

Z,W+jets, ttbar+jet and W+HF at ATLAS

Masaki Ishitsuka

Tokyo Institute of Technology

On behalf of **the ATLAS collaboration**



Overview

- Results on experimental test of QCD by ATLAS
 - **Z+jets, W+jets, $t\bar{t}$ +jets and W+heavy flavor**
 - Based on dataset in pp collision at $\sqrt{s} = 7$ TeV at LHC
- Measurements of the cross-sections and kinematics provide important tests of QCD predictions/modeling, including
 - Higher order perturbative QCD calculations
 - Proton structure encapsulated in parton distribution function (PDF)
 - Parton shower and fragmentation processes
 - Interactions of proton remnants, referred to as 'underlying event'
- Theoretical prediction hard \Rightarrow Input from experiment is essential**
- Understanding of background to Higgs boson and beyond the SM

+ Z+jets

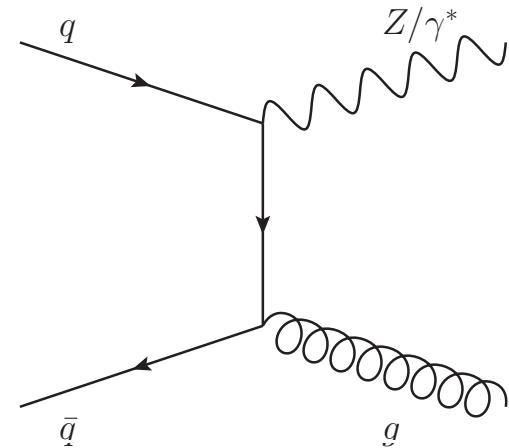
*JHEP07(2013)032
(4.6 fb^{-1} @ 7 TeV)*

- Event selection
 - $Z(\rightarrow ee)$ or $Z(\rightarrow \mu^+ \mu^-)$ + jets ($\mathbf{p}_T > 30\text{GeV}$, $|y| < 4.4$)

- Background
 - $N_{\text{jet}} \leq 1$: multi-jet (QCD), diboson
 - $N_{\text{jet}} > 1$: top-pair production

- Systematic uncertainty
 - Jet energy scale and resolution dominant

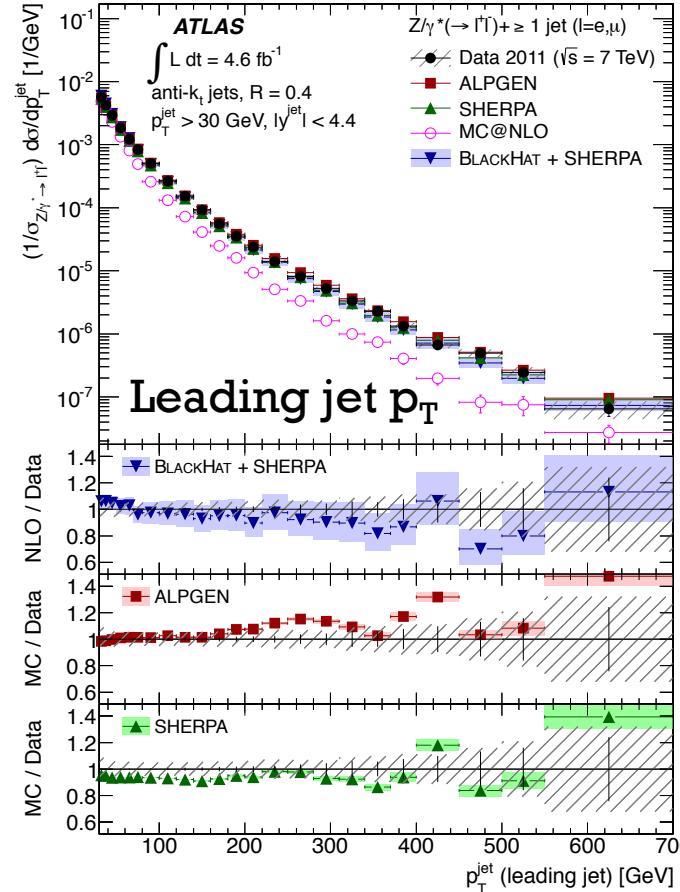
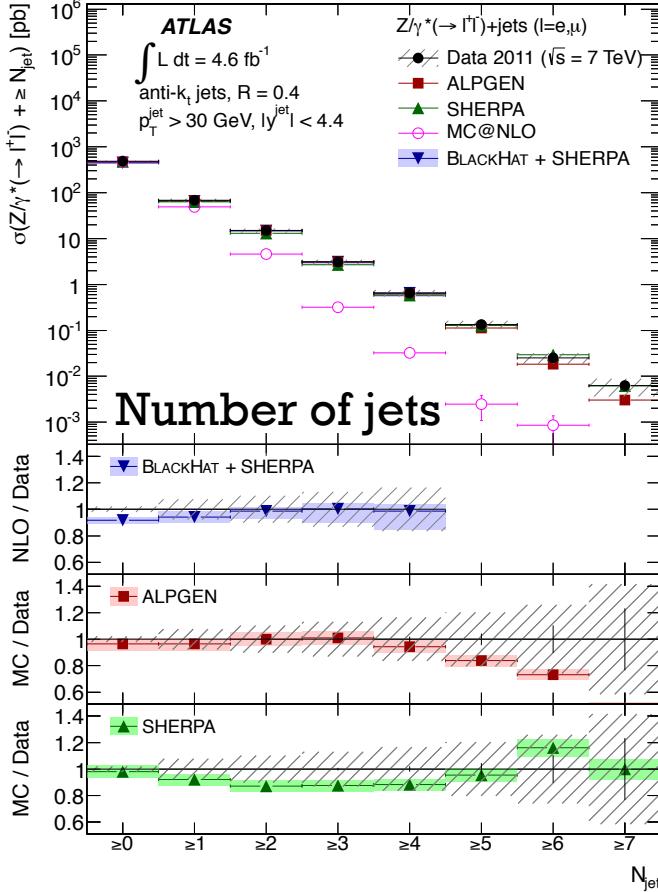
- Prediction
 - MC simulation with **ALPGEN** and **SHERPA**
 - ALPGEN interfaced to HERWIG for parton shower and fragmentation
 - PDF from CTEQ6L1 (ALPGEN) or CT10 (SHERPA)
 - Normalized to NNLO inclusive Z production cross-section
 - **Fixed-order NLO pQCD** calculation with **BLACKHAT+SHERPA**
 - Corrected for non-perturbative effects





Z+jets: jet multiplicity and p_T

JHEP07(2013)032
(4.6fb⁻¹ @ 7 TeV)

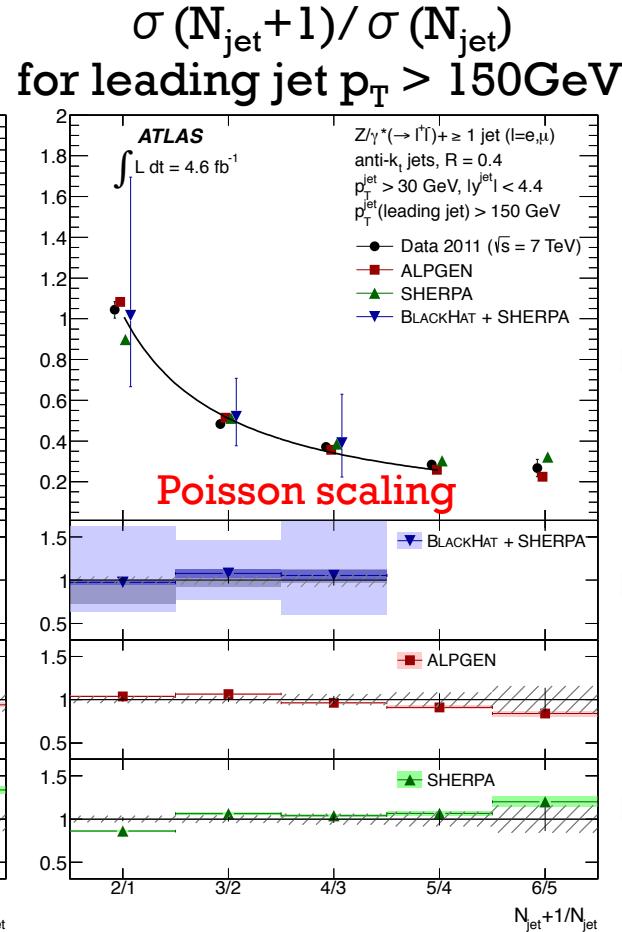
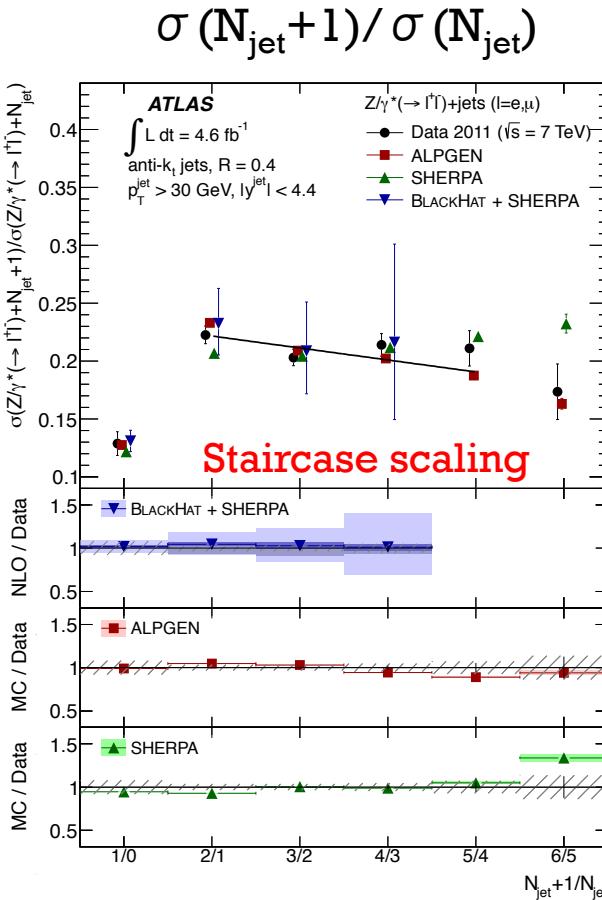


- Test of perturbative QCD prediction up to 7 jets and 700 GeV
- Overall in good agreement between data and prediction



Z+jets: scaling properties

*JHEP07(2013)032
(4.6 fb^{-1} @ 7 TeV)*



Exclusive ratio:

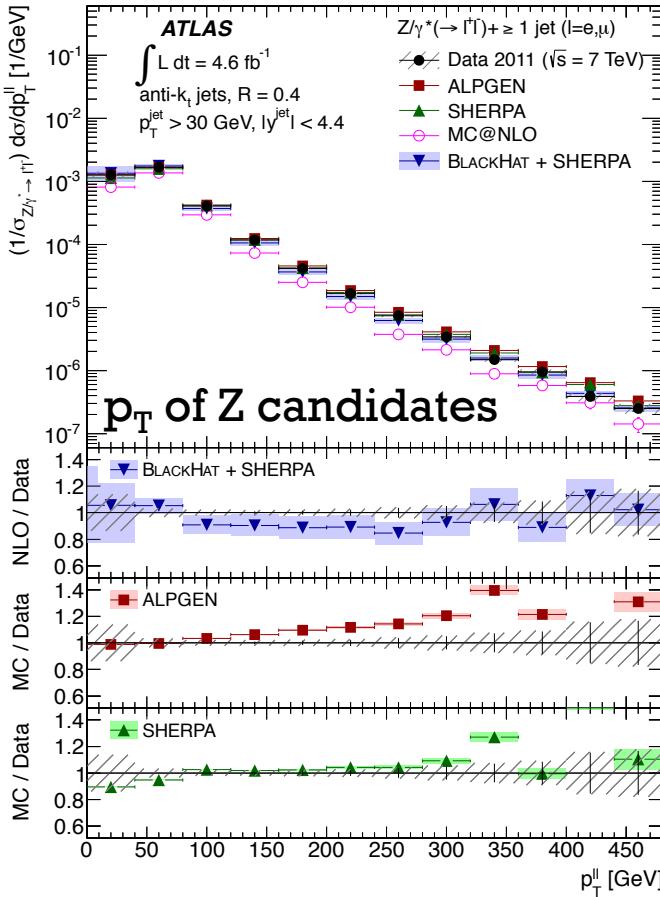
$$R_{(n+1)/n} = \sigma(N_{jet}+1)/\sigma(N_{jet})$$

- With symmetric jet p_T
- $R_{(n+1)/n}$ consistent with flat
⇒ **Staircase scaling**
- With asymmetric jet p_T
- $R_{(n+1)/n}$ follows \bar{n}/n
⇒ **Poisson scaling**
- **Scaling properties well modeled by theory**



Z+jets: p_T of recoiled Z boson

*JHEP07(2013)032
(4.6 fb^{-1} @ 7 TeV)*



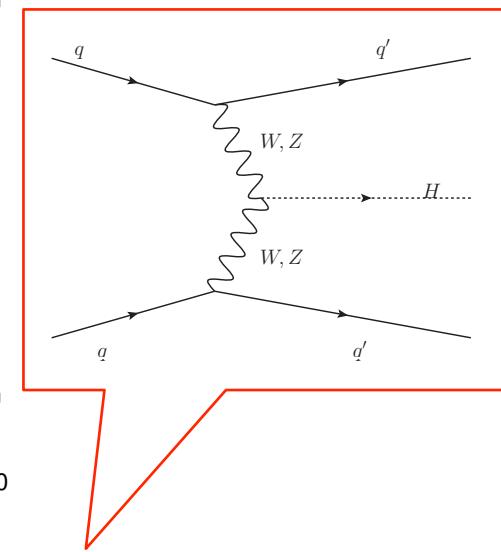
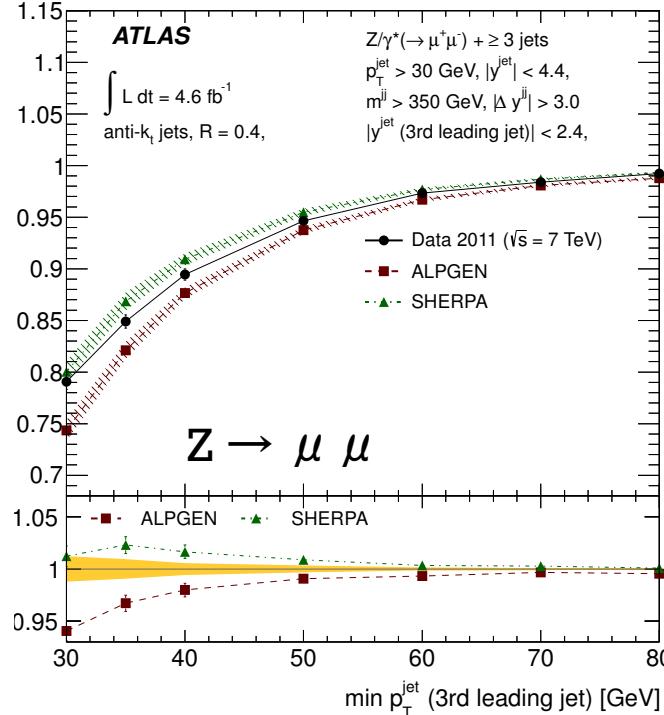
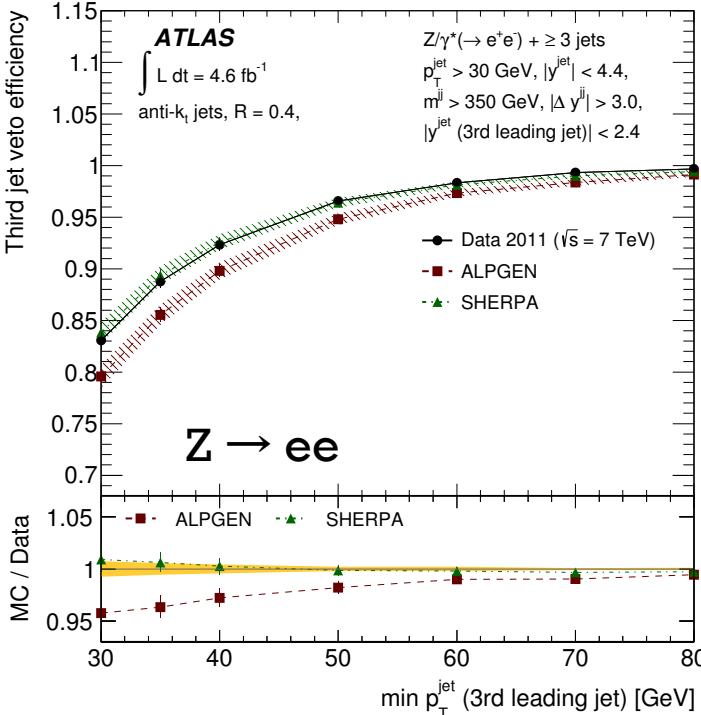
- Softer spectrum with **BLACKHAT+SHERPA**
- Missing higher jet multiplicities in fixed order calculation (higher jet multiplicities at larger p_T)
- Harder spectrum with **ALPGEN** and **SHERPA**
- Discrepancy comparable to expected higher-order EW corrections (not in MC prediction)



Z+jets: 3rd jet veto efficiency

JHEP07(2013)032
(4.6 fb^{-1} @ 7 TeV)

Veto efficiency as a function of 3rd jet p_T threshold



- Veto on 3rd jet is used to reject Z+jets background in VBF Higgs selection
- Modeling of 3rd jet veto efficiency tested
 - ALPGEN: underestimate veto efficiency at low p_T regime
 - SHERPA: better agreement with data

+ W+jets

Phys. Rev. D85, 092002 (2012)
 $(36\text{pb}^{-1} @ 7\text{TeV})$

■ Event selection

- $\text{W}(\rightarrow e \nu) \text{ or } \text{W}(\rightarrow \mu \nu) + \text{jets}$ ($\mathbf{p}_T > 30\text{GeV}$, $|y| < 4.4$)
- W selection: missing $E_T > 25\text{GeV}$, $m_T(\text{W}) > 40\text{GeV}$

■ Background

- multi-jet (semi-leptonic decay of HF hadrons), gauge boson, top-pair

■ Systematic uncertainty

- Jet energy scale (dominant), top-pair cross section and shape, etc.

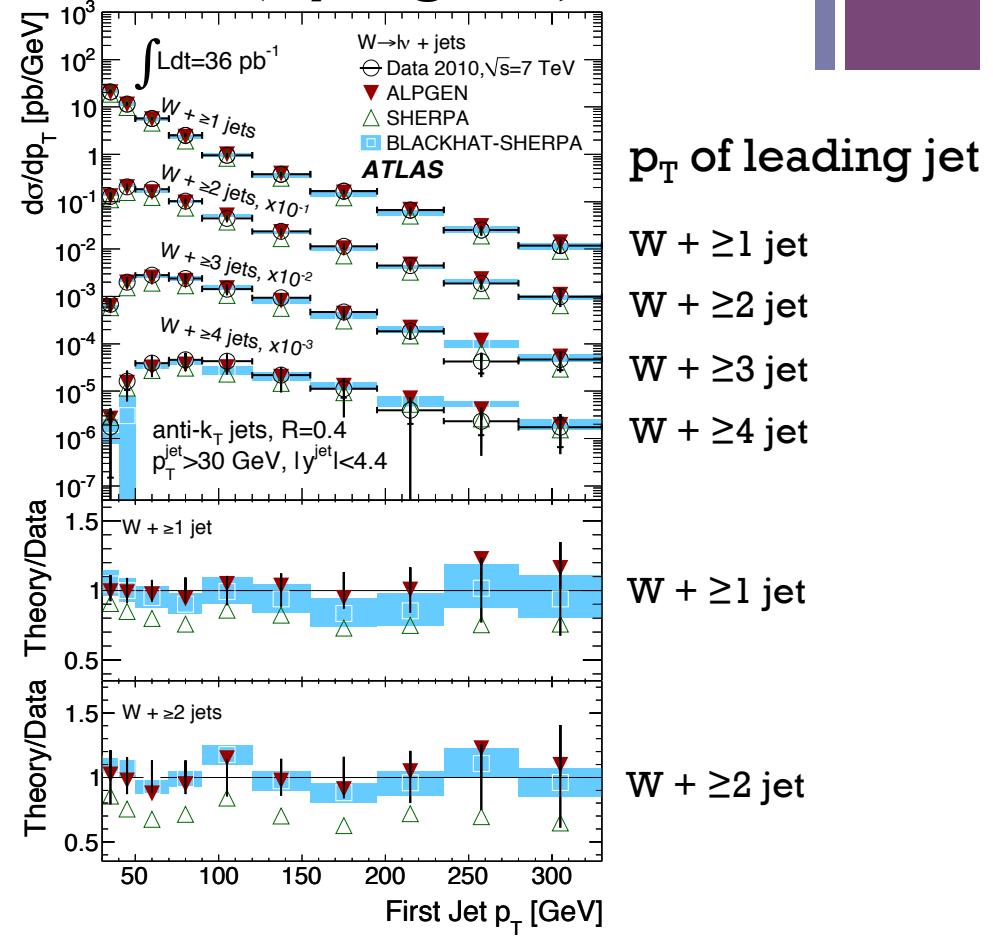
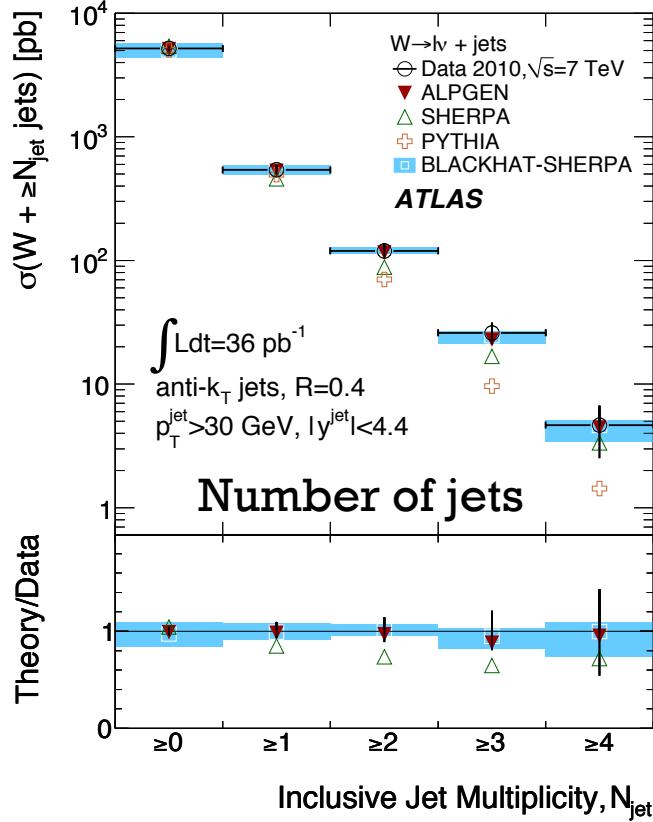
■ Prediction

- MC simulation with **ALPGEN** and **SHERPA**
 - Normalized to NNLO inclusive W production cross-section
- **Fixed-order NLO pQCD** calculation with **BLACKHAT+SHERPA**
 - Corrected for non-perturbative effects



W+jets: jet multiplicity and p_T

Phys. Rev. D85, 092002 (2012)
 $(36\text{pb}^{-1} @ 7\text{TeV})$



- Good agreement with prediction by ALPGEN and BLACKHAT+SHERPA (worse with SHERPA)

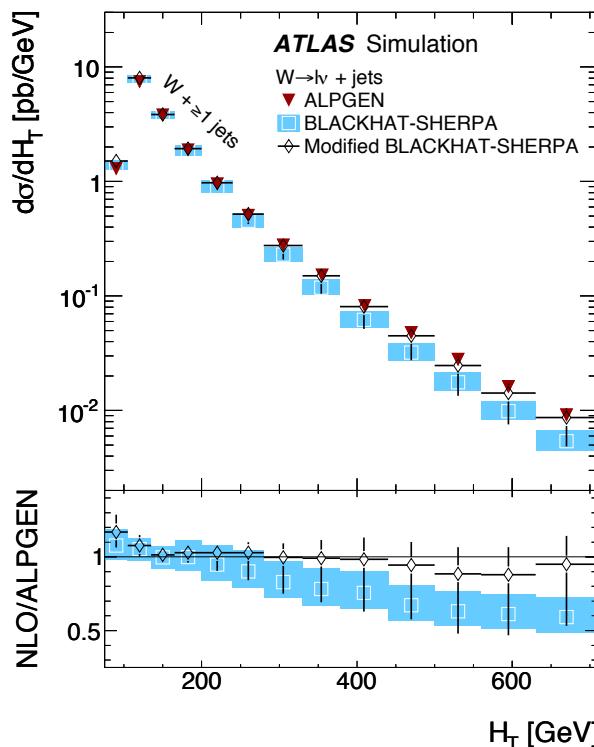
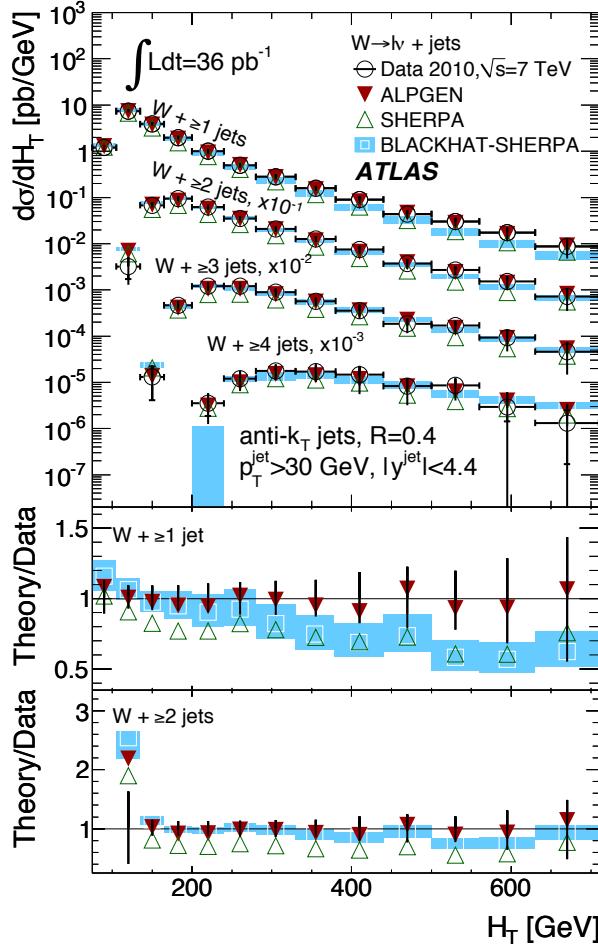


W+jets: scalar p_T sum (H_T)

Phys. Rev. D85, 092002 (2012)
 $(36\text{pb}^{-1} @ 7\text{TeV})$

$$H_T = \sum_{\text{leptons, jets}} |\mathbf{p}_T|$$

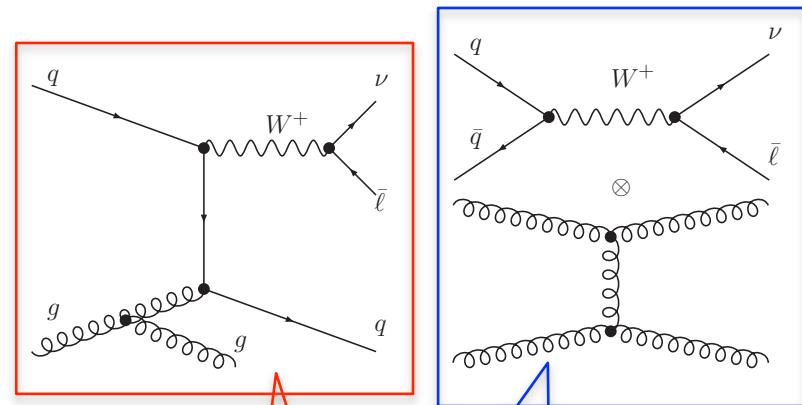
(neutrino \mathbf{p}_T = missing E_T)



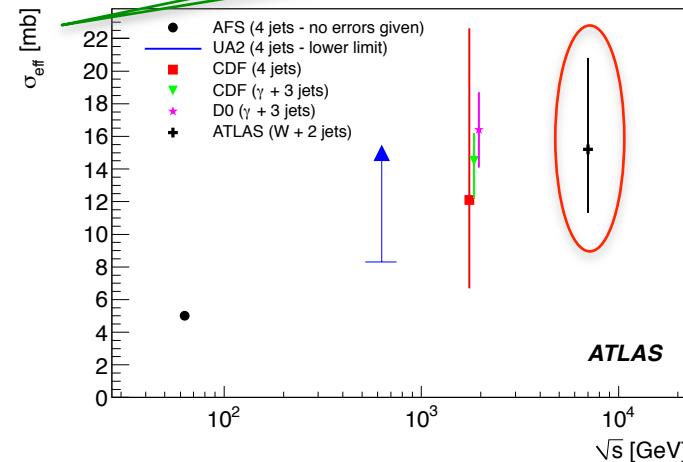
- H_T is used to set renormalization and factorization scales in fixed-order calculations
- Discrepancy at large H_T (higher jet multiplicity) in BLACKHAT due to limited order of calculation
- Agreement improved by adding different number of parton emissions exclusively
⇒ Confirmed by Z+jets analysis

+ W+jets: double-parton interactions

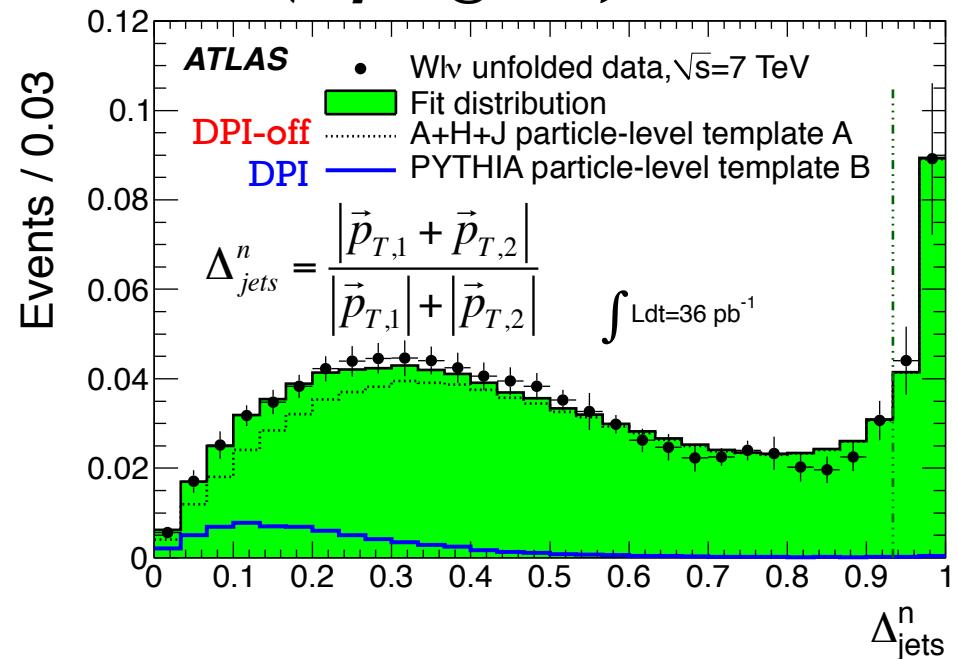
*New J. Phys. 15 (2013) 033038
(36 pb⁻¹ @ 7 TeV)*



$$d\sigma_{Y+Z}^{(tot)} = d\sigma_{Y+Z}^{(SPI)} + \frac{d\sigma_Y \cdot d\sigma_Z}{\sigma_{eff}}$$



QCD@LHC2013, DESY



- Two parton scatterings in the same pp-collision
- Experimentally measured by W+2 jets
 - DPI contribution at low Δ^n_{jets}
- Fraction of events arising from DPI
 - $f_{DP} = 0.08 \pm 0.01(\text{stat}) \pm 0.02(\text{syst})$
- Rate and kinematics in good agreement with predictions of MC models

+ $t\bar{t}+jets$

Single lepton: Phys. Lett. B 711(2012) 244-263

Two leptons: JHEP 1205 (2012) 059

■ Event selection

- Single lepton + ≥ 3 jets ($p_T > 25\text{GeV}$, $|\eta| < 2.5$)
 - Primary analysis using b-tag, while consistent results obtained without b-tag
- Two leptons (opposite charge) + ≥ 2 jets ($p_T > 25\text{GeV}$, $|\eta| < 2.5$)
 - b-tagged and non-b-tagged samples combined
 - Larger branching fraction and smaller BG contamination in $e\mu$ channel

■ Background

- Single lepton: W+jets dominant
- Two lepton: Z/ γ^* + jets, W+jets (+ fake lepton), single top, diboson

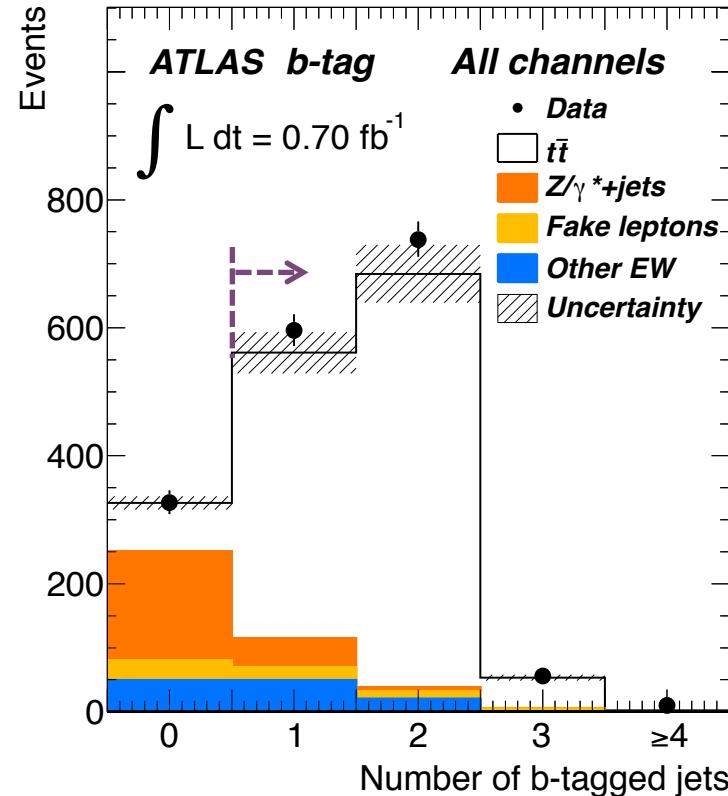
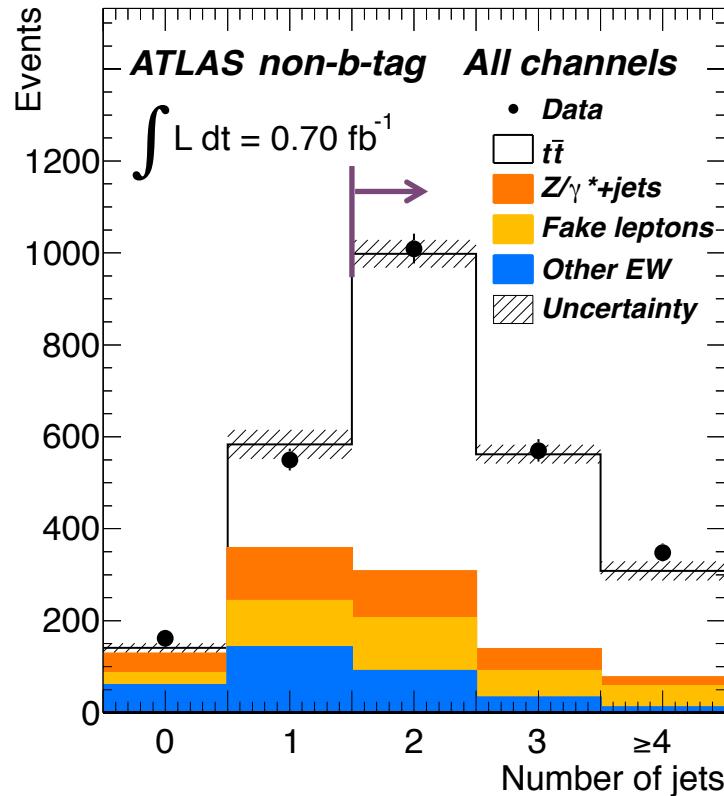
■ Measured cross-section

- Single lepton (35 pb $^{-1}$ @ $\sqrt{s}=7\text{TeV}$): $\sigma_{tt} = 187 \pm 11(\text{stat})^{+18}_{-17}(\text{syst}) \pm 6(\text{lumi}) \text{ pb}$
- Two leptons (0.70 fb $^{-1}$ @ $\sqrt{s}=7\text{TeV}$): $\sigma_{tt} = 176 \pm 5(\text{stat})^{+14}_{-11}(\text{syst}) \pm 8(\text{lumi}) \text{ pb}$
- SM prediction ($m_t=172.5\text{GeV}$): $\sigma_{tt} = 165^{+11}_{-16} \text{ pb}$
- Both measurements are in good agreement with SM prediction



$t\bar{t}+jets$: jet and b-jet multiplicity

Two leptons: JHEP 1205 (2012) 059
 $(0.7 \text{ fb}^{-1} @ 7 \text{ TeV})$



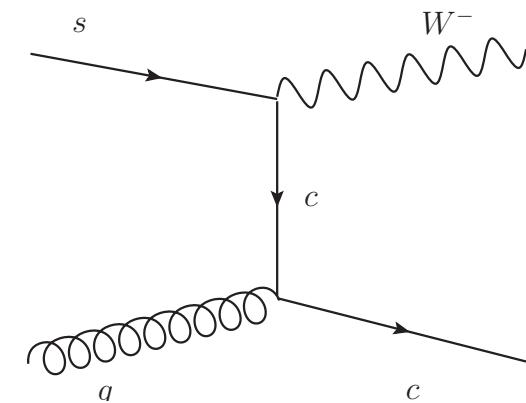
- All channels combined
- Background suppressed by b-tagging
- Good agreement between data and predictions



W+charm hadron

ATLAS-CONF-2013-045
 $(4.6 \text{ fb}^{-1} @ 7 \text{ TeV})$

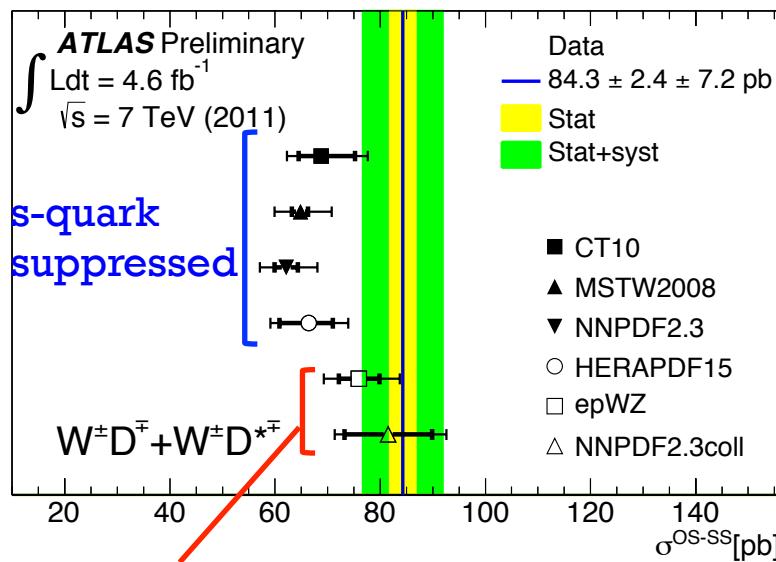
- Inclusive $\sigma(W^\pm + D^{(*)\mp})$ sensitive to strange quark PDF
 - 10% contribution from initial d-quark at 7TeV
- Event selection
 - $W(\rightarrow e \nu)$ or $W(\rightarrow \mu \nu) + \text{charm hadron } (D)$
 - D meson reconstructed in decay modes:
 - $D^{*+} \rightarrow D^0 \pi^+$ with $D^0 \rightarrow K^- \pi^+$, $D^0 \rightarrow K^- \pi^+ \pi^0$ or $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$
- Background largely canceled after subtracting ‘same-sign’ events from ‘opposite-sign’ events (OS – SS)
 - W+c signal: W and D with opposite charge (OS)
- Systematic uncertainty
 - Tracking efficiency (results in D reconstruction efficiency) dominant
- Prediction
 - NLO OCD calculation based on **aMC@NLO**
 - Various PDF models with different strange quark densities tested (next slide)



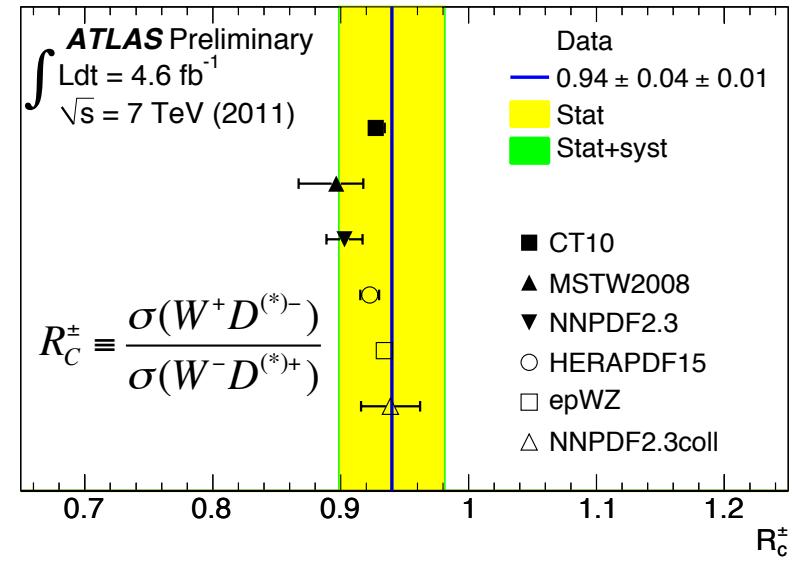
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W+charm hadron: test of PDF

- **CT10, MSTW2008, NNPDF2.3, HERAPDF15:** s-quark suppressed wrt d-quark
 - CT10 less suppressed than others
- **epWZ:** s-quark and d-quark comparable at $x \sim 0.01$
- **NNPDF2.3coll:** larger s-quark sea than d-quark for all x
 - NNPDF2.3coll tuned only by collider data (neutrino charm production data not used)

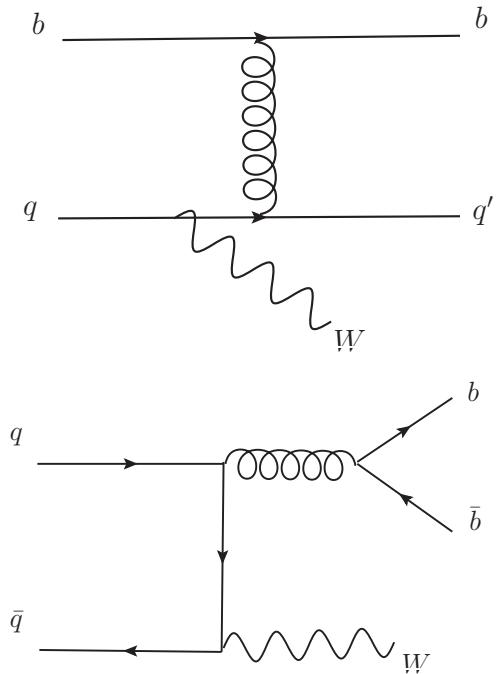


s-quark not suppressed

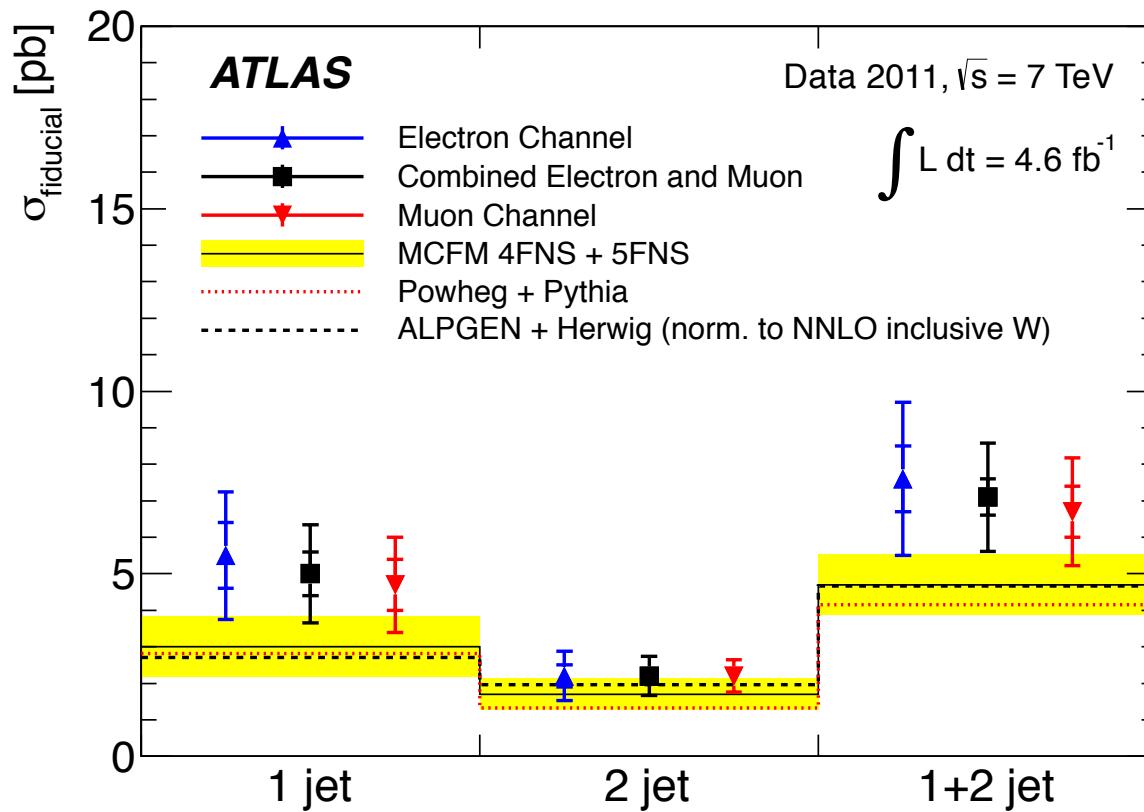


- Data agree with predictions for epWZ and NNPDF2.3coll PDFs
 - CT10 PDF at 1.1 (1.7) σ off for D $^{(*)+}$ (D $^+$)
- Charge asymmetry consistent with predictions from all PDFs

- **Single b final states** require heavy flavor in initial states
 - Modeled by five-flavor number scheme (5FNS)
- **Two b final states** modeled by 4FNS (u, d, c, s)
 - One of main backgrounds to $H \rightarrow bb$ measurement
- Contribution from DPI expected in W + b-jets
 - Included in measurement (not subtracted)
- Event selection
 - $W(\rightarrow e \nu)$ or $W(\rightarrow \mu \nu) + 1$ or 2 jets ($p_T > 25 \text{ GeV}$, $|y| < 2.1$)
 - One b-tagged jet
 - In order to suppress top-quark background
 - Rejected W+bb events are accounted by unfolding
- Background
 - W+c, single top and top-pair production
- Prediction
 - NLO calculation by MCFM corrected for non-perturbative effects and contribution of DPI, and including 5FNS
 - NLO calculation by POWHEG, and ALPGEN MC (normalized to NNLO inclusive W production) are also tested
 - DPI contribution corrected for POWHEG and included in APLGEN

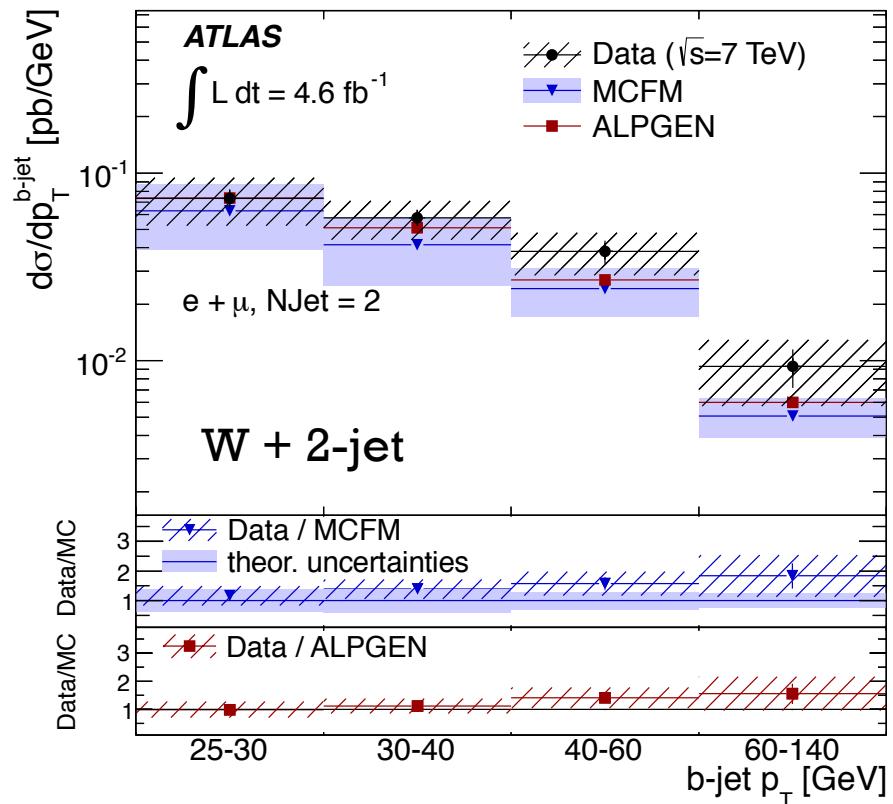
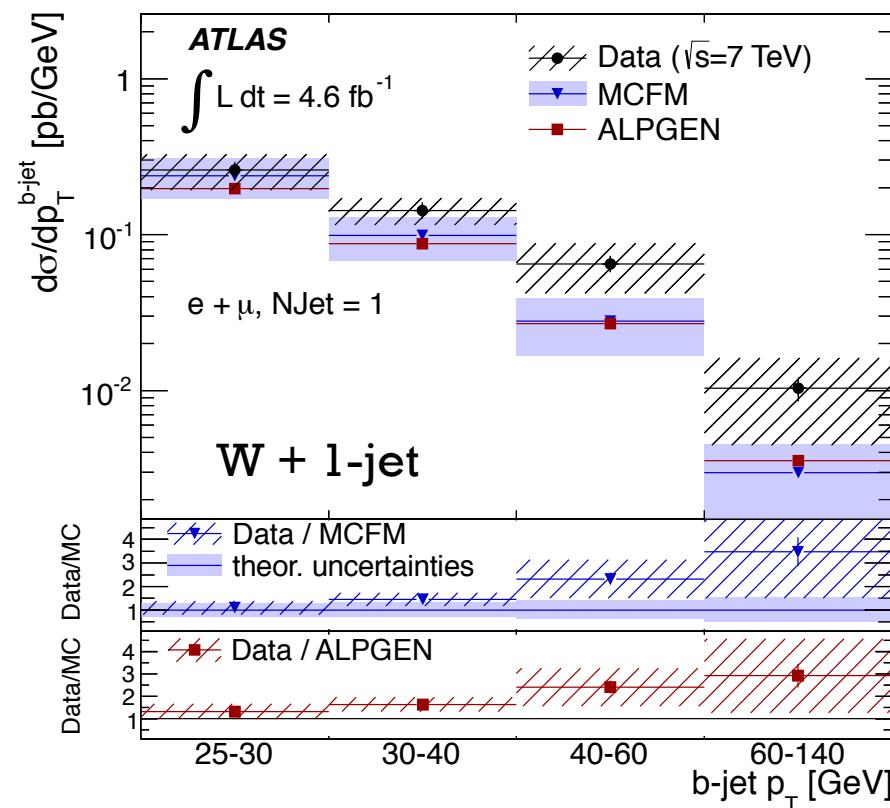


W + b-jets: cross-section



- Measured cross-sections agree with the prediction for both electron and muon channels with 1 or 2 jets
 - Slightly higher cross-section measured but within uncertainties

W + b-jets: b-jet p_T



- Single-top and other backgrounds subtracted
 - Slightly harder spectrum measured but consistent with prediction within their uncertainties
 - Similar trend found without single-top subtraction



Summary

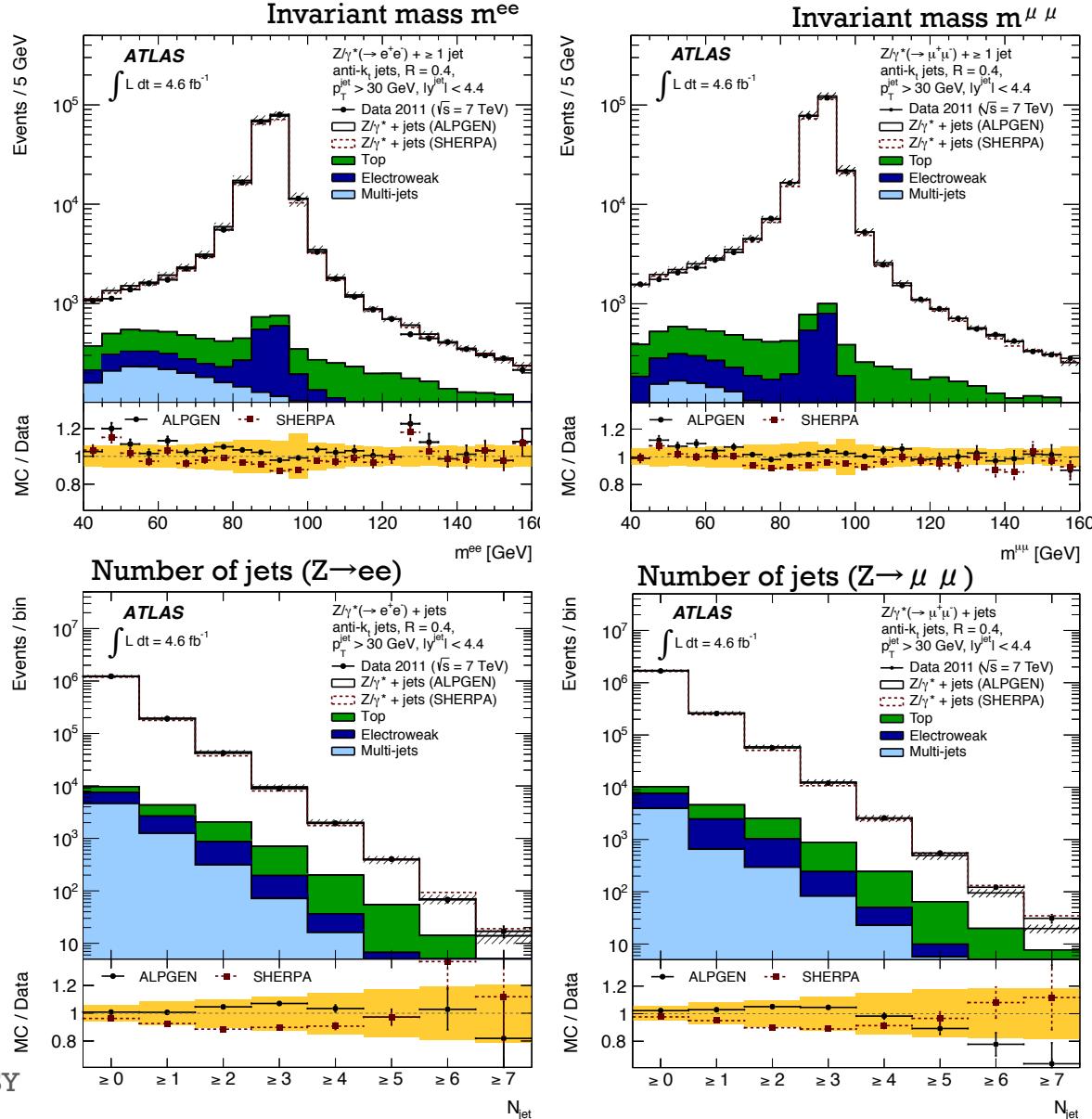
- Extended tests of QCD in pp-collision performed by ATLAS at LHC
 - Various channels including $Z+jets$, $W+jets$, $t\bar{t}+jets$ and $W+HF$
 - Wide kinematic ranges: jet multiplicity and p_T of jets
- Experimental study provides insight on QCD models
 - Small experimental error than those in prediction give constraint to models
 - Constraint on PDF: flavor symmetric light quark sea favored ($W+c$)
 - Impact of missing higher jet multiplicity and modification by exclusive summation ($Z+jets$, $W+jets$)
- Input to Higgs and other searches
 - Validation of 3rd jet veto in VBF selection
- More results will come with 2012 ATLAS data
 - High precision measurements expected

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backup



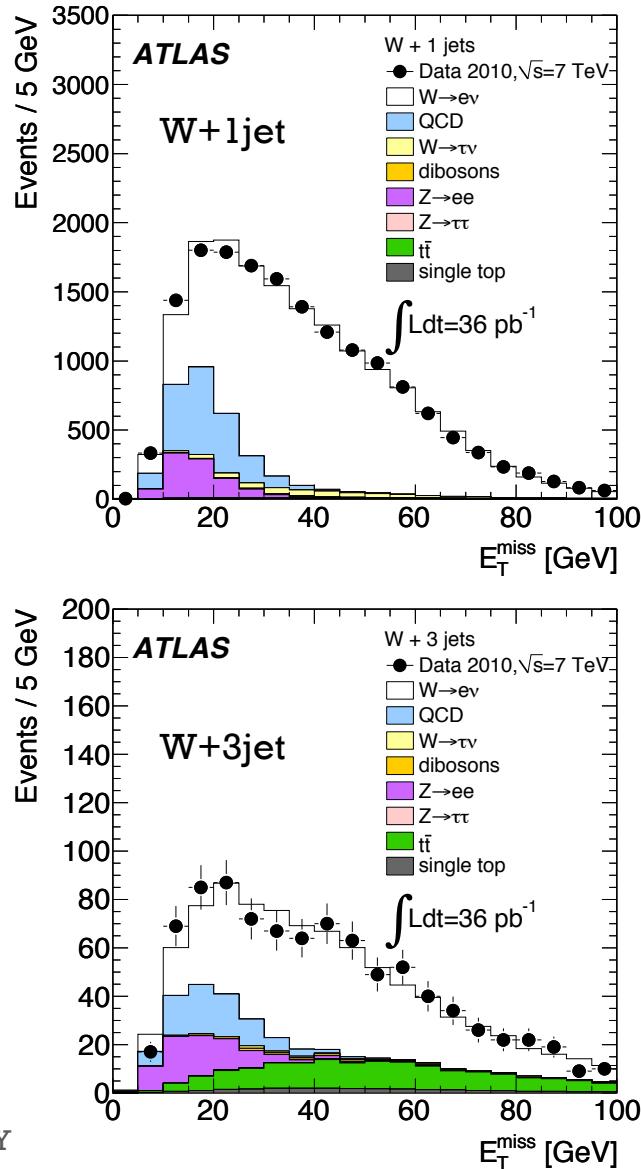
Z+jets: before BG subtraction



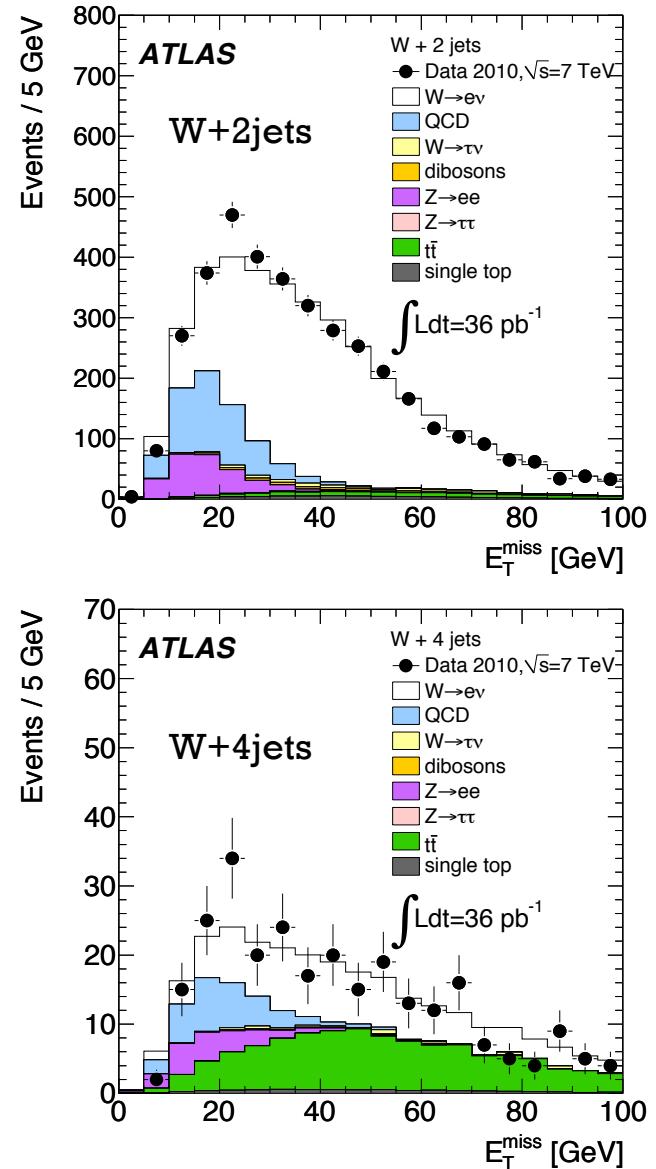


W+jets: missing E_T

$W \rightarrow e \nu$



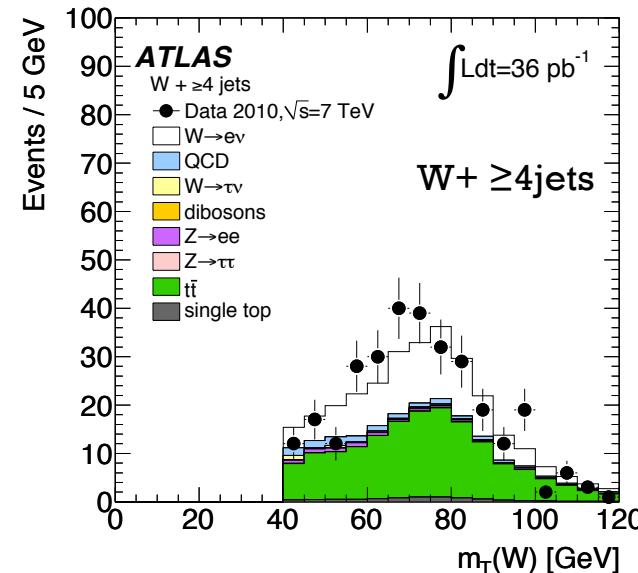
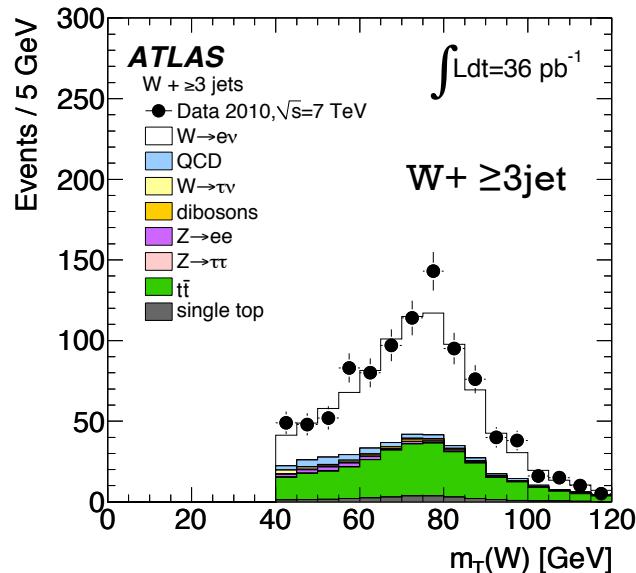
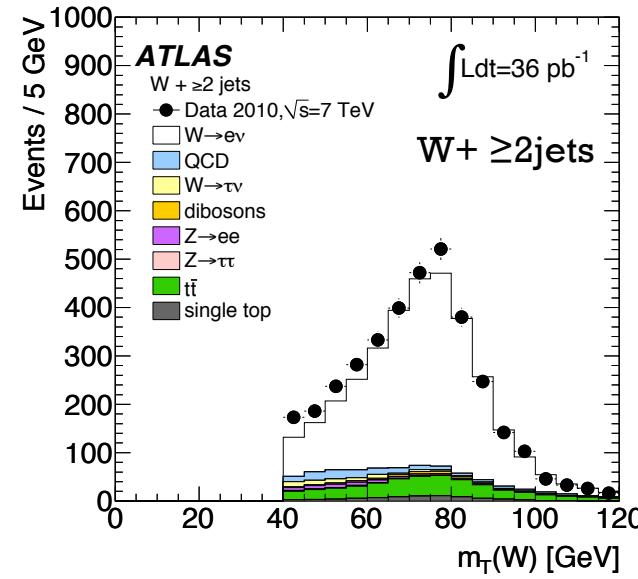
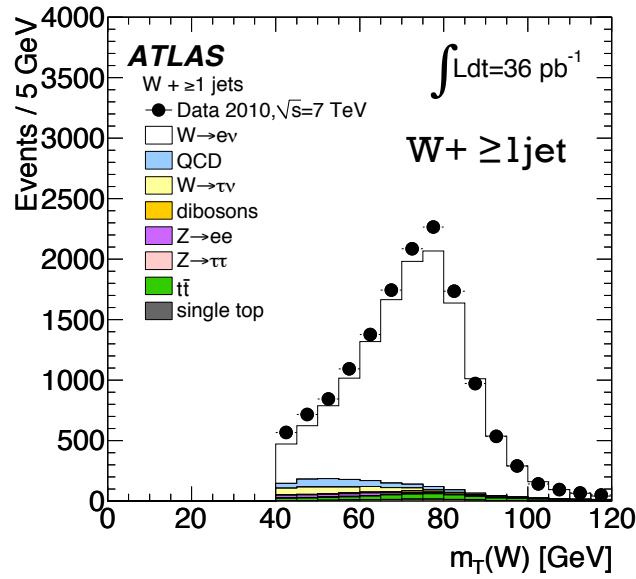
Phys. Rev. D85, 092002 (2012)
 $(36\text{pb}^{-1} @ 7 \text{TeV})$





W+jets: $m_T(W)$

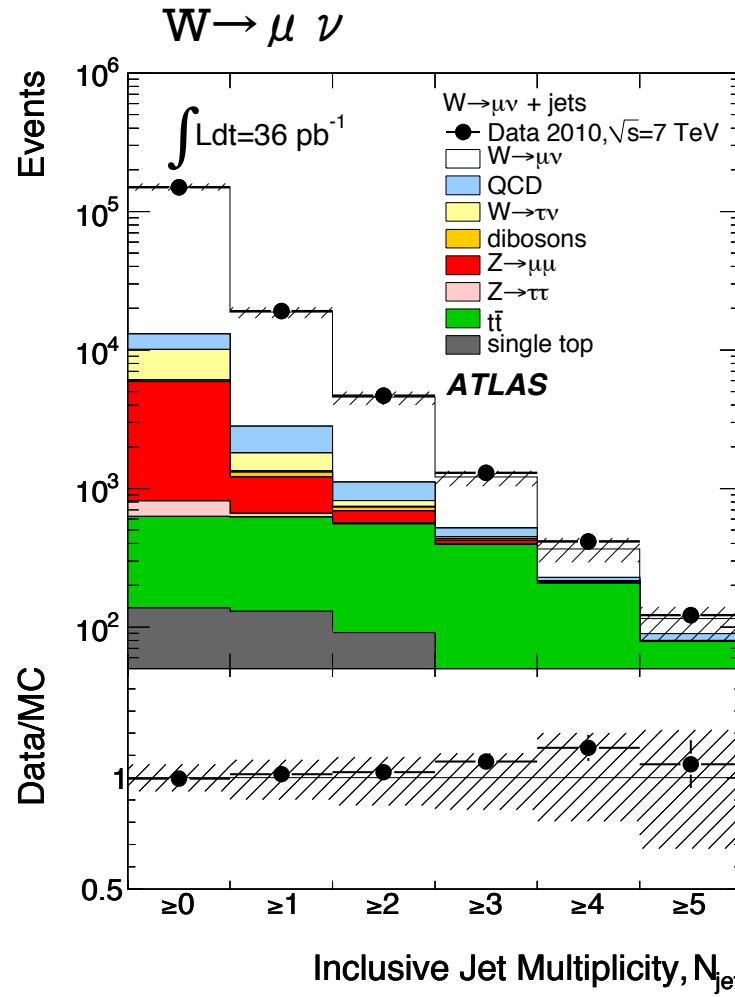
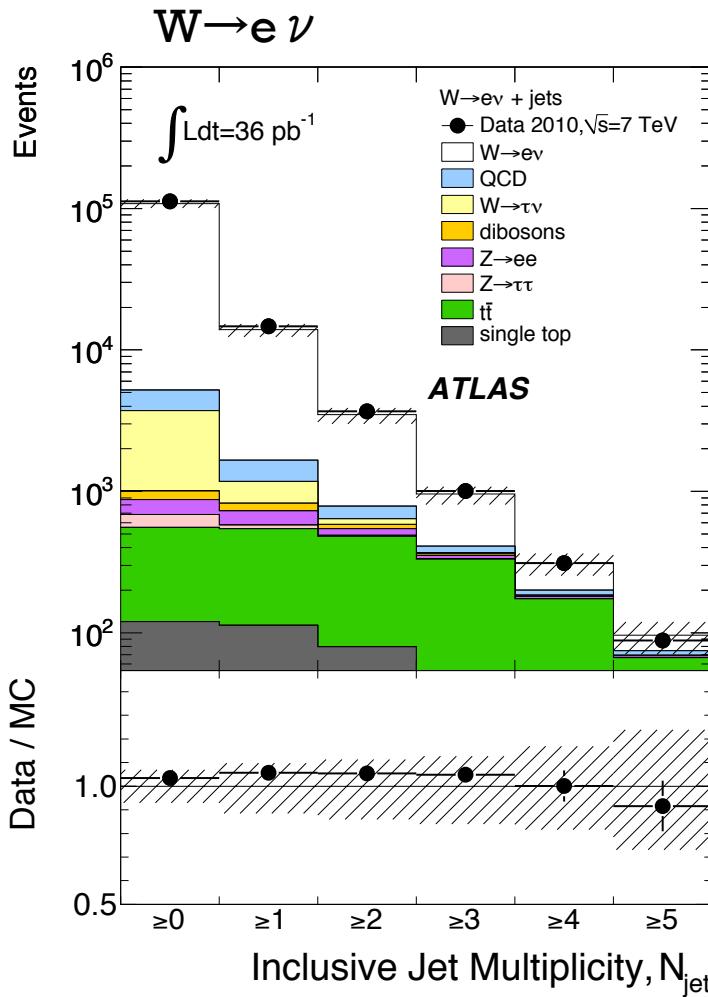
$W \rightarrow e \nu$





W+jets: before BG subtraction

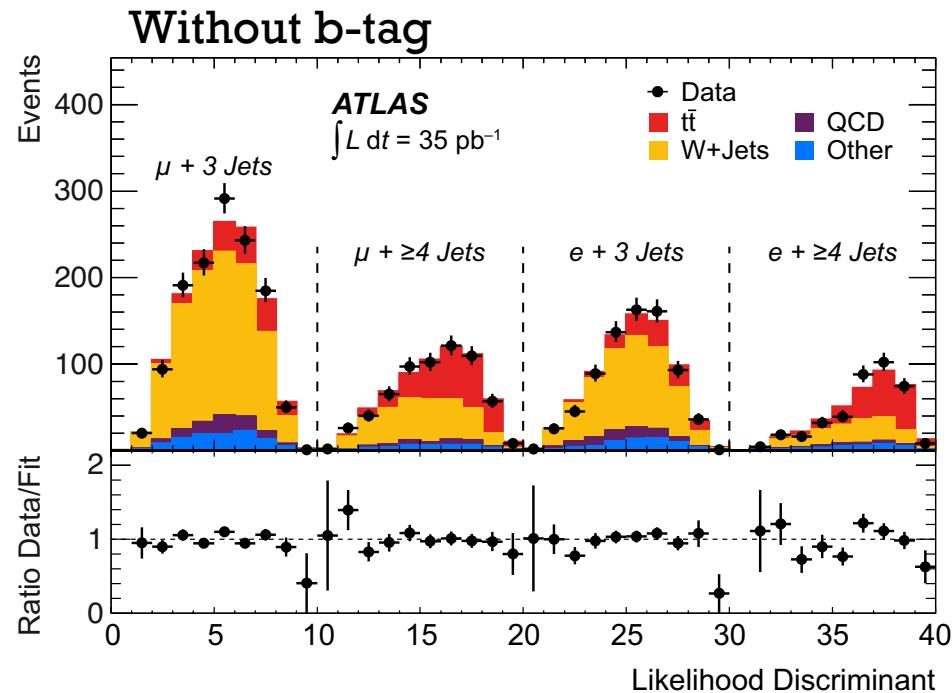
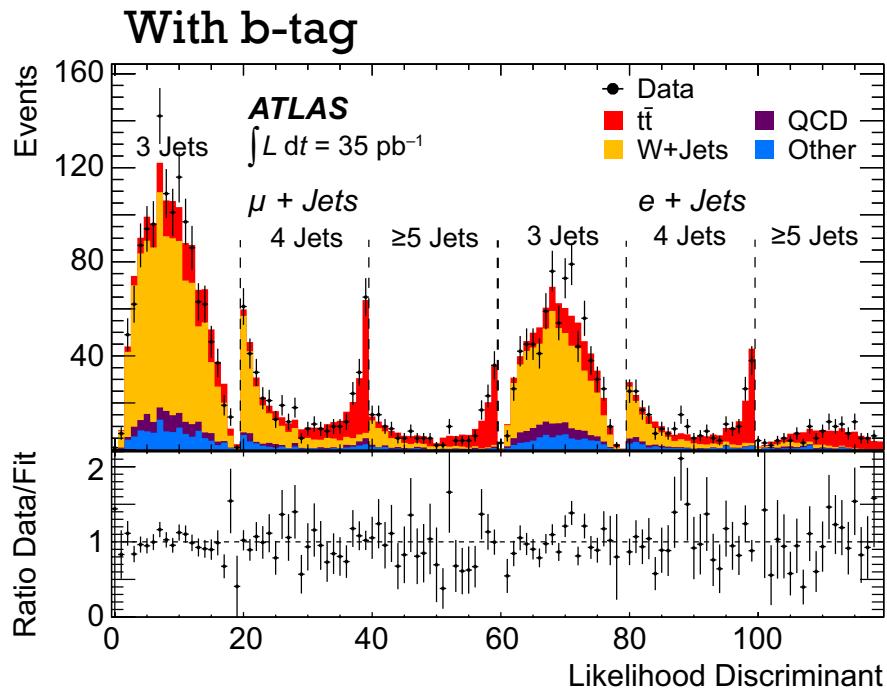
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$t\bar{t}+jets$: single lepton channel

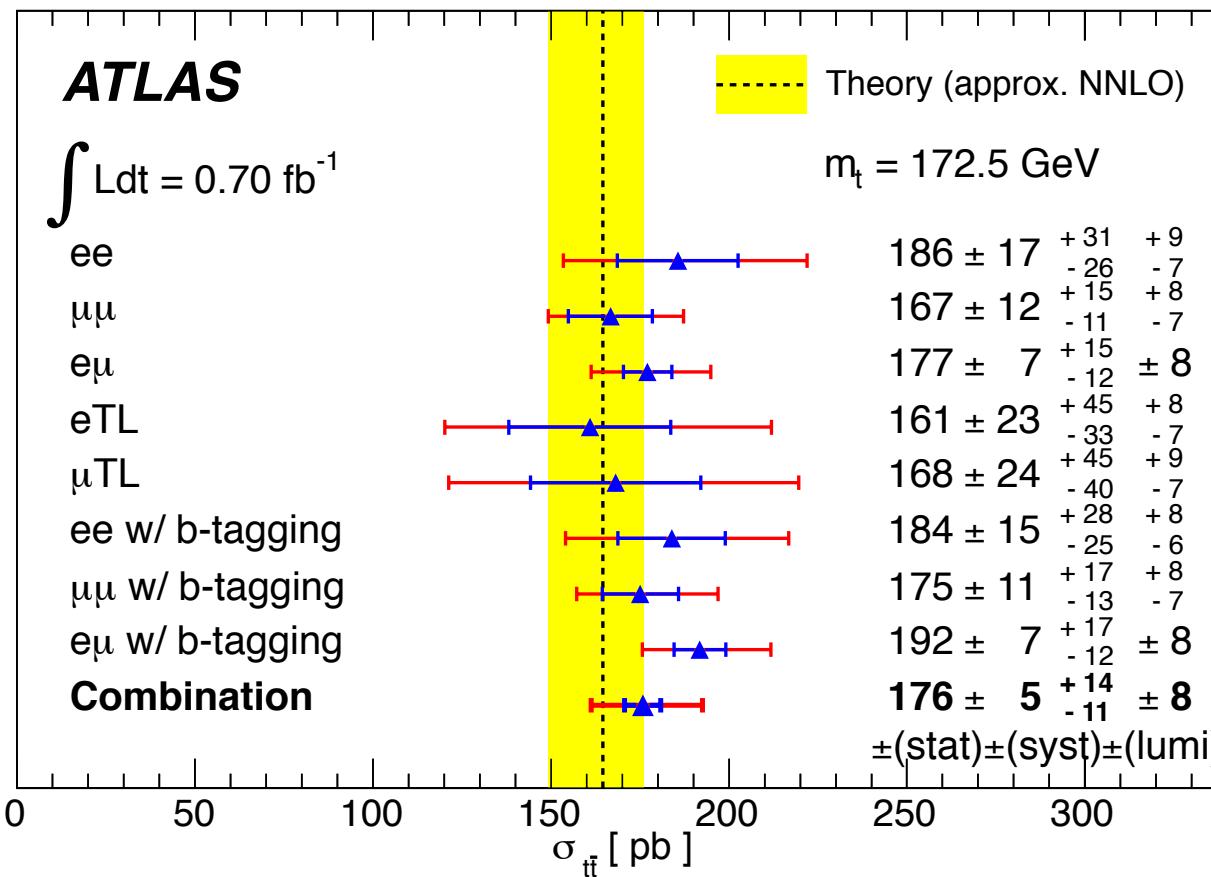
Phys. Lett. B 711(2012) 244-263
 $(35\text{pb}^{-1} @ 7\text{TeV})$



+ $t\bar{t}+jets$: two lepton channel

JHEP 1205 (2012) 059
 $(0.7 \text{ fb}^{-1} @ 7 \text{ TeV})$

Comparison of cross-section measured by each sample
and the combination

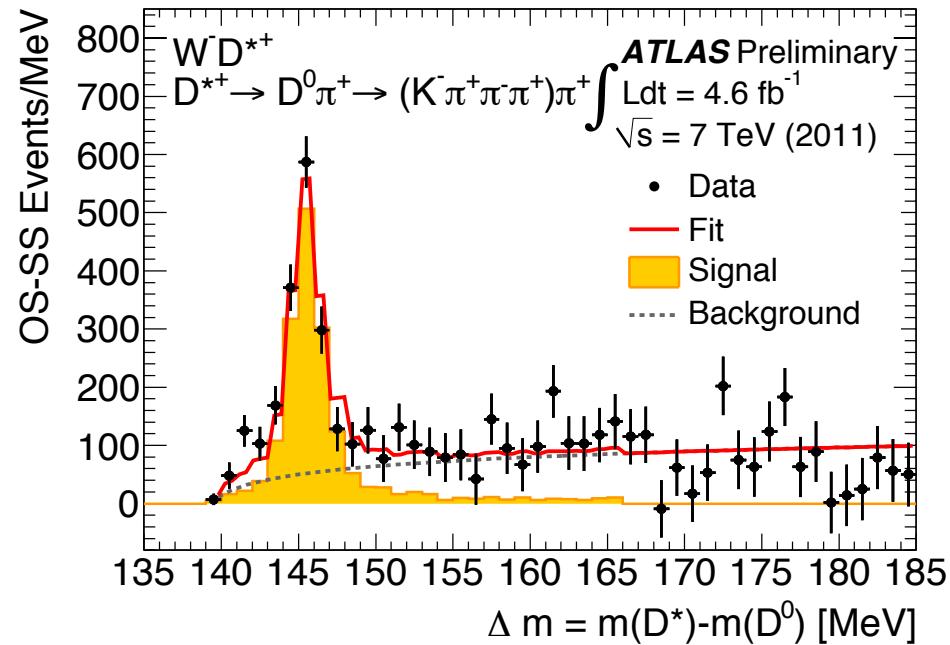
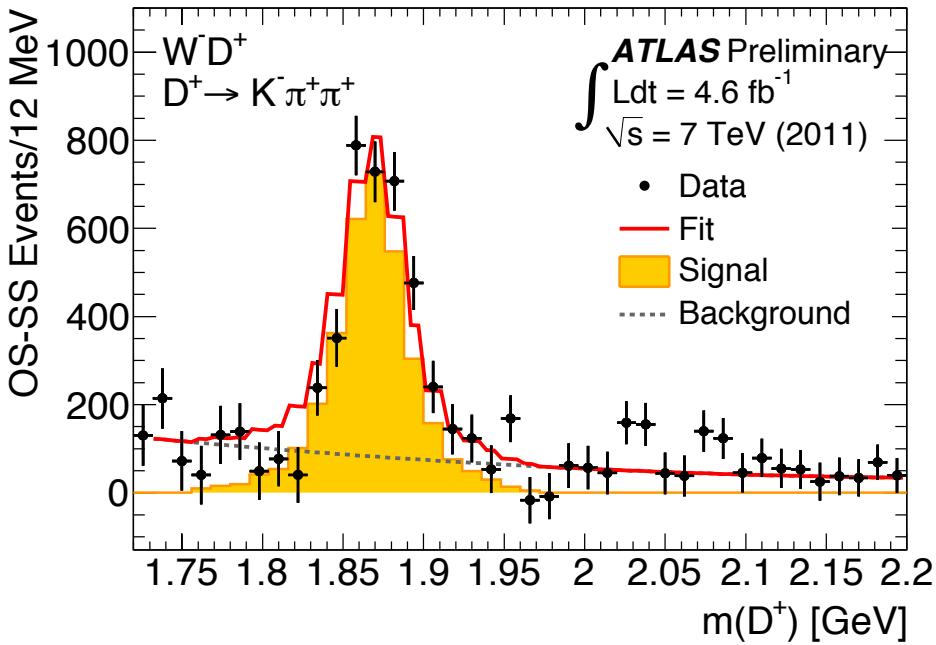




W+charm hardon: signal + BG fit

ATLAS-CONF-2013-045
 $(4.6 \text{ fb}^{-1} @ 7 \text{ TeV})$

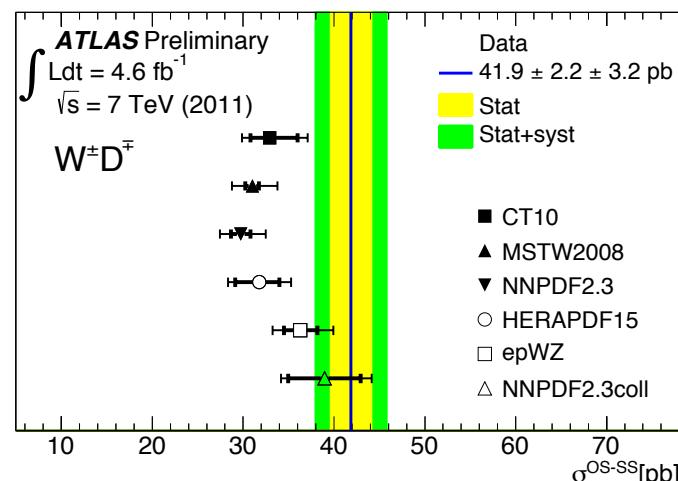
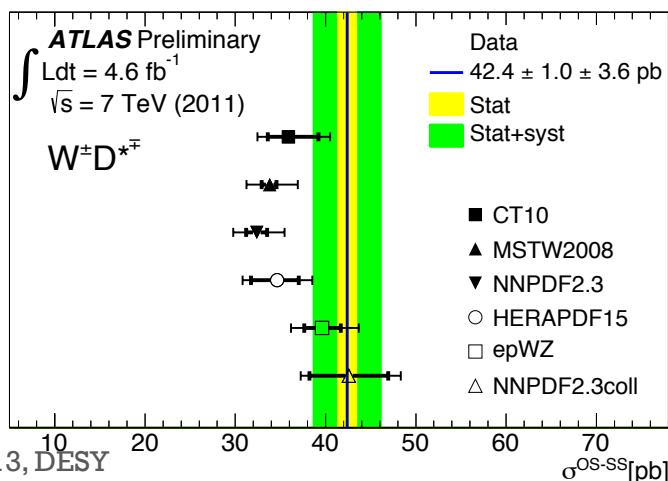
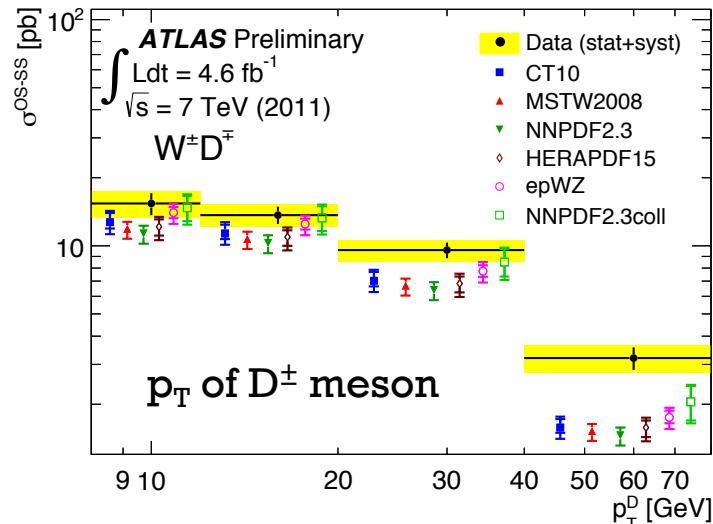
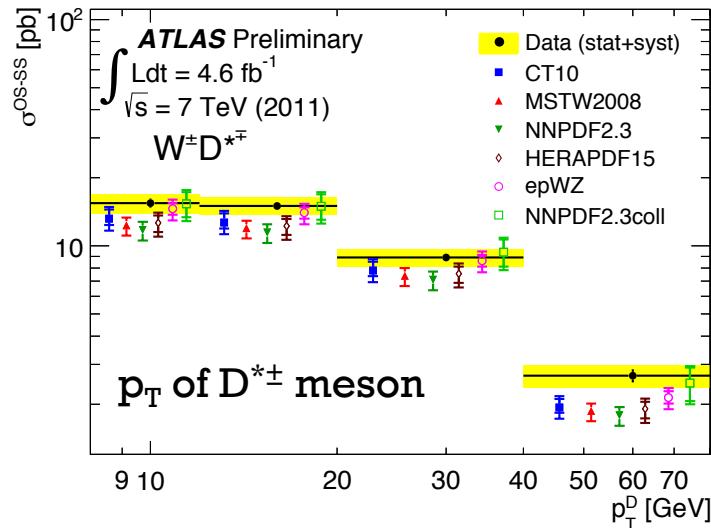
OS – SS events





W+charm hardon

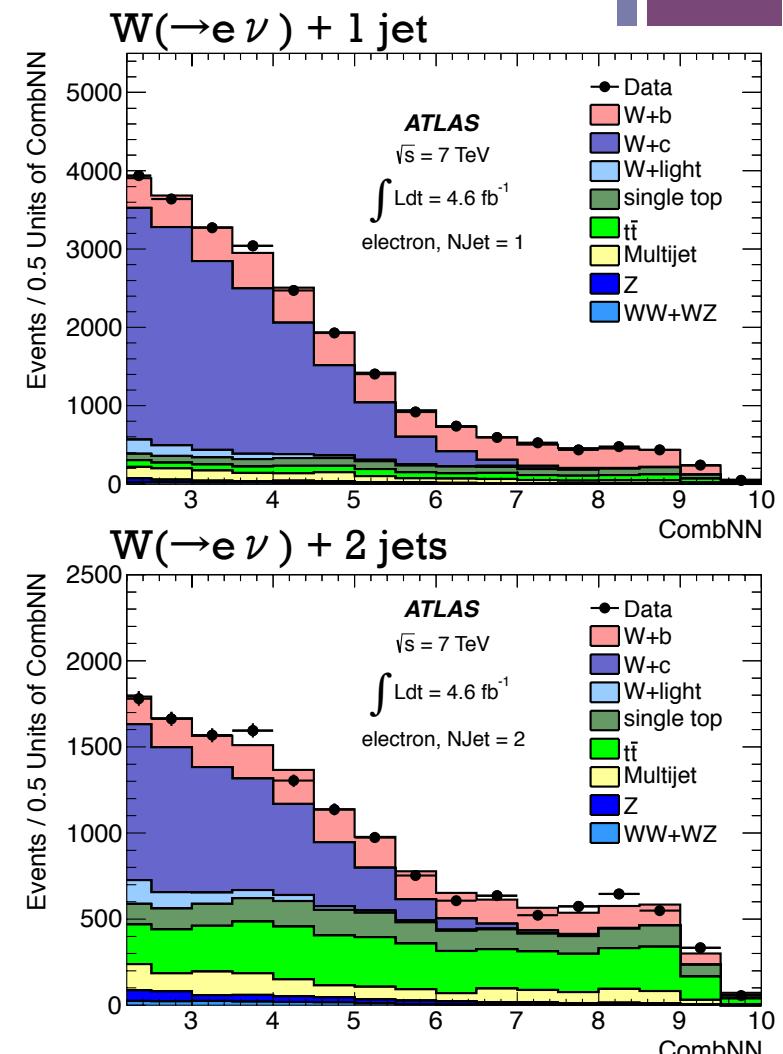
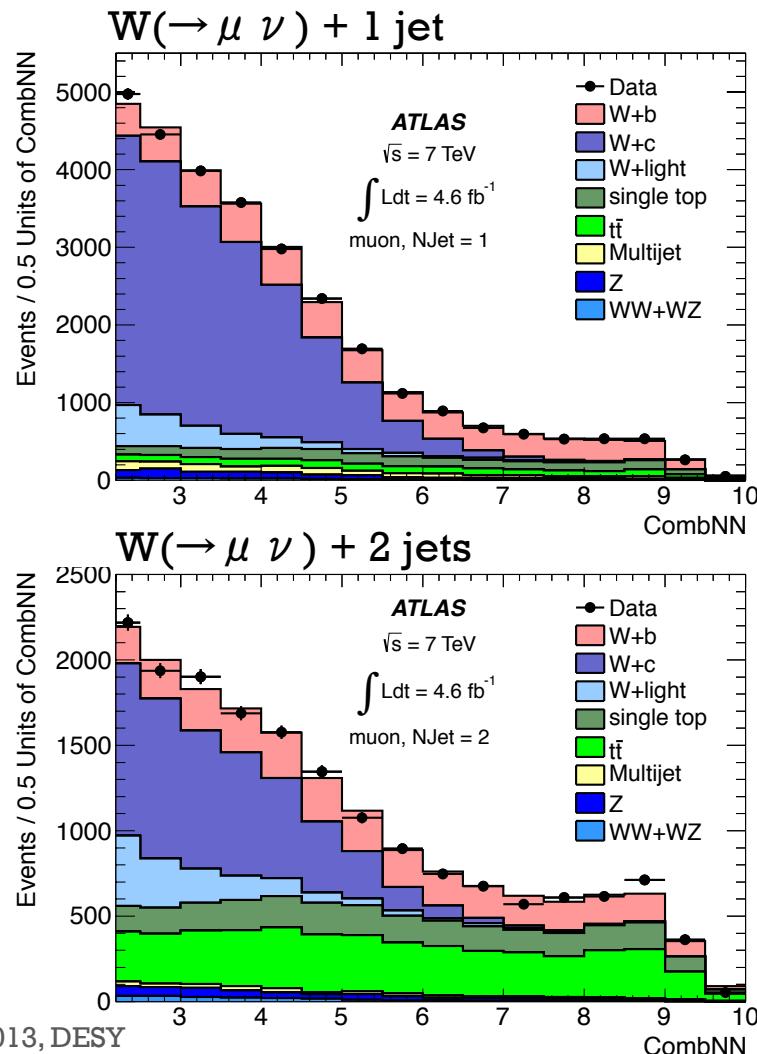
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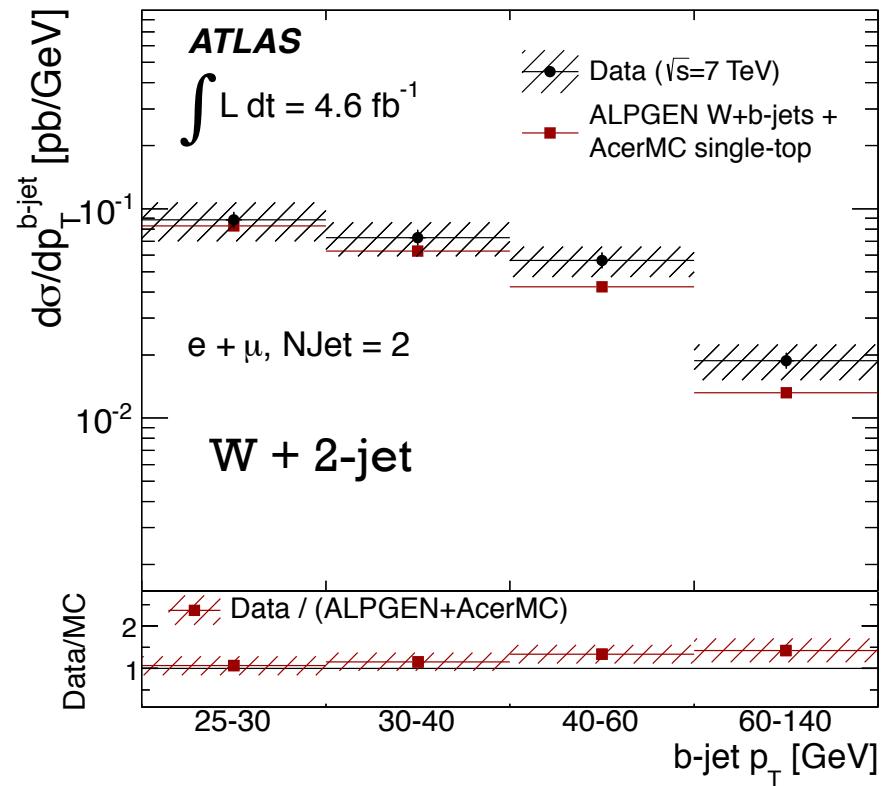
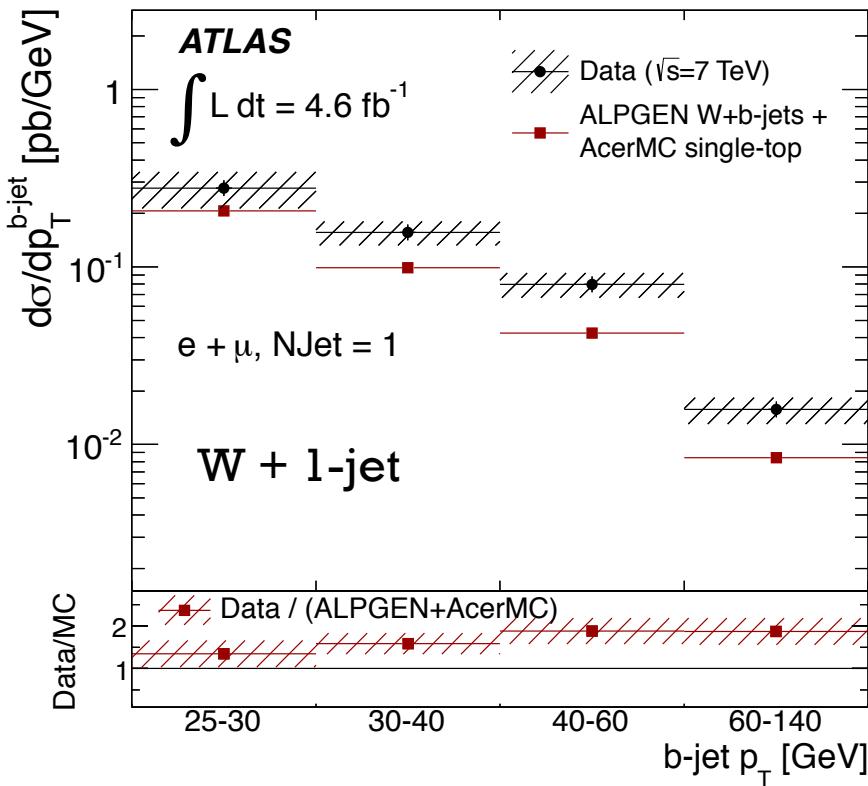


W + b-jets: signal and BGs

CombNN (signal discriminant variable) distributions for b-tagged jets



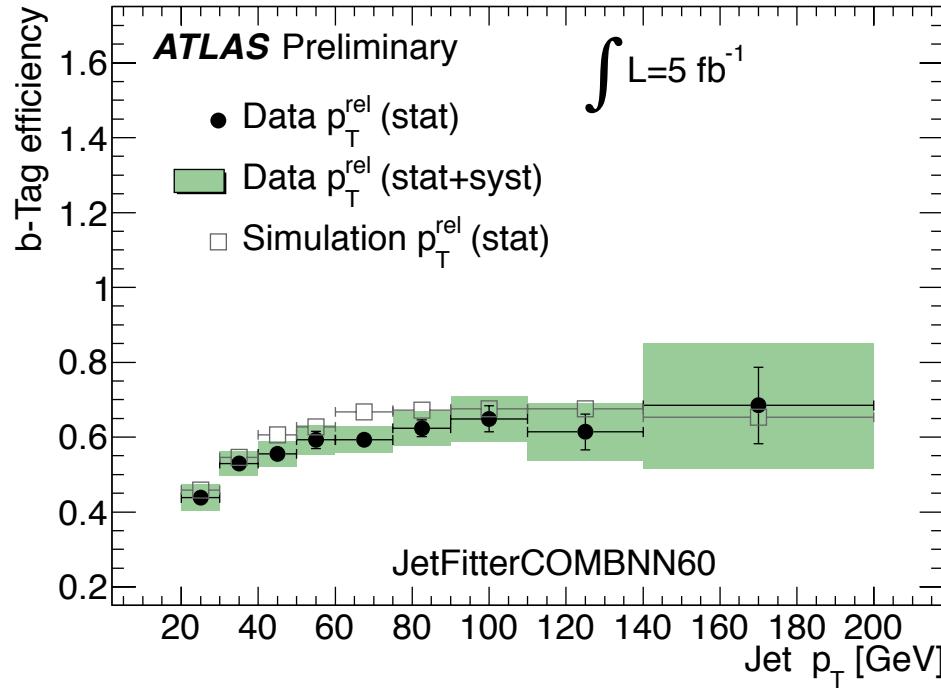
+ W + b-jets: b-jet p_T (w/o single-top subtraction)



- W + b-jets cross-section measured including single-top
 - Higher statistical precision, especially at high $p_T^{\text{b-jet}}$
- Similar trend found without single-top subtraction
 - Harder spectrum measured compared to the prediction

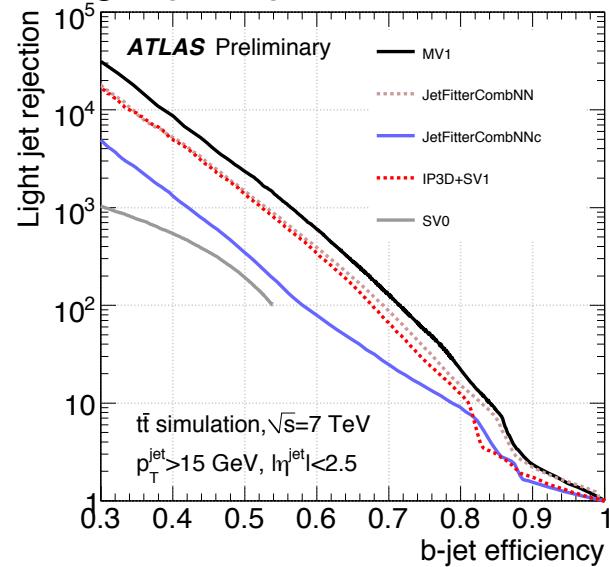
b-tagging

b-jet efficiency

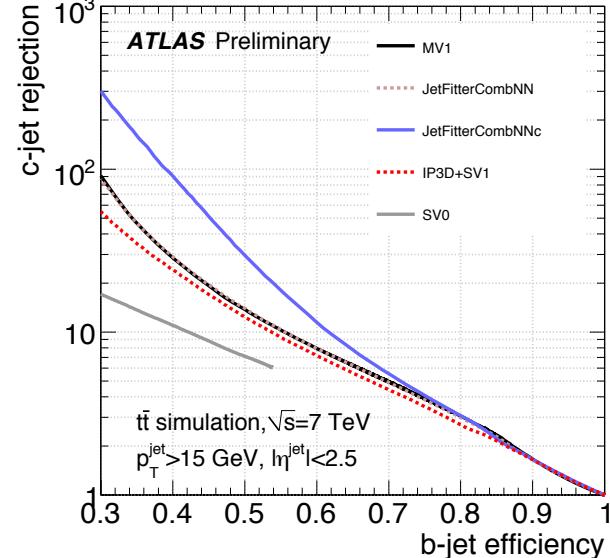


- JetFitterCombNN algorithm used for W+b measurement (2011)

Light-jet rejection



c-jet rejection





Jet energy scale (2011)

ATLAS-CONF-2013-004

