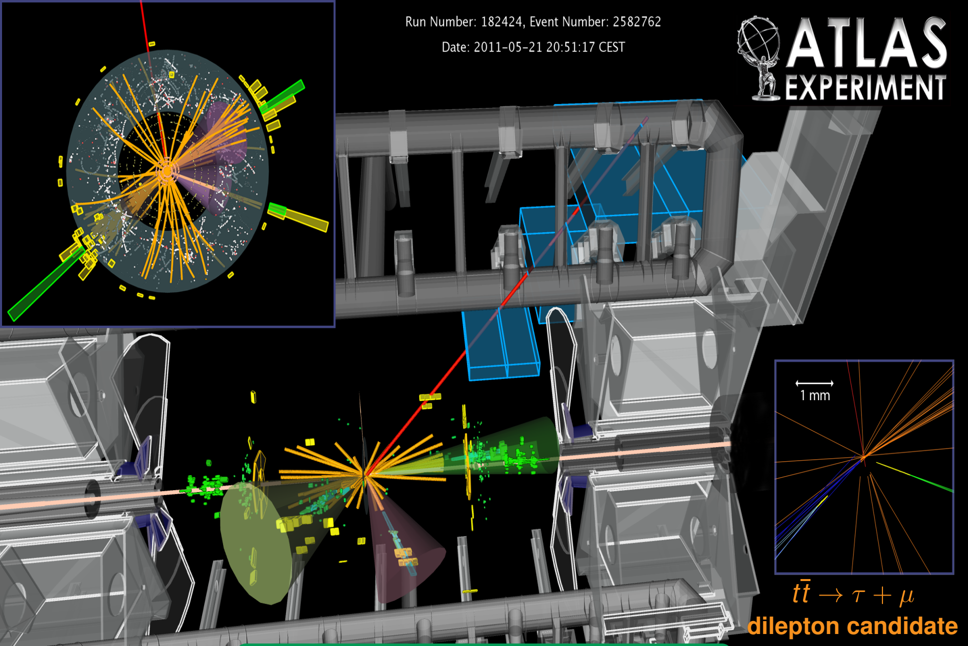
- For single top and $t\bar{t}$ signal modelling several MC are used:

Matrix element	Shower & Hadronization	PDF	Tune
MC@NLO	Herwig + Jimmy	cteq66 or CT10	AUET1/2
POWHEG	Pythia 6	cteq66 or CT10	Perugia 2011 C
ALPGEN	Herwig + Jimmy	cteq6ll	AUET2

- Alternative MC samples are produced to estimate the generator, parton shower/fragmentation modelling and IFSR uncertainties
- Calculations of the theoretical cross-section for $t\bar{t}$ and single top are available at NNLO, including the resummation of next-to-next-to-leading logarithmic (NNLL) soft gluon terms

Physics analysis steps

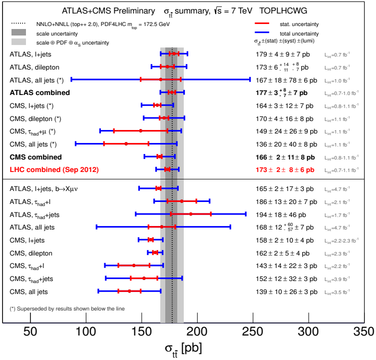
- Start with the output of reconstruction and apply an event selection:
  - Select sample(s) enriched in top quark events with requirement on the reconstructed kinematic objects quantities
  - Event selection designed to improve the signal (S) over background (B) in your event sample
- Extract measured distributions by technique that involves:
  - subtracting/accounting for the effect of the background
  - correcting for detector effects (unfolding the measured distribution)
  - accounting for efficiency/acceptance corrections
- Assess statistic and systematic uncertainties on the measured quantity
- Comparing data to theory

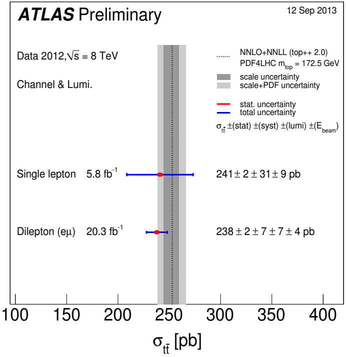


TOP PAIR PRODUCTION

Inclusive top-pair cross-section summary

Summary of measurements of the top-pair cross-section compared to the corresponding theoretical expectation

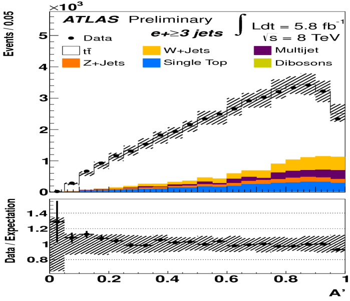


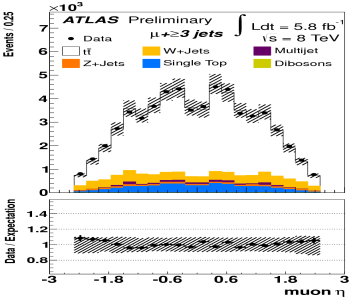


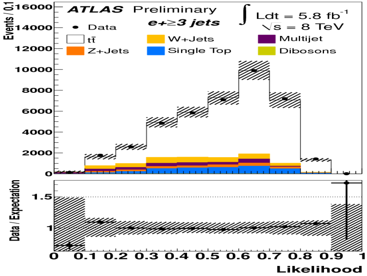
- LHC $\sigma_{t\bar{t}}$ results at 7 TeV:
  - Broad range of measurements from ATLAS and CMS experiments for nearly all of the expected final states
  - Results consistent with standard model at 7 TeV
  - LHC combination: $\sigma_{t\bar{t}} = 173 \pm 8\ (\text{stat.}) \pm 6\ (\text{syst.})$ pb
- ATLAS $\sigma_{t\bar{t}}$ results at 8 TeV:
  - First measurements in Single lepton and Dilepton channels
    - Following slides shows these NEWEST measurements

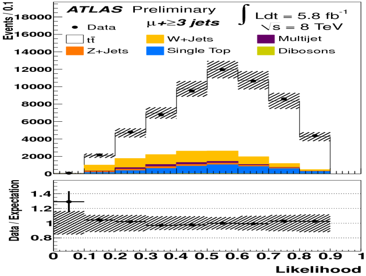
Single lepton channel @ 8 TeV: analysis strategy

- Analysed data corresponding to 5.8 fb^{-1} (ATLAS-CONF-2012-149)
- **Selection**:
  - One isolated e or μ with $p_T > 40$ GeV, $|\eta| < 2.5$
  - At least 3 jets with $p_T > 25$ GeV, $|\eta| < 2.5$ with at least 1 b-tagged
  - e+jets: $E_T^{miss} > 30$ GeV, $m_T(W) > 30$ GeV
  - μ+jets: $E_T^{miss} > 20$ GeV, $m_T(W) + E_T^{miss} > 60$ GeV
- **Main backgrounds:**
  - vector boson production ($Z/\gamma*$+jets, W+jets), single top and diboson (ZZ,WZ,WW) are simulated with MC
  - multijet is estimated using the data-driven Matrix Method.
- **Analysis:**
  - Number of $t\bar{t}$ events ($N_{t\bar{t}}$) is extracted using a likelihood discriminant template fit.
  - Discriminant variables using in the fit: $\eta_{e,\mu}$ and aplanarity (A')









- The $t\bar{t}$ production cross section:

$$\sigma_{t\bar{t}} = \frac{N_{t\bar{t}}}{\mathcal{L} \times BR \times \varepsilon_{sig}}$$

$\mathcal{L}$: integrated luminosity, *BR*: branching ratio,

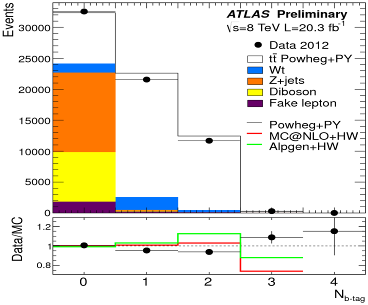
ε_{sig} product of signal acceptance and efficiency

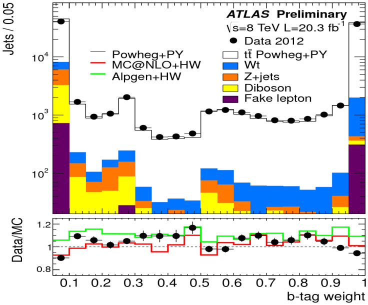
$$\sigma_{t\bar{t}} = 241 \pm 2\ (\mathrm{stat.}) \pm 31\ (\mathrm{syst.}) \pm 9\ (\mathrm{lumi.})\ \mathrm{pb}$$

- Main systematic sources:
  - Signal modelling (11%) and jet uncertainties (5 – 6%)

Dilepton channel @ 8 TeV: event selection

- Analysed data corresponding to 20.3 fb^{-1} (ATLAS-CONF-2013-097)
- **Selection**:
  - Require exactly one $e\mu$ pair with opposite sign each isolated
  - One or two *b*-tagged jets (very pure signal selection)
  - For all objects: $p_T > 25$ GeV, $|\eta| < 2.5$
- **Main backgrounds all modelled with MC:**
  - With two real leptons: single top Wt production and $Z \to \tau\tau$+jets and diboson (ZZ, WZ, WW)
  - With one real lepton and one fake lepton: Z+jets and single top t-channel





Dilepton channel @ 8 TeV: results

- **Analysis:**
  - Number of $t\bar{t}$ events in the 1 b-tag (N_1) and 2 b-tag (N_2) signal region is extracted using a maximum likelihood fit.
  - Simultaneous estimation of $\sigma_{t\bar{t}}$ and the efficiency to reconstruct b-tag jets (ϵ_b)
    - reduces jets and modelling uncertainties

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

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

- $\epsilon_{e\mu}$: efficiency to pass $e\mu$ preselection
- C_b correlations between two b-tagged jets

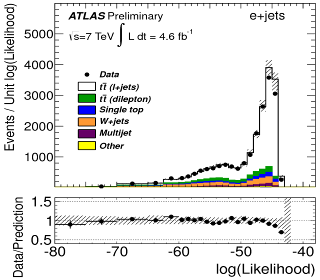
$\sigma_{t\bar{t}} = 237.7 \pm 1.7\,\text{(stat.)} \pm 7.4\,\text{(syst.)} \pm 7.4\,\text{(lumi.)} \pm 4.0\,\text{(beam energy) pb}$

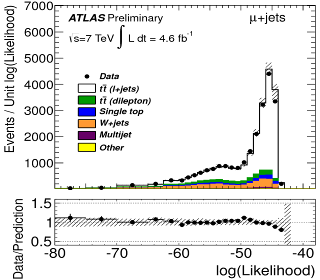
- Main systematic sources:
  - Luminosity (3.1%), beam energy (1.7%), signal modelling (1.5%) and electron ID (1.4%)

Differential top quark pair cross section

$d\sigma_{t\bar{t}}/dX$ @ 7 TeV: event selection

- Analysed data corresponding to 4.6 fb^{-1} (ATLAS-CONF-2013-099)
- Lepton + jets **selection**:
  - Exactly one isolated lepton e or μ with $p_T > 25$ GeV and $|\eta| < 2.5$
  - At least 4 jets with $p_T > 25$ GeV and $|\eta| < 2.5$ and at least one b-tagged jet
  - $E_T^{miss} > 30$ GeV & $m_T^W > 35$ GeV
- **Method:**
  - $d\sigma_{t\bar{t}}/dX$ spectra measurement in bins of p_T^t, $m_{t\bar{t}}$, $y_{t\bar{t}}$ and p_T^{tt}
  - $t\bar{t}$ kinematics spectra reconstructed using a maximum likelihood fitter to the reconstructed objects (m_T^W, E_T^{miss}, 1st b-tag p_T).
    - Likelihood function includes Breit-Wigner functions taking advantage of the known W boson and top quark masses, as well as transfer functions relating the measured lepton and jet energies to the corresponding parton level energies
    - $log\mathcal{L} > -50$





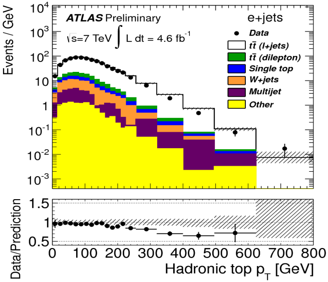
$d\sigma_{tt}/dX$ @ 7 TeV: reconstructed variables

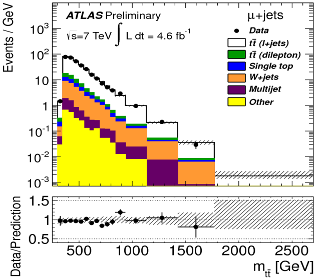
- Differential cross-section **determination:**
  - Reconstructed variables are unfolded used regularised unfolding (SVD) after background subtraction
    - To correct for detector effects and acceptance

$$\frac{d\sigma}{dX_j} = \frac{1}{\Delta X_j} \cdot \frac{\sum_i \mathcal{M}^{-1}_{ji}[D_i - D_i]}{BR \cdot \mathcal{L} \cdot \epsilon_j}$$

$\mathcal{M}$: migration matrix derived from simulation, ϵ: efficiency

- Differential cross-sections are **normalised**
  - systematics not related to the shape cancelled in the ratio
- Main **systematics**:
  - Jet energy scale ($\sim$ 3%), signal modelling ($\sim$ 2%), *b*-tagging efficiency ($\sim$ 2%)
- **The unfolded distributions are compared to different MC generators and theoretical predictions**

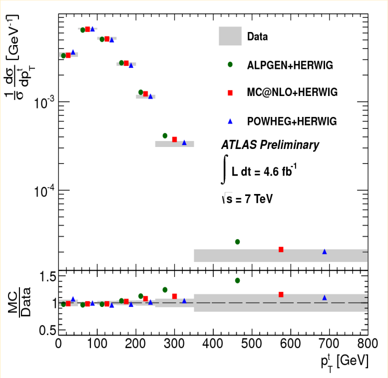




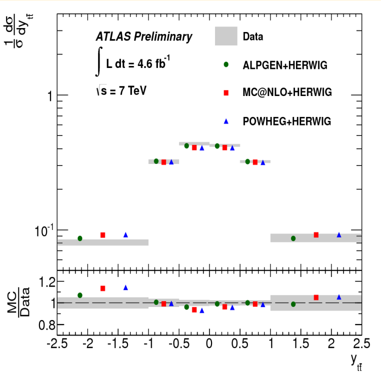
$d\sigma_{tt}/dX$ @ 7 TeV: MC generators

- Comparison to several generators ALPGEN, MC@NLO and POWHEG:

Data is softer than prediction
Best data description by POWHEG+HERWIG



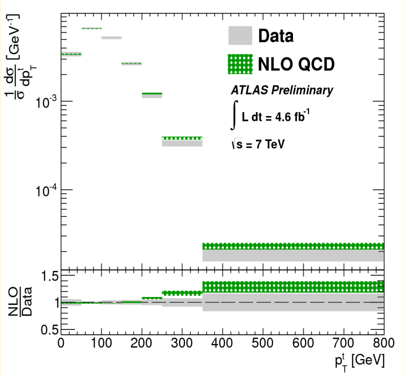
Overestimation by MC@NLO and POWHEG for $y < -1$
Best data description by ALPGEN+HERWIG



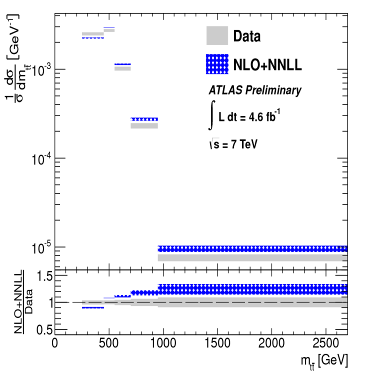
$d\sigma_{tt}/dX$ @ 7 TeV: predictions

- Comparison to several predictions:
  - NLO QCD predictions with CT10 PDF
  - NLO + NNLL calculations using the MSTW2008NNLO PDF
- Some trend visible but they agree within uncertainties
- Worst agreement is observed for NLO + NNLL predictions

Comparison with NLO



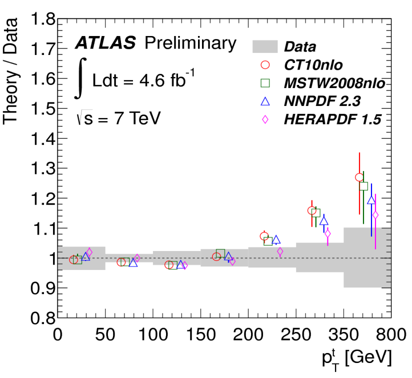
Comparison with NLO+NNLL



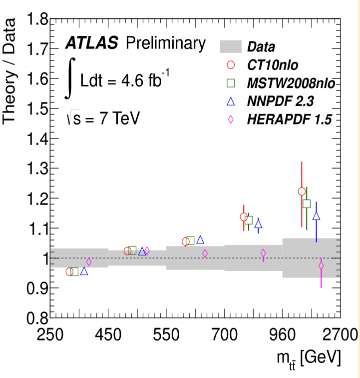
$d\sigma_{tt}/dX$ @ 7 TeV: PDF sets

- Predictions of various PDF sets are compared: CT10, MSTW2008, NNPDF and HERAPDF using NLO theory calculation

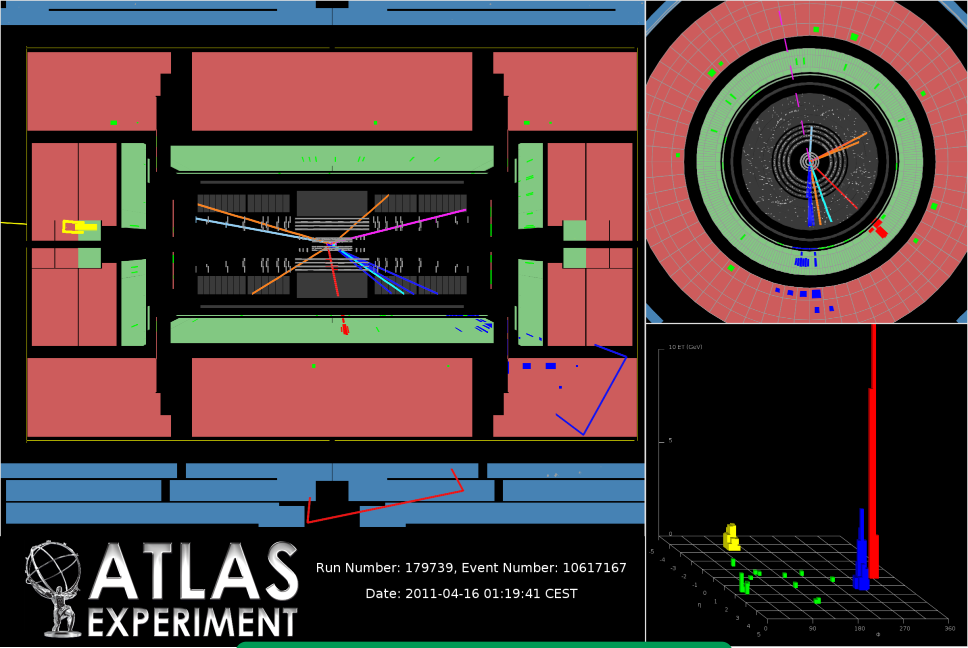
Disagreement at high p_T for all predictions need more data to gain significance



HERAPDF gives the best data description deviation at high m_{tt} for others



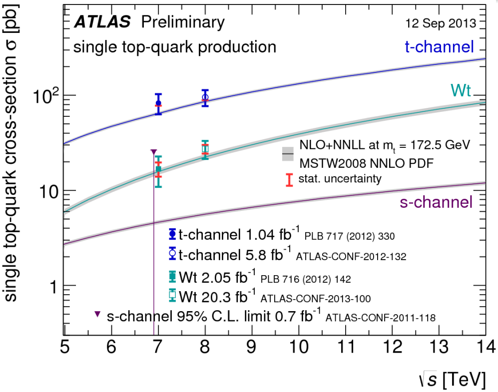
- Data has the sensitivity to test the predictions, indicates that including these measurements could improve future PDF fits.



SINGLE TOP QUARK PRODUCTION

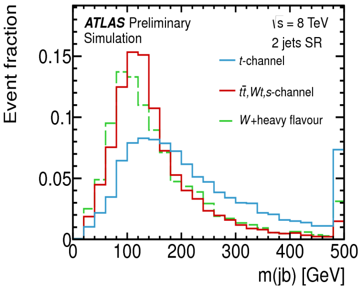
Single top quark production summary

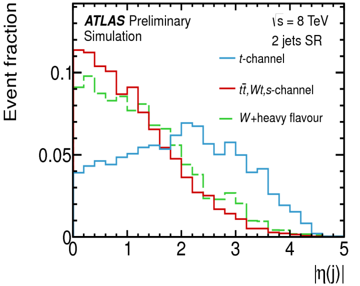
Summary of measurements of the single top-quark cross-section compared to the corresponding theoretical expectation



- Results in all channels in the single top quark sector at 7 and 8 TeV
- Present here the LATEST results at 8 TeV

- Analysed data corresponding to 5.8 fb^{-1} (ATLAS-CONF-2012-132)
- **Selection**:
  - Require exactly one isolated lepton (e/μ) with $p_T > 25$ GeV
  - Two or three jets with $|\eta| < 4.5$ and $p_T > 30$ GeV and exactly one *b*-tagged jet
  - $E_T^{miss} > 30$ GeV, $m_T(W) > 50$ GeV
- Main **backgrounds**: *W*+jets, top pairs and multijet
- **Analysis**:
  - For signal/background discrimination combine several kinematic variables into one discriminant by using a Neural Network (NN) technique
  - 11 highest-ranking variables are chosen in the two-jet (signal region) and three-jets (control region) samples

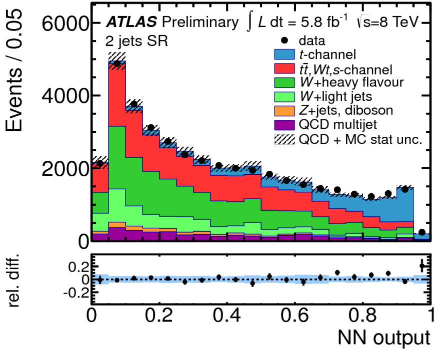


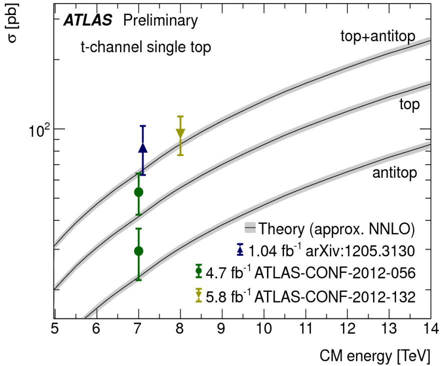


t-channel @ 8 TeV: results

- The *t*-channel cross-section is measured from the maximum likelihood fit to the NN output distributions

$$\sigma_{t-channel} = 95 \pm 2\ (\text{stat.}) \pm 18\ (\text{syst.})\ \text{pb}$$

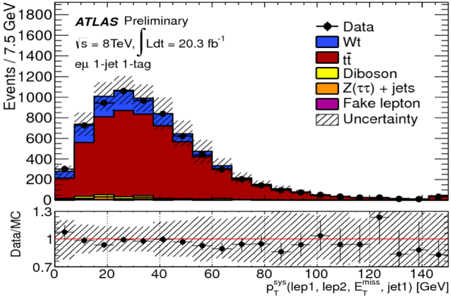


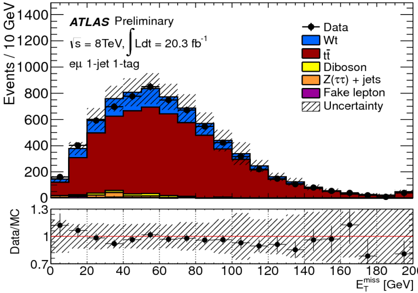


- Main systematics: IFSR (9.1%), *b*-tagging efficiency (8.5%) and jet energy scale (7.7%)

Wt channel @ 8 TeV: analysis strategy

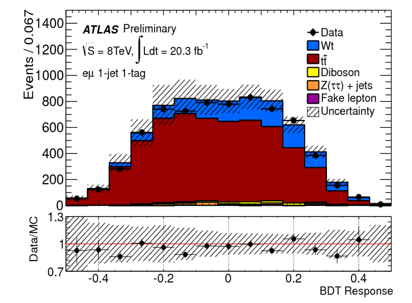
- Analysed data corresponding to 20.3 fb^{-1} (ATLAS-CONF-2012-100)
- **Selection**:
  - Require two opposite sign leptons (only $e\mu$) with $p_T > 25$ GeV
  - One or two central jets with $p_T > 30$ GeV and at least one b-tagged jet
- The main **background** is the top pair production
- **Analysis**:
  - To separate the *Wt* signal from the large $t\bar{t}$ background a multivariate method called BDT is used.
  - 19 highest-ranking variables are chosen in the signal region (exactly 1 b-tag) and 20 for the control region (at least 1 b-tag)



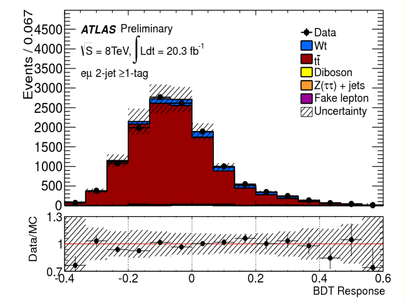


Wt channel @ 8 TeV: cross-section measurement

1-jet signal region; $S/B \sim 0.16$; 80% top-pair



2-jet control region; $S/B \sim 0.05$; 90% top-pair



- The *Wt* cross-section is measured from a maximum likelihood fit to the full BDT clasifier distributions
  - The 2-jets control region constrain the $t\bar{t}$ background uncertainties
  - The impact of systematic uncertainties is evaluated using ensembles of pseudo-experiments
    - Few systematics are profiled in the fit to data: *b*-tag, JES detector modelling component, E_T^{miss} scale contributions

$\sigma_{Wt} = 27.2 \pm 2.8\,(\text{stat.}) \pm 5.4\,(\text{syst.})$ pb
Significance: 4.2σ (4.0σ exp.)

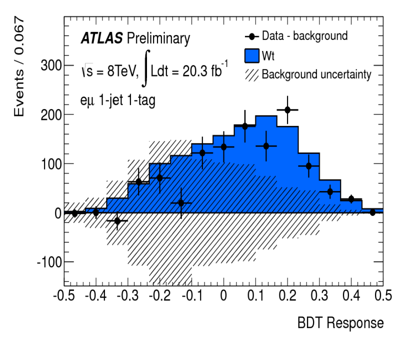
Consistent with SM expectation at 8 TeV:
$\sigma_{Wt} = 22.2 \pm 0.6 \pm 1.4$ pb

- Main **Systematics**: generator & PS modelling ($\sim$ 8%), *b*-tagging ($\sim$ 9%) and JES

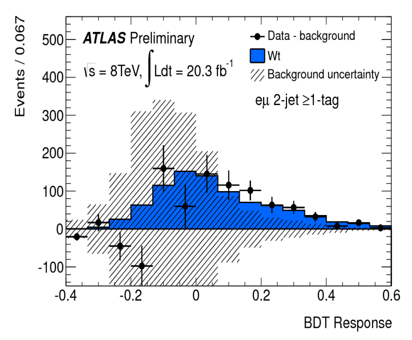
Wt-channel @ 8 TeV: background-subtracted BDT

- Subtracted the background prediction from the data to check the robustness of our analysis
  - Data points follow the *Wt* signal prediction (blue distribution)
  - *Wt* signal is clearly visible
    - The systematic uncertainties affect the lower part of the 1-jet bin distribution

1-jet signal region



2-jet control region



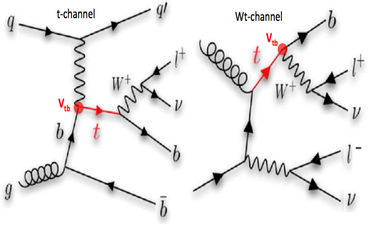
Direct $|V_{tb}|$ measurement (t and Wt channel)

- Measure of $|V_{tb}|$ assuming left-handed SM-like W-t-b coupling and $|V_{tb}| >> |V_{ts}|, |V_{td}|$:

$$|V_{tb} \cdot f|^2 = \frac{\sigma^{obs.}}{\sigma^{theory}}$$

with $f = 1$ in SM

- Independent of N_{quark} generations or CKM unitarity



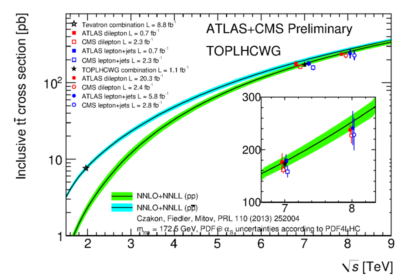
t-channel: $|V_{tb} \cdot f| = 1.04^{+0.10}_{-0.11} > 0.80$ (95% CL)

Wt: $|V_{tb} \cdot f| = 1.10 \pm 0.12 > 0.72$ (95% CL)

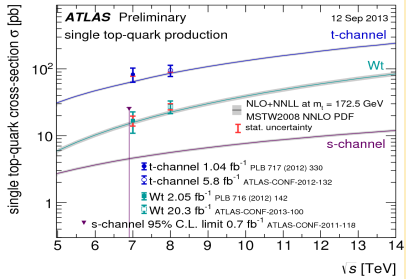
Summary

- Top pair production cross section is measured in ATLAS for all of the expected final states
- Differential cross section measurements important to constraint SM modelling differences
  - Current measurements start to be discriminanting

- ATLAS has performed a complete set of single top analysis:
  - Measure production cross-sections
  - Direct extraction of $|V_t b|$



Summary of LHC and Tevatron measurements of $\sigma_{t\bar{t}}$ compared to the NNLO + NNLL resummation



Summary of measurements of the σ (single top) compared to the NNLO + NNLL resummation

Measurements are in good agreement with theoretical predictions

Prospects

- We have learned a lot about the top quark recently:
  - LHC experiments measure the mass, properties and cross-section with good precision
  - CMS and ATLAS started to combine their results understanding the different analysis strategies and systematic determination approaches
- Challenges for future top analyses at LHC:
  - Increase the precision by constraints of main systematics uncertainties: generator modelling, jet energy scale and *b*-tagging efficiency (in situ)
  - Effort on boosted top topologies
- Even more interesting at higher pp energy:
  - The rapidly increasing dataset and detector understanding is quickly opening unprecedented phase space for exploit sensitivity to new physics linked to top production

BACKUP

Single lepton channel @ 8 TeV

Number of observed/expected events from signal and backgrounds.

	e+≥3 jets	μ+≥3 jets
$t\bar{t}$	31000^{+2900}_{-3100}	44000±4000
W+jets	5700±2400	9000±4000
Multijet	1900± 900	1100± 500
Z+jets	1400± 600	1200± 500
Single top	3260± 160	4610± 230
Dibosons	115± 6	158± 8
Total Expected	43000±4000	61000±6000
Data	40794	58872

Systematic uncertainties (%) on the inclusive $t\bar{t}$ cross section

Source	$e+$ ≥3 jets	$\mu+\geq 3 jets$	combined
Jet/MET reconstruction, calibration	6.7, -6.3	5.4, -4.6	5.9, -5.2
Lepton trigger, identification and reconstruction	2.4, -2.7	4.7, -4.2	2.7, -2.8
Background normalization and composition	1.9, -2.2	1.6, -1.5	1.8, -1.9
b-tagging efficiency	1.7, -1.3	1.9, -1.1	1.8, -1.2
MC modelling of the signal	±12	±11	±11
Total	±14	±13	±13

Dilepton channel @ 8 TeV (1)

Number of observed/expected events from signal and backgrounds.

Event counts	N_1	N_2
Data	21559	11682
Wt single top	2070 ± 220	360 ± 120
Dibosons	120 ± 90	3^{+6}_{-3}
$Z(\rightarrow \tau\tau \rightarrow e\mu)$+jets	210 ± 10	8 ± 1
Misidentified leptons	240 ± 70	110 ± 60
Total background	2640 ± 250	480 ± 140

Dilepton channel @ 8 TeV (2)

Systematic uncertainties (%) on the inclusive $t\bar{t}$ cross section

Uncertainty	$\Delta\epsilon_{e\mu}/\epsilon_{e\mu}$ (%)	$\Delta C_b/C_b$ (%)	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)	$\Delta\sigma_{t\bar{t}}$ (pb)	$\Delta\epsilon_b/\epsilon_b$ (%)
Data statistics	-	-	0.72	1.7	0.57
$t\bar{t}$ modelling	0.91	-0.61	1.52	3.6	0.61
Initial/final state radiation	-0.76	0.26	1.23	2.9	0.37
Parton density functions	1.08	-	1.09	2.6	0.06
QCD scale choices	0.30	-	0.30	0.7	0.00
Single-top modelling	-	-	0.38	0.9	0.56
Single-top/$t\bar{t}$ interference	-	-	0.15	0.4	0.25
Single-top Wt cross-section	-	-	0.70	1.7	0.24
Diboson modelling	-	-	0.42	1.0	0.19
Diboson cross-sections	-	-	0.03	0.1	0.01
Z+jets extrapolation	-	-	0.05	0.1	0.02
Electron energy scale/resolution	0.43	0.01	0.48	1.1	0.03
Electron identification/isolation	1.28	0.00	1.42	3.4	0.05
Muon momentum scale/resolution	0.01	0.01	0.05	0.1	0.02
Muon identification/isolation	0.50	0.00	0.52	1.2	0.01
Lepton trigger	0.15	0.00	0.16	0.4	0.01
Jet energy scale	0.46	0.07	0.49	1.2	0.11
Jet energy resolution	-0.44	0.04	0.59	1.4	0.08
Jet reconstruction/vertex fraction	0.02	0.01	0.04	0.1	0.01
b-tagging	-	0.13	0.42	1.0	0.09
Pileup modelling	-0.30	0.05	0.28	0.7	0.05
Misidentified leptons	-	-	0.38	0.9	0.12
Total systematic	2.29	0.69	3.12	7.4	1.02
Integrated luminosity	-	-	3.11	7.4	0.11
LHC beam energy	-	-	1.70	4.0	0.00
Total uncertainty	2.29	0.69	4.77	11.3	1.17

$d\sigma_{tt}/dX$ @ 7 TeV (1)

Number of observed/expected events from signal and backgrounds.

	e+jets	μ+jets
$t\bar{t}$ (ℓ+jets)	11200 ± 1500	13100 ± 1600
$t\bar{t}$ (dilepton)	850 ± 140	930 ± 140
Single top	560 ± 120	660 ± 150
W+jets	920 ± 360	1300 ± 400
Multijet	400 ± 200	200 ± 40
Other	180 ± 80	113 ± 30
Prediction	14100 ± 1600	16300 ± 1700
Data	13167	15752

$d\sigma_{tt}/dX$ @ 7 TeV (2)

Unfolded normalised diferential cross-sections for the different variables

p_T^t [GeV]	$\frac{1}{\sigma}\frac{d\sigma}{dp_T^t}$ $[10^{-3}]$	stat. [%]	syst. [%]
0 to 50	3.4±0.1	± 2	± 4
50 to 100	6.7±0.1	± 1	± 1
100 to 150	5.2±0.1	± 2	± 2
150 to 200	2.66±0.08	± 2	± 3
200 to 250	1.14±0.04	± 2	± 3
250 to 350	0.33±0.02	± 3	± 5
350 to 800	0.018±0.002	± 6	± 10

$m_{t\bar{t}}$ [GeV]	$\frac{1}{\sigma}\frac{d\sigma}{dm_{t\bar{t}}}$ $[10^{-3}]$	stat. [%]	syst. [%]
250 to 450	2.50±0.08	± 1	± 3
450 to 550	2.73±0.07	± 1	± 2
550 to 700	1.02±0.04	± 2	± 4
700 to 950	0.23±0.01	± 3	± 4
950 to 2700	0.0076±0.0005	± 4	± 5

$p_T^{t\bar{t}}$ [GeV]	$\frac{1}{\sigma}\frac{d\sigma}{dp_T^{t\bar{t}}}$ $[10^{-3}]$	stat. [%]	syst. [%]
0 to 40	14±2	± 3	± 10
40 to 170	3.1±0.4	± 2	± 10
170 to 340	0.25±0.06	± 4	± 20
340 to 1000	0.008±0.002	± 8	± 20

$y_{t\bar{t}}$	$\frac{1}{\sigma}\frac{d\sigma}{dy_{t\bar{t}}}$ $[10^{-3}]$	stat. [%]	syst. [%]
-2.5 to -1.0	81±3	± 2	± 3
-1.0 to -0.5	321±9	± 1	± 3
-0.5 to 0.0	436±9	± 1	± 2
0.0 to 0.5	423±7	± 1	± 1
0.5 to 1.0	321±5	± 1	± 1
1.0 to 2.5	87±5	± 3	± 4

t-channel @ 8 TeV (1)

Number of observed/expected events from signal and backgrounds.

	Control region		Signal region	
	2 jets	3 jets	2 jets	3 jets
t-channel	2500 ± 100	951 ± 38	5210 ± 210	1959 ± 78
s-channel	123 ± 5	38 ± 2	343 ± 14	100 ± 4
Wt	1000 ± 70	840 ± 60	1570 ± 110	1363 ± 95
$t\bar{t}$	5710 ± 570	7790 ± 780	11700 ± 1200	15300 ± 1500
W+light flavour	21300 ± 6400	6700 ± 2000	5500 ± 1700	1160 ± 350
W+heavy flavour	41000 ± 20000	12500 ± 6200	12000 ± 6000	3900 ± 2000
Z+jets, diboson	3800 ± 2300	1640 ± 990	1200 ± 720	410 ± 240
QCD multijet	5400 ± 2700	3200 ± 1600	3000 ± 1500	1650 ± 830
Total Expectation	81000 ± 22000	33600 ± 6900	41600 ± 6600	25800 ± 2700
Data	73668	29177	40663	23687

t-channel @ 8 TeV (2)

Breakdown of the uncertainty on the t-channel cross-section.

Source	$\Delta\sigma_t/\sigma_t$ [%]
Data statistics	± 2.4
MC statistics	± 2.9
Background normalisation	± 1.5
QCD multijet normalisation	± 3.1
Jet energy scale	± 7.7
Jet energy resolution	± 3.0
Jet reconstruction	± 0.5
Jet vertex fraction	± 1.6
Mistag modeling	± 0.3
c-tagging efficiency	± 0.4
b-tagging efficiency	± 8.5
E_T^{miss}	± 2.3
Lepton efficiencies	± 4.1
Lepton energy resolution	± 2.2
Lepton energy scale	± 2.1
PDF	± 2.8
W+jets shape variation	± 0.3
W+jets extrapolation	± 0.6
t-channel generator	± 7.1
$t\bar{t}$ generator	± 3.3
ISR / FSR	± 9.1
Parton shower	± 0.8
Luminosity	± 3.6
Total systematic	± 18.8
Total	± 19.0

Wt channel @ 8 TeV

Number of observed/expected events from signal and backgrounds.

Process	1-jet	2-jet
Wt	1140 ± 190	710 ± 100
$t\bar{t}$	5700 ± 800	12700 ± 1400
Diboson	120 ± 30	79 ± 28
$Z(\tau\tau)$ + jets	110 ± 40	90 ± 40
Fake lepton	27 ± 14	22 ± 11
Total Expected	7100 ± 1100	13600 ± 1600
Data Observed	6906	13159

Breakdown of the uncertainty on the Wt cross-section.

Source	$\Delta\sigma/\sigma$ [%]	
	observed	**expected**
Data statistics	7.1	8.6
MC statistics	2.8	3.5
Experimental uncertainties		
Lepton modeling	2.4	2.4
Jet identification	0.2	0.6
Jet energy scale	10	12
b-jet energy scale	5.0	6.3
Jet energy resolution	0.7	0.2
E_T^{miss} scale	4.1	5.0
E_T^{miss} resolution	4.5	5.3
Flavor tagging	8.4	9.4
Theory uncertainties		
$Wt/t\bar{t}$ overlap modeling	1.4	1.6
PDF	2.5	3.2
Background normalization	3.6	4.4
ISR/FSR	5.9	6.0
Wt generator and PS	11	11
$t\bar{t}$ generator and PS	7.5	9.2
Luminosity	3.7	3.9
Total (syst)	20	23
Total (syst+stat)	21	24