Single Top Quark Production and Measurements of V_{tb} in the ATLAS Experiment

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ATLAS EXPERIMENT

HUMBOLDT-UNIVERSITÄT ZU BERLIN

Studienstiftung des deutschen Volkes

GRADUIERTENKOLLEG Masse-Spektrum-Symmetrie

Outline

Single Top Quark Reconstruction

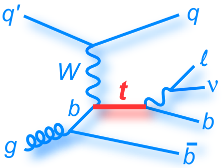
t-Channel Cross Sections at $\sqrt{s}=7$ TeV and $\sqrt{s}=8$ TeV

V_{tb} Measurements

New Physics Searches in Single Top Topologies

Single Top Quark Reconstruction
Basic Challenges

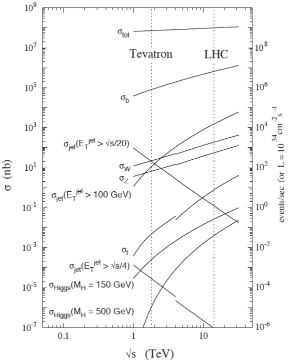
- Three production modes
  - *t*-channel
  - *Wt* associated production
  - *s*-channel (interference with *t*-channel $\mathcal{O}(\alpha_S^2)$)



- Complex topology of top quark events
  - Charged leptons
  - Neutrinos / $\not\!\!E_T$
  - *b*-jets and light jets

$\Rightarrow$ Need to reconstruct many different objects

- Typical Selection, *t*-channel
  - Single *e* or μ-trigger
  - Exactly one *e* or μ reconstructed
  - 2 - 3 jets with 1 - 2 *b*-tags
  - Large $\not\!\!E_T$

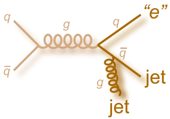


- Need to understand large backgrounds

Single Top Quark Reconstruction

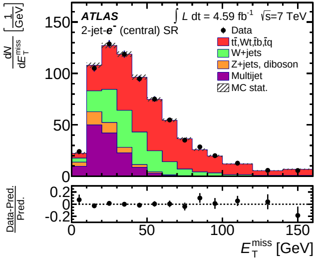
Multijet Modelling

- Background from jets misidentified as leptons or from non-promt leptons
- Hard to simulate, in particular due to high statistics demand
  $\Rightarrow$ Use data-driven techniques



Fitting Method

- Find model for the $\not{E}_T$ shape of a variable in fake lepton events, e.g. jet-electron: select a jet likely to fake an electron (high EM fraction)
- Fitting fake lepton template together with other MC samples $\Rightarrow$ normalization



[arXiv:1406.7844v1, subm. to PRD]

Matrix Method

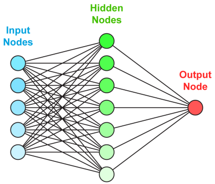
- Estimation of fake leptons from tight and loose lepton selection in data using efficiencies $P(\text{Tight}|\text{Loose})$ for real and for fake leptons

Single Top Quark Reconstruction

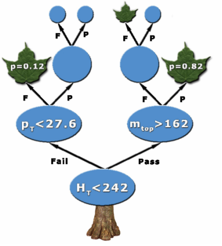
Signal Discrimination

- Usually insufficient reduction of backgrounds by using a cut-and-count approach
- Build final discriminant separating signal and background
- Different methods with similar separation, but different speed and different impact of systematics
- So far in ATLAS: choice of one fast method (NN or BDT)

Neural Network

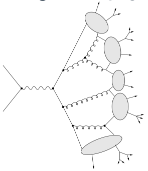


Boosted Decision Tree

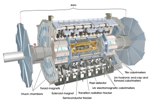


Matrix Element Method

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

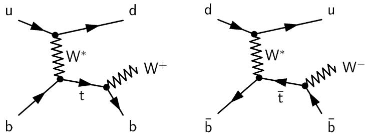


x



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

t-channel single top production

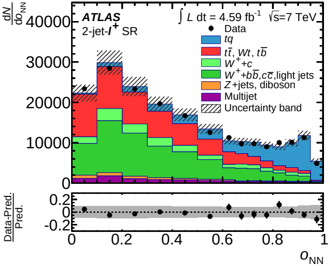


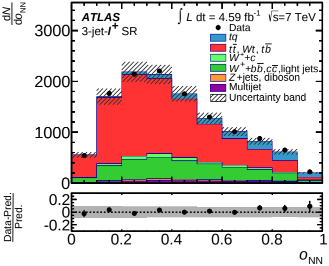
- Largest single top cross section
- Sensitive to:
  - V_{tq} due to weak top quark production
  - $W-t-b$ coupling structure
  - Parton density functions - u/d, b
  - FCNCs (see dedicated talk later on)

ATLAS t-channel measurements at $\sqrt{s} = 7\,\text{TeV}$

- Comprehensive measurements using $4.59\,\text{fb}^{-1}$: $\sigma(tq)$, $\sigma(\bar{t}q)$, $\sigma(tq+\bar{t}q)$, $R_t = \sigma(tq)/\sigma(\bar{t}q)$, $|V_{tb}|$ and differential cross sections [arXiv:1406.7844v1, subm. to PRD]
- Cuts:
  - 1 electron or muon, $p_T > 30\,\text{GeV}$
  - $\not{E}_T > 30\,\text{GeV}$
  - $m_T^W > 30\,\text{GeV}^*$
  - 2 or 3 jets, $p_T > 30\,\text{GeV}$, $|\eta| < 4.5$ (t-channel forward scattering)
  - 1 or 2 b-tags (see next slide)

$^* m_T^W = \sqrt{2 p_T^l \not{E}_T \left(1 - \cos\left(\Delta\varphi(l, \not{E}_T)\right)\right)}$





- Training of 2 Neural Networks - 2-jet and 3-jet channel ($l^\pm$ combined)
- Choosing best separating variables as input, check variable modeling 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
- Observation of t-channel single top production at $\sqrt{s}=7$ TeV

[ATLAS-CONF-2011-088]

* Neutrino reconstruction using W mass constraint

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
- Profiling of most bkg. normalizations and of b-tagging efficiency
- Other nuisance parameters integrated out of the likelihood function (hybrid approach)

Cross Sections

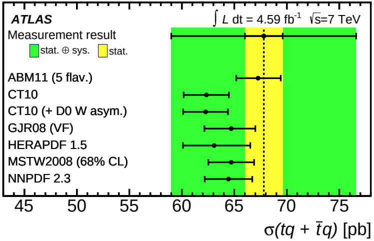
$$\sigma(tq+\bar{t}q) = 68 \pm 2(\text{stat.}) \pm 8(\text{syst.})\text{pb}$$
$$\sigma(tq) = 46 \pm 1(\text{stat.}) \pm 6(\text{syst.})\text{pb}$$
$$\sigma(\bar{t}q) = 23 \pm 1(\text{stat.}) \pm 3(\text{syst.})\text{pb}$$
$$R_t = 2.04 \pm 0.13(\text{stat.}) \pm 0.12(\text{syst.})$$

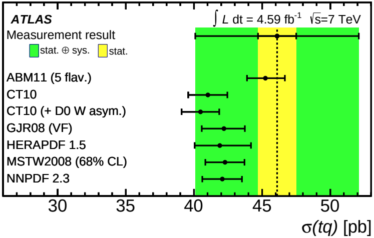
- All measurements in agreement with the standard model predictions.

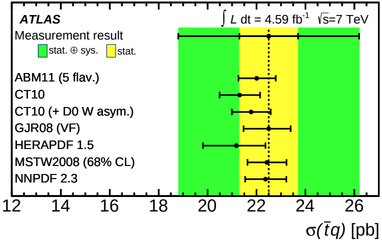
Source	$\frac{\Delta R_t}{R_t}$ [%]	$\frac{\Delta\sigma(tq+\bar{t}q)}{\sigma(tq+\bar{t}q)}$ [%]
data stat.	6.2	2.7
MC stat.	3.6	1.9
JES η intercalib.	<2	7.3
b-tagging ε	<2	3.9
$\not{E}_T$	<2	2.6
Leptons	<2	2.8
PDF	2.5	3.2
tq μ_R & μ_F	<2	2.6
others	<2 each	<2 each
Total	8.7	12.4

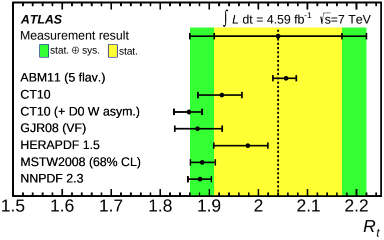
t-Channel Measurements at $\sqrt{s} = 7$ TeV

Total Cross Sections and top/anti-top Ratio



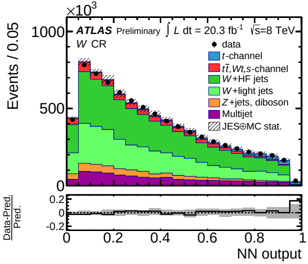


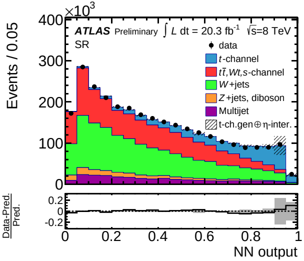


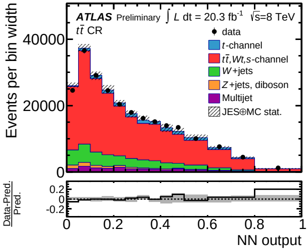


t-Channel Fiducial Cross Section, $\sqrt{s}=8$ TeV
Analysis Approach

- Measurement of inclusive and fiducial t-channel cross section using $\mathcal{L}=20.3\,\text{fb}^{-1}$
- Similar to 7 TeV analysis, but requiring exactly 2 jets
- Signal discrimination using a neural network
- Input variable modeling checked in control regions (W+jets: loosened b-tagging, $t\bar{t}$: 2 b-jets)



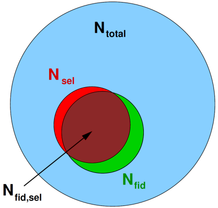




t-Channel Fiducial Cross Section, $\sqrt{s}=8$ TeV

Result

- Referring to a fiducial volume within the detector acceptance ⇒ reduction of modeling uncertainties
- Definition of fiducial volume:
  - W.r.t. stable particles ($\tau > 30\,\text{ps}$)
  - e/μ and neutrino ($\not{E}_T$) from W decay
  - Particle level jets
  - B-hadron matching as b-tagging
  - Kinematic cuts similar to detector level cuts



$$\sigma_{\text{fid}} = \frac{P\,(\text{fiducial}\,|\,\text{selected})}{P\,(\text{selected}\,|\,\text{fiducial})} \cdot \frac{\hat{\nu}}{\mathcal{L}}$$

- Max. likelihood fit to NN output to estimate $\hat{\nu}$

$$\sigma_{\text{fid}} = 3.37 \pm 0.05(\text{stat.}) \pm 0.47(\text{syst.}) \pm 0.09(\text{lumi})\,\text{pb}$$

Source	$\frac{\Delta\sigma_{\text{fid}}}{\sigma_{\text{fid}}}$ [%]
data stat.	1.5
JES η intercalib.	7.9
JES physics modelling	3.0
b-tagging ε	3.5
$\not{E}_T$ modelling	3.0
t-channel generator	7.9
others	< 3 each
Total	14

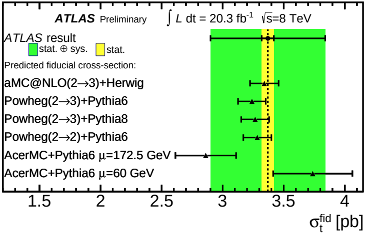
t-Channel Fiducial Cross Section, $\sqrt{s} = 8$ TeV

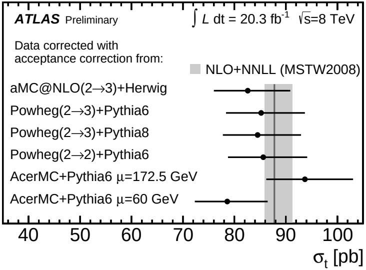
Generator Comparisons

- Agreement between NLO generators, large scale uncertainty for LO generator
- Determine inclusive cross section by extrapolating to the full phase space

$$\sigma = \frac{1}{\varepsilon_{\text{fid}}} \sigma_{\text{fid}}$$

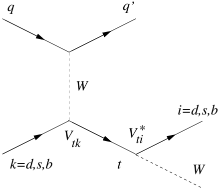
- Smaller uncertainty of fiducial compared to inclusive cross section: 14% vs. 17%
- Inclusive cross sections using acceptances from NLO generators in agreement with fixed order QCD calculation

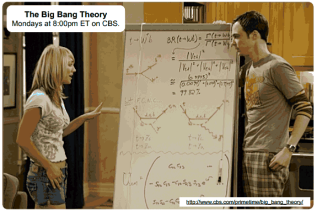




V_{tb} Measurements

Basics





$$N \sim \underbrace{|V_{tk}|^2}_{\text{production}} \cdot \underbrace{\frac{|V_{ti}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}}_{:=R_i,\ \text{decay}}$$

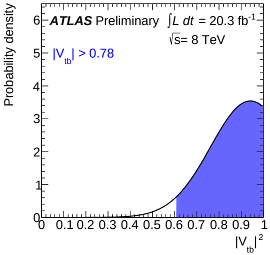
- *t*-channel much more sensitive to V_{td} and V_{ts} than *s*-channel due to initial state *d* and *s*-quark-contributions
- Combined V_{td}, V_{ts}, V_{tb} extraction needs $\sigma_{t\text{-channel}}$ *and* R_i
- Tevatron results for R_b from $t\bar{t}$ measurements:*

D0	CDF single lepton	CDF di-lepton
0.90 ± 0.04	0.94 ± 0.09	0.87 ± 0.07

* PRL107.121802, PRD87.111101, PRL112.221801

- Current practice is to assume
  1. $|V_{tb}| \gg |V_{td}|, |V_{ts}| \Leftrightarrow R_b = 1$
  2. $\bar{b}\gamma_\mu \frac{1}{2}(1-\gamma_5)\, W^\mu t \;+\; h.c.$

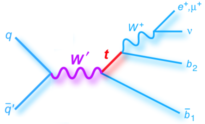
  $$\Rightarrow |V_{tb}|^2 = \frac{\sigma^{\text{measured}}}{\sigma^{\text{SM}}}$$



- For lower limits: use gaussian distribution of $|V_{tb}|^2$ according to $\sigma^{\text{measured}}/\sigma^{\text{SM}}$ truncated to [0, 1] as p.d.f.
- Determine $|V_{tb}|$ in t-channel at $\sqrt{s}$=7 TeV and $\sqrt{s}$=8 TeV and in Wt associated production at $\sqrt{s}$=8 TeV [ATLAS-CONF-2013-100]

	t-channel $\sqrt{s}$=7 TeV	t-channel $\sqrt{s}$=8 TeV	Wt $\sqrt{s}$=8 TeV
$\lvert V_{tb}\rvert$	1.02 ± 0.07	$0.97^{+0.08}_{-0.09}$	1.10 ± 0.12
95% CL lower limit	0.88	0.78	0.72

- Proposed by several new physics models (extra-dimensional excitations of the W-boson, technicolour, little Higgs)



- Effective model:

$$\mathcal{L} = \frac{V'_{ij}}{2\sqrt{2}} \bar{f}_i \gamma_\mu \left(g'_{L_{ij}} (1 - \gamma^5) + g'_{R_{ij}} (1 + \gamma^5) \right) W'^\mu f_j + h.c.$$

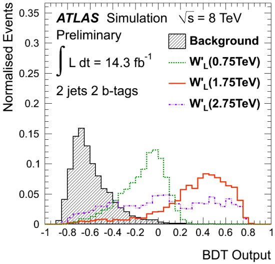
$$g'_{L,R} = \text{left/right-handed couplings}, \qquad V' = \begin{cases} V_{CKM} \text{ for quarks} \\ \delta_{ij} \text{ for leptons} \end{cases}$$

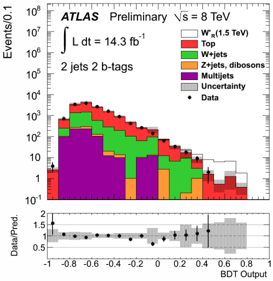
- Allowed decays:

Decay	hadronic	leptonic
W'_L	✓	✓ + SM interference
W'_R, $m(\nu_R) < m(W')$	✓	✓
W'_R, $m(\nu_R) > m(W')$	✓	–

- Motivation for $W' \to tb$ search
  - Direct leptonic searches have lower sensitivity to a leptophobic W′
  - Many models with large 3rd generation couplings

    ➔ disfavours all-hadronic searches



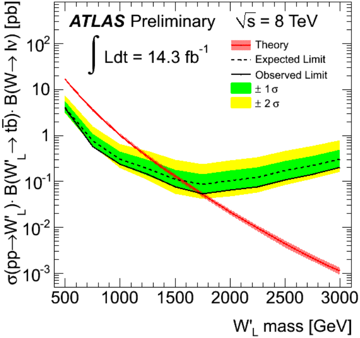


- Analysis of $\sqrt{s}=8$ TeV data, $\mathcal{L}=14.3\,\text{fb}^{-1}$
- Signal modelling by MadGraph+Pythia, scaled to NLO
  - Two scenarios $W'_L : g'_L = g_{SM},\ g'_R = 0$
    $W'_R : g'_R = g_{SM},\ g'_L = 0$
  - *s*-channel interference neglected
- Backgrounds modeled by MC, *W*+jets and multijets normalized to data
- Single lepton events, 2-3 jets, at least one *b*-tag
- Boosted Decision Trees, trained for specific $W'_{L/R}$ mass points

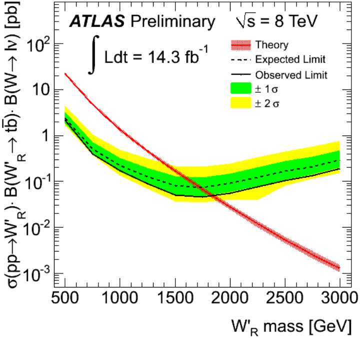
W' Search

Mass Limits

ATLAS-CONF-2013-050



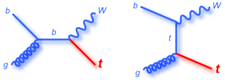
$m(W'_L) > 1.74$ TeV @95% CL_S



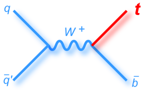
$m(W'_R) > 1.84$ TeV @95% CL_S

Standard Model Physics

- Evidence for associated *Wt* production in di-lepton events at $\sqrt{s}=8$ TeV (4.2σ)
  [ATLAS-CONF-2013-100]

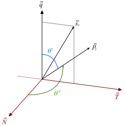


- *s*-channel search at $\sqrt{s}=7$ TeV, most challenging channel, current limit $\approx 6 \cdot \sigma^{\mathrm{SM}}_{s\text{-channel}}$
  [ATLAS-CONF-2011-118]

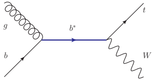


New Physics

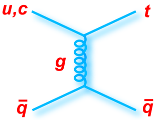
- Search for CP-Violation in *t*-quark decays [ATLAS-CONF-2013-032]



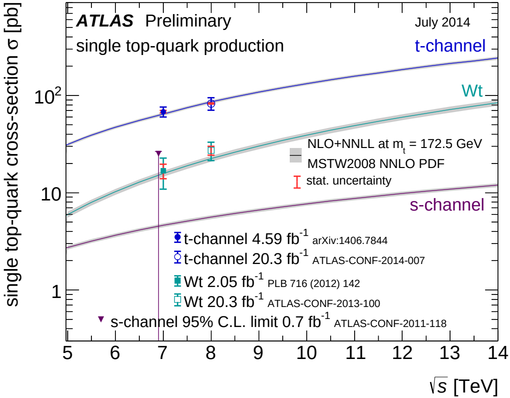
- b^* search, probe coupling of excited quarks to 3rd generation quarks
  [PLB 721 (2013)]



- FCNC in top quark production, $qg \to t$, see dedicated talk by O. Arslan this afternoon [ATLAS-CONF-2013-063], [PLB712 (2012) 351]



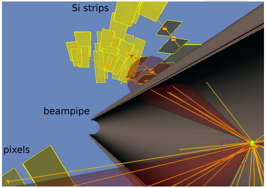
Conclusion



- Performing various single top measurements
- t-channel cross section at $\sqrt{s} = 7$ TeV: $|V_{tb}| = 1.02 \pm 0.07$
- Started to exploit new physics potential in single top topologies

Backup

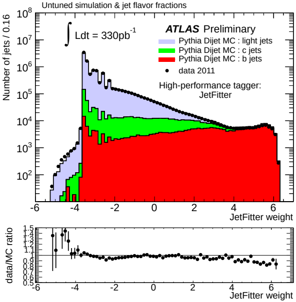
Single Top Quark Reconstruction
b-Tagging



- $\mathcal{B}(t \to Wb)$ is close to 1:
  Necessity of *b*-tagging to reduce backgrounds like W/Z+jets and multijets

  - Gather secondary vertex information (d_0 significance, vertex mass etc.)

  - Combination in neural network, trained to separate *b*-jets



Maximum Likelihood Fit

Likelihood Function

$$L(\beta^S, \beta_j^B) = \prod_{k \in \{\text{bins}\}} \frac{\mu_k^{n_k} e^{-\mu_k}}{n_k!} \cdot \sum_{j \in \{\text{Profiled NPs}\}} \text{Gauß}\left(\beta_j^B | 1, \Delta_j\right)$$

$$\mu_k = \mu_k^S + \sum_j \mu_{jk}^B, \quad \mu_k^S = \beta^S \cdot \nu^S \cdot \alpha_k^S, \quad \mu_{jk}^B = \beta_j^B \cdot \nu_j \cdot \alpha_{jk}$$

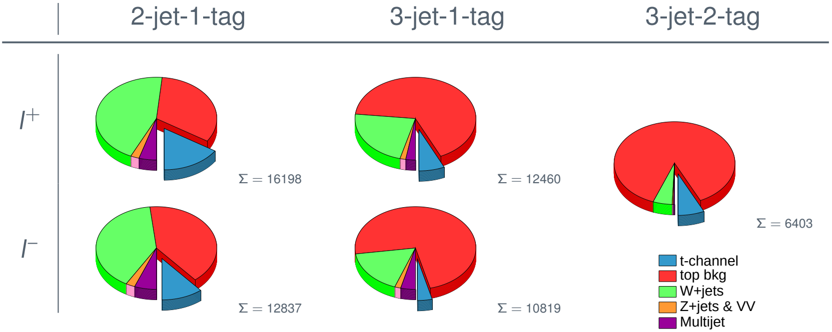
Procedure

- In pseudo-experiments generate all nuisance parameters according to priors (not matter if present in the likelihood function above or not)
- For eacht pseudo-experiment fit L w.r.t. β^S, $\{\beta_j^B\}$ and possibly other NPs (e.g. *b*-tagging efficiency)
- Determine the uncertainty of signal strength from the spread of fitted β^S

Measurement	$\lvert V_{tb} \rvert$	95%CL lower limit
t-channel $\sqrt{s}=7$ TeV	$1.02 \pm 0.01(\text{stat.}) \pm 0.06(\text{syst.}) \pm 0.02(\text{theory})^{+0.01}_{-0.00}(m_t)$	0.88
t-channel $\sqrt{s}=8$ TeV	$0.97^{+0.06}_{-0.07}(\text{exp.}) \pm 0.06(\text{gen.+PDF+theory})$	0.78
Wt $\sqrt{s}=8$ TeV	$1.10 \pm 0.12(\text{exp}) \pm 0.03(\text{theory})$	0.72

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

Event Yields

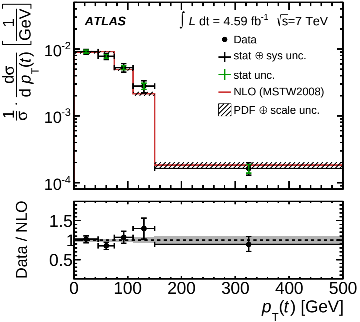


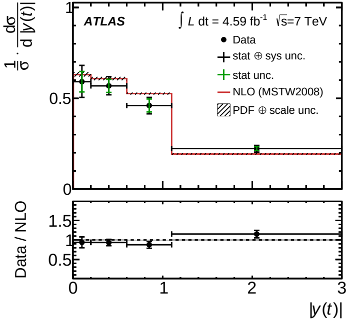
- More l^+ than l^- t-channel events due to higher u-quark luminosity compared to d-quarks in pp collisions *
- Using 3-jet-2-tag control region in order to in-situ constrain b-tagging efficiency when fitting

*Σ = Observed Event Yield

- Using high purity region $NN_{output} > 0.8$ 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

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

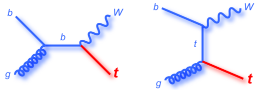




Wt Measurement at $\sqrt{s} = 8$ TeV

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

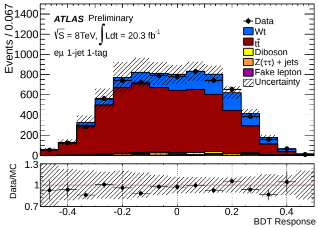


ATLAS measurement [ATLAS-CONF-2013-100]

- Using $\sqrt{s} = 8$ TeV, $\mathcal{L} = 20.3\,\text{fb}^{-1}$
- Event selection:
  - One electron and one muon
  - One or two jets, one or two *b*-tags
  - Missing transverse momentum
- Boosted decision trees (1-jet and 2-jet)
- Max. likelihood fit, partial profiling

$$\sigma_{Wt} = 27.2 \pm 2.8(\text{stat.}) \pm 5.4(\text{syst.})\text{pb}$$

- Significance of 4.2σ (4.0σ expected)
- Agreement with standard model prediction



Source	$\frac{\Delta\sigma_{Wt}}{\sigma_{Wt}}$ [%]
data stat.	7.1
JES	10
Flavour tagging	8.4
Wt generator + PS	11
others	< 8 each
Total	21