# Measurements of heavy flavour production in association with W and Z bosons with the ATLAS detector

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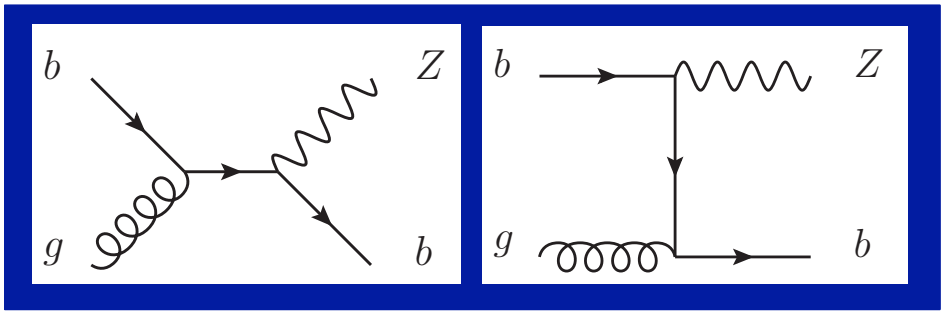
On behalf of the ATLAS Collaboration

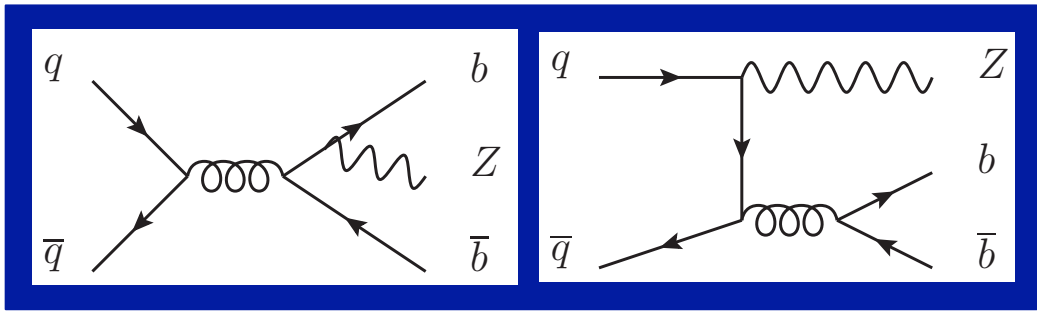
ATLAS EXPERIMENT

# Why is VB + HF Interesting?

- Test QCD modelling of heavy flavour (HF) production, with potential for separation of initial and final state.

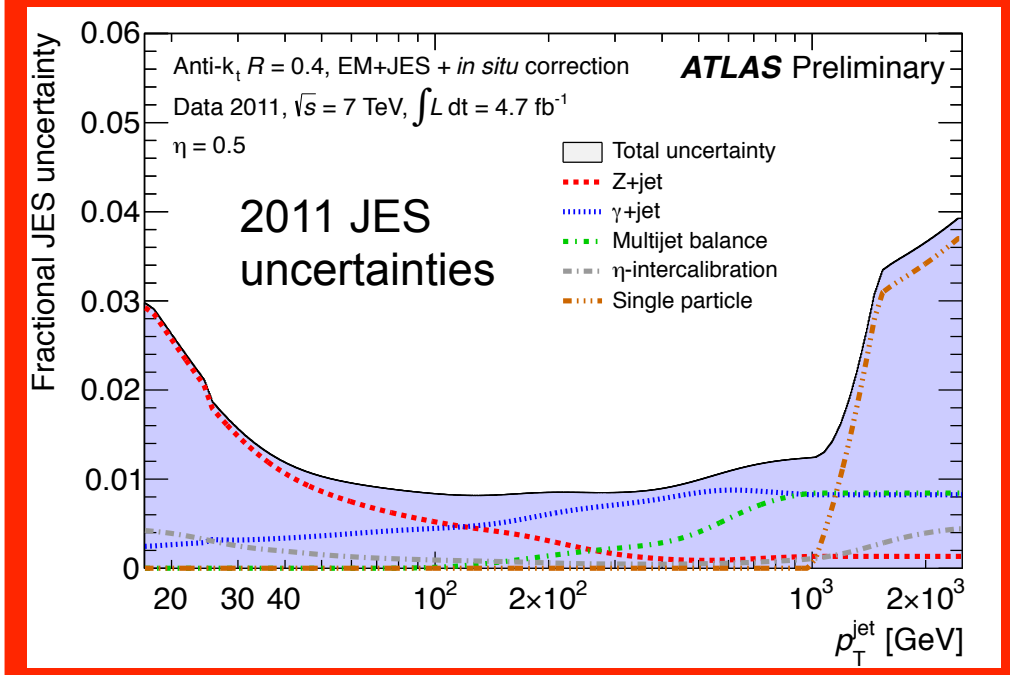



- Single b final states require heavy flavour in the initial state.
- Modelled either by initial state gluon splitting (4FNS) or via b-quark density in the p.d.f (5FNS). Which is best?
- Sensitivity to HF content of PDF.



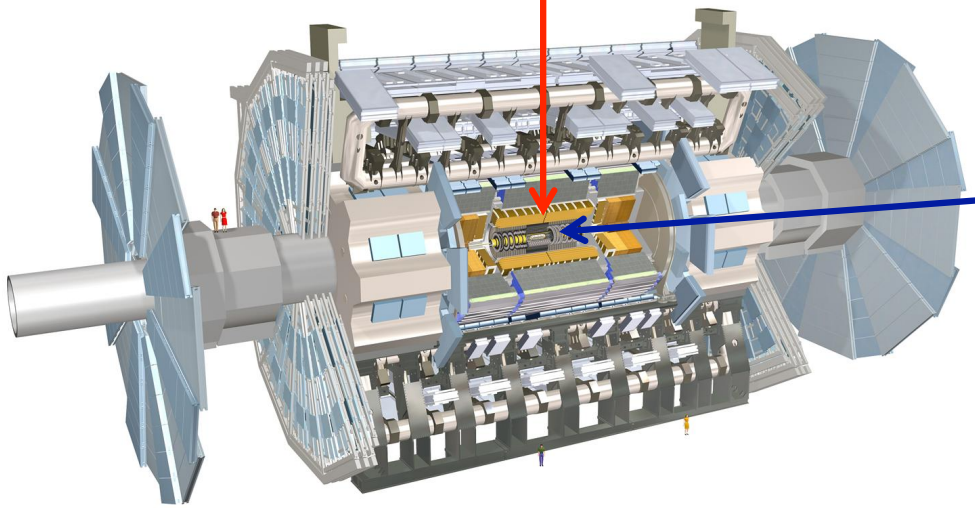

- Two b final states generally require gluon splitting in final state.
- One of the main backgrounds to e.g. H→bb production in association with W or Z.
- Therefore very important to test the modelling of V+bb kinematics by current generators.

# The ATLAS Detector



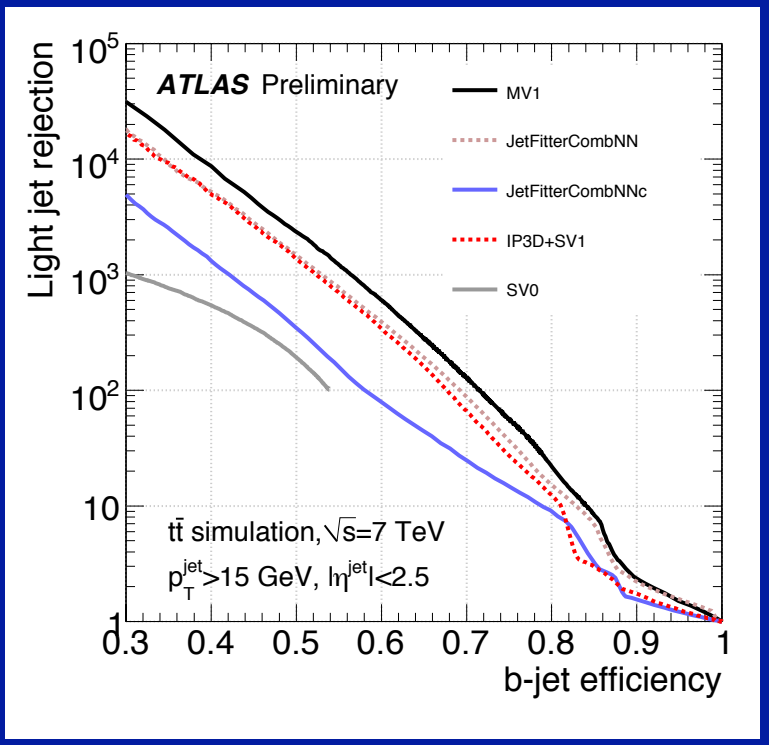

ATLAS-CONF-2013-004

Accurate jet energy scale determination



These measurements would not be possible without the excellent level of performance and understanding of the ATLAS detector that has been achieved.

ATLAS-CONF-2012-043




Excellent b-tagging performance

# Z + b-jet Cross-Section

2010 dataset: 36 $pb^{-1}$ @ $\sqrt{s}$ = 7 TeV

*Phys.Lett. B706 (2012) 295-313*

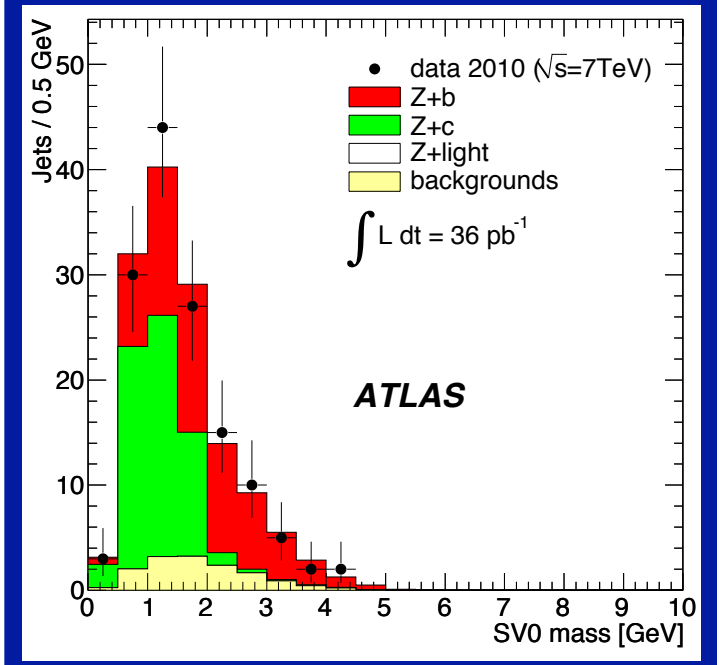
# Z + b-jet Cross-Section

- Two unfolded particle-level measurements:
  - The inclusive (per jet) cross-section for b-jet production in association with a Z boson ($\sigma_b$):

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

  - The average number of b-jets per Z event ($\sigma_b$/Z):

| 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 | $(6.2 \pm 0.1$ (stat only)$) \times 10^{-3}$ |
| SHERPA | $(9.3 \pm 0.1$ (stat only)$) \times 10^{-3}$ |




b-jet yield after tagging determined from MC template fit to secondary vertex mass

- The MCFM (5FNS) parton-level prediction is corrected for non-perturbative effects and lepton FSR – in good agreement with data!
- Alpgen (4FNS) and Sherpa (5FNS) also agree with data in $\sigma_b$/Z.

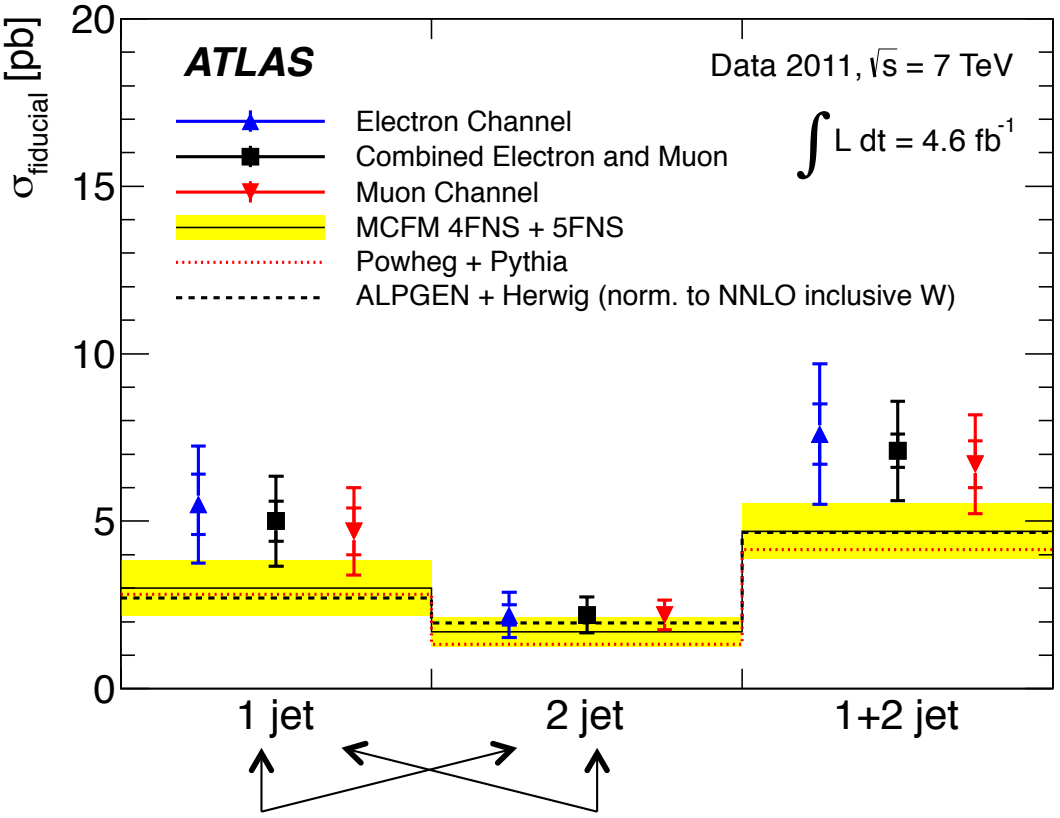
# W + ≥ 1 b-jet Cross-Section

Full 2011 dataset: 4.6 $fb^{-1}$ @ $\sqrt{s}$ = 7 TeV

*JHEP 06 (2013) 084*

# W + ≥ 1 b-jet Cross-Section

- Measurement of the W + ≥ 1 b-jet production cross-section in exclusive 1 jet, 2 jet and 1 + 2 jet bins
- Jets are anti-$K_T$ R=0.4, $p_T$ > 25 GeV, |y| < 2.1.




5FNS:
bq→Wbq
bg→Wbqq

4FNS:
qq→Wbb
gq→Wbbq

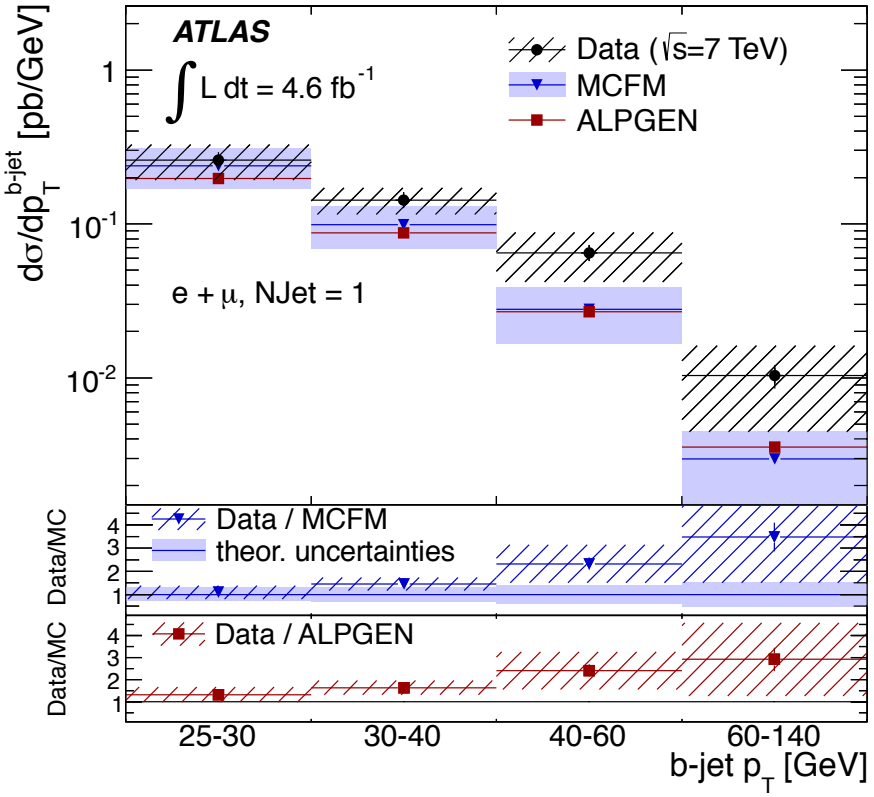
+ DPI contributions
(~25% of 1+2 jet)

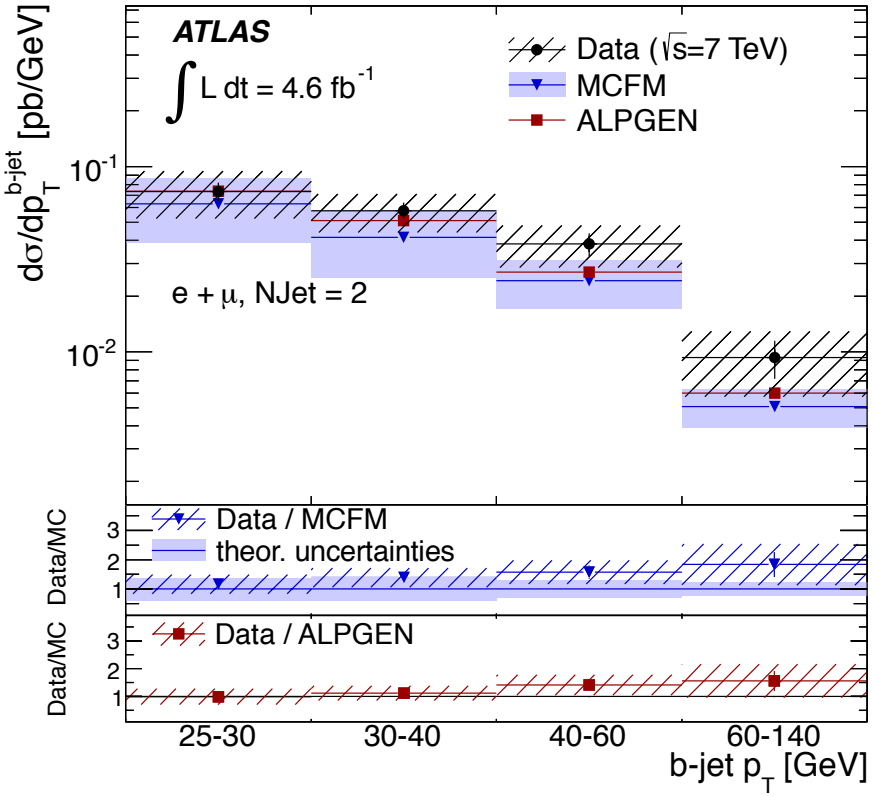
- Event selection:
  - Exactly one b-tagged jet.
  - Exactly one or exactly two jets (1 jet, 2 jet regions).
- Rejected W+bb events are "put back in" by unfolding in each 1 jet, 2 jet region.

MCFM (+DPI +non. perturb.) prediction in agreement with data within uncertainties

# W + ≥ 1 b-jet Cross-Section

- Update of previous 35pb$^{-1}$ (2010 data) measurement.
- 2011 data statistics enabled unfolded differential cross-section versus b-jet $p_T$ for the first time in VB + HF.

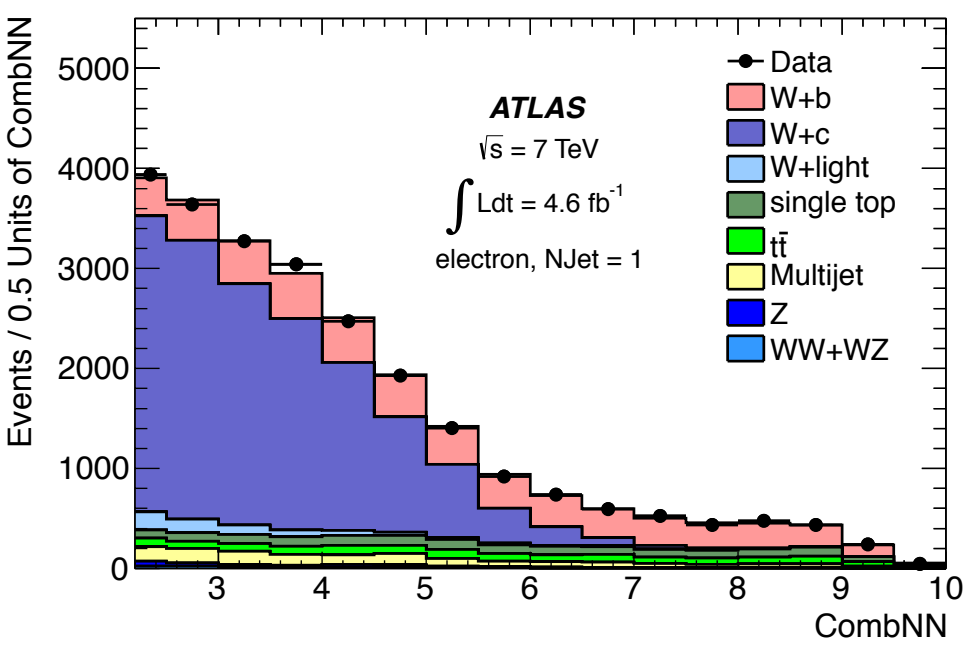


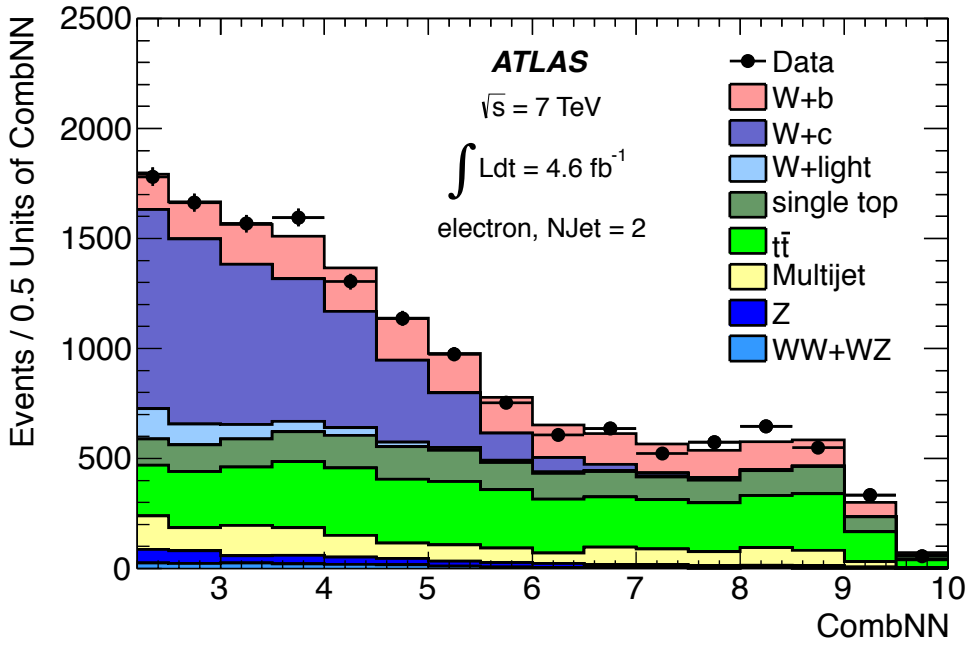




- Again, agreement within errors of data and theory. But starting to see systematic mismodelling of the shape? (Data errors are correlated).

# Method: W + b-jet Yield

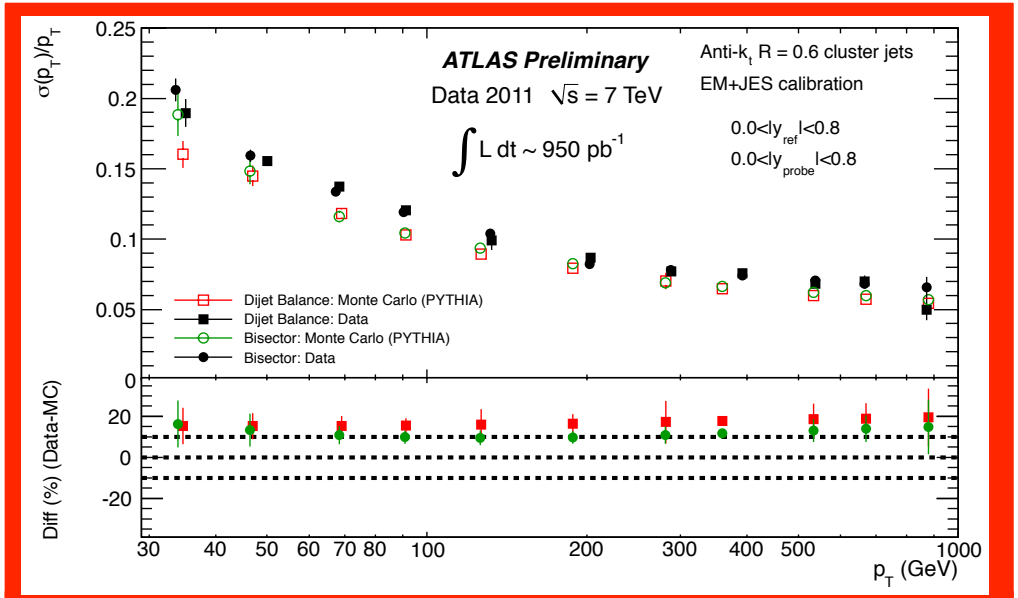
- Fit b-tagger “weight” distribution of selected events to determine yield of W+b-jet events in 1 jet and 2 jet bin, and versus b-jet $p_T$.



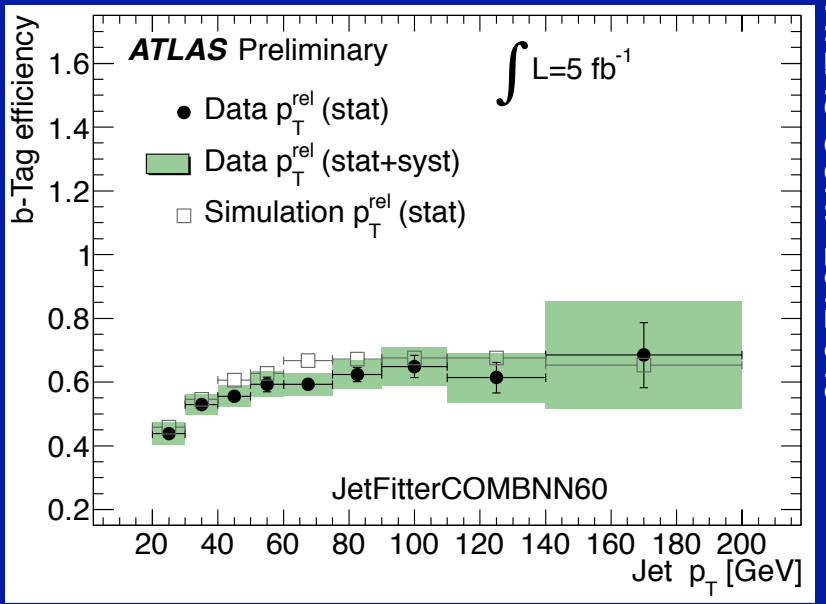

- Fit components:
  - Single top/top pair: shape from MC but normalisation constrained using data control regions/distributions.
  - Multijet: both shape and normalisation using data control regions.
  - W+b-jets, W+c-jets and W+light jet templates from MC, all float.

# Method: Systematics




Uncertainty in the modelling of jet energy scale and resolution in simulation.

Measurement is systematics dominated.




Uncertainty in the calibration of b-tagging in simulation

| Systematic | 1 jet | 2 jet | 1 + 2 jet |
|---|---|---|---|
| Jet energy scale | 15% | 15% | 15% |
| Jet energy resolution | 14% | 4% | 8% |
| B-jet efficiency | 6% | 4% | 5% |
| Top ISR/FSR | 4% | 8% | 3% |
| MC modelling | 8% | 4% | 6% |
| Other | 7% | 10% | 7% |
| Total | 24% | 23% | 20% |

Theoretical uncertainties on MC modelling of signal and Top backgrounds

# W + Charm Hadron Cross-Section

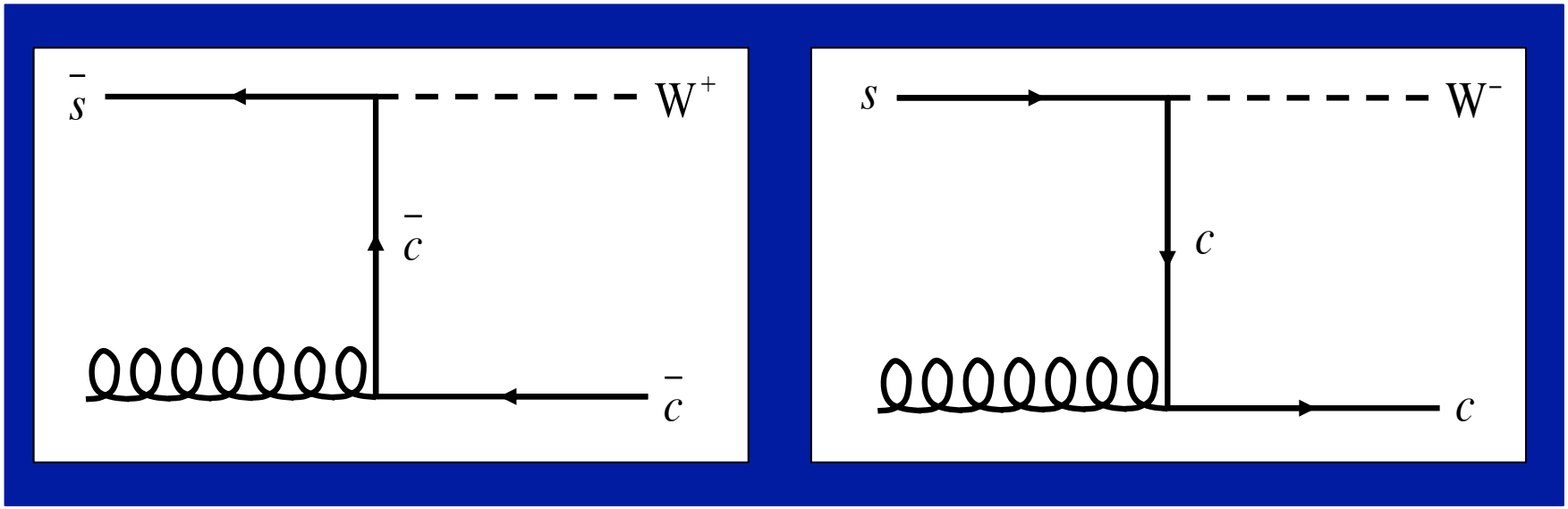
Full 2011 dataset: 4.6 $fb^{-1}$ @ $\sqrt{s}$ = 7 TeV

ATLAS-CONF-2013-045

(See also W + J/psi cross-section covered in “Review of ATLAS Heavy-Quark and Quarkonium results” by Miriam Watson in the QCD Session)

# W + Charm Hadron Cross-Section

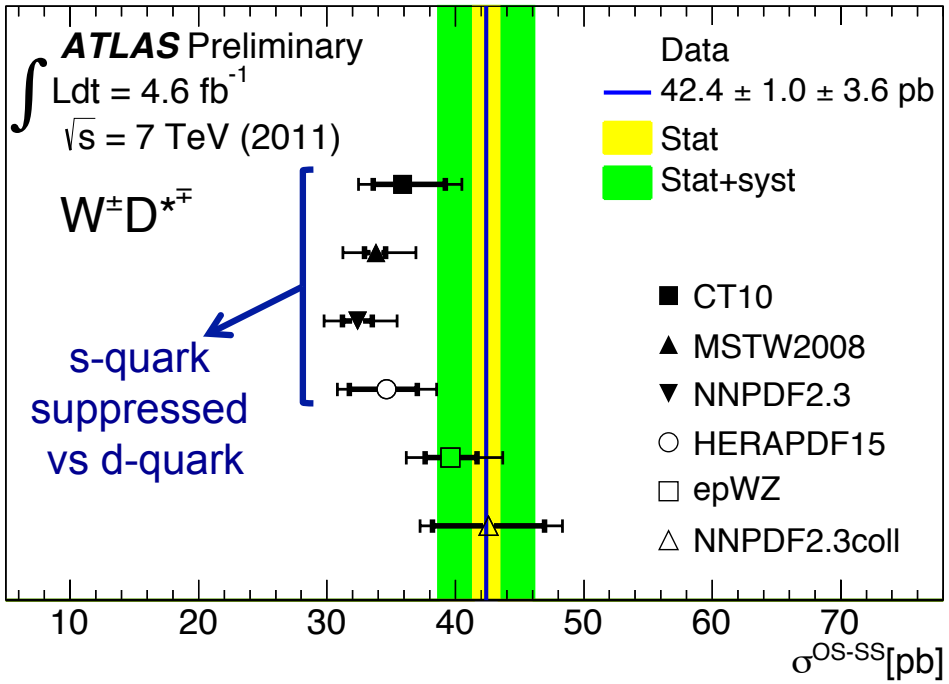
- Measurement of $\sigma(W^{+/-} + D^{(*)-/+})$ and $\sigma(W^{-/+} + D^{(*)+/-})/\sigma(W^{-/+})$ in a fiducial region where the same-sign contribution is subtracted.
- OS-SS enables isolation of the W + c final state from W + $c\bar{c}$.

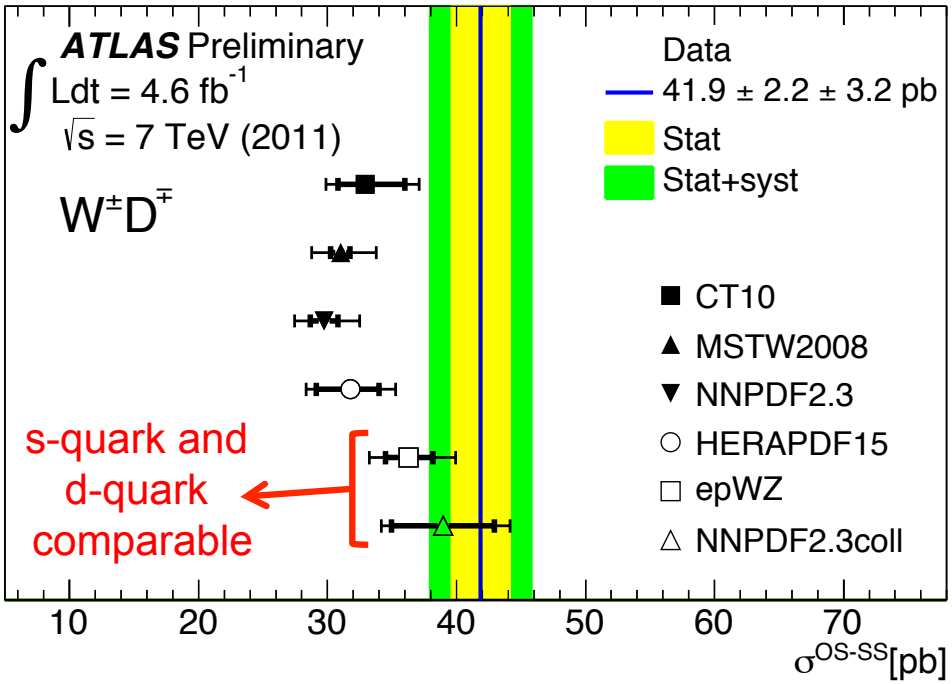



- Inclusive $\sigma(W^{+/-} + D^{(*)-/+})$ result sensitive to strange quark PDF.
- Differential $\sigma(W^{+/-} + D^{(*)-/+})/\sigma(W^{+/-})$ as a function of $p_T^D$ and $\eta^{lep}$ enables examination of kinematics.

# W + Charm Hadron Cross-Section

- Inclusive $\sigma(W^{+/-} + D^{(*)-/+})$ result compared to aMC@NLO prediction using PDFs with differing strange quark density treatment:
  - CT10, MSTW2008, NNDF2.3, HERAPDF15: s-quark suppressed vs d-quark.
  - epWZ: s-quark and d-quark comparable at x~0.01.
  - NNPDF2.3coll: larger s-quark vs d-quark at all x.

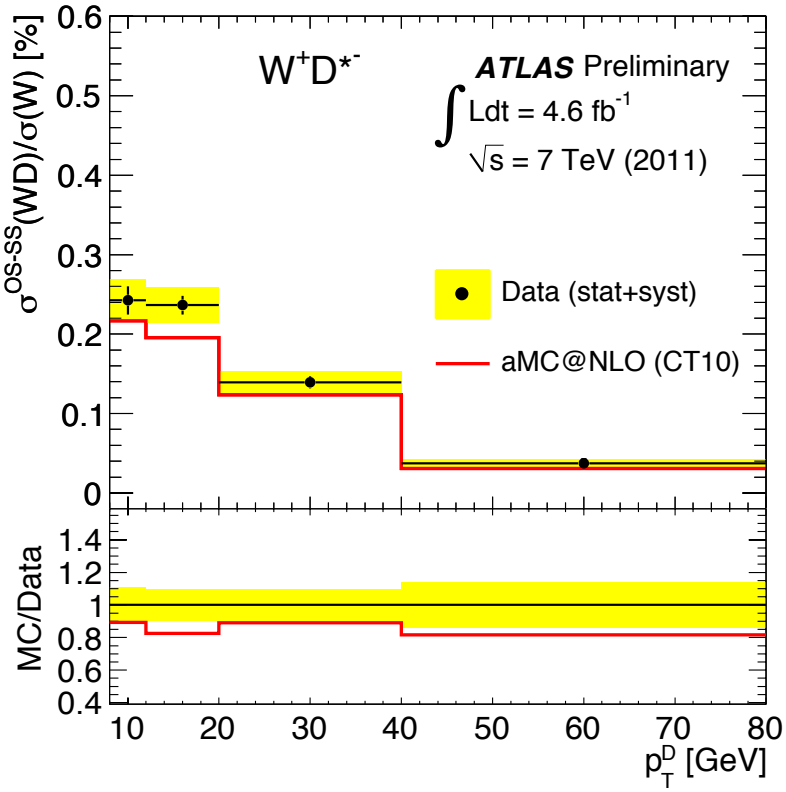


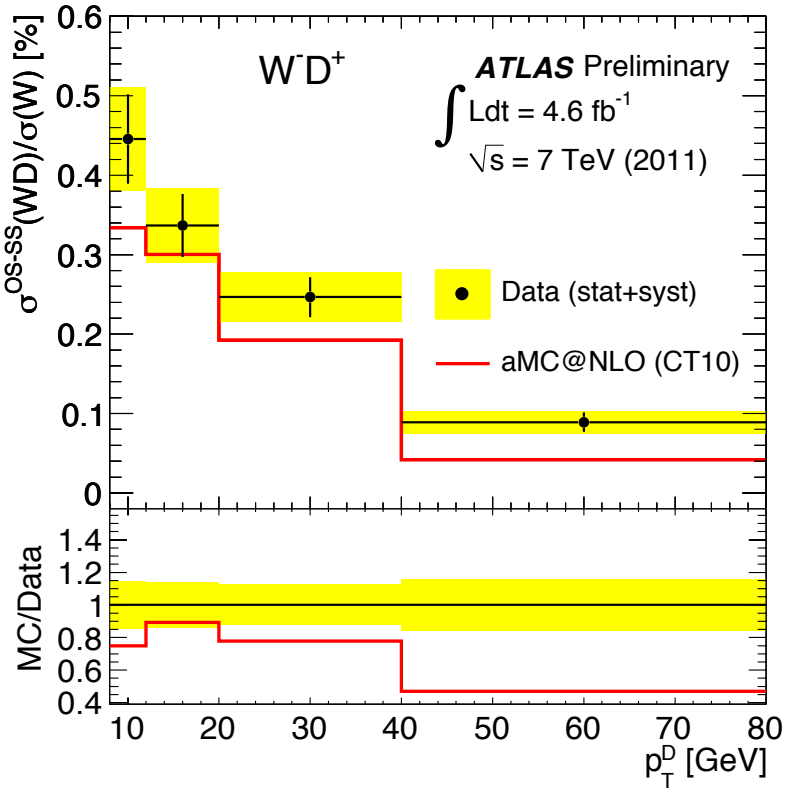




- Results seem to favour p.d.f's where the s-quark and d-quark sea contributions are comparable at x~0.01.

# W + Charm Hadron Cross-Section

- Differential $\sigma(W^{+/-} + D^{(*)-/+})/\sigma(W^{+/-})$ measurement as a function of $p_T^D$ and $\eta^{lep}$.



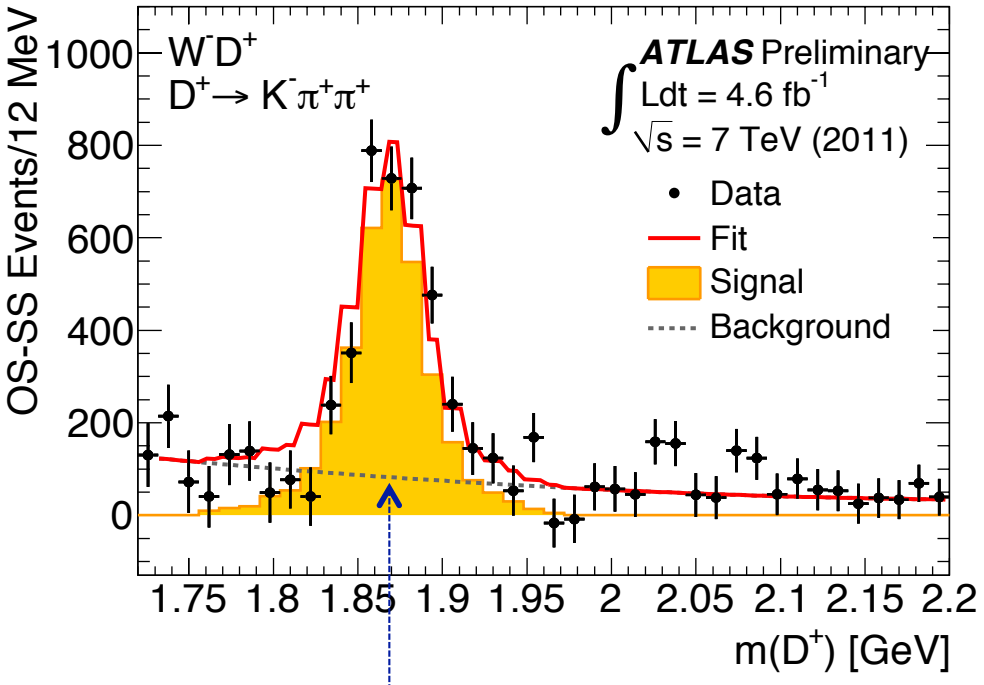

- Compared to aMC@NLO prediction using CT10 NLO p.d.f.
  - Suggestion of a harder $p_T^D$ spectra in data than NLO?
  - Shapes consistent between data and NLO in $\eta^{lep}$ comparison.

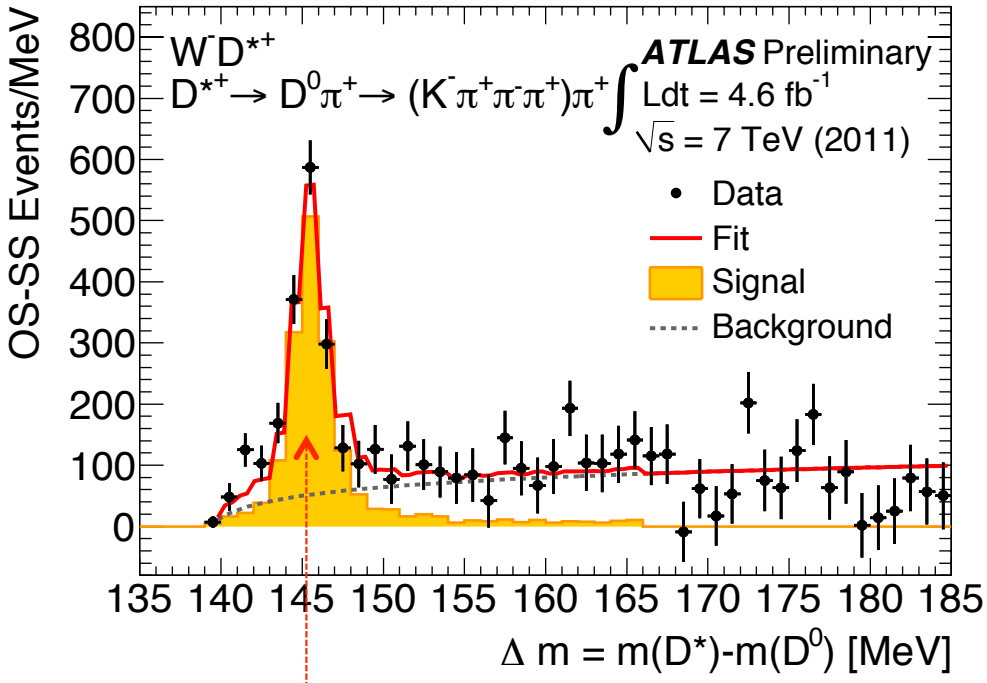
# Method: Charm Hadron Yield

- Select samples of $W^{-/+} + D^{+/-}$ and $W^{-/+} + D^{*+/-}$ by explicitly reconstructing $D^{(*)+/-}$ decays in the ATLAS inner detector:
  - $D^- \rightarrow K^+\pi^-\pi^-$
  - $D^{*+} \rightarrow D^0\pi^+$ with $D^0 \rightarrow K^-\pi^+$, $D^0 \rightarrow K^-\pi^+\pi^0$ or $D^0 \rightarrow K^-\pi^+\pi^-\pi^+$

  ] Plus the charge conjugate states

– Form OS-SS distributions of $m(K\pi\pi)$ for $D^{+/-}$ and $\Delta m = m(D^*) - m(D^0)$ and fit:




W+light jets combinatoric bkgd modelled with functional form

Separate data driven correction for heavy flavour production bkgd under peak

# Method: Systematics

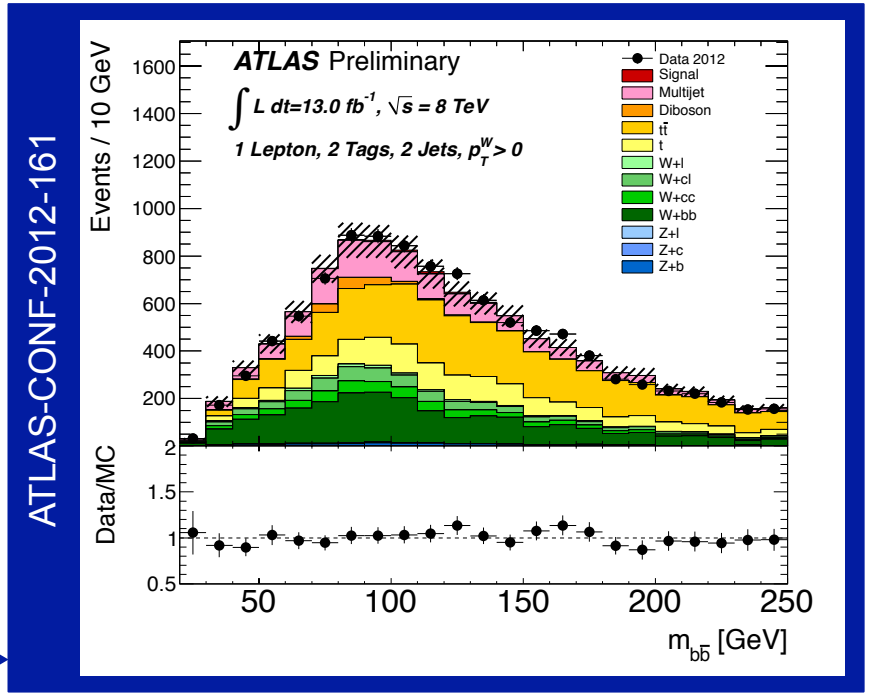
| Systematic | $\sigma(W^{+/-}D^{-/+})/\sigma(W^{+/-})$ | $\sigma(W^{+/-}D^{*-/+})/\sigma(W^{+/-})$ |
|---|---|---|
| Tracking Efficiency | 6.5% | 6.8% |
| $D^{*+}$ isolation | - | 2% |
| Jet veto | 2% | 2% |
| W yields | 1.4% | 1.4% |
| D/D* relative BRs | 2.1% | 2.2% |
| Other | 2% | 1.9% |
| Total | 7.4% | 8.0% |

- Measurement does not suffer from large jet related uncertainties!
- Dominant systematic is uncertainty in modelling of tracking efficiency by the simulation:
  - Affects modelling of $D^{*(+)}$ decay reconstruction efficiency in signal MC.
  - Arising from potential mis-modelling of detector material in the simulation.

# Conclusions

# Conclusions

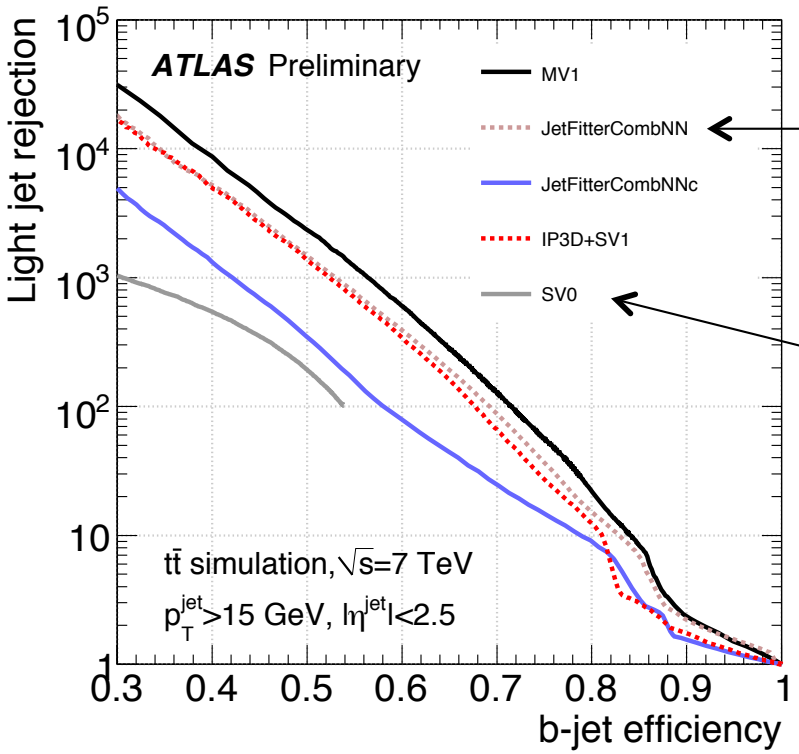
- VB + HF measurements give us a unique handle on the creation of heavy flavour in proton-proton collisions:
  - Study of HF creation in the initial state and final state.
- Measurements are challenging:
  - W+b: hard to separate signal from Top backgrounds.
  - W+c: understanding of tracking efficiency.
  - Excellent understanding of detector performance needed!
- Measurement of W + charm demonstrates the potential for the constraint of the s-quark distribution function at the LHC.
- Differential VB+HF measurements are starting to challenge the theory and will provide vital input to many searches/measurements.
  - Not least H→bb!



# Backup Slides

# 2010/2011 B-tagging at ATLAS

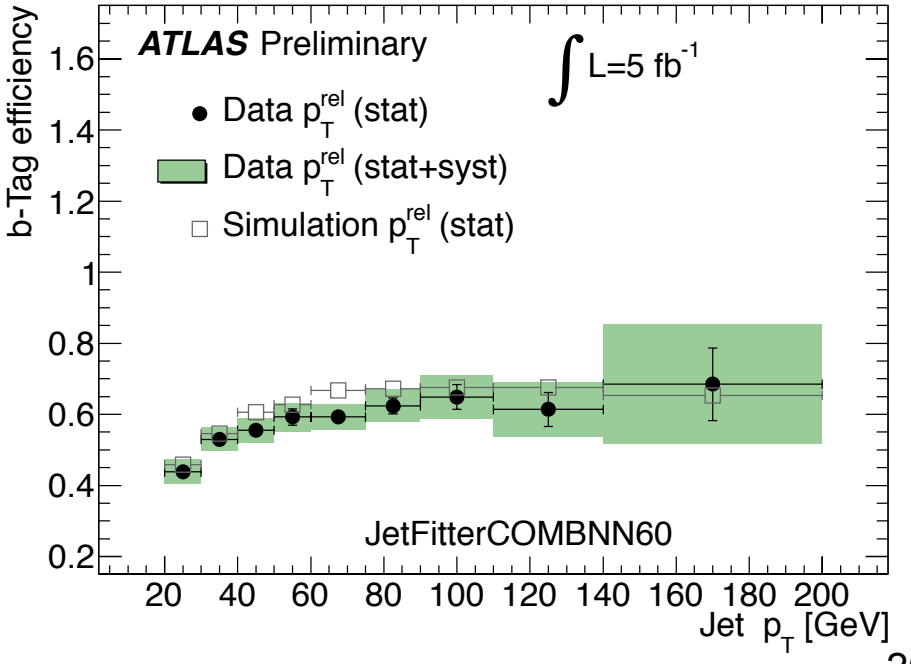
ATLAS-CONF-2012-043




JetFitterCombNN algorithm used for 2011 W+b measurement: NN combination of 3D impact parameter-based algorithm and "JetFitter" decay chain reconstruction algorithm.

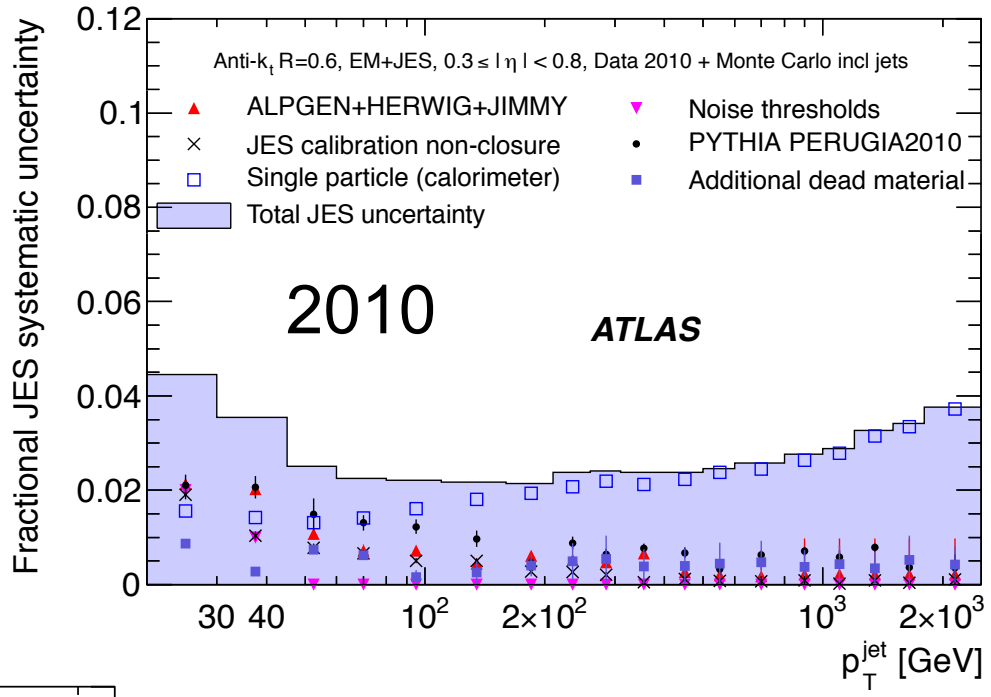
SV0 algorithm used for 2010 Z+b measurement: based on 3D decay length significance $L_{3D}/\sigma_{L_{3D}}$ for b-jet/ light-jet discrimination.

- Algorithms calibrated on data using a sample of muon-in-jet events:
  - Enriched in b semi-leptonic decays.
  - Can fit $p_T^{rel}$ distribution of muon to determine flavour composition before and after tagging

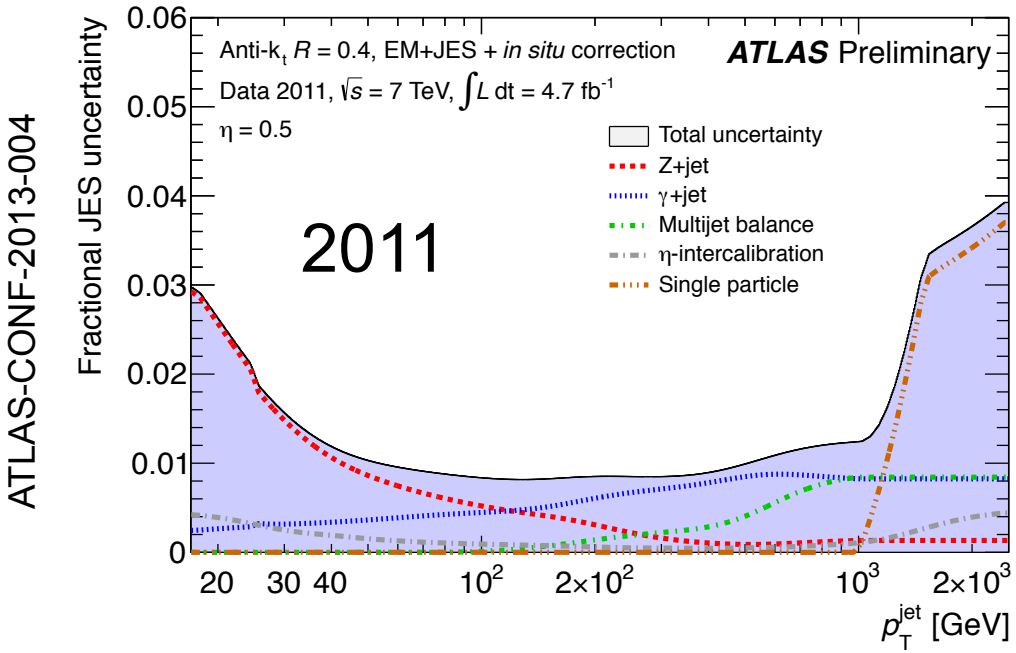


# Jet Energy Scale at ATLAS

- 2010 JES calibrations determined from MC with uncertainties from MC, single hadron response and dijet balancing.
- 2010 JES uncertainties validated using *in situ* techniques.



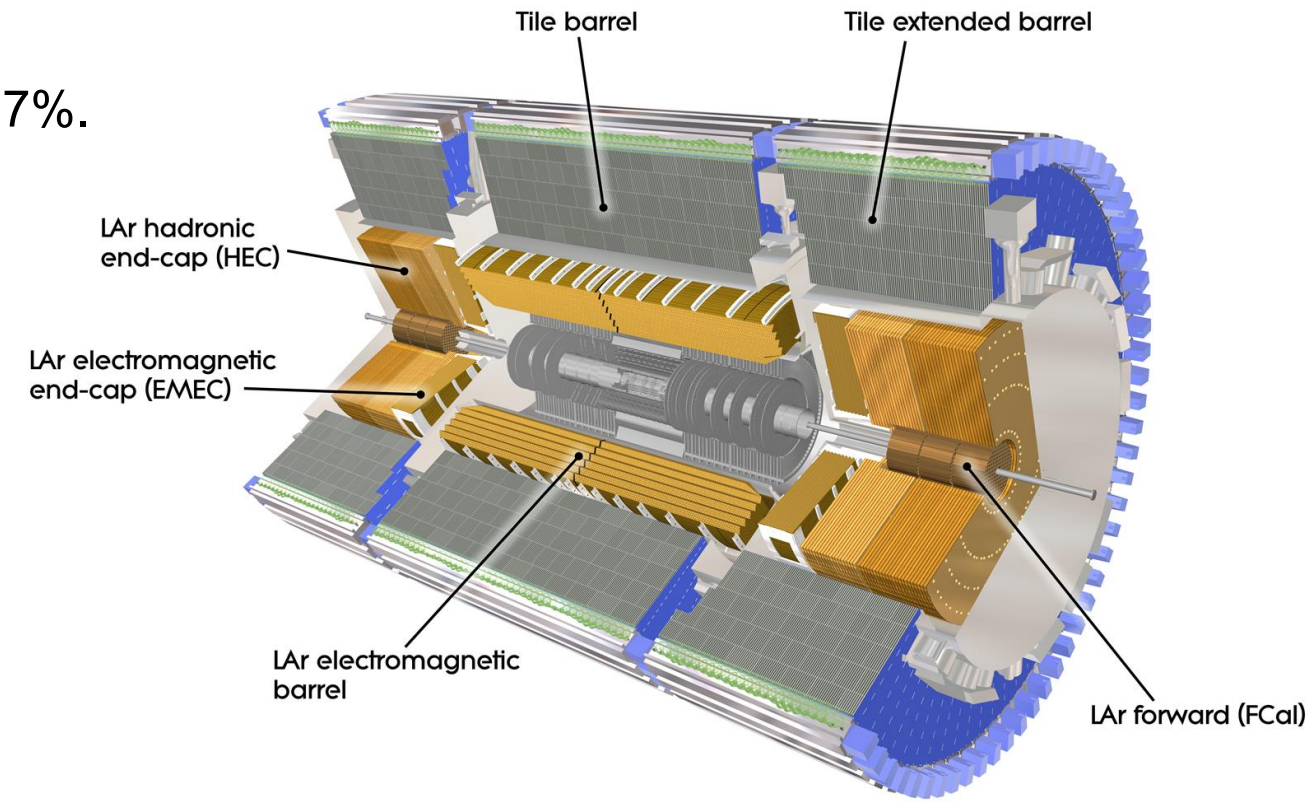

*Eur. Phys. J. C, 73 3 (2013) 2304*




- 2011 JES calibrations determined using MC but with corrections determined using *in situ* techniques.
- 2011 JES uncertainties are those associated with these *in situ* analyses.
- No specific b-jet calibrations.

# ATLAS Calorimetry

- EM barrel/endcap:
  - Pb/LAr accordion
  - $|\eta| < 3.2$
  - $\sigma/E \approx 10\text{-}17\%/\sqrt{E} + 0.7\%$.
- HAD barrel:
  - Fe/scintillator tiles.
  - $|\eta| < 1.7$
  - $\sigma/E \approx 50\%/\sqrt{E} + 3\%$.
- HAD endcap:
  - Cu/LAr
  - $1.5 < |\eta| < 3.2$
  - $\sigma/E \approx 50\%/\sqrt{E} + 3\%$.
- EM/HAD forward (FCal):
  - Cu/W-LAr
  - $3.1 < |\eta| < 4.9$
  - $\sigma/E \approx 100\%/\sqrt{E} + 10\%$.



# Common Features of Analyses

- W's and Z's are identified in their decays to electrons or muons, with the σ x BR(ll or lν) measured. Electron and muon channels combined.
- Lepton identification criteria and cuts:
  - Single lepton triggers (threshold 15/13 in 2010, 18/22 in 2011).
  - Lepton $p_T$ thresholds dictated by trigger plateaus: $p_T > 20$ or 25 GeV.
  - Lepton pseudorapidity dictated by tracker coverage: $|\eta| < 2.5$.
  - QCD fake-lepton backgrounds reduced by:
    - Isolation criteria
    - Z mass window or W transverse mass requirements.
    - Missing $E_T > 25$ GeV (in case of W)
  - Lepton-jet overlap removal.

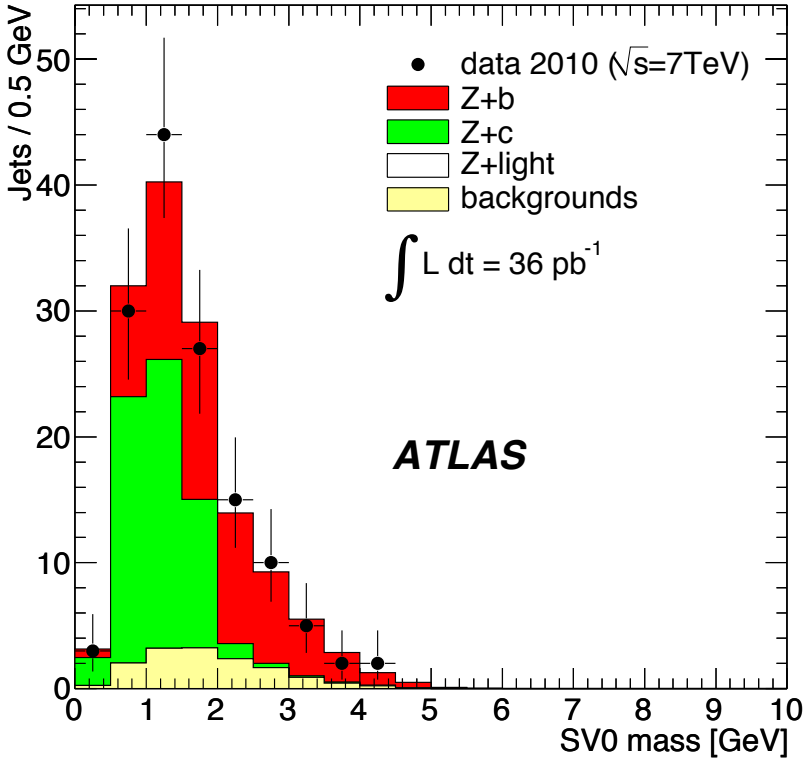
- B-jets labelled at particle-level as weakly decaying b-hadron $p_T > 5$ GeV within $\Delta R < 0.3$ of jet axis.

# Z+b: Determining Z + b-jet Yield

- Events containing leptonic Z decays selected.
- Anti-$K_T$ R=0.4 jets within these events with $p_T$ > 25 GeV, |y| < 2.1 are b-tagged using the SV0 algorithm.
- However, this does not produce a pure Z + b-jet sample!

Small backgrounds after b-tagging:

- Top pair: shape from MC and normalisation from NNLO calculation.
- QCD: shape and normalisation both data-driven.




Z+b, Z+c and Z+light template shapes from MC simulation (Alpgen/Sherpa)

- Fit mass distribution of the reconstructed secondary vertex of b-tagged jets to determine composition and hence Z + b-jet yield.

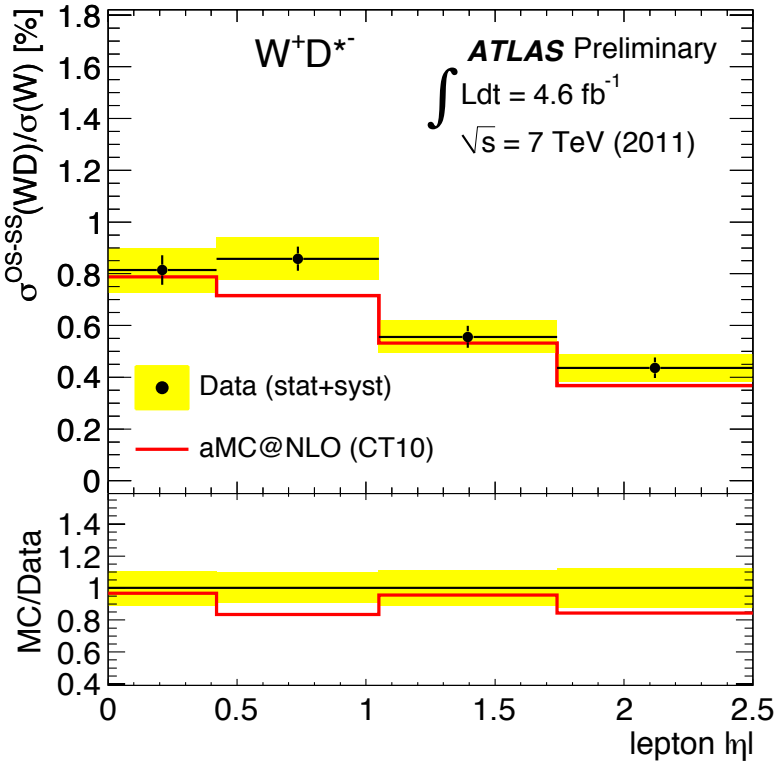
# Z+b: Systematics

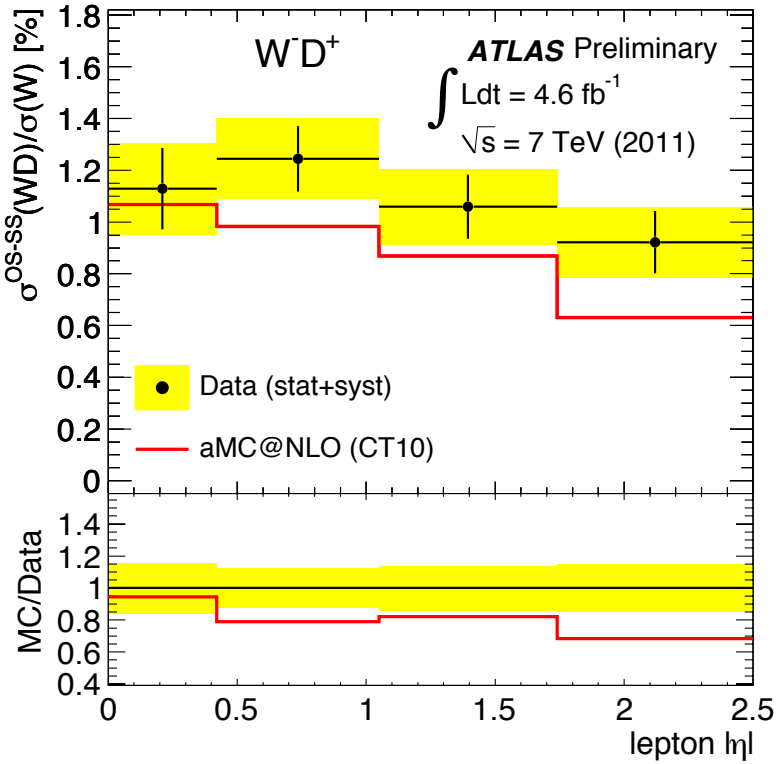
| Source | SV0-mass fit (%) | Acceptance (%) |
|---|---|---|
| Both electron and muon | | |
| $b$-Tagging efficiency | 1.7 | 9.1 |
| SV0-mass templates | 3.5 | – |
| Model dependence | 2.7 | 10.0 |
| Jet energy scale | 0.7 | 4.0 |
| $t\bar{t}$ cross-section | 2.0 | – |
| MPI model | negl. | 1.0 |
| Electron 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% | |

- Largest systematics from uncertainties in the calibration of b-tagging efficiency, and from signal model dependence in the unfolding.
- But this 2010 measurement is still statistics limited.

# W+D: $\sigma(W^{+/-} + D^{(*)-/+})$ vs $\eta^{lep}$

- Differential $\sigma(W^{+/-} + D^{(*)-/+})/\sigma(W^{+/-})$ measurement as a function of $\eta^{lep}$.

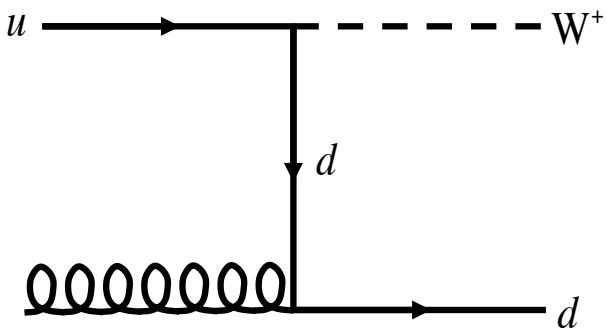



- Compared to aMC@NLO prediction using CT10 NLO p.d.f.

# W+D: Background Correction

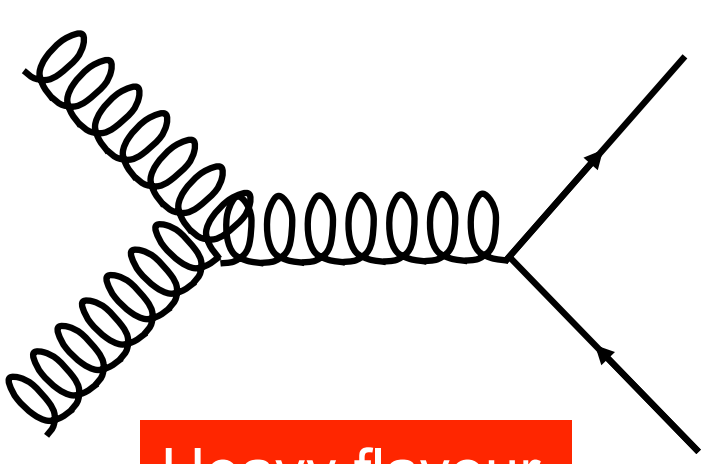
- After same sign subtraction the only backgrounds remaining are:




Light jet fakes D meson decay signal

**W + light jets**

Forms combinatoric background in fit modelled by a simple functional form, normalised in sidebands.




Fakes W signature

Real D meson decay

**Heavy flavour production**

Contains real D meson decay so peaks under signal in OS-SS distributions. Corrected for using ABCD method.