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Measurement of V+heavy flavour production at ATLAS

Motivation
Measurement of b-jets in association with a Z boson (2010 data)
Measurement of b-jets in association with a W boson (2011 data)

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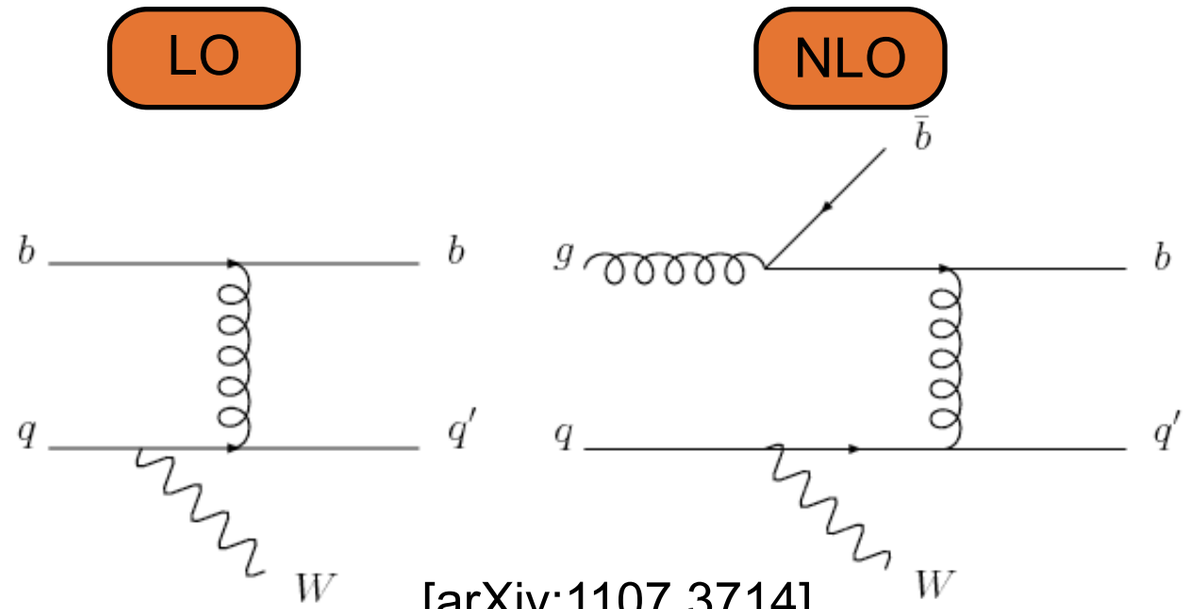
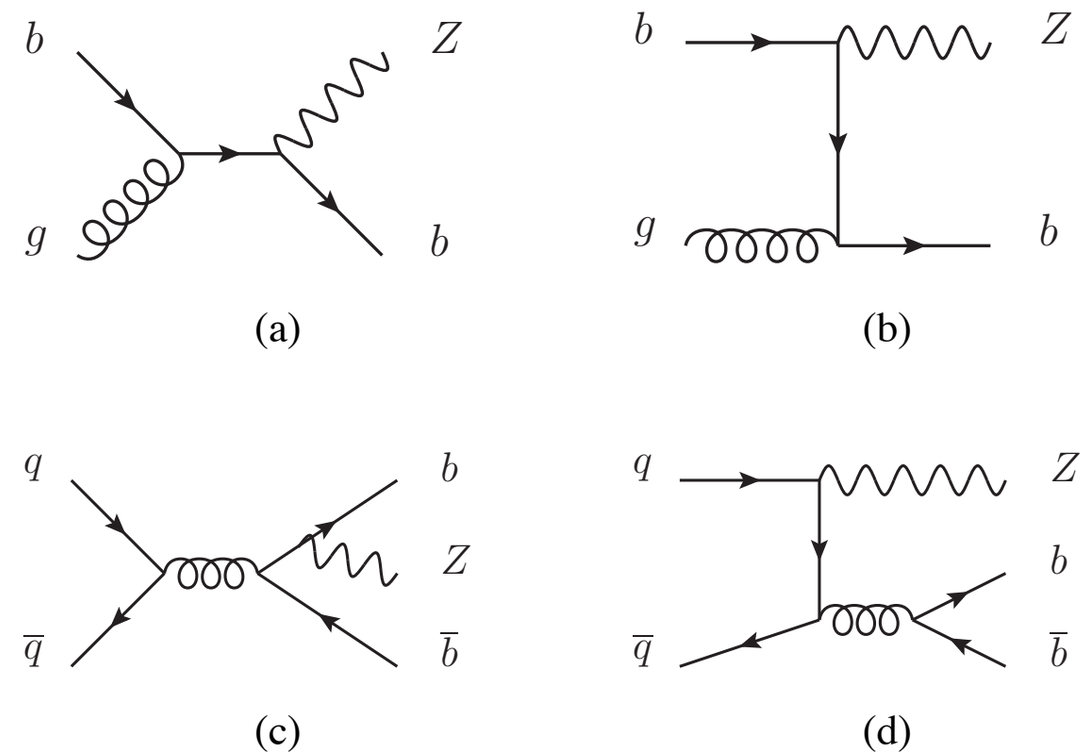
Motivation

- V+heavy flavour (HF) production is an important test of perturbative QCD
- several processes contribute at NLO:
  - study heavy flavour content of PDFs
  - test different flavour schemes and calculation approaches
- expect contributions from double-parton interactions
- important background to Higgs, top quark and beyond Standard Model measurements



[arXiv:1107.3714]

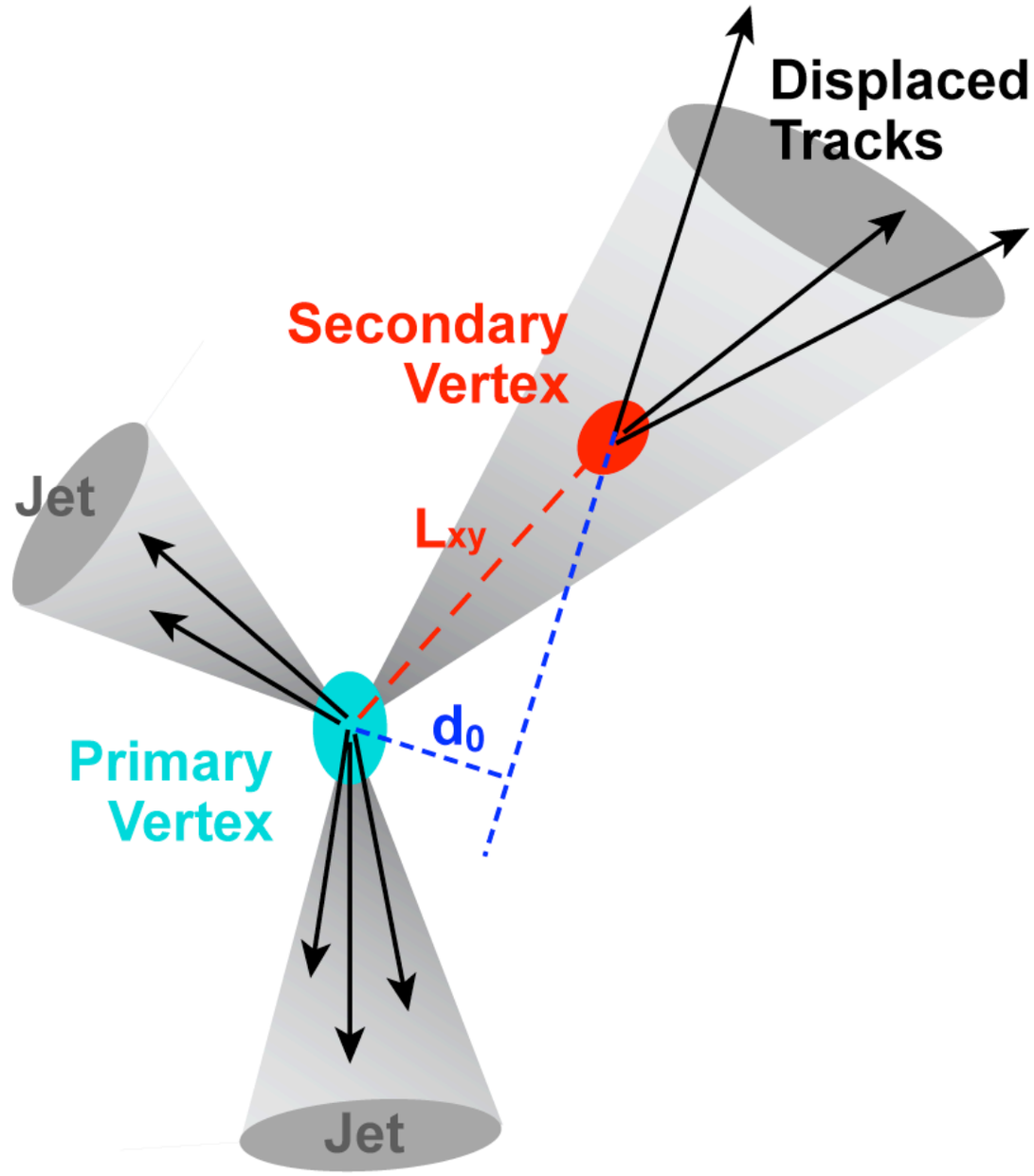


[arXiv:1109.1403v2]

Identification of b-jets

- W/Z+heavy flavour challenging
  - especially W+b with large background
- use b-tagging: exploit the long lifetime and mass of B-hadrons
- Z+heavy flavour analysis: require displaced secondary vertex in a jet with decay length significance of > 5.85 (50% efficiency)
- W+heavy flavour analysis: combine two algorithms into artificial neural network (CombNN)
  - secondary vertex (as above)
  - impact parameter significance
  - 40-57% efficiency, rejection rates: 10 for c-jets, 1000 for light jets

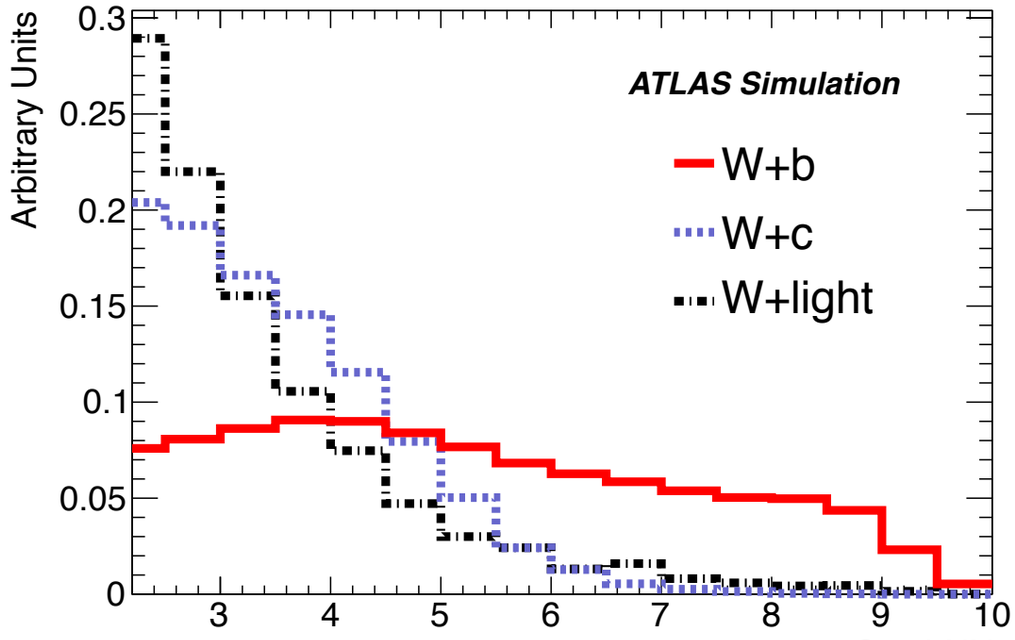
Mind: use of jets as opposed to track-based B-hadron reconstruction (CMS)

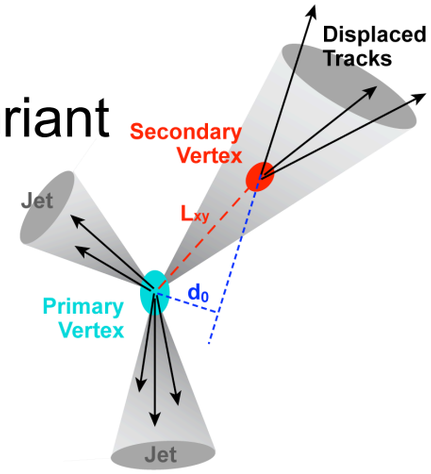


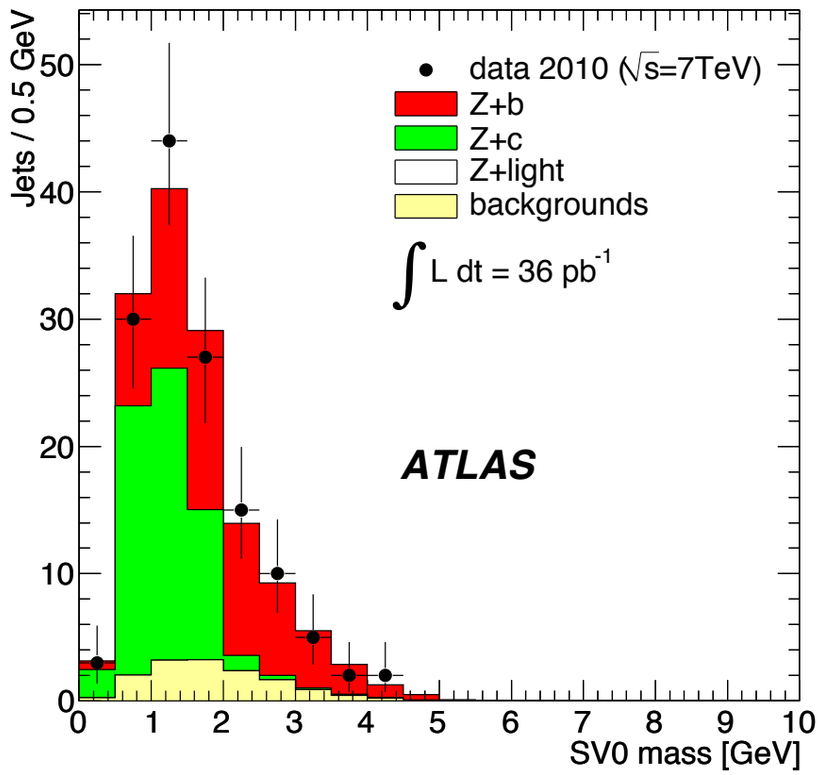
[http://www-d0.fnal.gov/Run2Physics/top/singletop_observation/]

Analysis approach

- both analyses performed in a fiducial volume
- multi-jet background (lepton fakes) are taken from data
- other backgrounds using shapes from simulation and normalisation from sideband regions (W+HF) or theory (Z+HF)
- estimate W+HF fitting distributions sensitive to flavour content:
  - CombNN b-tagging probability distribution (W+HF)
  - secondary vertex mass (Z+HF) - invariant mass of all charged particle tracks originating from secondary vertex







Event selection

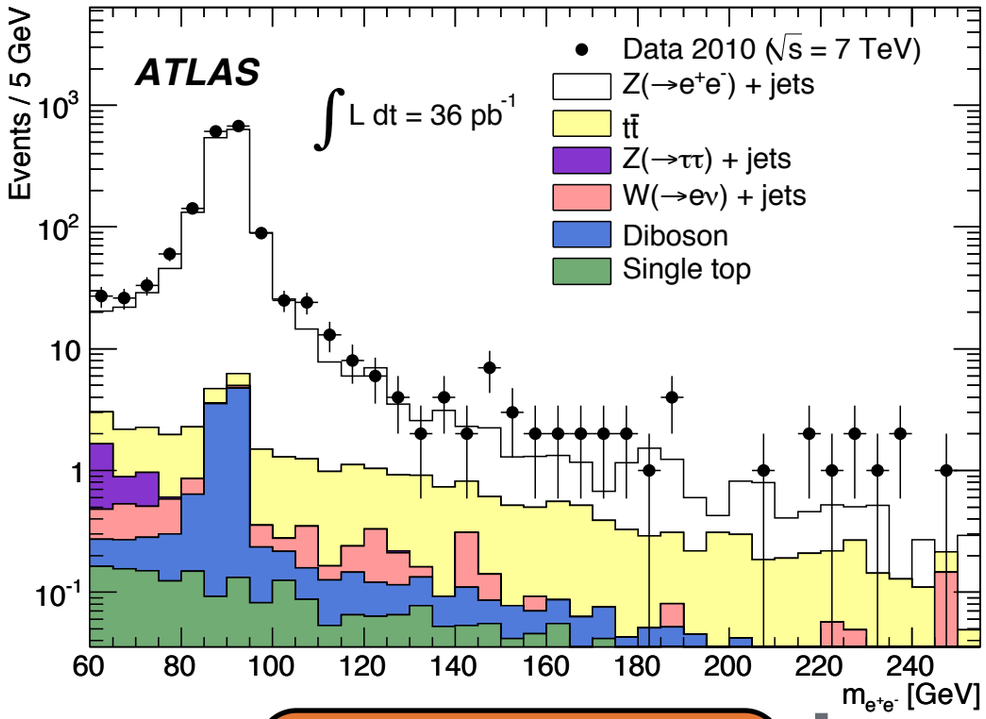
- consider only jets with p_T > 25 GeV within tracker coverage, |y| < 2.1 found using anti-k_T algorithm (R=0.4)
- leptons: only electrons and muons in central detector region |η| < 2.5

W+HF selection

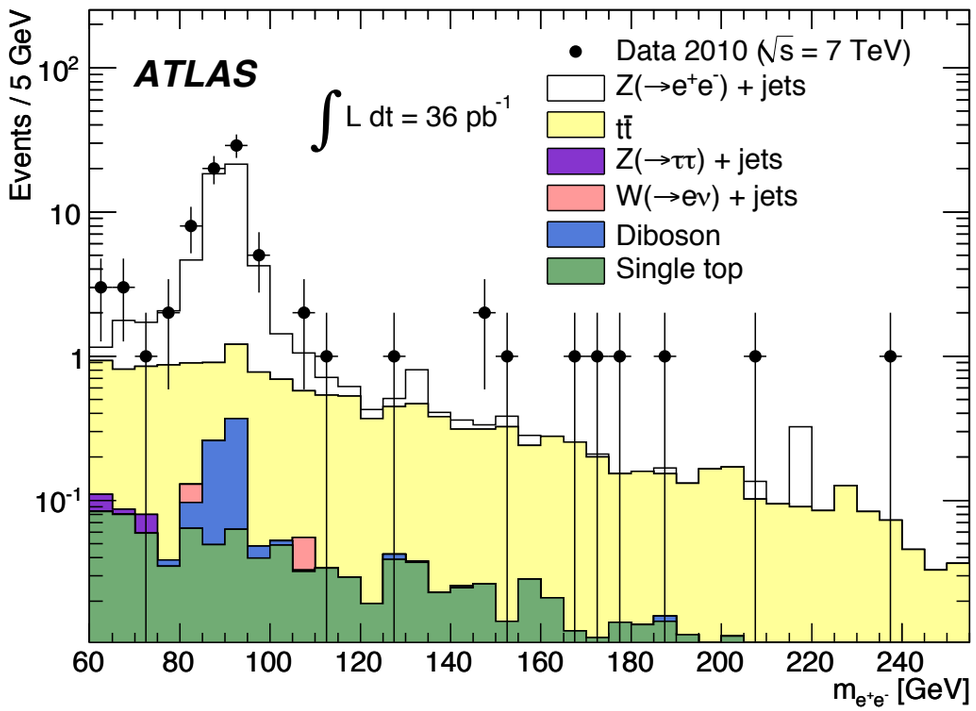
- one or two jets, **exactly one** b-tagged
- exactly one lepton, p_T > 25 GeV
- additional cuts on missing transverse energy and the transverse mass of the W

Z+HF selection

- any number of jets, **at least one** b-tagged
- opposite charge pair of leptons, each p_T > 20 GeV
- invariant mass cut: 76 GeV < m_{ll} < 106 GeV



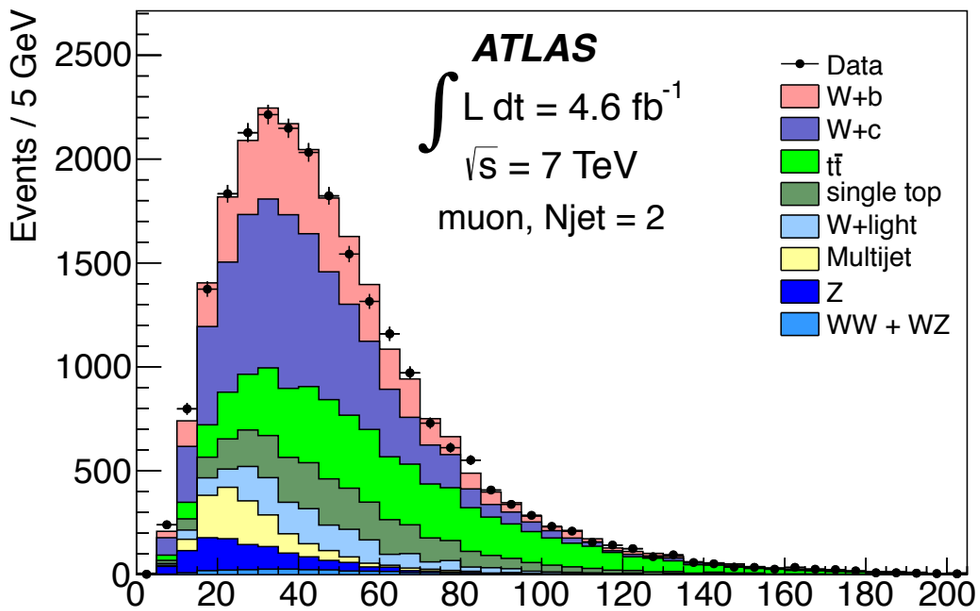
b-tag requirement



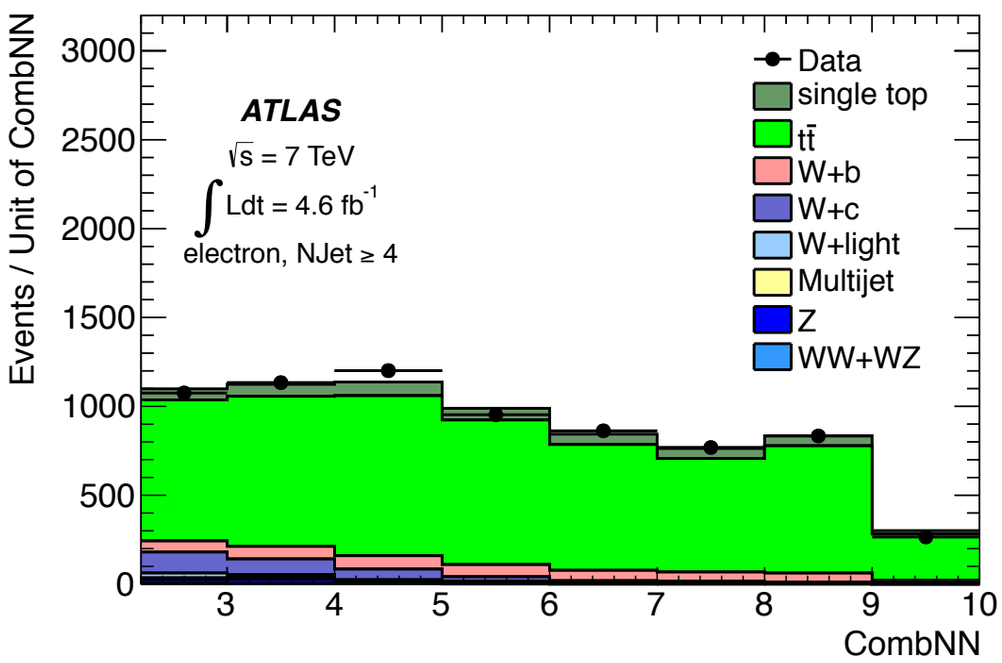
[arXiv:1109.1403]

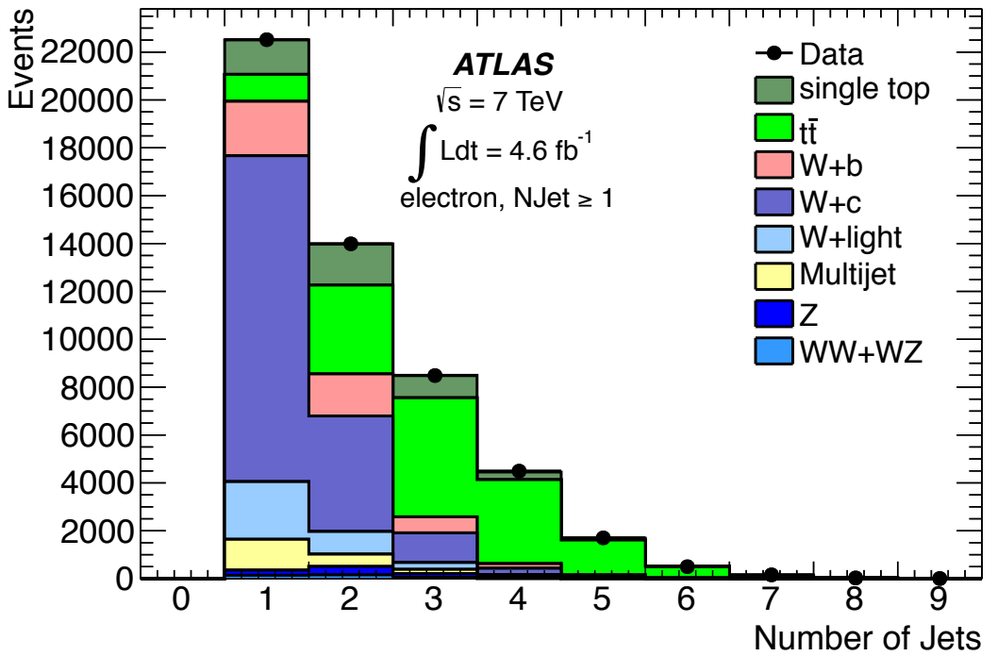
Non-W+jets background estimation in W+heavy flavour analysis (1)

- signal region: 1 and 2 jets, exactly one b-tagged
- multijets:
  - obtain model by inverting isolation (muons) or identification requirements (electrons)
  - fit in low missing E_T sideband region
- top quark pairs:
  - fit to CombNN distribution in region with ≥ 4 jets, exactly one b-tagged



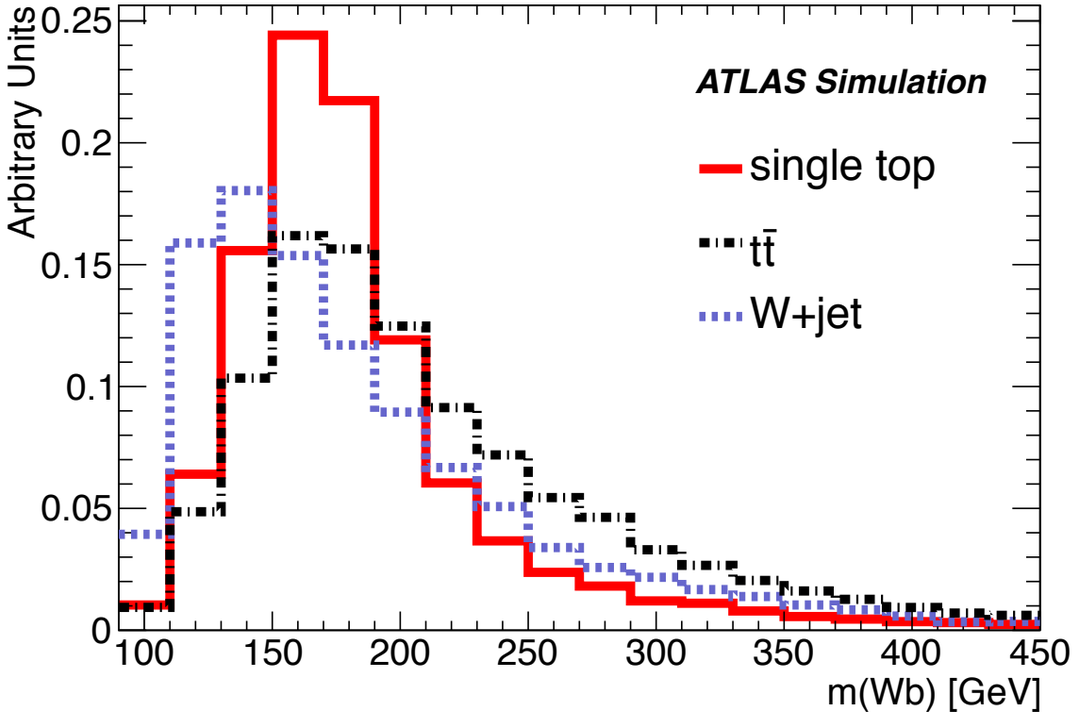
[arXiv:1302.2929]

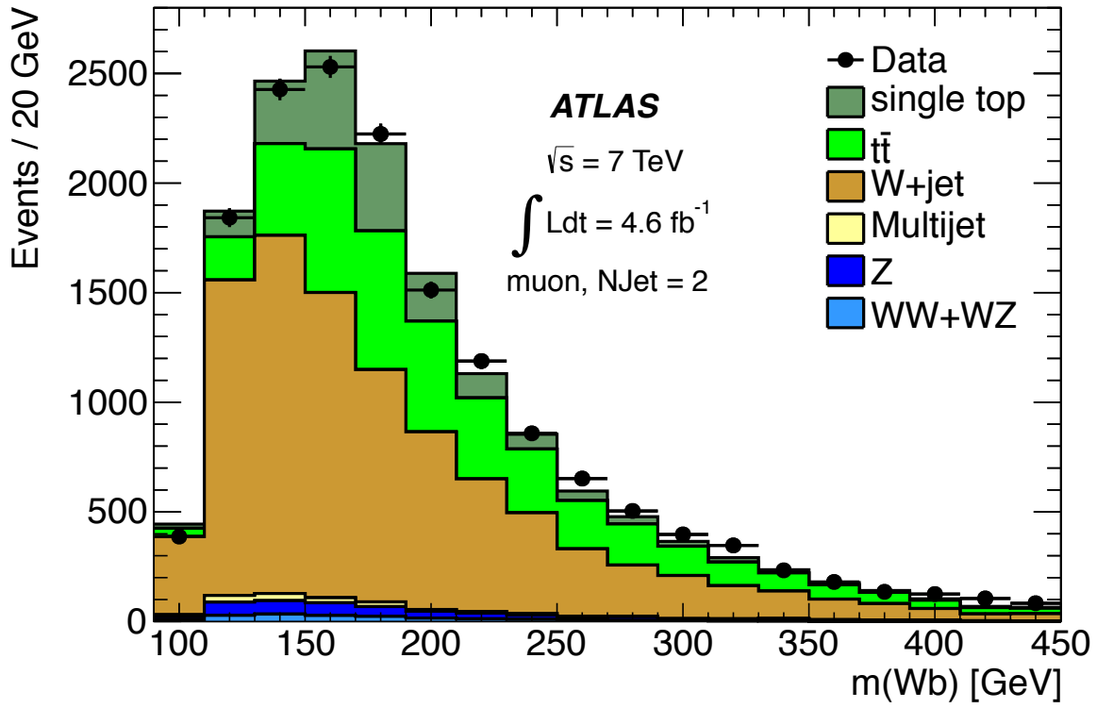




Non-W+jets background estimation in W+heavy flavour analysis (2)

- single top:
  - irreducible, fit in signal region using invariant mass distribution of the combined W boson and the b-tagged jet
  - verify result using H_T distribution (sum of transverse energies/momenta in event)
- other smaller backgrounds from simulation

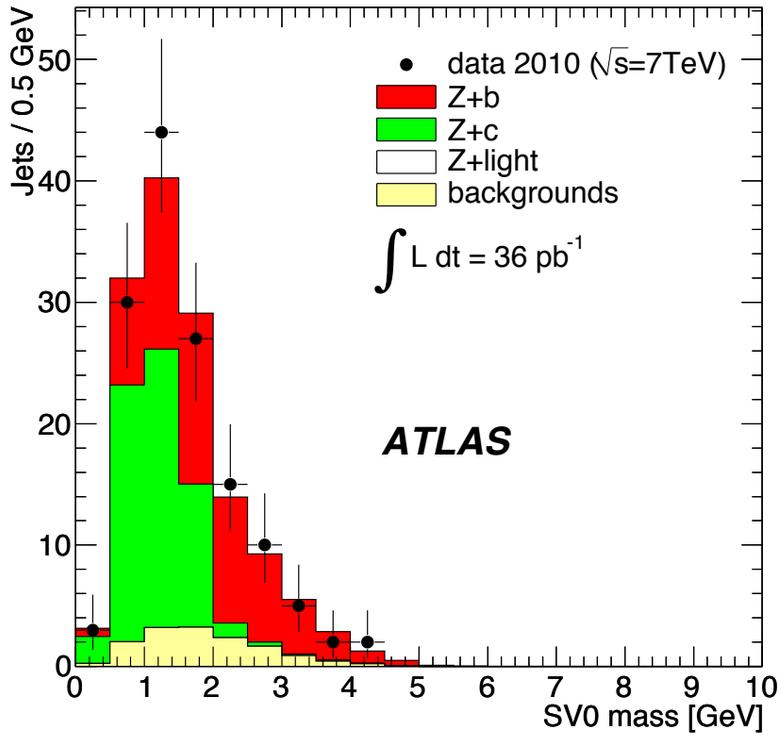




[arXiv:1302.2929]

Backgrounds and signal extraction

- **Z+HF analysis**: backgrounds fixed, fit only Z+jets contributions (SV mass)
- **W+HF analysis**: non-W backgrounds estimated in fit, constrained by sideband measurements, W+jets without constraints (CombNN)
  - W+c dominant background (55% 1 jet, 30% 2 jets)
  - single top (6% 1 jet, 14% 2 jets)
  - top quark pairs in events with 2 jets



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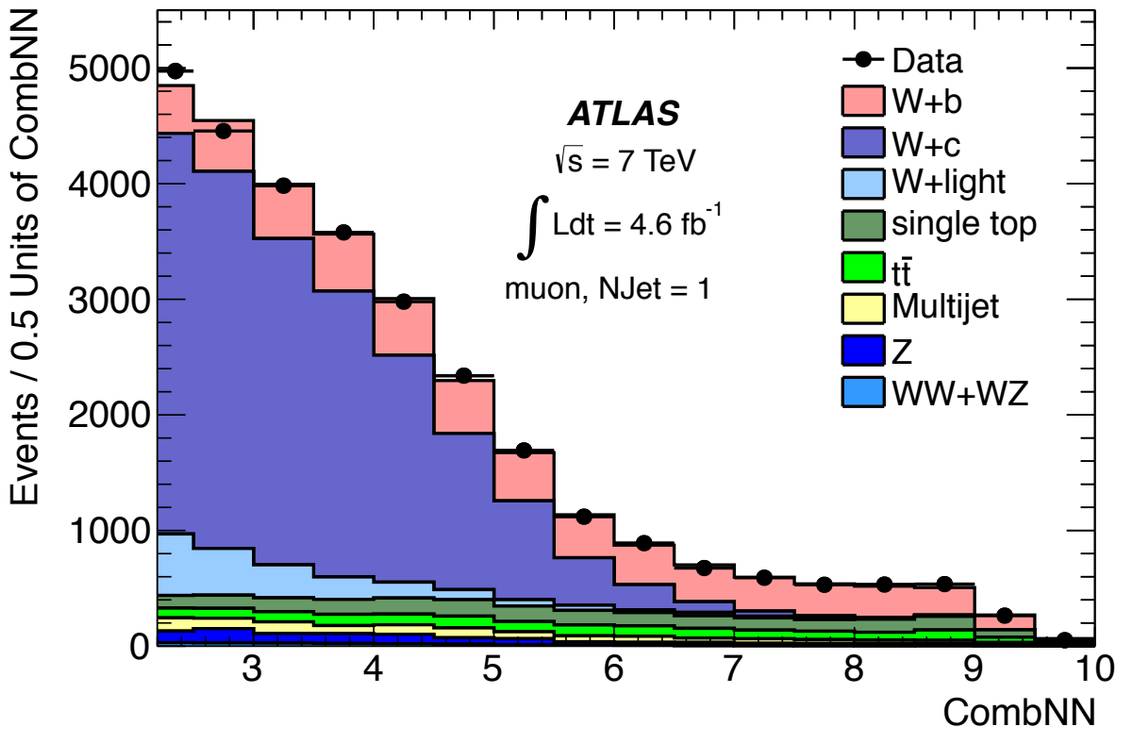
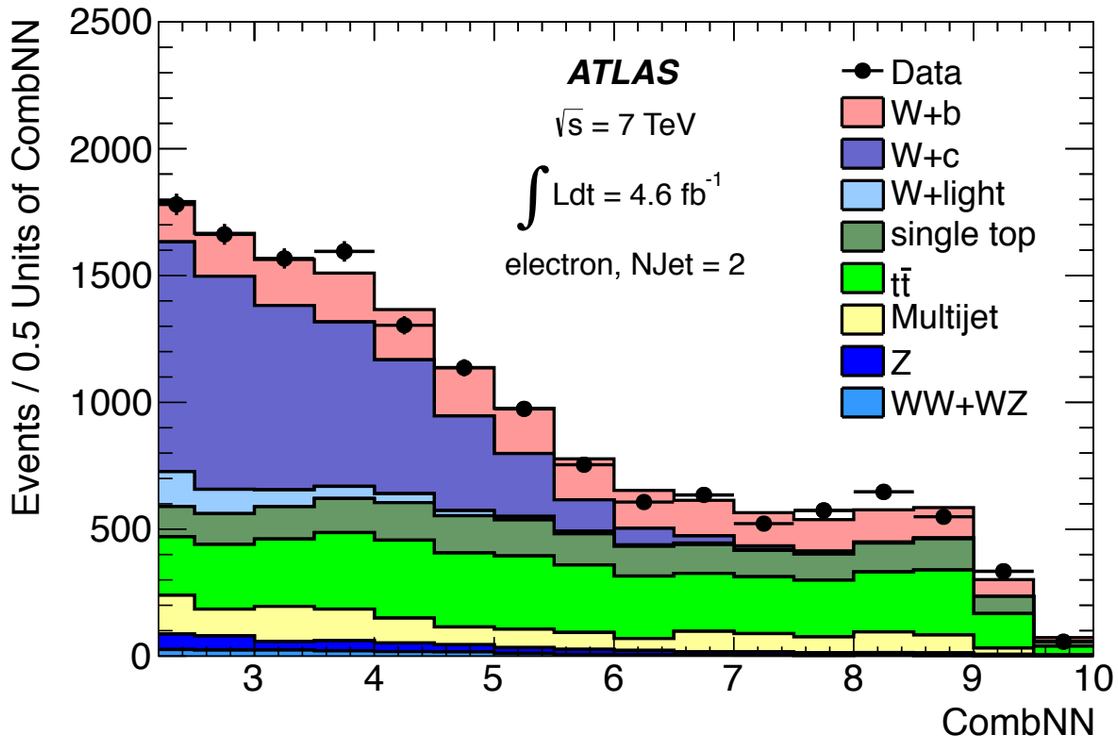




[arXiv:1302.2929]

Cross-section extraction

- Bayesian unfolding to particle level performed with respect to fiducial region
- particle level b-jet: find b-hadron with p_T > 5 GeV within ΔR < 0.3 of the jet
- trigger and object reconstruction efficiencies accounted for
- AlpGEN MC used to obtain correction factors for events passing particle level selection but not reconstruction level and vice versa
- W+HF also extracts cross section as a function of the p_T of the leading b-jet

W+HF fiducial phase space region:

Requirement	Cut
Lepton transverse momentum	$p_{\mathrm{T}}^{\ell} > 25$ GeV
Lepton pseudorapidity	$\lvert\eta^{\ell}\rvert < 2.5$
Neutrino transverse momentum	$p_{\mathrm{T}}^{\nu} > 25$ GeV
W transverse mass	$m_{\mathrm{T}}(W) > 60$ GeV
Jet transverse momentum	$p_{\mathrm{T}}^{j} > 25$ GeV
Jet rapidity	$\lvert y^{j}\rvert < 2.1$
Jet multiplicity	$n \leq 2$
b-jet multiplicity	$n_b = 1$ or $n_b = 2$
Jet-lepton separation	$\Delta R(\ell, \mathrm{jet}) > 0.5$

Z+HF analysis similar

Systematic uncertainties

- Z+HF is statistically limited, ~22% (2010 data set)
- systematic uncertainties 5.5% in fiducial volume, ~15% acceptance

Source	SV0-mass Fit (%)	Acceptance (%)
Both Electron and Muon		
b-tagging efficiency	1.7	9.1
SV0-mass templates	3.5	-
Model dependence	2.7	10.0
Jet energy scale	0.7	4.0
tt cross-section	2.0	-
MPI model	negl.	1.0
Electron only		
MC statistics	negl.	1.3
Multi-jet background	1.6	-
Electron efficiency	negl.	5.0
Total Electron	5.6	15.0
Muon only		
MC statistics	negl.	1.3
Multi-jet background	0.7	-
Muon efficiency	negl.	2.0
Total Muon	5.4	14.3
Total Systematic Uncertainty	+21% -16%	

- W+HF analysis systematically limited, ~20%

Fiducial cross-section [pb]			
	1 jet	2 jet	1+2 jet
σ_{fid}	5.0	2.2	7.1
Statistical uncertainty	0.5	0.2	0.5
Systematic uncertainty	1.2	0.5	1.4
Breakdown of systematic uncertainty [%]			
Jet energy scale	15	15	15
Jet energy resolution	14	4	8
b-jet efficiency	6	4	5
c-jet efficiency	1	1	0
light-jet efficiency	1	3	2
ISR/FSR	4	8	3
MC modelling	8	4	6
Lepton resolution	1	1	0
Trigger efficiency	1	2	2
Lepton efficiency	1	2	1
$E_{\text{T}}^{\text{miss}}$ scale	3	6	2
$E_{\text{T}}^{\text{miss}}$ pile-up	2	2	2
b-jet template	3	5	4
c-jet template	4	2	3
light-jet template	0	0	0
Multijet template	2	2	2
Total syst. uncertainty	24	23	20

Results of the Z+heavy flavour analysis

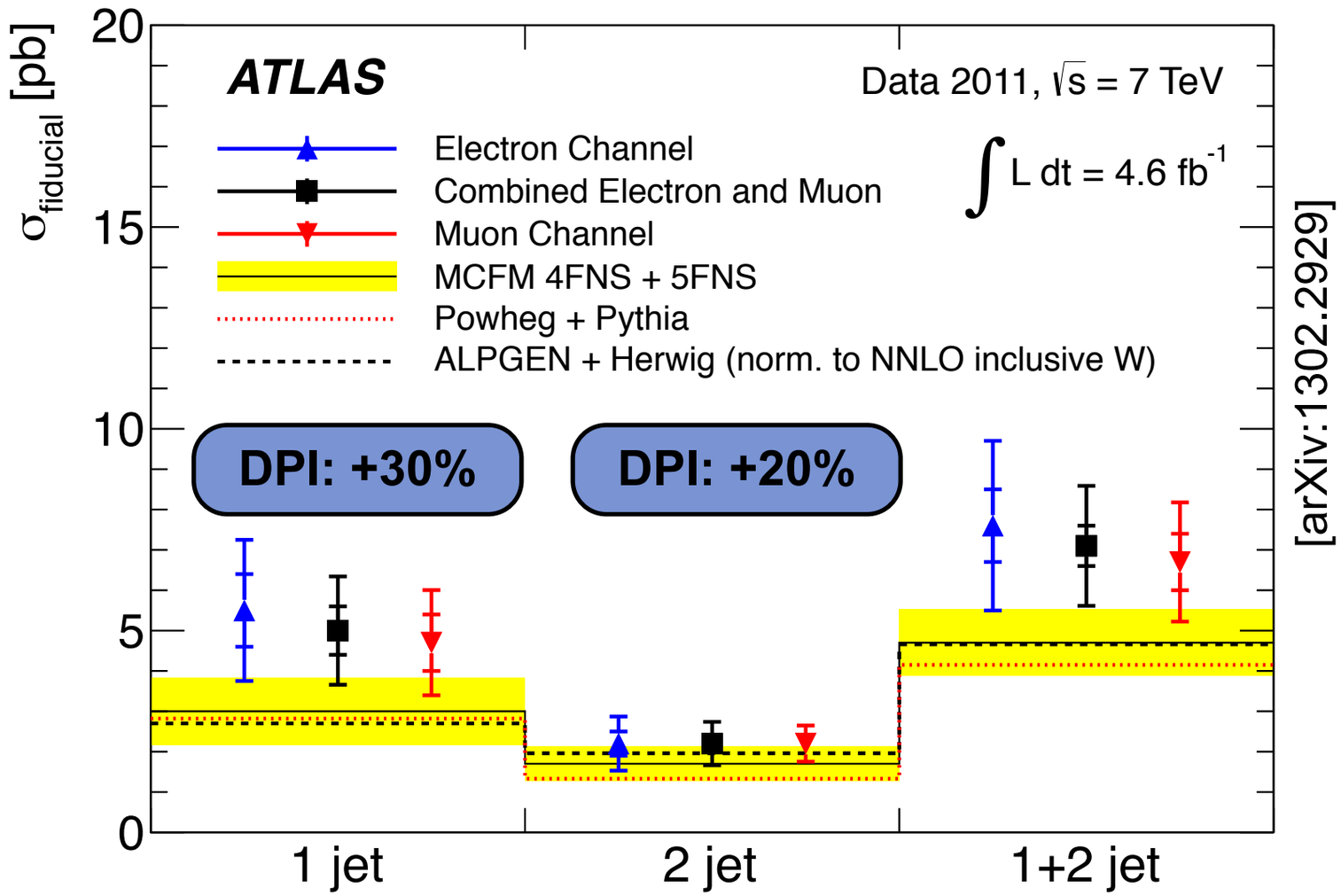
- significant theoretical uncertainties
- uncertainty for MCFM taken from scale variations

Experiment	$3.55^{+0.82}_{-0.74}(\text{stat})^{+0.73}_{-0.55}(\text{syst}) \pm 0.12(\text{lumi})$ pb
MCFM	3.88 ± 0.58 pb (NLO)
ALPGEN	2.23 ± 0.01 (stat only) pb (LO)
SHERPA	3.29 ± 0.04 (stat only) pb (LO)

- additionally measurement of the average number of b-jets produced in association with a Z boson
- again, theory predictions differ significantly, but in agreement with data

Experiment	$(7.6^{+1.8}_{-1.6}(\text{stat})^{+1.5}_{-1.2}(\text{syst})) \times 10^{-3}$
MCFM	$(8.8 \pm 1.1) \times 10^{-3}$
ALPGEN	$(6.2 \pm 0.1\ (\text{stat only})) \times 10^{-3}$
SHERPA	$(9.3 \pm 0.1\ (\text{stat only})) \times 10^{-3}$

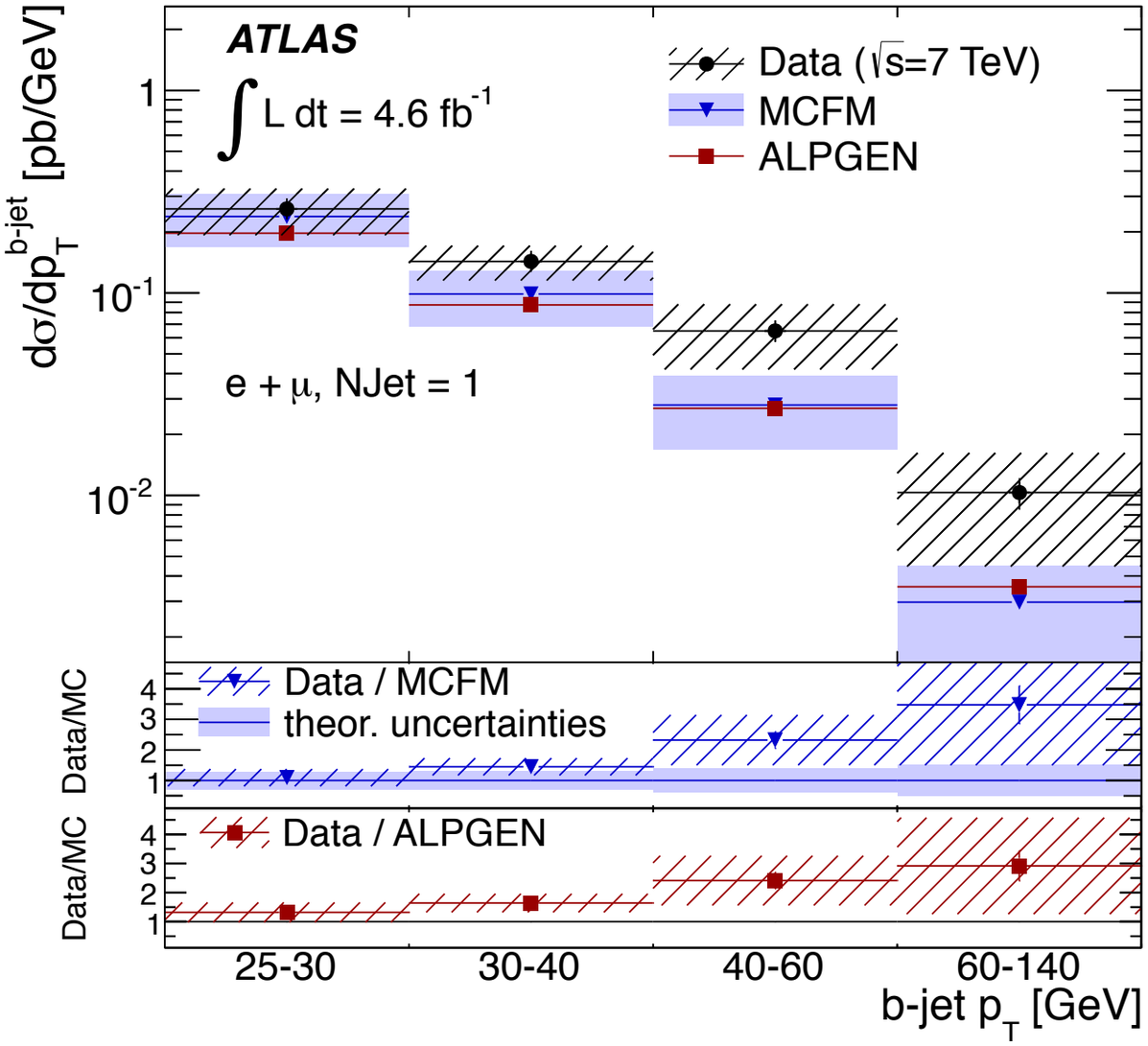
Results of the W+heavy flavour analysis

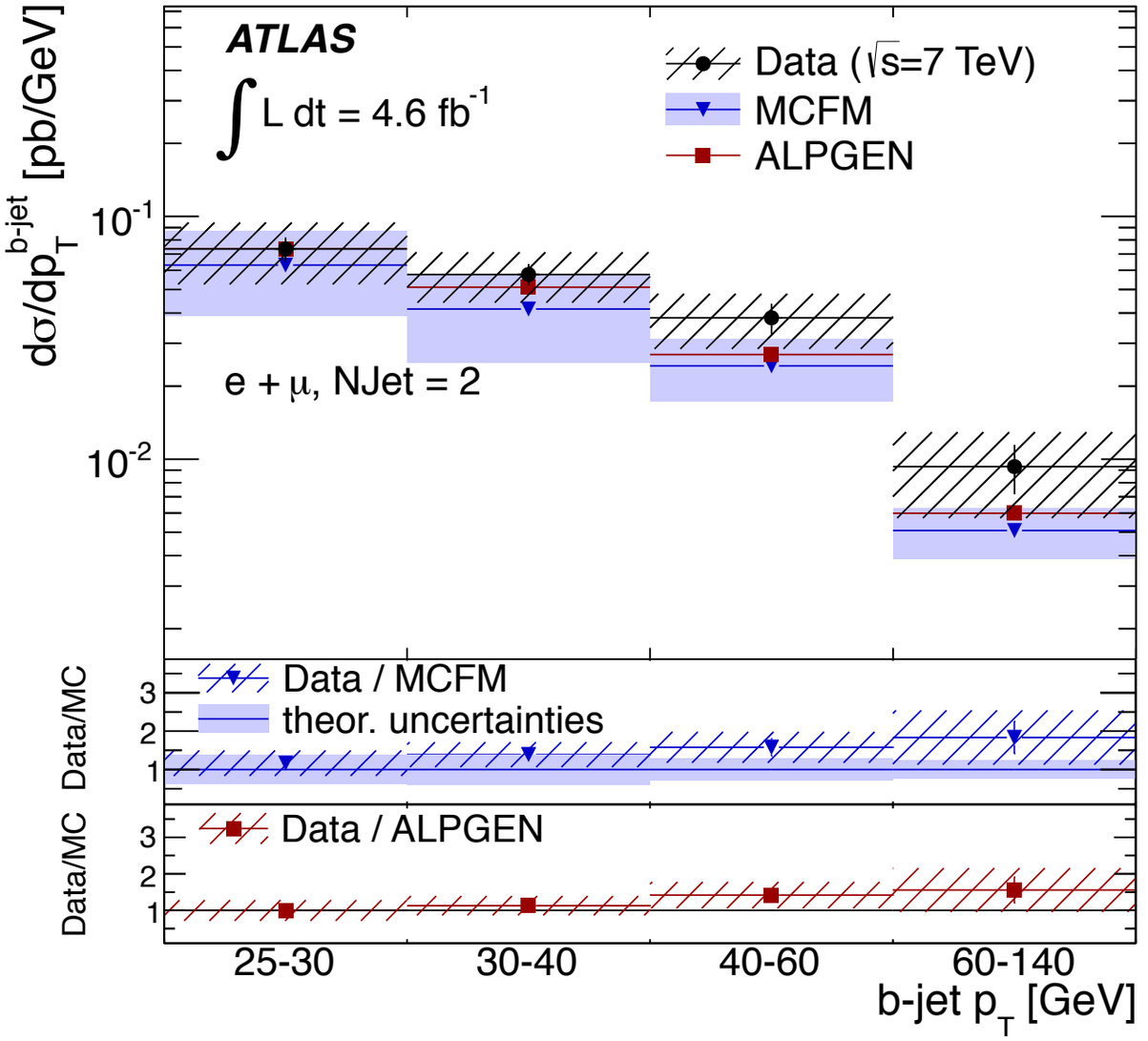


data-MC agreement within uncertainties

	MCFM	Powheg+Pythia	AlpGEN+Herwig
order pQCD	NLO	NLO	LO (normalised to incl. W+jets NNLO)
flavour scheme	5FNS	4FNS	4FNS
PDF	MSTW2008NLO	MSTW2008NLO	CTEQ6L1
DPI correction	from AlpGEN	from AlpGEN	intrinsic

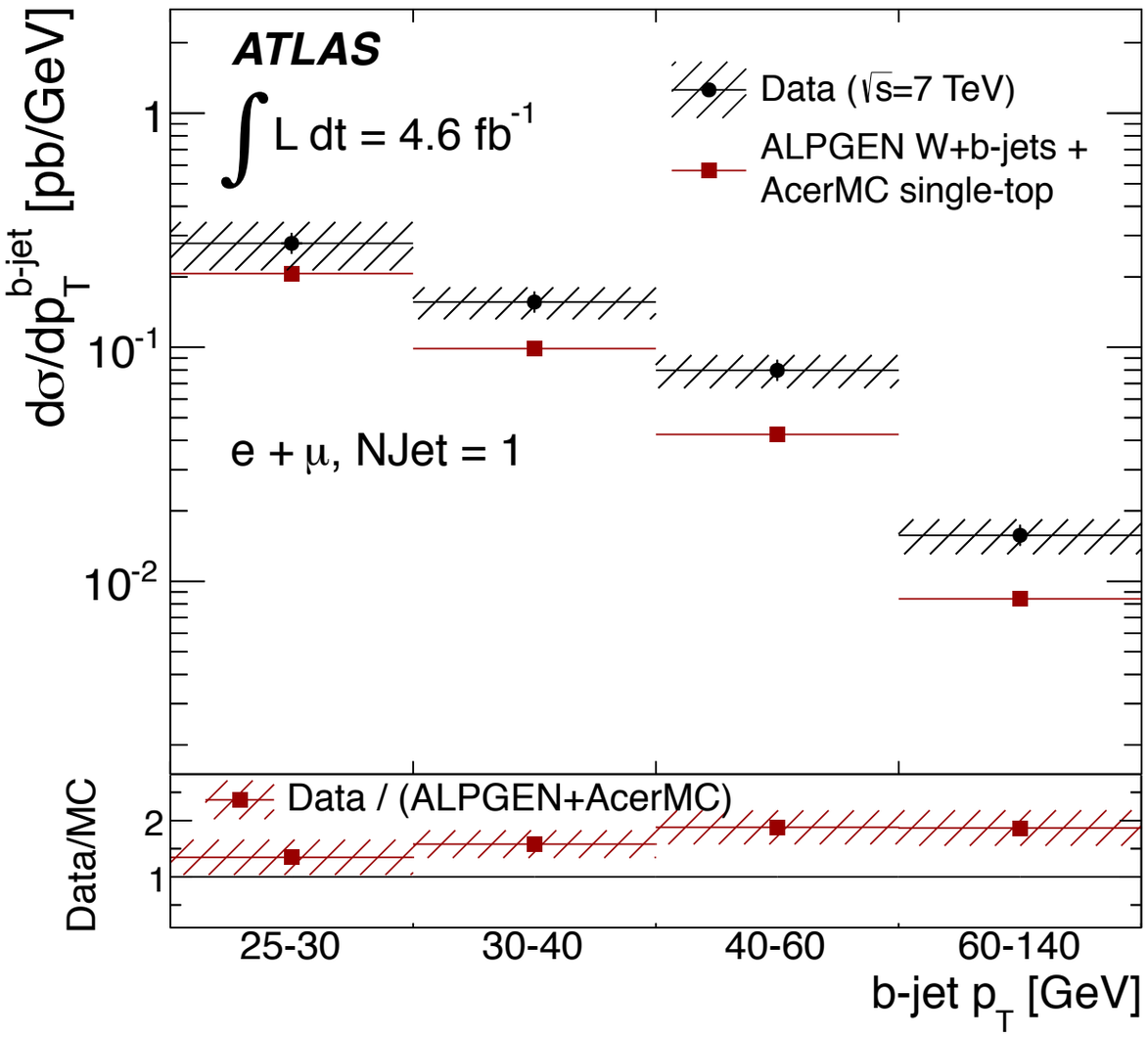
Differential W+b cross section

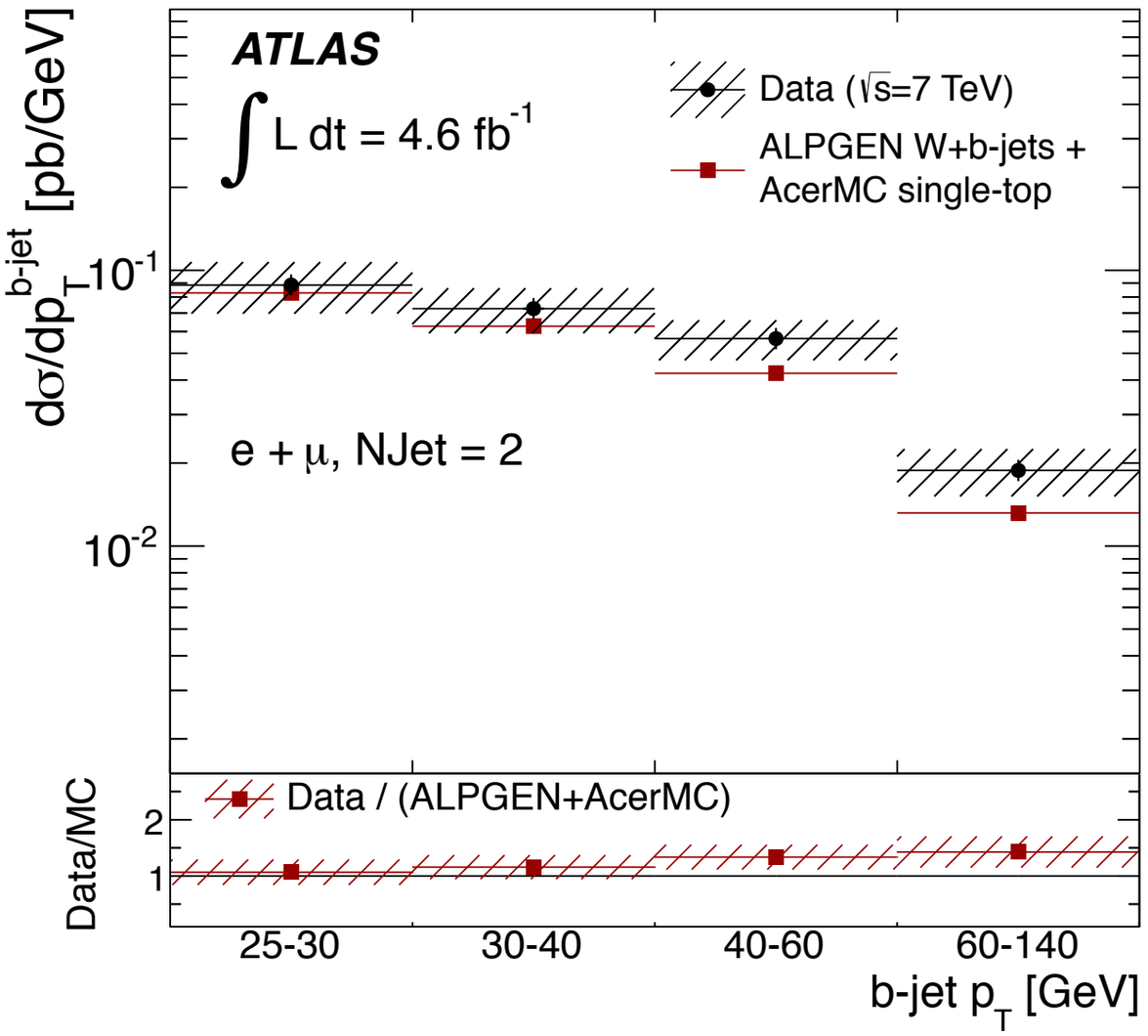




- first measurement of W+b differential cross section $d\sigma/dp_T$
- degeneracy at large p_T between W+b and single top, but still covered by uncertainties (not related to DPI)

Differential W+b cross section without single-top subtraction





- complementary measurement without subtracting single top prediction
  - higher experimental precision
  - mind that AlpGEN+AcerMC has additional theory uncertainties, not shown here

Conclusions

- presented to V+heavy flavour measurements performed with the ATLAS experiment
- heavy flavour quark jets identified using b-tagging techniques
- Z+heavy flavour measurements promise smaller systematic uncertainties, but 2010 analysis statistically limited
- W+b measurement using 2011 data set in agreement with theory predictions
- first differential measurement of W+b $d\sigma/dp_T$
- measurement of W+b and single top reduces experimental uncertainties, but needs more input from theory

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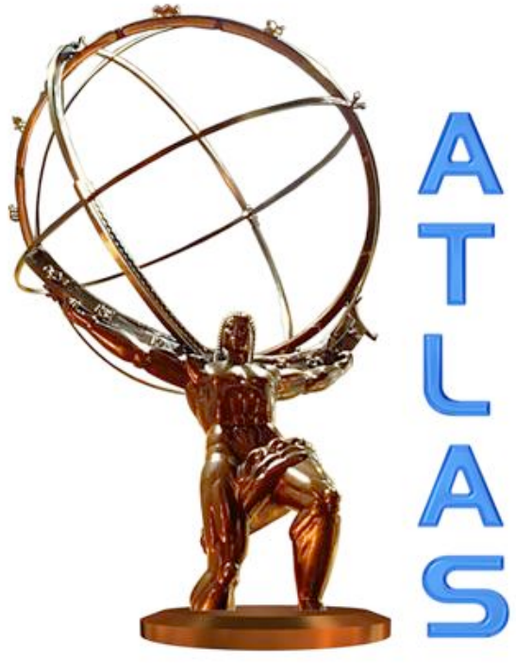
additional plots and information



W+HF signal region