Measurement of the production cross section for heavy quark jets in association with a W boson with the ATLAS detector at the LHC

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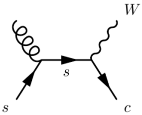
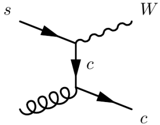
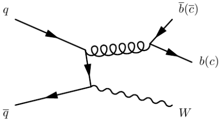
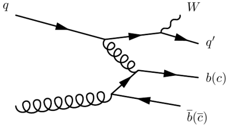
1st March 2012 - DPG Conference

Production of heavy flavour partons in association with a W boson









$W + c - quark(s)$

- Both $W + c$ and $W + c\bar{c}$ significant
- No c-tagging algorithm available
- 2011 analysis in preparation for $W + c$ exclusive cross section measurement
- Main strategy based on muon decays of $c - quark$ and on charge correlation between W and c
- Chance to study $s - quark$ pdf

$W + b - quark(s)$

- $W + b$ Cabibbo supressed, only $W + b\bar{b}$ observable
- In 2010 published inclusive cross section measurement $W + b + X$
- The analysis is based on b-jet tagging algorithms

$W + b - jet$: phase space definition and simulated samples

Requirement	Cut
Lepton transverse momentum p_T	$p_T^l > 20\ GeV$
Lepton pseudo-rapidity η	$\lvert\eta_l\rvert < 2.5$
Neutrino	$p_T^\nu > 25$ GeV
W mass	$m_T > 40$ GeV
Jet transverse momentum p_T	$p_T^j > 25$ GeV
Jet rapidity y	$\lvert y^j\rvert < 2.1$
Jet Multiplicity	$n^j \leq 2$
b-Jet Multiplicity	$nb^j \geq 1$
Jet Isolation	$\Delta R(l, jet) > 0.5$

Measurement performed

- Muon and Electron decays of W boson
- 1, 2 jets bin and combined
- 2010 data, $\int \mathcal{L} = 35\ pb^{-1}$

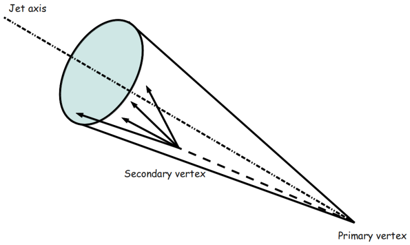
Truth b-jet definition

Jet matched in $\sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.3$ with b parton with $p_T > 5$ GeV

Physics process	Generator	$\sigma \cdot$ BR (nb)	
$W \rightarrow \ell\nu$ + jets ($0 \leq N_{parton} \leq 5$)	ALPGEN 2.13	10.46	NNLO
$Z \rightarrow \ell\ell$ + jets ($m_{\ell\ell} > 40$ GeV, $0 \leq N_{parton} \leq 5$)	ALPGEN 2.13	1.07	NNLO
$t\bar{t}$	MC@NLO 3.1.3.1	89.7×10^{-3}	approx. NNLO
Single-top (s-channel)	MC@NLO	4.3×10^{-4}	NLO
Single-top (t-channel)	AcerMC 2.0	6.34×10^{-3}	NLO
Single-top (Wt)	AcerMC 2.0	13.1×10^{-3}	NLO
WW	HERWIG 6.510	44.9×10^{-3}	NLO
WZ	HERWIG 6.510	18.5×10^{-3}	NLO
ZZ	HERWIG 6.510	5.96×10^{-3}	NLO

QCD is estimated on data

$W + b - jet$: event selection



2010 b-jet tagging

- Relies on long life time of b-hadrons

  $\rightarrow$ fly for $\approx mm$

- The long life time makes it possible to reconstruct secondary vertices

  $\rightarrow$ ID resolution $\approx 10\mu m$

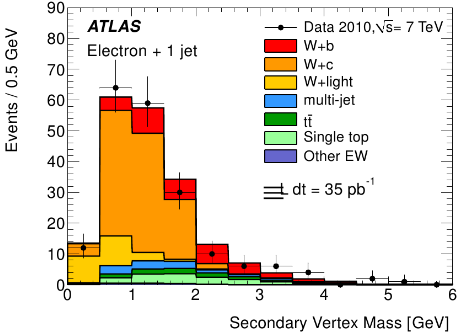
Jet reconstruction and selection

- Electromagnetic calibration
- $anti - k_T$ algorithm used for reconstruction
- 1 or 2 jets with $p_T > 25\ GeV$, $|y| < 2.1$, $> 75\%$ momentum coming from primary vertex
- Exactly 1 b-jet, tagged using secondary vertex association algorithm (50% efficiency working point)

Expected number of events in the muon channel

Source	1-jet	2-jet (1 b-tag)	2-jet (2 b-tag)
W+b+X	24.8	25.9	1.6
W+c+X	108.4	44.9	0.4
W+light	38.2	20.2	0
Total W+Jet	171.4	91	2
$t\bar{t}$	10	39.7	7.4
SingleTop	17.2	23.1	2.5
QCD	8	9.9	-0.1
Z+Jet	3.7	2.4	0.2
Diboson	0.2	0.1	0
Total Predicted	210.6	166.2	12.1
Data	261	217	13

Secondary vertex mass fit in the electron channel, 1 jet bin



Secondary vertex mass ($SV0_{mass}$)

- Secondary vertex produced by B hadrons have higher masses

Fit to $SV0_{mass}$

- $SV0_{mass}$ distributions produced on simulation for backgrounds and signal
- QCD $SV0_{mass}$ distribution produced on data
- The distributions are validated in control regions
- Input to the fit: all non W+jet backgrounds normalizations
- Output of the fit: W+jet flavour fractions

Background normalizations

$t\bar{t}$ and QCD estimated with data driven method. For single t not enough data, estimated on simulations. Other BGs are small, estimated on simulations.

$W + b - jet$: cross section extraction

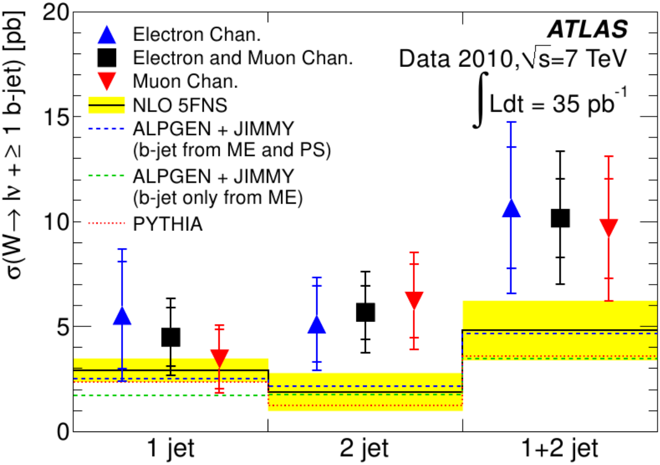
$$\sigma_{W+b-\mathrm{jet}} \times \mathcal{B}(W \to \ell\nu) = \frac{(n^{tag} - n_{\mathrm{non}-WBG}) \cdot f_{W+b-\mathrm{jet}}}{\int \mathcal{L} \cdot \mathcal{U}}$$

- n^{tag} is the number of selected events
- $n_{\mathrm{non}-WBG}$ is the estimated number of non-Wjet events
- $f_{W+b-\mathrm{jet}}$ is the fitted fraction of W+b-jet events
- $\int \mathcal{L}$ is the integrated luminosity
- $\mathcal{U}$ is the unfolding factor, ie the fraction of events in the phase space which passes the analysis selection

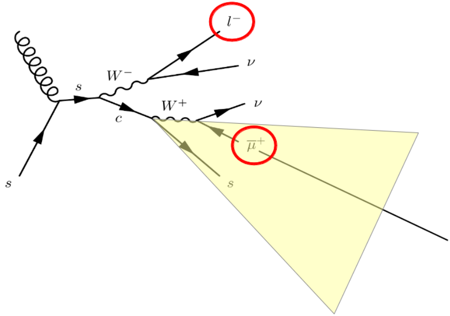
Channel	Jet bin	$\mathcal{U}_{e(\mu)}$ (%)
Electrons	1	16.32±0.84
	2	19.94±0.83
Muons	1	22.6±1.0
	2	27.8±1.0

$W + b - jet$: results on 2010 data

Theory predictions: NLO QCD predictions for W + 1 jet and W + 2 jet production with at least one b jet at the 7 TeV LHC; arXiv:1107.3714



$W + c - jet$: analysis on 2011 data



Signature

- One jet with a reconstructed muon inside
- Missing transver energy
- One high p_T, isolated lepton (electron or muon)
- Lepton and muon in jet with opposite charge

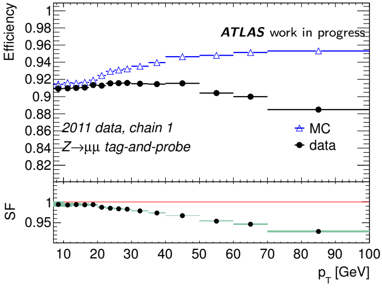
Analysis on 2011 data

- The analysis will be performed on full $4.7 fb^{-1}$ 2011 data

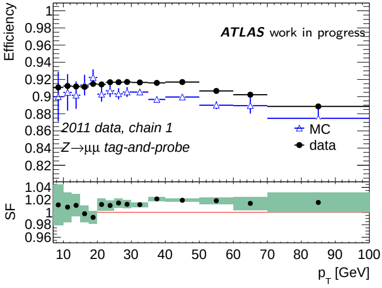
- Backgrounds are charge-blind, and can be mostly rejected using soft-muon and W-lepton charge anticorrelation
- To increase the sensitivity of the measurement, the backgrounds must be reduced as much as possible before using the anticorrelation method
- The background due to soft muons in light jets can be reduced cutting on some quantities (see next slide)

The Soft Muon Tagger

- The selected soft muons in jets are Combined Muons, a combination of the Inner Detector and the Muon Spectrometer tracks
- The χ^2_{match} of the combination can be used to separate $b, c \to \mu + X$ from $\pi, K \to \mu + X$ decays
  $\to \pi, K$ have long life time, they decay late in the Inner Detector, producing track combinations with higher χ^2_{match} values
- The tagger cuts at $\chi^2_{match}/NDOF < 3.2$ to reject light jets ($\epsilon_b \approx 10\%$, $R_{light} \approx 470$)
- A data driven estimation of the performance of the tagger is needed for the analysis
- Efficiency scale factors evaluation using $Z \to \mu\mu$ events is being finalised in these days



MC simulation with ideal alignment



MC simulation test with realistic alignment

$W + b - jet$ cross section measurement

- A measurement was published using the 2010 ATLAS dataset ($35pb^{-1}$) arXiv:1109.1470v2 [hep-ex]

  1-jet bin: $\sigma^{Fiducial}(W \rightarrow l\nu + \geq 1\ b - jet) = 4.5 \pm 1.3_{stat} \pm 1.3_{syst}\ pb$

  2-jet bin: $\sigma^{Fiducial}(W \rightarrow l\nu + \geq 1\ b - jet) = 5.7 \pm 1.3_{stat} \pm 1.4_{syst}\ pb$

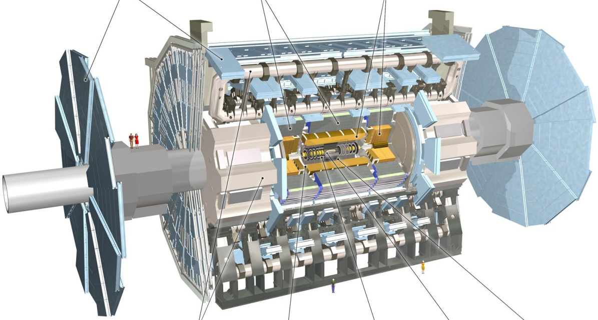
  combined: $\sigma^{Fiducial}(W \rightarrow l\nu + \geq 1\ b - jet) = 10.2 \pm 1.9_{stat} \pm 2.6_{syst}\ pb$
- The analysis will be extended with the 2011 dataset

$W + c - jet$ cross section measurement

- A method for a $W + c - jet$ cross section measurement was presented
- The analysis will be performed on full $4.7fb^{-1}$ 2011 dataset

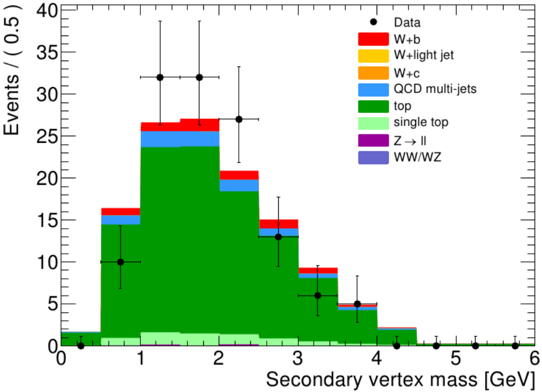
BACKUP

The ATLAS detector



Subdetectors

- Inner Detector (solenoidal field)
  - Silicon tracker up to $|\eta| < 2.5$
- Calorimeters
  - EM up to $|\eta| < 3.2$
    - Liquid Argon sampling calorimeter
  - Hadronic up to $|\eta| < 4.9$
    - Tile sampling calorimeter
    - Liquid Argon Calorimeter (forward)
- Muon Spectrometer (toroidal field)
  - Tracking up to $|\eta| < 2.7$
  - Trigger up to $|\eta| < 2.4$



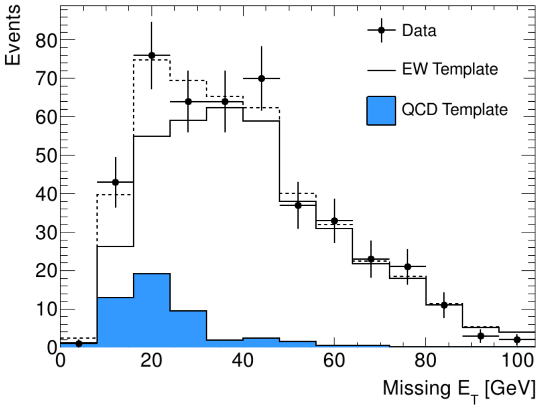
The method

- Select events with ≥ 4 jets, ≥ 1 b-tagged jet
- This defines a control region, dominated by $t\bar{t}$ events
- Apply the secondary vertex mass fit to extract the $t\bar{t}$ fraction
- Extrapolate back to signal region (1 or 2 jets, 1 b-tagged jet) using MC simulations prediction
- Most uncertainties cancels out (b tagging uncertainty above all)
- Alternative method (tag-counting) gives compatible results

$W + b - jet$: QCD background, electron channel

Multijet QCD backgrounds

- No intrinsic transverse momentum imbalance
- Contribution due to limited resolution of detector and mis-reconstructed objects



Electron channel

- Look at E^T_{miss} on full range after all other cuts
- Produce one template shape on simulation for EW
- Produce one template shape on data for QCD in a QCD enriched sample (non isolated electrons)
- Fit the templates to obtain QCD normalization on data
- Good agreement between data and fit results

QCD background, muon channel

Multijet QCD backgrounds

- No intrinsic transverse momentum imbalance
- Contribution due to limited resolution of detector and mis-reconstructed objects

Muon channel: the matrix method

Two samples defined, with a loose or tight isolation requirement
real= prompt muons from W,Z
fake= non-isolated or mis-identificated muons

$N^{loose} = N^{loose}_{real} + N^{loose}_{fake}$

$N^{tight} = N^{tight}_{real} + N^{tight}_{fake} = \epsilon_{real} N^{loose}_{real} + \epsilon_{fake} N^{loose}_{fake}$

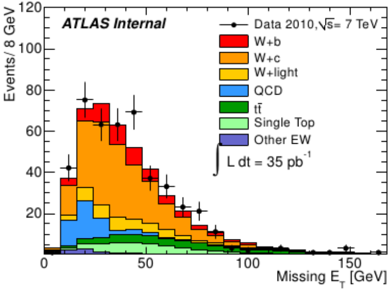
Measure ϵ_{real} and ϵ_{fake} on data, calculate

$N^{tight}_{fake} = \frac{\epsilon_{fake}}{\epsilon_{real} - \epsilon_{fake}} (\epsilon_{real} N^{loose} - N^{tight})$

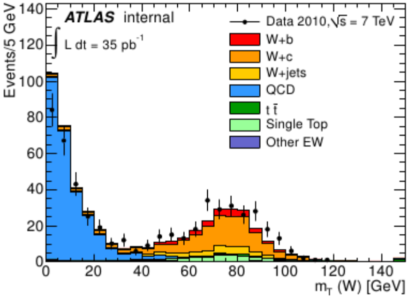
The measurement

- ϵ_{real} measured with tag and probe method on data, using $Z \rightarrow \mu\mu$ events
- ϵ_{fake} estimated in a QCD enriched sample, $M_T^W < 20\ GeV$

Validation of QCD background normalization

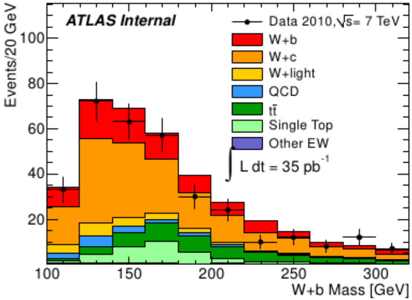


E_{miss}^{T} in the electron channel, combined 1+2 jet bins

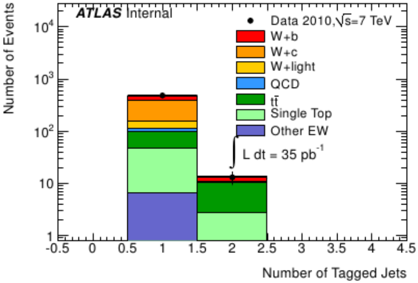


M_{T}^{W} in the muon channel, 1 jet bin

Validation of $t\bar{t}$ background normalization



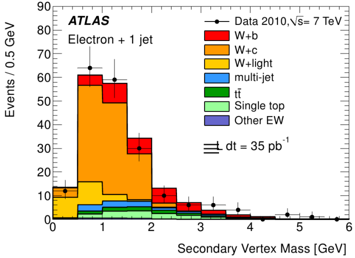
Invariant mass of the W+b-jet system in the electron channel, combined 1+2 jet bins

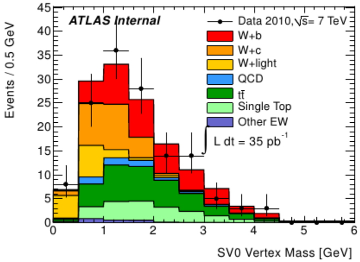


Number of b-tagged jets in the muon channel, combined 1+2 jet bins

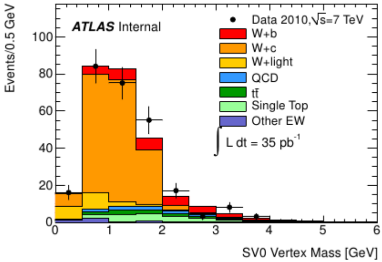
Fit results -1

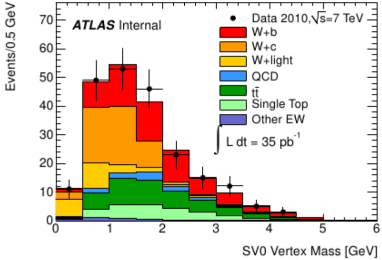
Electron channel, 1 (top) and 2 (bottom) jets





Muon channel, 1 (top) and 2 (bottom) jets





Fit results -2

Given the non W-jets background normalizations as input, the secondary vertex mass fit extracts the W+b, W+c, W+light fractions

	μ				e			
	1-jet		2-jet		1-jet		2-jet	
	MC	Fit result	MC	Fit result	MC	Fit result	MC	Fit result
QCD multi-jet	-	8	-	9.9	-	10.4	-	5.8
W+b	24.8	28.4 ± 13.0	25.9	62.4 ± 17.7	17.9	32.6 ± 13.1	18.9	37.7 ± 14.4
W+c	108.4	169.6 ± 19.5	44.9	54.1 ± 18.6	84.3	104.7 ± 17.5	35.5	24.0 ± 14.7
W+light	38.2	21.9 ± 10.4	20.2	21.2 ± 9.9	30.3	22.3 ± 10.1	17.2	14.4 ± 7.6
$t\bar{t}$	10.0	11.0	39.7	43.7	7.6	8.1	31.6	33.4
single top	17.2	-	23.1	-	13.6	-	18.4	-
WW/WZ	0.2	-	0.1	-	1.3	-	1.6	-
$Z \to \ell\ell$	3.7	-	2.4	-	0.6	-	0.5	-

Results

Cross Section [pb]									
	1 jet			2 jet			1+2 jet		
	μ	e	μ & e	μ	e	μ & e	μ	e	μ & e
Measured	3.5	5.5	4.5	6.2	5.1	5.7	9.7	10.7	10.2
Syst. $\oplus$ Stat.	1.9	2.7	1.8	2.3	2.4	1.9	3.4	4.1	3.2
Statistical	1.6	2.1	1.3	1.8	1.9	1.3	2.4	2.8	1.9
Systematic	1.1	1.7	1.3	1.5	1.5	1.4	2.4	3.0	2.6
Systematics breakdown %									
b-tag efficiency & template shape	22	19	19	14	16	14	16	16	16
Jet uncertainties	9	6	7	7	10	8	7	7	7
QCD background	7	18	11	4	8	4	5	13	7
Missing Energy	1	1	1	2	2	1	1	1	1
$t\bar{t}$ & single top	14	9	11	12	17	14	12	12	12
Lepton uncertainties	3	5	3	2	5	3	2	5	3
Model dependence	9	8	9	10	10	10	9	9	9
Pile-up	5	4	5	3	3	3	3	4	3
Luminosity	5	5	5	4	5	5	5	5	5

Systematics

- For each systematic variation considered, the full chain of the analysis is repeated
- Main systematics
  - b-jet efficiency: the limiting systematics. It affects W+b unfolding and single top estimate in correlated way. It is reduced thanks to the data driven $t\bar{t}$ estimate.
  - jet energy scale has the biggest impact in the $t\bar{t}$ estimate.
  - single top and top pair theory uncertainties are significant
- Signal modeling systematics were taken into account
- b tagging efficiency, therefore the unfolding, depends strongly
  - on b-jet momentum
  - on the angle between the two b partons (if they end in the same jet, the efficiency is higher)
- An estimate on this was produced varying the contribution to signal of
  - $g \rightarrow b\overline{b}$
  - $q\overline{q} \rightarrow Wb\overline{b}$