Single top-quark production cross-section measurements using the ATLAS detector at the LHC

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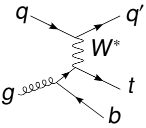
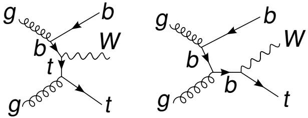
Single top-quark production

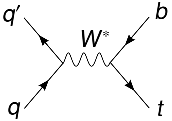
- Three production modes
  - *t*-channel
  - *Wt* associated production
  - *s*-channel (interference with *t*-channel negligible)
- Decay $t \to Wb$, $W \to \ell\nu$ or $W \to qq'$
  $\Rightarrow$ complex event topologies
- Sensitivity to new phenomena
  - New forces (FCNCs, W', ...)
  - Coupling structure at the Wtq vertex
  - Flavour physics (V_{tq})



t-channel



Wt production



s-channel

Outline

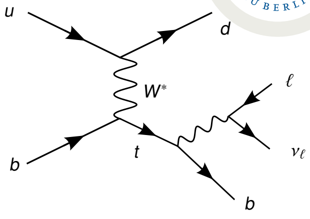
- t-channel cross-section measurement at $\sqrt{s} = 13\,\text{TeV}$
- Search for anomalous *Wtb* couplings in t-channel events at $\sqrt{s} = 7\,\text{TeV}$
- *Wt* production cross-section measurement at $\sqrt{s} = 8\,\text{TeV}$
- Evidence for s-channel single top-quark production at $\sqrt{s} = 8\,\text{TeV}$

t-channel cross-section measurement at $\sqrt{s} = 13\,\text{TeV}$

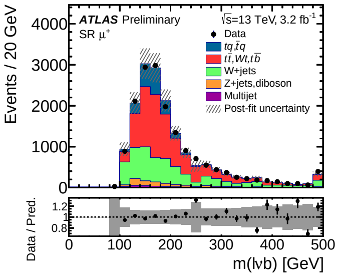
Collision events

[ATLAS-CONF-2015-079]

- *t*-channel: mode with highest rate
  - Sensitivity to PDFs – b, u/d
- Dataset: $\sqrt{s} = 13\,\mathrm{TeV}$, $\mathcal{L}$=3.2 fb^{-1}, recorded in 2015
- Selecting events with
  - Two jets, at least one b-tag, $p_\mathrm{T} > 30\,\mathrm{GeV}$, $|\eta| < 3.5$ ($|\eta_{b\mathrm{-tag}}| < 2.5$)
  - One muon, $p_\mathrm{T} > 30\,\mathrm{GeV}$, $|\eta| < 2.5$
  - Missing transverse momentum $E_\mathrm{T}^\mathrm{miss} > 30\,\mathrm{GeV}$, $m_\mathrm{T}^W > 50\,\mathrm{GeV}$ ⋆
  - Veto against $t\bar{t}$ background - no additional e or μ (loose object definition)
- In addition: two control regions (modelling validation)



t-channel single top-quark production



$$\star\; m_\mathrm{T}^W = \sqrt{2 p_\mathrm{T}^\ell E_\mathrm{T}^\mathrm{miss}\left(1 - \cos\Delta\varphi\left(p_\mathrm{T}^\ell, E_\mathrm{T}^\mathrm{miss}\right)\right)}$$

Signal extraction

[ATLAS-CONF-2015-079]

- Usage of a Neural Network to separate the signal from the backgrounds
- Max.-likelihood fit using the NN output distribution
- cross-section measurement

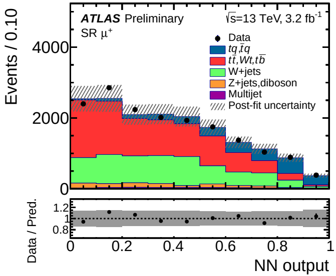
$$\sigma(tq) = 0.98 \pm 0.05 \cdot \sigma(tq)^{\text{SM,NLO}} = 133\,\text{pb} \pm 19\%$$

$$\sigma(\bar{t}q) = 1.18 \pm 0.06 \cdot \sigma(\bar{t}q)^{\text{SM,NLO}} = 96\,\text{pb} \pm 25\%$$

- CKM matrix element $|f_{\text{LV}} V_{tb}|$ assuming $|V_{tb}| \gg |V_{ts}||V_{td}|$:

$$|f_{\text{LV}} V_{tb}|^2 = \sigma^{\text{observed}} / \sigma^{\text{SM,NLO}}$$

$$|f_{\text{LV}} V_{tb}| = 1.03 \pm 11\%$$



Source	$\frac{\Delta\sigma(tq)}{\sigma(tq)}$ [%]	$\frac{\Delta\sigma(\bar{t}q)}{\sigma(\bar{t}q)}$ [%]
Data stat.	4.6	5.0
MC stat.	6.3	6.5
t-channel modelling	11	15
b-tagging	7.1	7.5
t-channel scale	5.9	7.7
Others	< 6 each	≤ 7 each
Total	19	25

Search for anomalous *Wtb* couplings in *t*-channel events at $\sqrt{s} = 7$ TeV

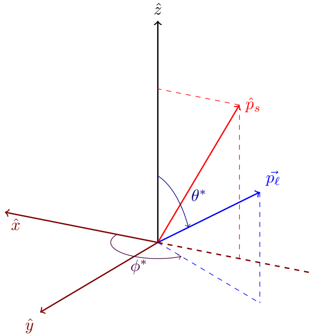
Model of the *Wtb* coupling

- General structure of the *Wtb*-vertex:

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}(V_L P_L + V_R P_R)tW^{-}_{\mu} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{m_W}(g_L P_L + g_R P_R)tW^{-}_{\mu} + \text{h.c.}$$

(SM: $V_L = V_{tb}$, $V_R = g_L = g_R = 0$)

- Measurement of angular distributions of $\ell^{\pm}$ in *t*-channel events
  $\Rightarrow$ constraint the coupling structure
- Coordinate system, momenta in the top-quark rest-frame:
  - $\vec{q}$: *W*-boson
  - $\vec{p}_s$: spectator-quark
- Double-differential top-quark decay, parametrized in terms of anomalous couplings
- Sensitivity mostly to V_L and g_R



Results

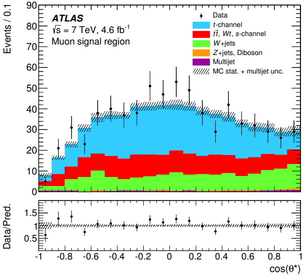
[arXiv:1510.03764]

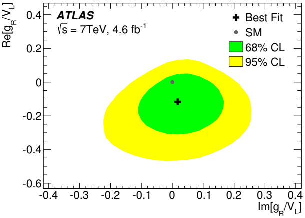
- Dataset: $\sqrt{s} = 7\,\text{TeV}$, $\mathcal{L}=4.59\,\text{fb}^{-1}$, recorded in 2011
- Selection of a relatively pure sample of t-channel events, in particular
  - Untagged, forward jet – $|\eta| > 2$
  - $\sum p_{\mathrm{T}} > 210\,\text{GeV}$
  - $m_t \in [150\,\text{GeV}, 190\,\text{GeV}]$
  - $|\Delta\eta(\text{light jet}, b\text{-jet})| < 1$
- Definition of the probability density of $(\cos\theta^\star, \phi^\star)$, construction of a likelihood fct.
- Results of a 2-dim. fit:

$$\mathrm{Re}\left[\frac{g_R}{V_L}\right] \in [-0.36, 0.10]$$

$$\mathrm{Im}\left[\frac{g_R}{V_L}\right] \in [-0.17, 0.23]$$

- First sim. measurement of $\mathrm{Re}\left[\frac{g_R}{V_L}\right]$ and $\mathrm{Im}\left[\frac{g_R}{V_L}\right]$, consistent with the SM





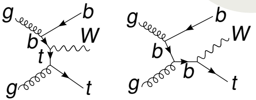
Wt production cross-section measurement at $\sqrt{s} = 8$ TeV

Wt measurement at $\sqrt{s}=8$ TeV

[JHEP01(2016)064]

Wt process

- Associated production of a top-quark and a W-boson
- Interference with $t\bar{t}$ production $\mathcal{O}(\alpha_S)$, but small within detector acceptance



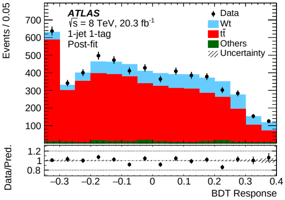
Wt production

ATLAS measurement

- Using $\sqrt{s}=8$ TeV, $\mathcal{L}=20.3\,\text{fb}^{-1}$, selection:
  - Two charged leptons – e or μ
  - One or two jets, one or two b-tags
  - Missing transverse momentum
- Boosted decision trees in signal and background regions to separate the signal, fit result:

$$\sigma_{Wt} = 1.03^{+0.16}_{-0.17} \cdot \sigma_{Wt}^{\text{SM,approx.NNLO}}$$
$$= 23.0^{+3.6}_{-3.8}\,\text{pb}$$
$$|f_{LV} V_{tb}| = 1.01 \pm 10\%$$

- Significance of 7.7σ (6.9σ expected)



Source	$\frac{\Delta\sigma_{Wt}}{\sigma_{Wt}}$ [%]
Statistics	5.8
QCD rad. modelling	+8.2 / -9.4
Jet reconstruction	+9.0 / -9.9
E_T^{miss}	5.5
others	< 5 each
Total	+16 / -17

Wt fiducial cross-section measurement

[JHEP01(2016)064]

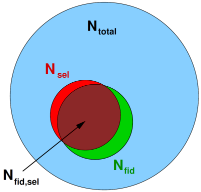
- Referring to a fiducial volume within the detector acceptance ⇒ reduction of modelling uncertainties

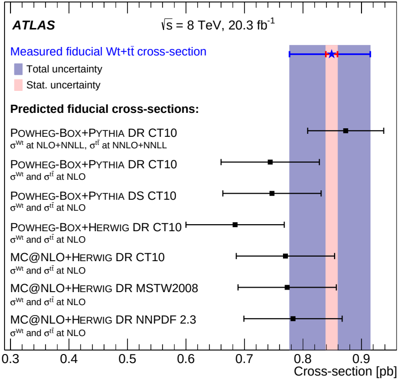
- *Wt* and $t\bar{t}$ as one signal in the 1-jet 1-tag region

$$\sigma_{Wt}^{\mathrm{fid}} = \frac{P(\text{fiducial} \,|\, \text{selected})}{P(\text{selected} \,|\, \text{fiducial})} \cdot \frac{N_{\mathrm{sel}}}{\mathcal{L}}$$

$$= 0.85 \pm 0.01(\mathrm{stat})^{+0.06}_{-0.07}(\mathrm{syst}) \pm 0.03(\mathrm{lumi})\ \mathrm{pb}$$

$$(\Delta_{\mathrm{rel}}\sigma_{Wt}^{\mathrm{fid}} = 8.5\%)$$



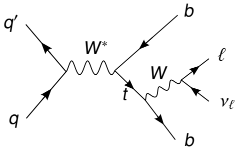


Evidence for s-channel single top-quark production at $\sqrt{s} = 8$ TeV

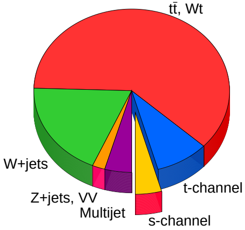
Collision events

[PLB(2016)228]

- Selecting events with
  - Two b-tagged jets,
    $p_{\mathrm{T},1} > 40\,\mathrm{GeV}$, $p_{\mathrm{T},2} > 30\,\mathrm{GeV}$, $|\eta| < 2.5$
  - One electron or muon,
    $p_{\mathrm{T}} > 30\,\mathrm{GeV}$, $|\eta| < 2.5$
  - Missing transverse momentum
    $E_{\mathrm{T}}^{\mathrm{miss}} > 35\,\mathrm{GeV}$, $m_{\mathrm{T}}^{W} > 30\,\mathrm{GeV}$
  - Veto against $t\bar{t}$ background -
    no additional e or μ (loose object definition)
- In addition: two control regions
  used for modelling validation
- Usage of a Matrix element method
  in order to separate the signal from the backgrounds – approximate signal probability $P(S|X)$



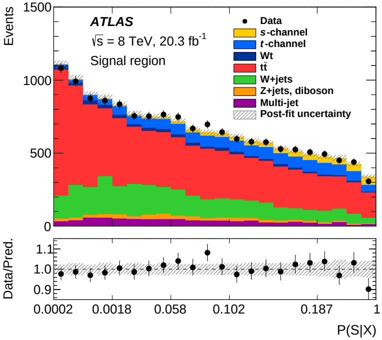
s-channel single top-quark production

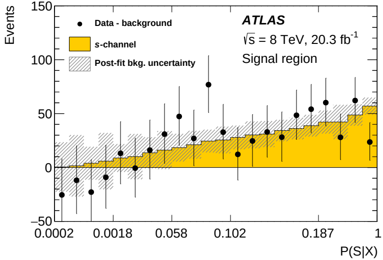


Event yields in the signal region,
$\Sigma = 14.000$

Signal discriminant distribution

[PLB(2016)228]





- Clear separation between signal and background processes
  ⇒ Possibility to measure the signal cross-section

Statistical evaluation

[PLB(2016)228]

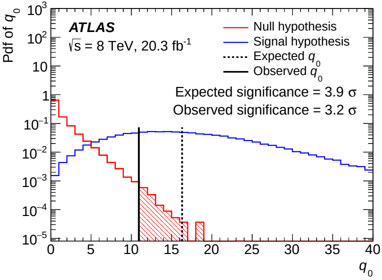
- **Profile likelihood fit** of signal and background templates of $P(S|X)$ to the data
- Test of B vs S+B hypothesis
  $\Rightarrow$ observe $3.2\,\sigma$ signal significance

First evidence for s-channel single top-quark production in *pp* collisions

- cross-section measurement

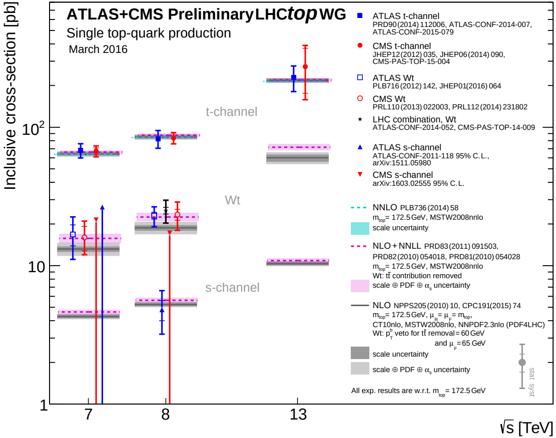
$$\sigma_s = 4.8^{+1.8}_{-1.6}\ \text{pb}$$
$$= 0.86^{+0.31}_{-0.28} \cdot \sigma_s^{\text{SM, approx. NNLO}}$$

- Agreement with the standard model
- Precision limited by data statistics



Source	$\frac{\Delta\sigma_s}{\sigma_s}$ [%]
Data stat.	16
MC stat.	12
Jet energy res.	12
t-channel generator	11
Others	< 10 each
Total	34

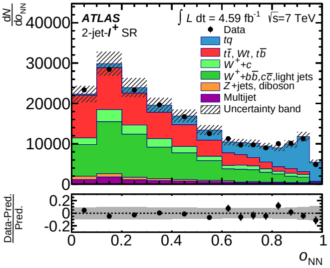
Summary

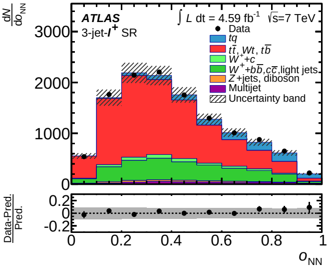


- Single top-quark production due to electroweak interactions
- Comprehensive measurements of SM processes and searches for new phenomena

Backup

t-Channel Measurements at $\sqrt{s}=7\,\text{TeV}$





- Analysis similar to the $\sqrt{s}=13\,\text{TeV}$ measurement shown above
- Training of 2 Neural Networks - 2-jet and 3-jet channel ($l^{\pm}$ combined)
- Choosing best separating variables as input, check variable modelling in control region similar to 2-jet selection but loosened b-tagging
  - 2-jet channel: 13 variables - $|\eta(j)|$, $m(l\nu b)$, $m(jb)$ most important
  - 3-jet channel: 11 variables - $\Delta y(j_1, j_2)$, $m(j_2 j_3)$, $m(l\nu b)$ most important

Signal Extraction

- Max. likelihood fit of t-channel signal strength(s) to the NN discriminant in all 1-tag channels, event counting in 3-jet-2-tag channel

Cross-Sections

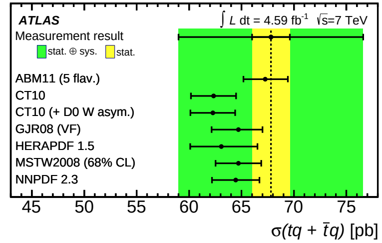
$$\sigma(tq+\bar{t}q) = 68 \pm 2(\text{stat.}) \pm 8(\text{syst.})\text{pb}$$
$$\sigma(tq) = 46 \pm 1(\text{stat.}) \pm 6(\text{syst.})\text{pb}$$
$$\sigma(\bar{t}q) = 23 \pm 1(\text{stat.}) \pm 3(\text{syst.})\text{pb}$$
$$R_t = 2.04 \pm 0.13(\text{stat.}) \pm 0.12(\text{syst.})$$

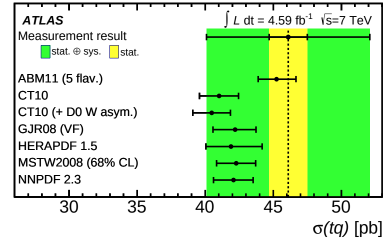
- All measurements in agreement with the standard model predictions.

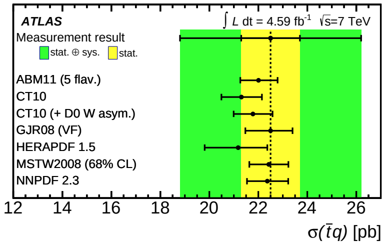
Source	$\frac{\Delta R_t}{R_t}$ [%]	$\frac{\Delta\sigma(tq+\bar{t}q)}{\sigma(tq+\bar{t}q)}$ [%]
data stat.	6.2	2.7
MC stat.	3.6	1.9
JES η intercalib.	<2	7.3
b-tagging ε	<2	3.9
E_T^{miss}	<2	2.6
Leptons	<2	2.8
PDF	2.5	3.2
tq μ_R & μ_F	<2	2.6
others	<2 each	<2 each
Total	8.7	12.4

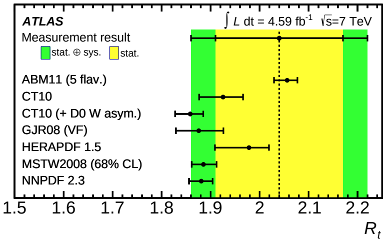
t-Channel Measurements at $\sqrt{s} = 7$ TeV

Total Cross-Sections and top/anti-top Ratio







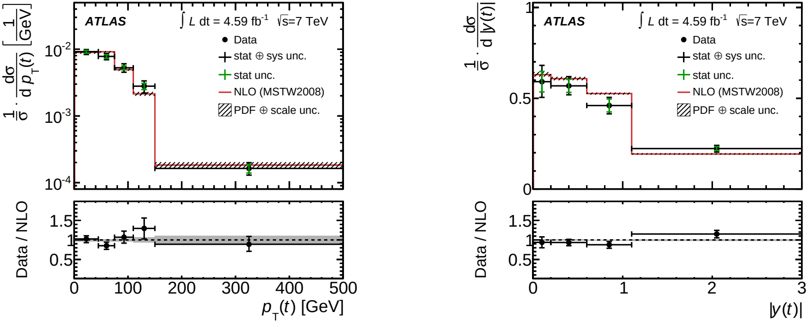


t-Channel Measurements at $\sqrt{s} = 7$ TeV

Differential Cross-Sections

- Using high purity region $\mathrm{NN}_{\mathrm{output}} > 0.8$ in 2-jet channels
  $\Rightarrow S/B \approx 2$ for l^+, $S/B \approx 1$ for l^-
- Normalization of samples according to cross-section fit results
- Unfolding of observed distributions to the parton level

$$\frac{d\sigma}{dX_j} = \frac{1}{\Delta X_j} \cdot \frac{\sum_i M_{ij}^{-1} \cdot (\mathrm{Data}_i - \mathrm{Bkg}_i)}{\mathcal{L} \cdot \varepsilon_j}$$



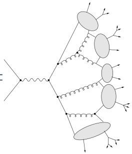
Matrix Element Method (MEM)

Ansatz and implementation

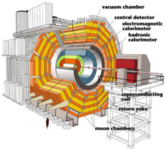
[PLB(2016)228]

- $\mathcal{P}(X|H)$: p.d.f. of the event X given the scattering process H
- Approximation of $\mathcal{P}(X|H)$ by means of a factorization
    - Hard scattering - leading order perturbation theory
    - Hadronization, detector effects: parametrizations known as transfer functions

$\mathcal{P}(X|H) =$



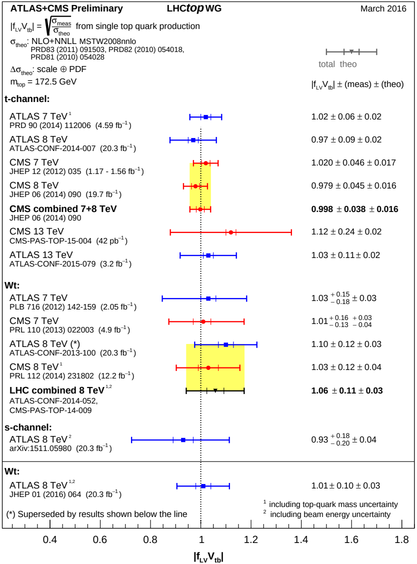
$\otimes$



$$\approx \int \mathrm{d}\Phi \frac{1}{\sigma} \frac{\mathrm{d}\sigma}{\mathrm{d}\Phi} W(X|\Phi)$$

- Development of a comprehensive MEM package from scratch
- Combination of several signal and background likelihoods $\mathcal{P}(X|H)$ into a signal discriminant $P(S|X)$

V_{tb} measurements using single top-quark production



Cross-section predictions

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- N. Kidonakis, *Two-loop soft anomalous dimensions for single top quark associated production with a W- or H-*, Phys. Rev. D 82 (2010) 054018, arXiv:1005.4451
- N. Kidonakis, *NNLL Resummation for s-Channel Single Top Quark Production*, Phys. Rev. D81 (2010) 054028 , arXiv:1001.5034