

Heavy Flavour Cross Section Measurements with the ATLAS Detector



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on behalf of the ATLAS Collaboration

Motivation for Heavy Flavour Measurements at LHC

- Heavy flavour production measured at lower energy hadron colliders ($\sqrt{s} = 0.63, 1.8, 1.96 \text{ TeV}$)
- LHC allows measurements at $\sqrt{s} = 7 \text{ TeV}$
Tests of QCD at much higher energy help constrain uncertainties on NLO calculations
- Heavy flavour production forms important background in searches for new phenomena
Better understanding of background improves sensitivity of searches

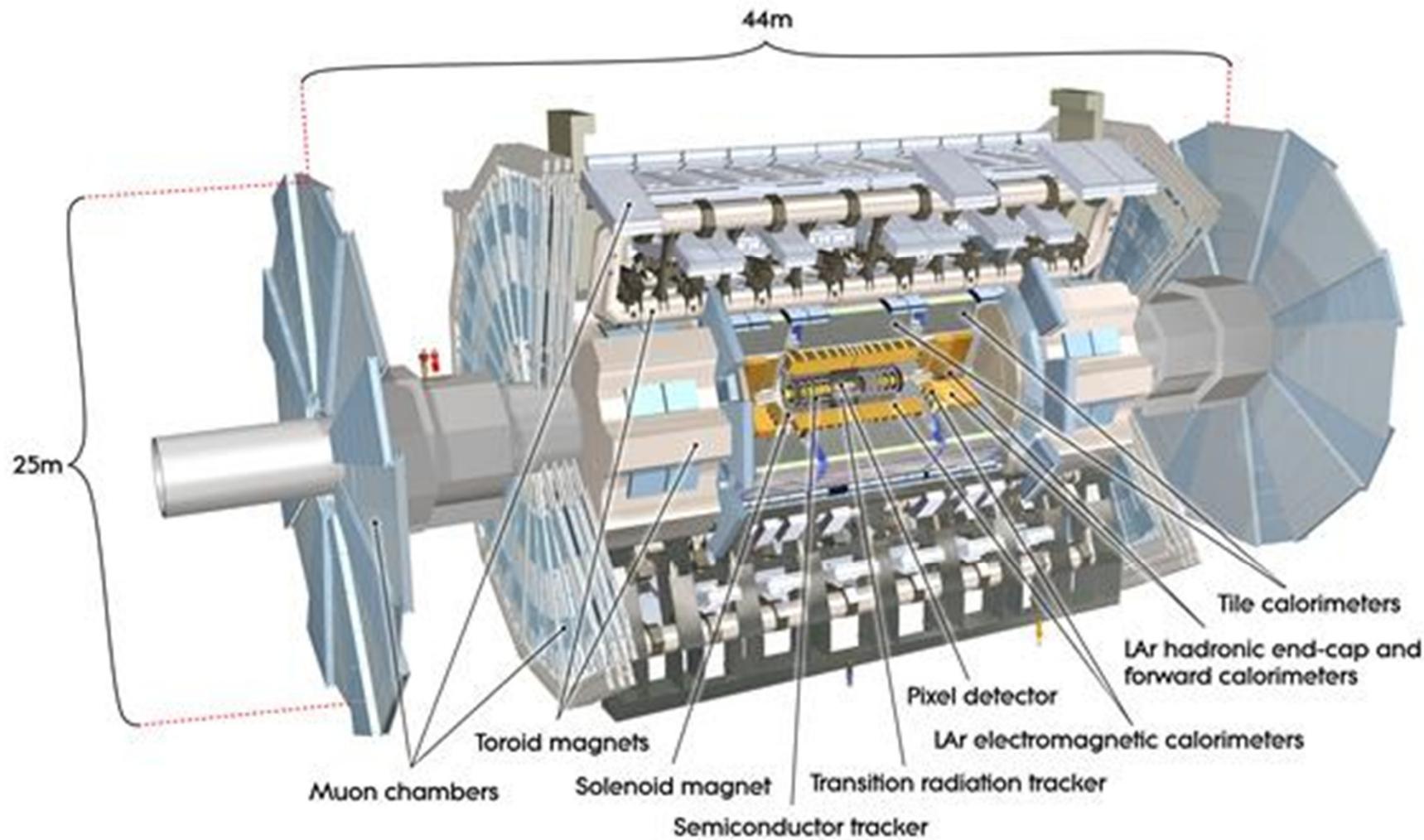
Overview

- ATLAS results on heavy flavour production in pp collisions at $\sqrt{s} = 7$ TeV using:
 - **b-hadrons decaying to $D^*\mu X$ final state**
 - Inclusive $D^{(*)}$ meson production
 - Inclusive electron and muon production
 - b-jet tagging (inclusive, dijet, and with Z or W)
- Compare results with NLO QCD calculations

Other ATLAS Heavy Flavour results to be presented in BEACH 2012:

• CP Violation	E. Kneringer	Tuesday
• $J/\psi, \Upsilon, \chi_b(3P)$ Production	R. Wang	Wednesday
• Rare Decays	S. Prell	Thursday

ATLAS Detector



Inner Detector $|\eta| < 2.5$

- 2T axial magnetic field
- Momentum resolution:
 $\sigma(p_T)/p_T = 3.8 \times 10^{-4} (\text{GeV}) \oplus 0.015$
- Vertex resolution:
~30 μm transverse
~50 μm longitudinal

$H_b \rightarrow D^{*+} \mu^- X$ Analysis Strategy

Measure differential cross section for
b-hadron (H_b) production in
pp collisions at $\sqrt{s} = 7$ TeV
(arXiv:1206.3122, accepted by NPB)

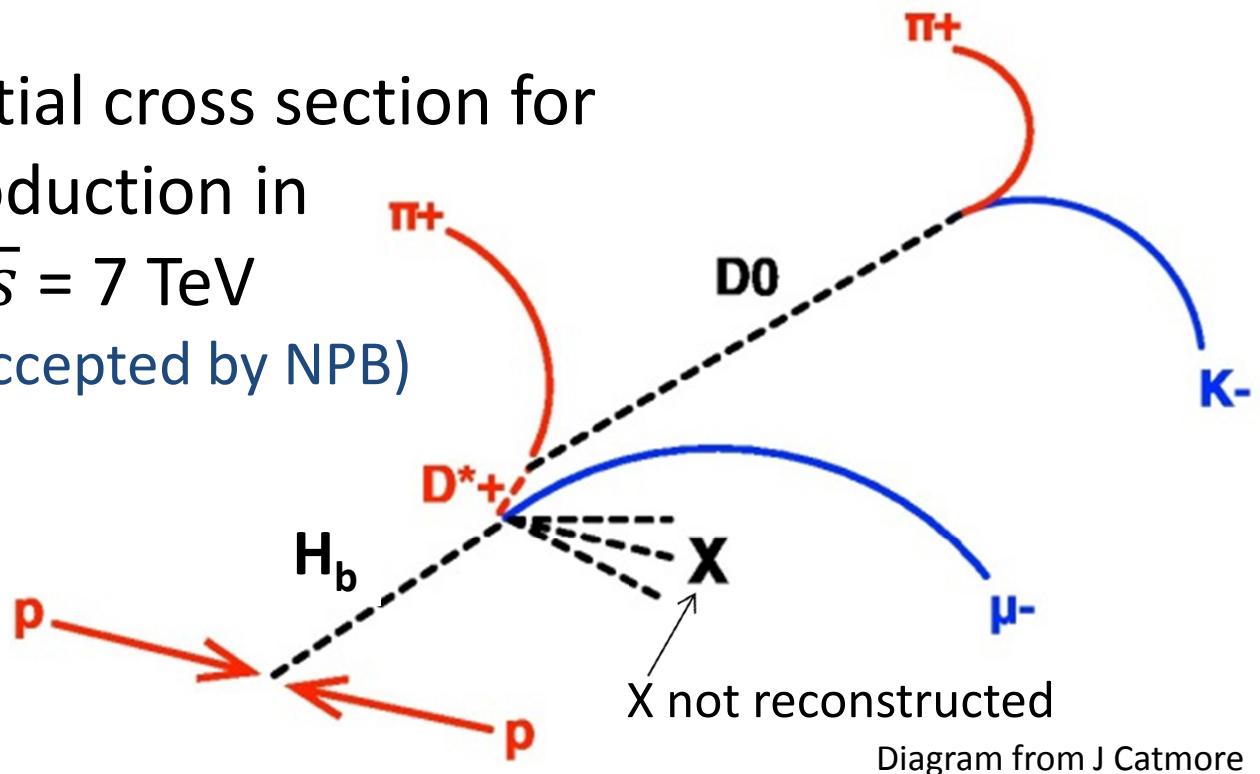


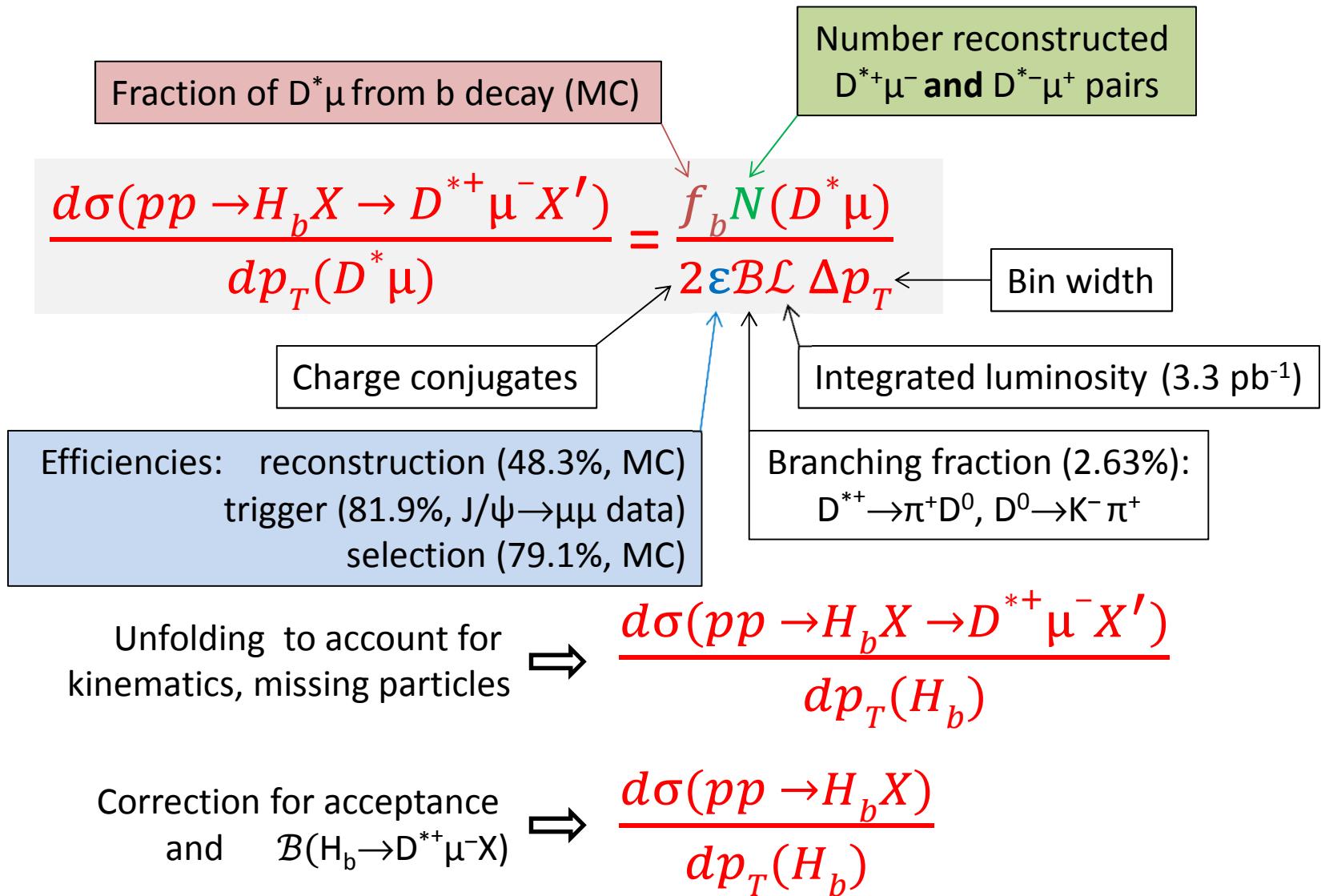
Diagram from J Catmore

b-hadrons observed through decays

$H_b \rightarrow D^{*+} \mu^- X$, $D^{*+} \rightarrow \pi^+ D^0$, $D^0 \rightarrow K^- \pi^+$
(and charge conjugate)

Muon + three other charged particles allow partial reconstruction of $D^* \mu X$ final state

Overview of Analysis Method



Data Selection

- Triggered by muon, $p_T(\mu) > 6 \text{ GeV}$ (2010 data, $\mathcal{L} = 3.3 \text{ pb}^{-1}$)
- $p_T > 1 \text{ GeV}$ (K, π from D^0), $p_T > 0.25 \text{ GeV}$ (soft π , from D^*), and $|\eta| < 2.5$ (all K, π)
- Simultaneous fit of H_b and D^0 vertices ($P(\chi^2) > 0.001$)

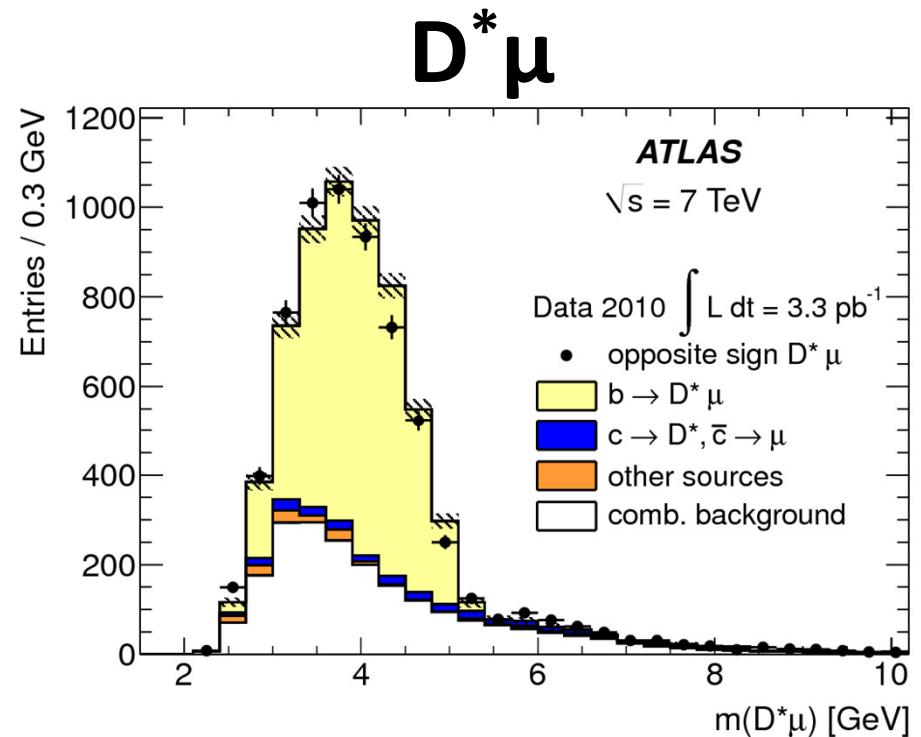
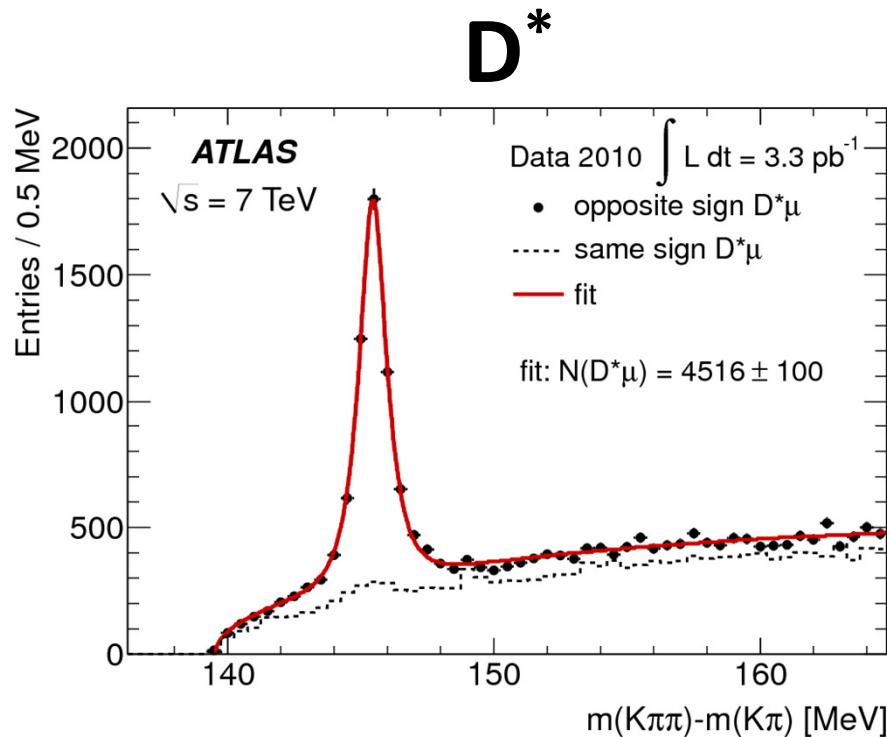
D^* selection:

- $m(K\pi) - m(D^0) < 64 \text{ MeV}$ for $p_T(D^*) > 12 \text{ GeV}$ and $|\eta(D^*)| > 1.3$,
 $m(K\pi) - m(D^0) < 40 \text{ MeV}$ otherwise
- $p_T(D^*) > 4.5 \text{ GeV}$ and $|\eta(D^*)| < 2.5$

$D^*\mu$ selection:

- $p_T(\mu) > 6 \text{ GeV}$ and $|\eta(\mu)| < 2.4$, matched to trigger muon
- $2.5 \text{ GeV} < m(D^*\mu) < 5.4 \text{ GeV}$

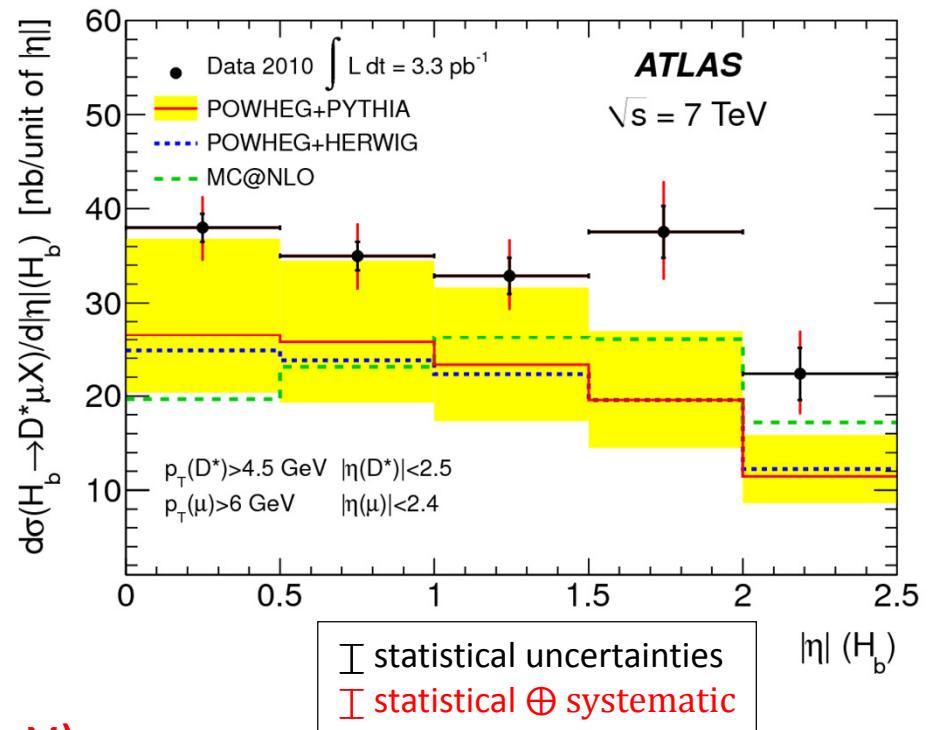
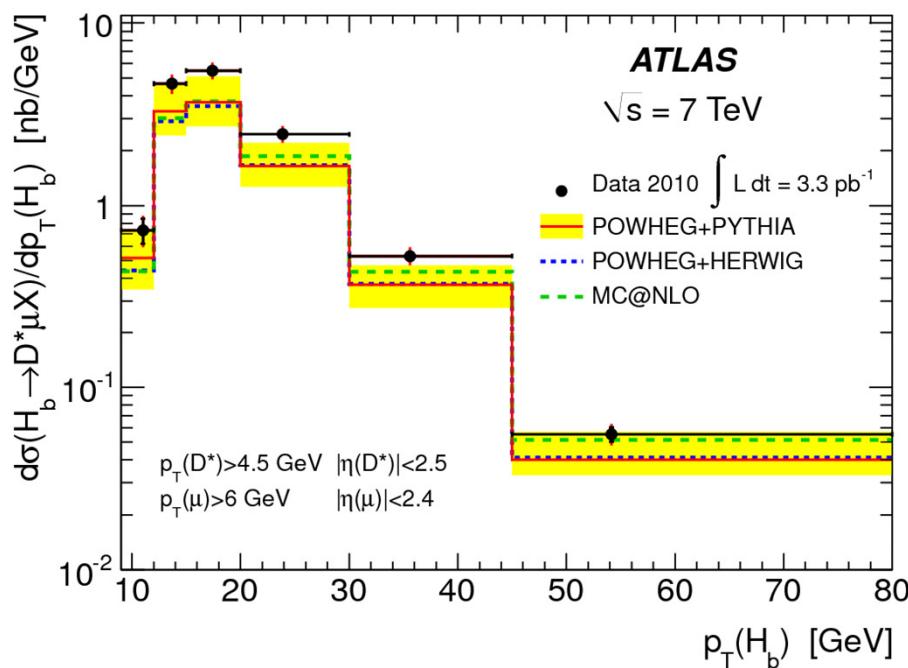
Reconstructed Mass Distributions



- $b \rightarrow D^* \mu X$ (signal)
 - 2 charm hadrons
 - $b \rightarrow D^* \tau X, \tau \rightarrow \mu v X$
 - + other smaller sources + combinatorial background
- 93.2 \pm 0.3 %** (mainly B^0)
- 3.8 \pm 0.2 %** composition
- 1.5 \pm 0.1 %** from MC

$pp \rightarrow H_b X \rightarrow D^* \mu X'$ Cross Section

within $p_T(D^*) > 4.5$ GeV, $|\eta(D^*)| < 2.5$; $p_T(\mu) > 6$ GeV, $|\eta(\mu)| < 2.4$



Integrated cross section, $\sigma(H_b \rightarrow D^* \mu X)$

Data: $78.7 \pm 2.0 \text{ (stat)} \pm 7.3 \text{ (syst)} \pm 1.2 \text{ (B)} \pm 2.7 \text{ (L)} \text{ nb}$

POWHEG+PYTHIA: $53^{+18}_{-11} \text{ (scale)} \pm 3(m_b) \pm 3 \text{ (PDF)}^{+6}_{-5} \text{ (hadronisation)} \text{ nb}$

NLO QCD predictions lower than data, but consistent within 1.2σ

Extract $pp \rightarrow H_b X$ Cross Section

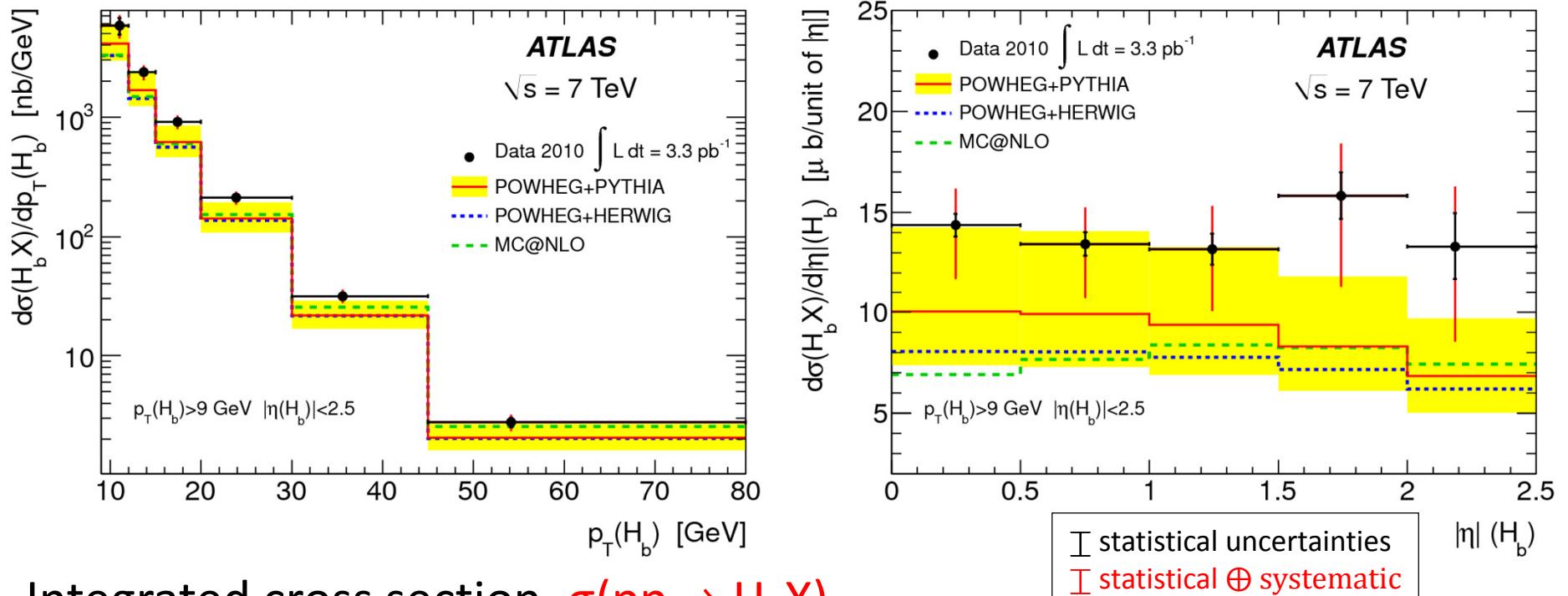
Now calculate the H_b production cross section:

- Cuts on D^* and μ constrain b-hadron to kinematic region: $p_T(H_b) > 9 \text{ GeV}$ and $|\eta(H_b)| < 2.5$
- Bin-by-bin correction (α) for acceptance of $H_b \rightarrow D^* \mu X$ decays within this kinematic range (NLO MC)
- Divide by $\mathcal{B}(H_b \rightarrow D^{*+} \mu^- X) = (2.75 \pm 0.19)\%$

$$\Rightarrow \frac{d\sigma(pp \rightarrow H_b X)}{dp_T(H_b)}$$

pp \rightarrow H_bX Cross Section

within $p_T(H_b) > 9$ GeV, $|\eta(H_b)| < 2.5$



Integrated cross section, $\sigma(pp \rightarrow H_b X)$

Data: $32.7 \pm 0.8 \text{ (stat)} \pm 3.1 \text{ (syst)} {}^{+2.1}_{-5.6}(\alpha) {}^{+2.3}_{-2.1}(B) {}^{+1.1}_{-1.5}(\mathcal{L}) \mu\text{b}$

POWHEG+PYTHIA: $22.2 {}^{+8.9}_{-5.4}(\text{scale}) {}^{+2.1}_{-1.9}(m_b) {}^{+2.2}_{-2.1}(\text{PDF}) {}^{+1.6}_{-1.5}(\text{hadron}) \mu\text{b}$

NLO QCD predictions lower than data, but consistent within 1σ

Main Systematic Uncertainties

(Ranges span p_T and $|\eta|$ dependences)

- NLO MC (used for unfolding, acceptance): **1-30%**
- Reconstruction, selection efficiencies: **10-15%**
- Luminosity: **3.4%**
- Fits to mass distributions for yields: **1-3%**
- Data/MC differences: **1-2%**
- Trigger efficiency: **1-2%**
- Branching fractions, f_b : **1-2%**

Extrapolated Cross Section

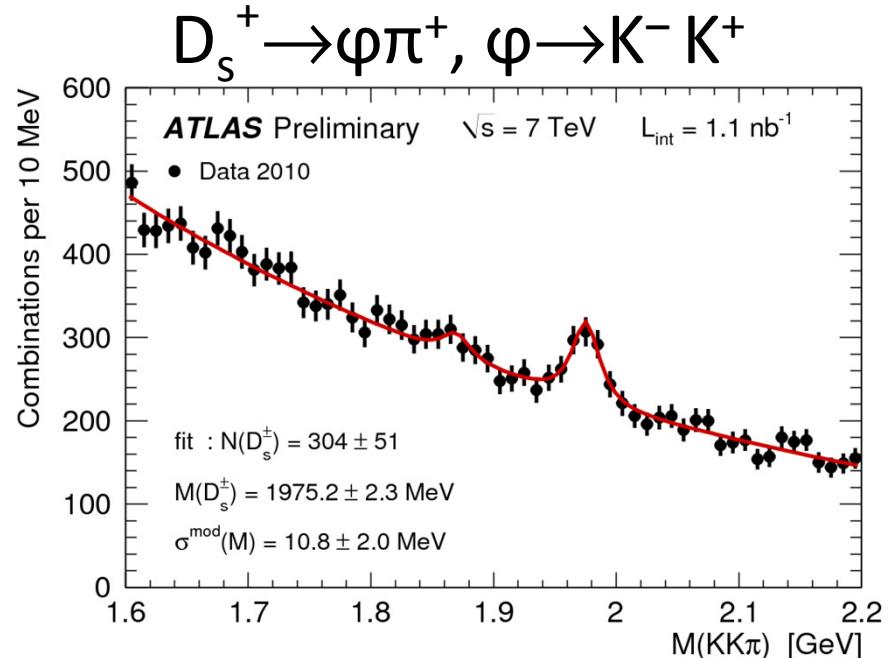
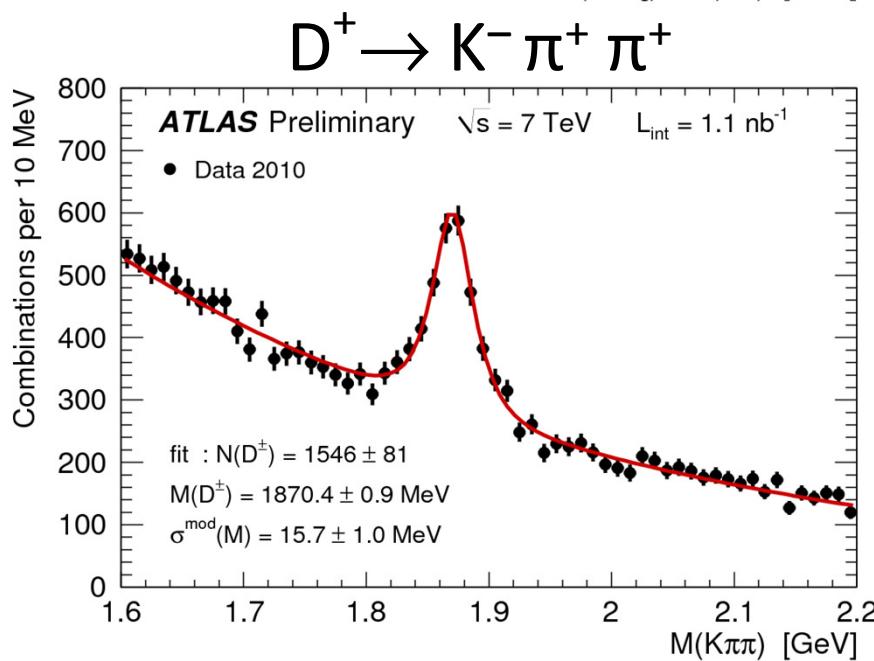
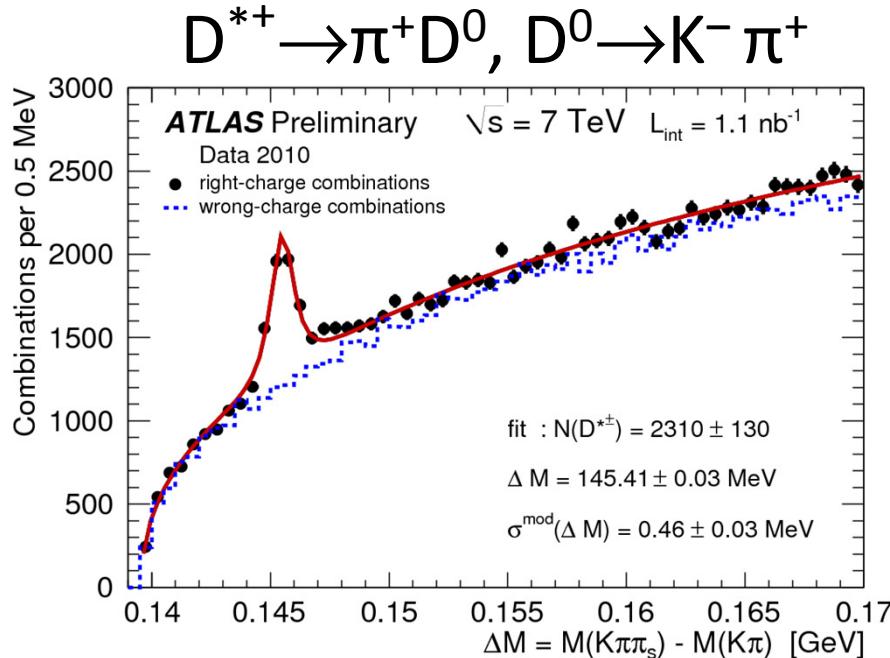
- Use NLO MC to extrapolate to full phase space
(arXiv:1206.3122, accepted by NPB)

$$\sigma_{\text{tot}}(\text{pp} \rightarrow H_b X) = 360 \pm 9 \text{ (stat)} \pm 34 \text{ (syst)} \\ \pm 25 \text{ (B)} \pm 12 \text{ (L)} \begin{array}{l} +77 \\ -69 \end{array} \text{ (accept} \oplus \text{extrap) } \mu\text{b}$$

- Compare with other $\sigma_{\text{tot}}(\text{pp} \rightarrow H_b X)$ measurements:
 - LHCb, $H_b \rightarrow D^0 \mu X$, extrapolated from $2 < \eta < 6$ (PLB694 (2010) 209)
 $284 \pm 20 \text{ (stat)} \pm 49 \text{ (syst) } \mu\text{b}$
 - LHCb, $H_b \rightarrow J/\psi X$, extrapolated from $2.0 < y < 4.5$ (EPJC71 (2011) 1645)
 $288 \pm 4 \text{ (stat)} \pm 48 \text{ (syst) } \mu\text{b}$
 - ALICE, $H_b \rightarrow J/\psi X$, extrapolated from $p_T > 1.3 \text{ GeV}$, $|y| < 0.9$
(arXiv:1205.5880, submitted to JHEP)
 $244 \pm 64 \text{ (stat)} \begin{array}{l} +50 \\ -59 \end{array} \text{ (syst)} \begin{array}{l} +7 \\ -6 \end{array} \text{ (extrap) } \mu\text{b}$
- Measurements consistent within large uncertainties

Inclusive $D^{(*)}$ Production Cross Sections

- $D^{*\pm}$, D^\pm , D_s^\pm meson differential cross sections measured within kinematic ranges
 $p_T(D^{(*)}) > 3.5 \text{ GeV}, \quad |\eta(D^{(*)})| < 2.1$
- Produced by c- and b-quark fragmentation
- Compare results with NLO QCD calculations
- Relies on minimum-bias trigger. First 1.1 nb^{-1} of data used in analysis (after prescale, March-July 2010)



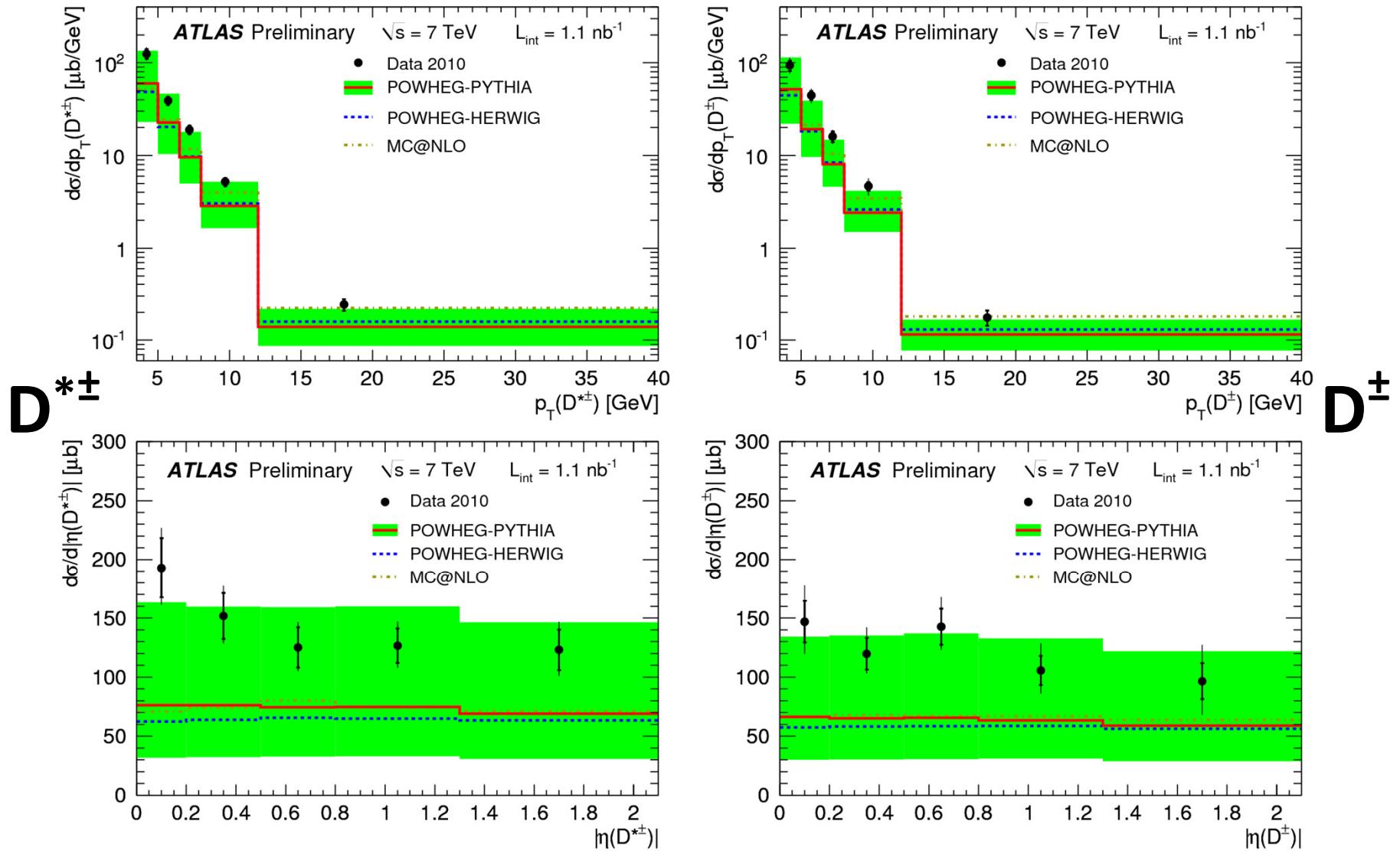
Selection strategies exploit:

- Hard charm production and fragmentation
- D meson lifetimes
- Angular distributions from D meson spins

Fitted masses and widths all consistent with PDG and MC values

Differential Cross Sections

within $p_T(D^{(*)}) > 3.5 \text{ GeV}$, $|\eta(D^{(*)})| < 2.1$



Integrated Cross Sections

within $p_T(D^{(*)}) > 3.5 \text{ GeV}$, $|\eta(D^{(*)})| < 2.1$

- ATLAS measurements (prelim. ATLAS-CONF-2011-017):

$$\sigma(D^{*\pm}) = 285 \pm 16 \text{ (stat)} {}^{+32}_{-27} \text{ (syst)} \pm 31 \text{ (L)} \pm 4 \text{ (B)} \mu\text{b}$$

$$\sigma(D^\pm) = 238 \pm 13 \text{ (stat)} {}^{+35}_{-23} \text{ (syst)} \pm 26 \text{ (L)} \pm 10 \text{ (B)} \mu\text{b}$$

$$\sigma(D_s^\pm) = 168 \pm 34 \text{ (stat)} {}^{+27}_{-25} \text{ (syst)} \pm 18 \text{ (L)} \pm 10 \text{ (B)} \mu\text{b}$$

- POWHEG+PYTHIA predictions:

$$\sigma(D^{*\pm}) = 153 {}^{+169}_{-80} \text{ (scale)} {}^{+13}_{-15} \text{ (m}_Q\text{)} {}^{+24}_{-21} \text{ (PDF)} {}^{+20}_{-16} \text{ (hadr)} \mu\text{b}$$

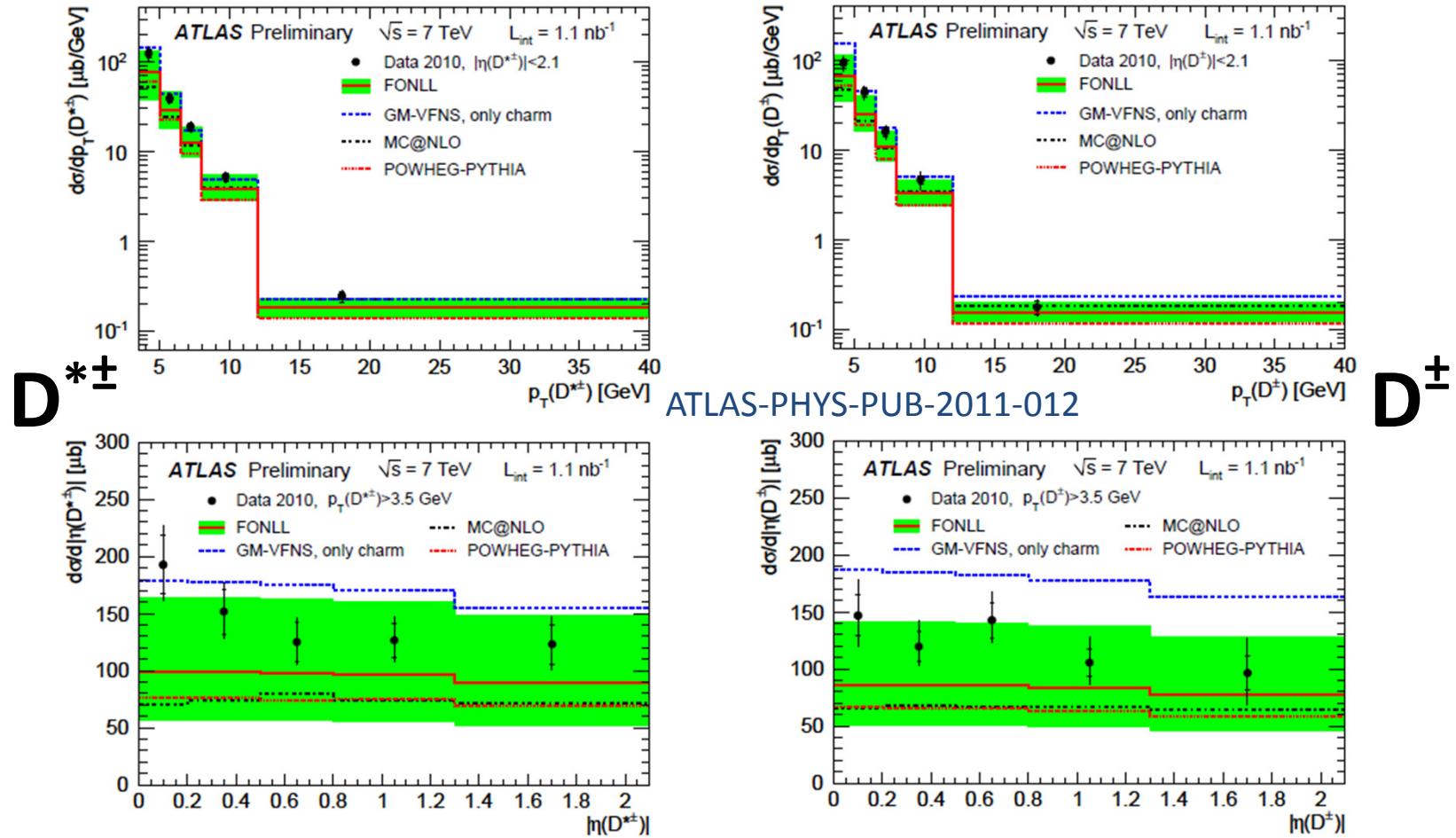
$$\sigma(D^\pm) = 132 {}^{+137}_{-65} \text{ (scale)} {}^{+11}_{-10} \text{ (m}_Q\text{)} {}^{+20}_{-18} \text{ (PDF)} {}^{+21}_{-11} \text{ (hadr)} \mu\text{b}$$

$$\sigma(D_s^\pm) = 59 {}^{+57}_{-28} \text{ (scale)} {}^{+4}_{-6} \text{ (m}_Q\text{)} {}^{+9}_{-8} \text{ (PDF)} {}^{+7}_{-8} \text{ (hadr)} \mu\text{b}$$

NLO QCD predictions lower than data, but consistent within 1.5σ

Comparison with Fixed-Order Next-to-Leading-Log QCD

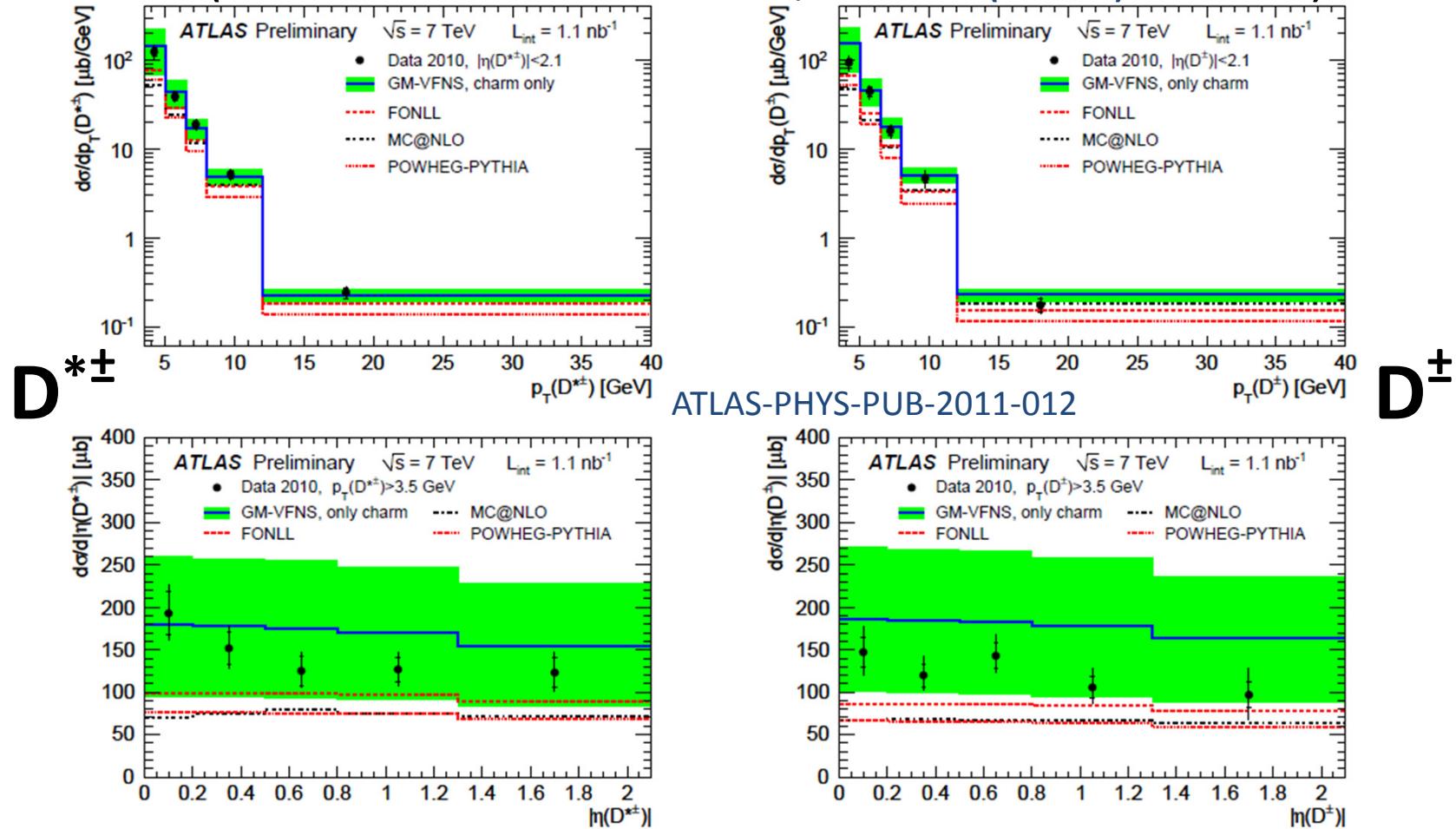
(FONLL: M. Cacciari et al, JHEP 0407 (2004) 033)



FONLL predictions slightly lower than data, but consistent within uncertainties

Comparison with General-Mass Variable-Flavor-Number Scheme

(GM-VFNS: BA Kniehl et al, PRD79 (2009) 094009)



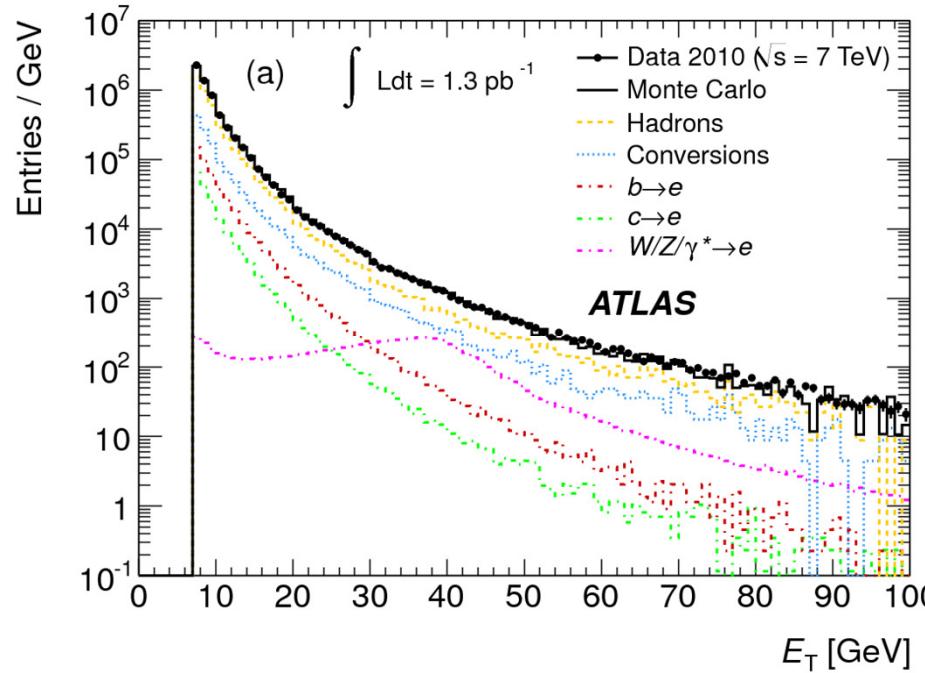
GM-VFNS (charm only) predictions slightly higher than data, but consistent

Inclusive Electron and Muon Cross Sections from Heavy Flavour Decays

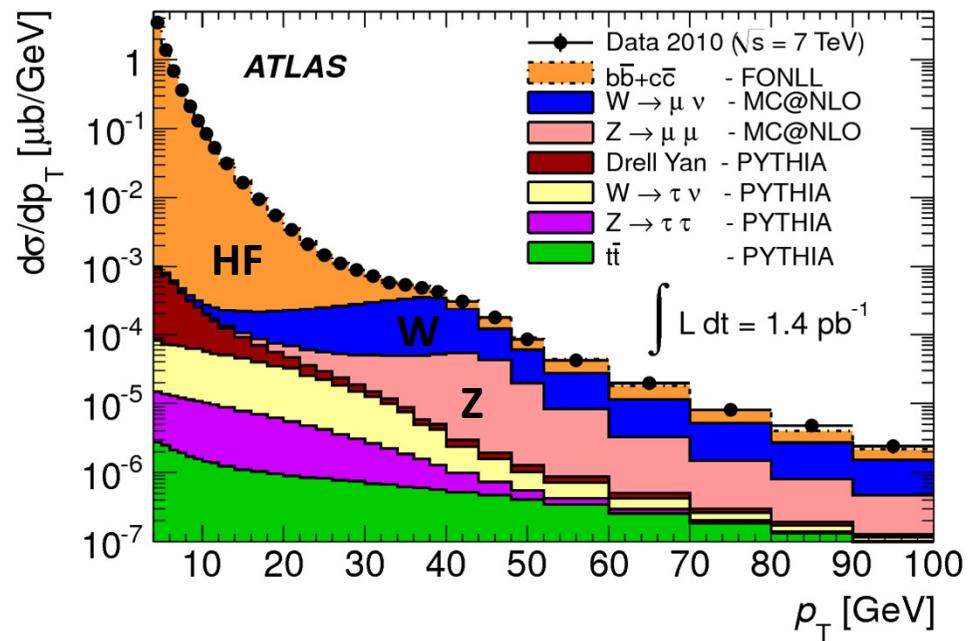
Overview of analysis method: (PLB707 (2012) 438)

- Measure lepton production in bins of E_T , p_T
- Fit to extract e and μ signals from background (QCD, fakes, conversions, π and K decays)
 - Heavy flavour decays dominate at low p_T
 - Leptons from W/Z/ γ^* at high p_T
- Subtract W/Z/ γ^* contributions to obtain heavy flavour component
- Compare with QCD calculations

Electron and Muon Spectra

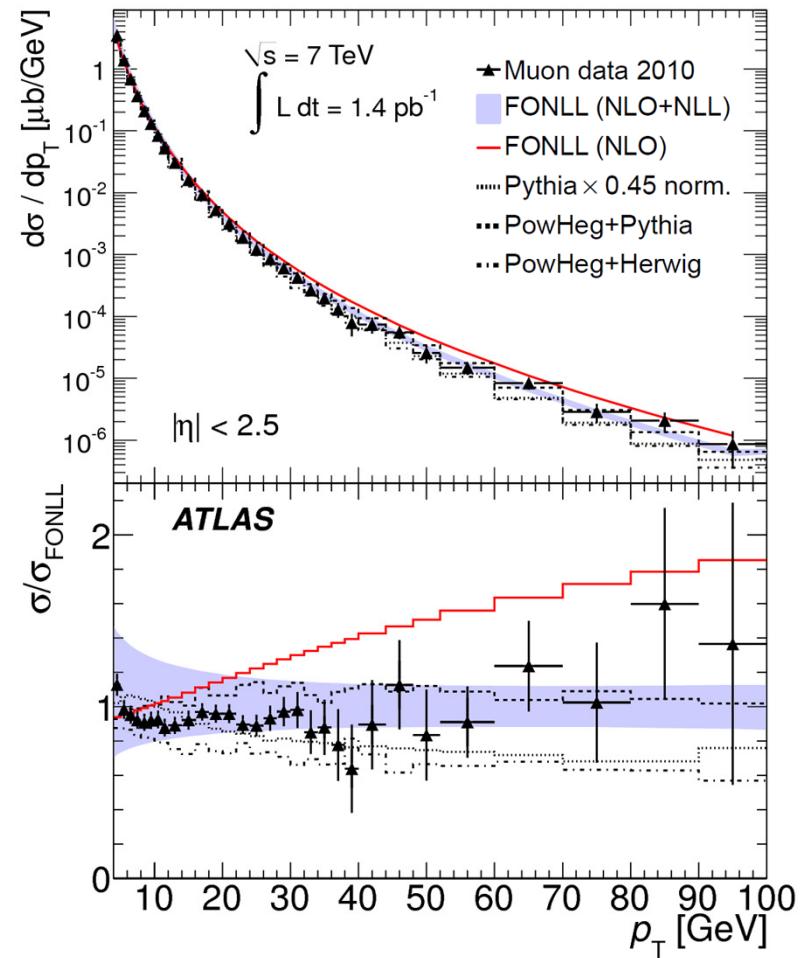
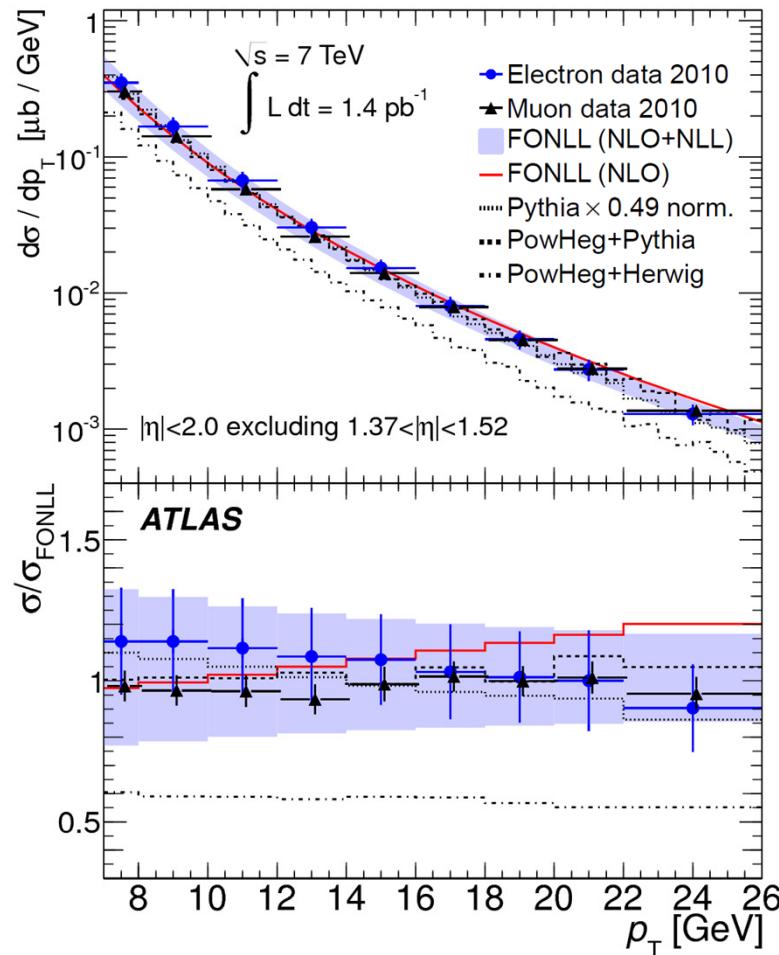


Transverse energy of
electron candidates



Transverse momentum
of muon candidates

Cross Sections from Heavy Flavour



Agreement with POWHEG+PYTHIA and with FONLL calculations

Muon data show sensitivity to NLL terms in FONLL at high p_T

Measurements using b-Jet Tagging

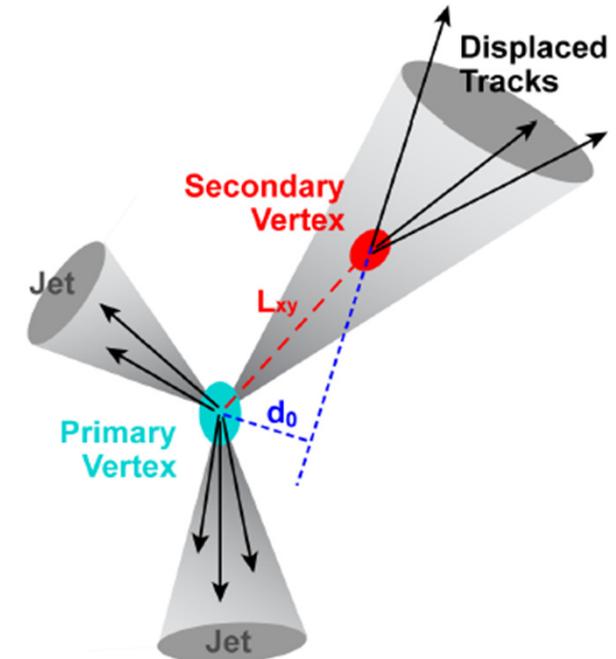
Overview of analysis method:

- Reconstruct secondary vertices
- Require large decay length significance (L/σ_L) to enrich b-jet component in sample
- Fit to secondary vertex mass distribution to extract b-jet fraction
- Measurements of cross sections for:

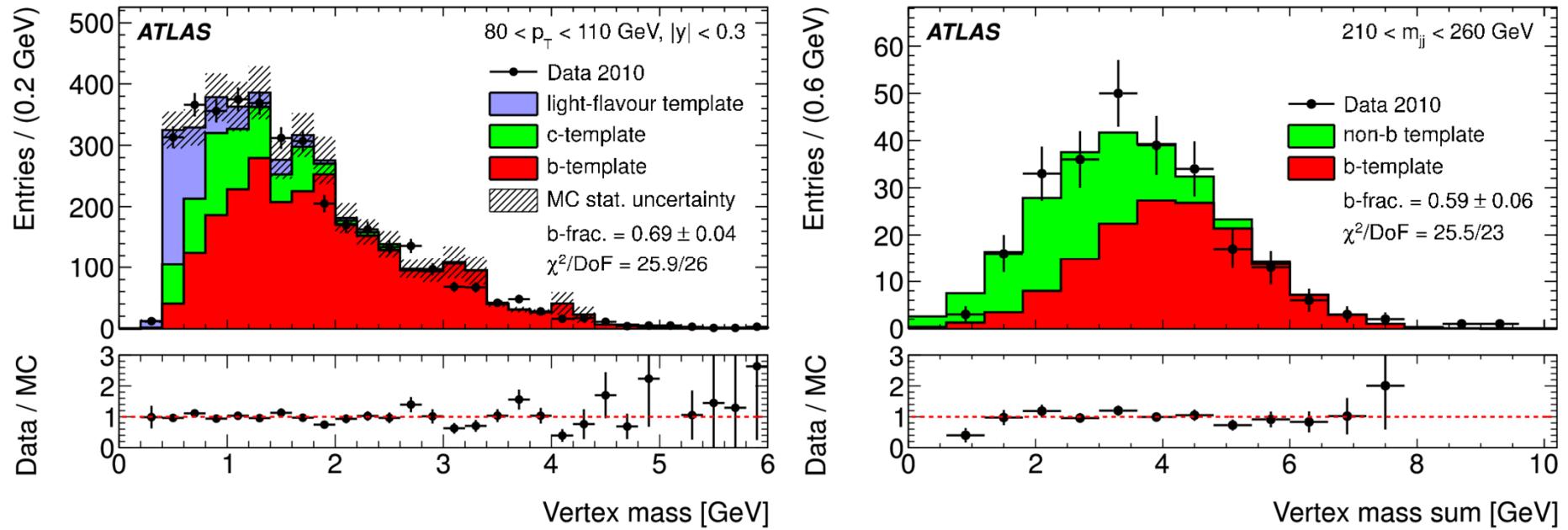
Inclusive b-jets and dijets (EPJC71(2011)1846)

Z or W boson in association with b-jets

(PLB706 (2012) 295, PLB707 (2012) 418)

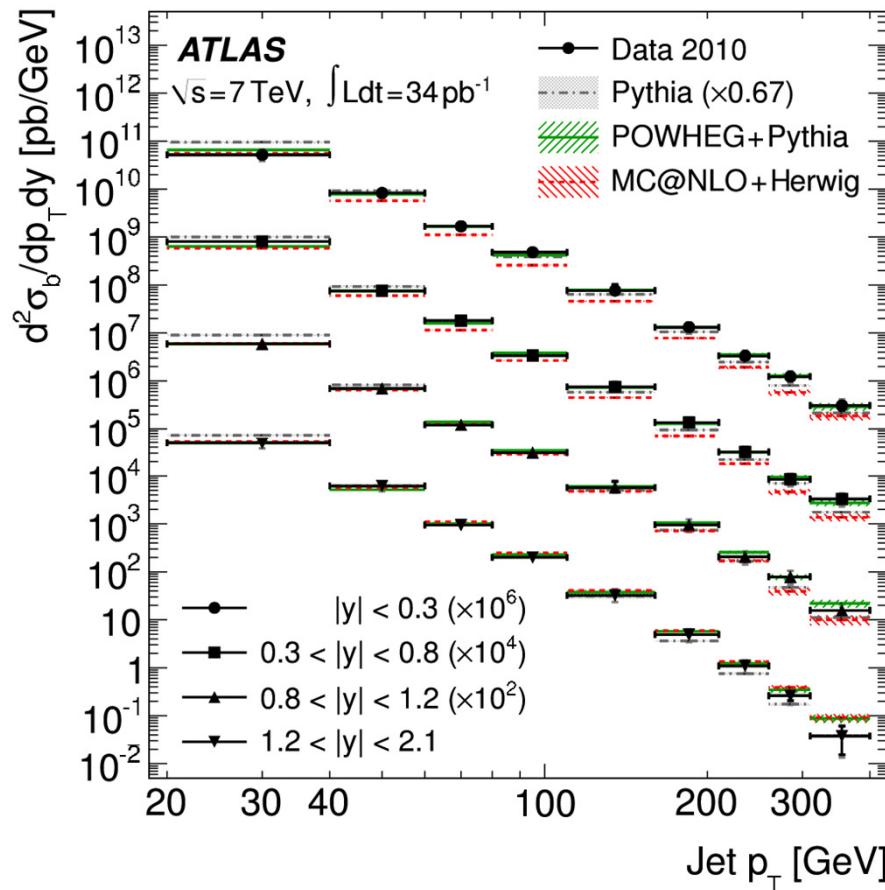


Extraction of Inclusive and Dijet Cross Sections for b-Jets

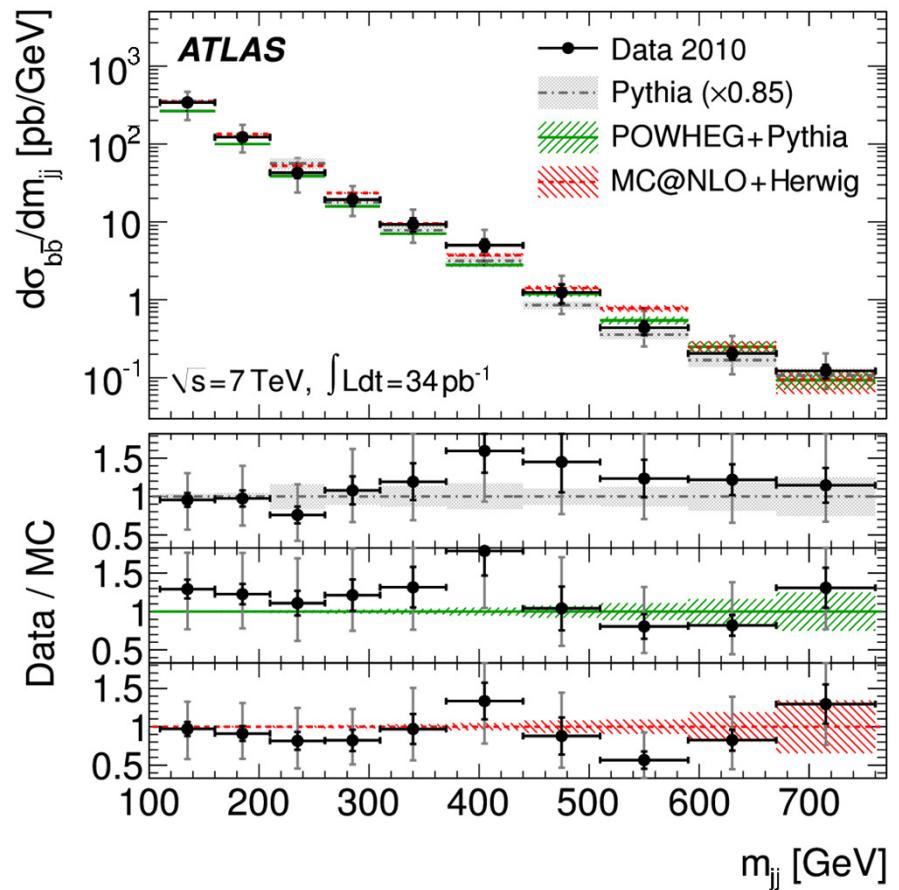


Examples of purity fits of light-flavour, charm and b-jet templates to the secondary vertex mass distributions to extract the b-jet fractions

Inclusive b-jet cross section



b-dijet cross section



Main experimental uncertainties from b-jet energy
scale and b-jet tagging efficiency and purity

Inclusive data agree with POWHEG+Pythia predictions
Dijets consistent with POWHEG+Pythia & MC@NLO+Herwig

Z or W in Association with b-Jets

Jets are reconstructed with anti- k_t algorithm[†] and have $p_T > 25 \text{ GeV}$ and $|y| < 2.1$

b-jet in association with a Z boson

Requires Z decay to high p_T electrons or muons and at least one tagged b-jet

ATLAS: $3.5^{+0.82}_{-0.74} \text{ (stat)}$
 $+0.73_{-0.55} \text{ (syst) } \pm 0.12 \text{ (lumi) pb}$

MCFM: $3.88 \pm 0.58 \text{ pb}$

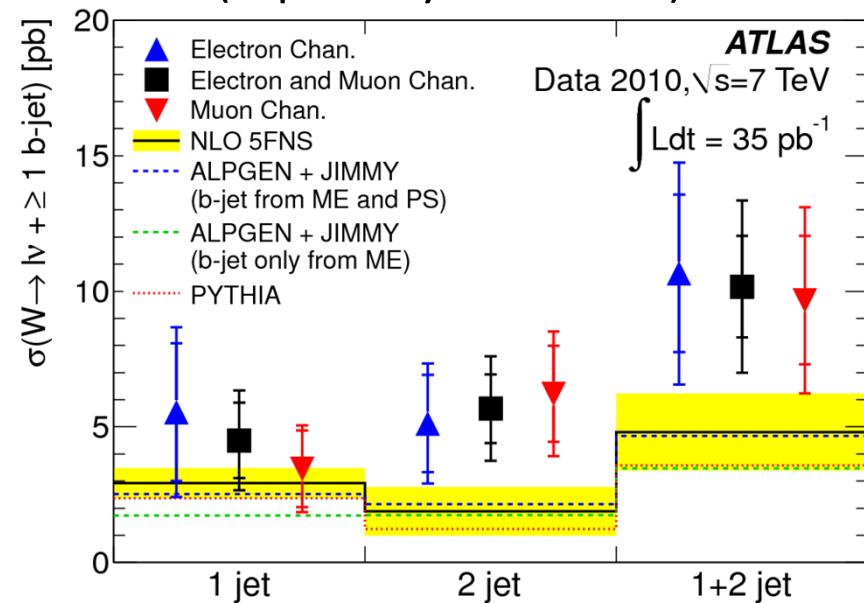
ALPGEN: $2.23 \pm 0.01 \text{ (stat only) pb}$

SHERPA: $3.29 \pm 0.04 \text{ (stat only) pb}$

Agreement with NLO QCD calculations within 1.4σ

b-jets in association with a W boson

Requires W decay to high p_T e or μ +1 or 2 jets, with ≥ 1 tagged as b-jet (top decays excluded)



NLO QCD predictions lower than data, but consistent within 1.5σ

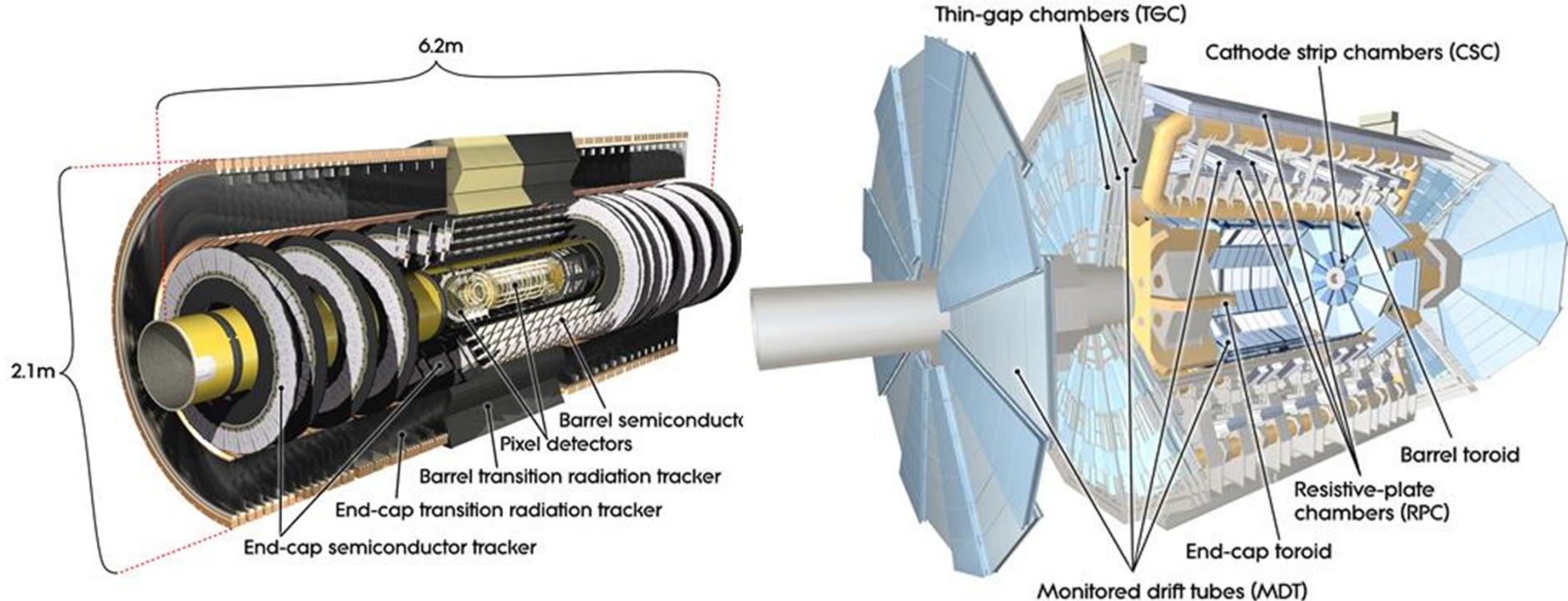
[†]M Cacciari, G Salam, G Soyez, JHEP 0804 (2008) 063

Summary

- ATLAS results on heavy flavour production in pp collisions at $\sqrt{s} = 7 \text{ TeV}$ presented using:
 - b-hadrons decaying to $D^* \mu X$ final state
 - Inclusive $D^{(*)}$ meson production
 - Inclusive electron and muon production
 - b-jet tagging
- Generally in agreement with NLO QCD calculations, within large uncertainties
- More results to follow in other decay channels and at $\sqrt{s} = 8 \text{ TeV}$

Backup Slides

Inner Detector and Muon Spectrometer



Inner Detector $|\eta| < 2.5$

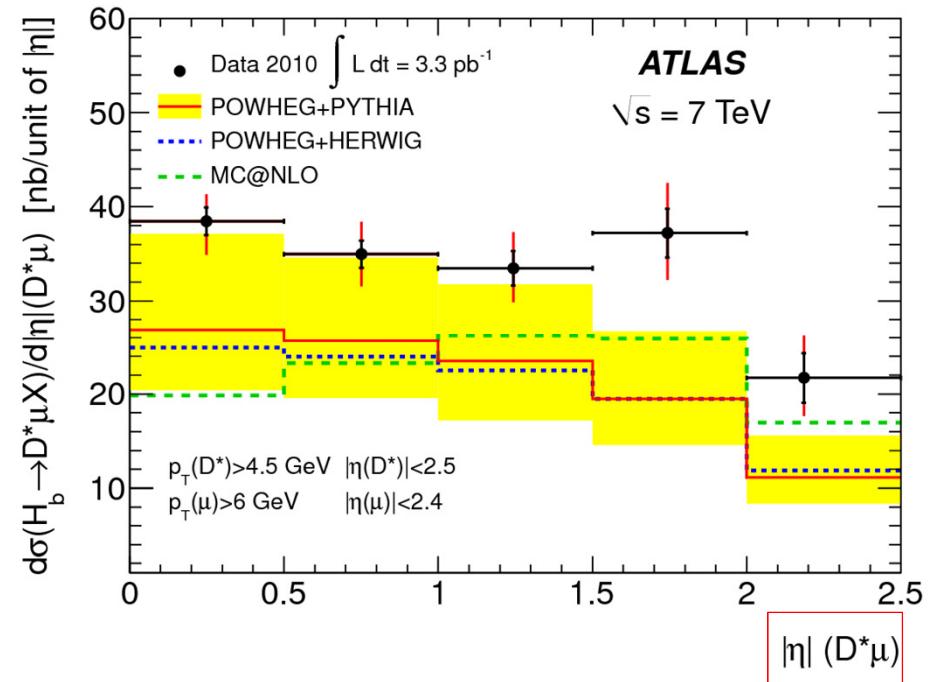
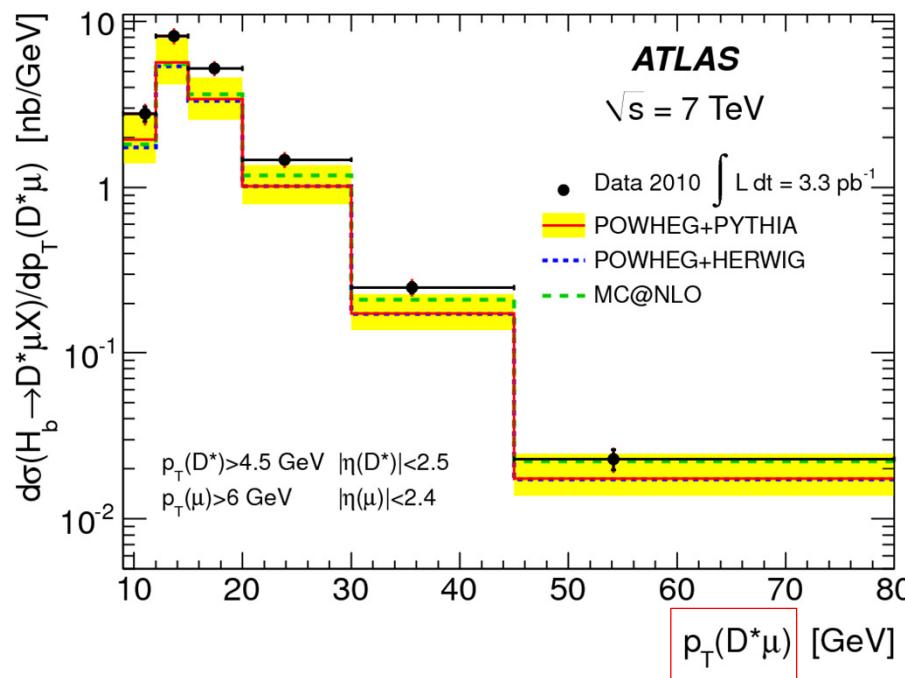
- 2T axial magnetic field
- Momentum resolution:
 $\sigma(p_T)/p_T = 3.8 \times 10^{-4} \text{ (GeV)} \oplus 0.015$
- Vertex resolution:
 $\sim 30\mu\text{m}$ transverse
 $\sim 50\mu\text{m}$ longitudinal

Muon Spectrometer

- Precision chambers (MDT, CSC)
- Fast trigger layers (RPC, TGC)
- Toroidal magnetic field:
 $1.5\text{-}5.5 \text{ Tm}$ (barrel), $1\text{-}7.5 \text{ Tm}$ (endcap)
 $\sigma(p_T)/p_T \approx 10\%$ ($|\eta| < 2.7$, $p_T < 1 \text{ TeV}$)

$pp \rightarrow H_b X \rightarrow D^* \mu X'$ Cross Section

within $p_T(D^*) > 4.5$ GeV, $|\eta(D^*)| < 2.5$; $p_T(\mu) > 6$ GeV, $|\eta(\mu)| < 2.4$



These are still functions of $p_T(D^* \mu)$ and $|\eta(D^* \mu)|$

They must be unfolded to get functions of $p_T(H_b)$ and $|\eta(H_b)|$
Use NLO MC calculation to do unfolding