Heavy Quark Production at LHCb

Michael Alexander

University of Glasgow

On behalf of the LHCb collaboration

Lake Louise Winter Institute 2017/02/25

Outline

Introduction

D meson production

B meson production

J/ψ production

$t\bar{t}$, $\mathrm{W} + b\bar{b}$ & $\mathrm{W} + c\bar{c}$ production

Conclusions

Outline

Introduction

D meson production

B meson production

J/ψ production

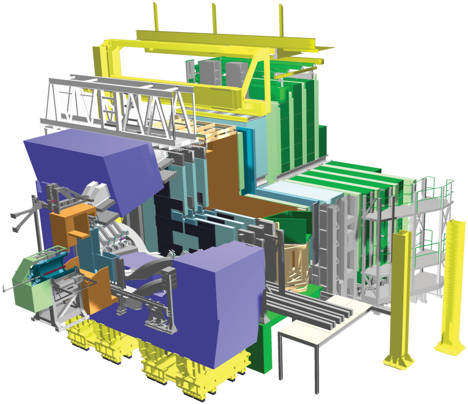
$t\bar{t}$, W + $b\bar{b}$ & W + $c\bar{c}$ production

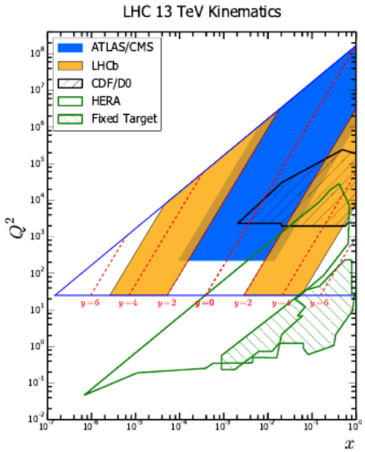
Conclusions

Production measurements test QCD

- Perturbative, non-perturbative & the region in between.
- Comparison of various models - what mechanisms are dominant, what approximations are good.
- Sensitive to parton density functions (PDFs), & particularly gluon density function.
- Verifies prediction of yields & sensitivities at different energies for future experiments.

LHCb has unique coverage





- Acceptance $2 < \eta < 5$ - can probe both low and high parton momentum fraction (Bjorken x).

Cross section measurements: count & correct

Differential cross section for production of X in bin i of variable k:

$$\frac{\mathrm{d}\sigma_i(X)}{\mathrm{d}k} = \frac{N_{\mathrm{obs}}(X \to f)}{\epsilon_i \, \Delta k_i \, \mathcal{B}(X \to f) \, \mathcal{L}}$$

$N_{\mathrm{obs}}(X \to f) \equiv$ number of observed signal decays to final state f.

$\epsilon_i \equiv$ detection & selection efficiency in bin i.

$\Delta k_i \equiv$ width of bin i.

$\mathcal{B}(X \to f) \equiv$ branching fraction of $X \to f$.

$\mathcal{L} \equiv$ integrated luminosity. Generally limiting systematic - LHCb achieves precision of few %.

Efficiency factorisation

Total efficiency

$$\epsilon \equiv \epsilon_{\mathrm{geom}}\epsilon_{\mathrm{reco}}\epsilon_{\mathrm{evt.\,sel}}\epsilon_{\mathrm{cand.\,sel}}$$

$\epsilon_{\mathrm{geom}} \equiv$ geometric acceptance of detector.

$\epsilon_{\mathrm{reco}} \equiv$ reconstruction efficiency.

$\epsilon_{\mathrm{evt.\,sel}} \equiv$ event selection efficiency (eg, event multiplicity).

$\epsilon_{\mathrm{cand.\,sel}} \equiv$ candidate selection efficiency (PID & kinematic criteria).

Evaluated in each kinematic bin with a variety of techniques: data driven where possible (tag & probe, calibration samples) and from simulation (weighted to match real data).

Generally a dominant source of systematic uncertainty.

Outline

Introduction

D meson production

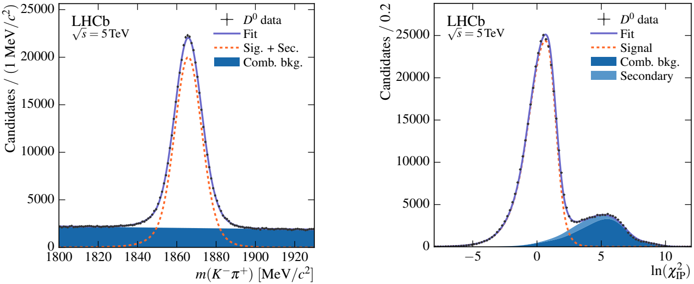
B meson production

J/ψ production

$t\bar{t}$, W + $b\bar{b}$ & W + $c\bar{c}$ production

Conclusions

Measure prompt D meson production

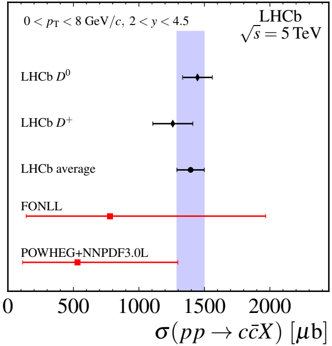


- Use $8.60 \pm 0.33\,\mathrm{pb}^{-1}$ of data at centre-of-mass energy 5 TeV.
- Same analysis strategy as previous measurements at 7 & 13 TeV.
- Count yields of $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$, $D_s^+ \to \phi(K^+K^-)\pi^+$, & $D^{*+} \to D^0(K^-\pi^+)\pi^+$.
- Fit $m(D)$ to discriminate combinatorial backgrounds (use $\Delta m \equiv m(K^-\pi^+\pi^+) - m(K^-\pi^+)$ for D^{*+}).
- Fit $\ln(\chi^2_{\mathrm{IP}})$ to distinguish prompt D mesons from those from B decays. $\chi^2_{\mathrm{IP}} \equiv \chi^2$ of hypothesis that D originates from the primary vertex.

Cross sections at 5 TeV agree with predictions

For $1 < p_T[\mathrm{GeV}] < 8$ & $2.0 < y < 4.5$ finds

$$\sigma(\mathrm{pp} \to \mathrm{D}^0 X) = 1190 \pm 3 \pm 64\,\mu\mathrm{b}.$$
$$\sigma(\mathrm{pp} \to \mathrm{D}^+ X) = 456 \pm 3 \pm 34\,\mu\mathrm{b}.$$
$$\sigma(\mathrm{pp} \to \mathrm{D}_s^+ X) = 195 \pm 4 \pm 19\,\mu\mathrm{b}.$$
$$\sigma(\mathrm{pp} \to \mathrm{D}^{*+} X) = 467 \pm 6 \pm 40\,\mu\mathrm{b}.$$



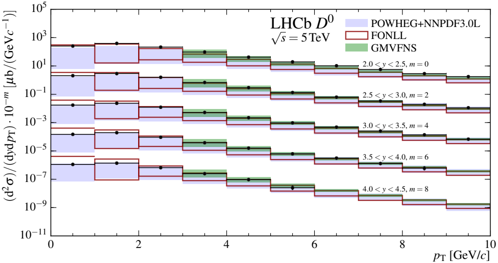
Correcting for hadronisation fractions, for $0 < p_T[\mathrm{GeV}] < 8$ & $2.0 < y < 4.5$, using D^0 and D^+ measurements yields

$$\sigma(\mathrm{pp} \to c\bar{c}X) = 1395 \pm 5 \pm 80 \pm 67\,\mu\mathrm{b},$$

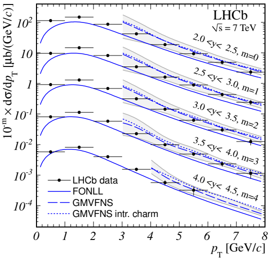
with the last uncertainty from hadronisation fractions.

General agreement with predictions at several energies

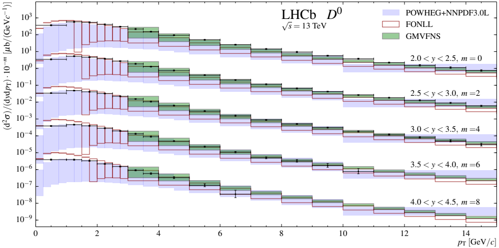
5 TeV



7 TeV



13 TeV



D^0 production cross section vs p_T & η.

Outline

Introduction

D meson production

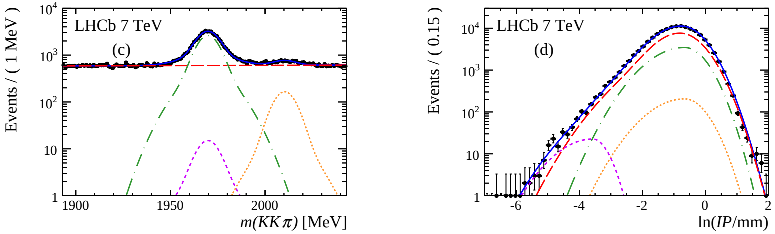
B meson production

J/ψ production

$t\bar{t}$, $W + b\bar{b}$ & $W + c\bar{c}$ production

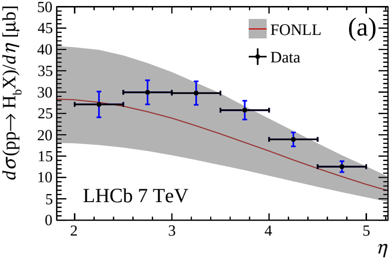
Conclusions

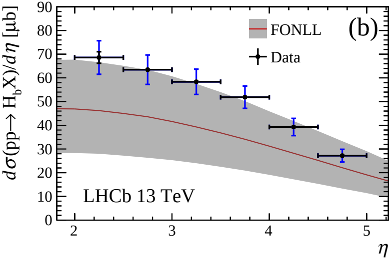
Count semileptonic B decays



- Use $284.10 \pm 4.86\,\mathrm{pb}^{-1}$ at 7 TeV & $4.60 \pm 0.18\,\mathrm{pb}^{-1}$ at 13 TeV.
- Count yields of $\mathrm{B}^0 \to \mathrm{D}^0 \mu X$, $\mathrm{B}^+ \to \mathrm{D}^+ \mu X$, $\mathrm{B}^0_s \to \mathrm{D}^+_s \mu X$ & $\Lambda_b \to \Lambda_c \mu X$.
- Fit $m(\mathrm{D})$ to discriminate combinatorial backgrounds, & $\ln(\mathrm{IP}_\mathrm{D})$ to distinguish prompt charm backgrounds.
- $\mathrm{IP}_D \equiv$ impact parameter of D meson.

Differential cross sections vs theory

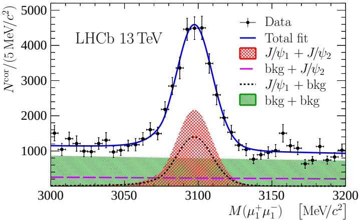


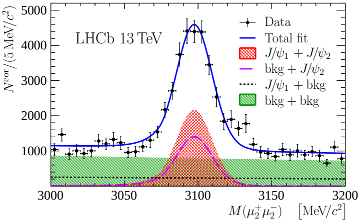


- Summing cross sections over B species gives, for $2 < \eta < 5$
  $\sigma(\mathrm{pp} \to H_\mathrm{b}X) = 72.0 \pm 0.3 \pm 6.8\,\mu\mathrm{b}$ at 7 TeV, and
  $\sigma(\mathrm{pp} \to H_\mathrm{b}X) = 154.3 \pm 1.5 \pm 14.3\,\mu\mathrm{b}$ at 13 TeV.
- Ratio $2.14 \pm 0.02 \pm 0.13$ agrees with prediction $1.79^{+0.21}_{-0.15}$.
- More results soon in other channels, eg $\mathrm{B}^+ \to \mathrm{J}/\psi\,\mathrm{K}^+$.

Outline

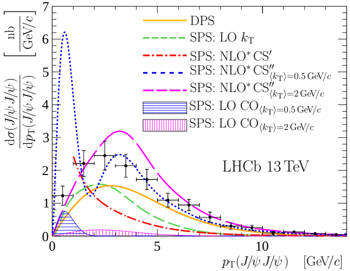
J/ψ pair production discriminates various production methods

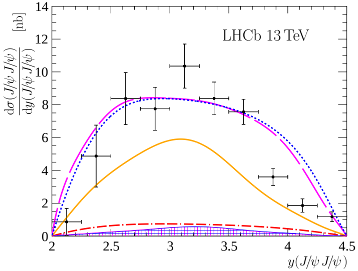




- Use $279 \pm 11\,\text{pb}^{-1}$ data at 13 TeV.
- Reconstruct pairs of $J/\psi \to \mu^+\mu^-$ that form a good common vertex.
- Simultaneous fit to J/ψ masses to discriminate combinatorial background.

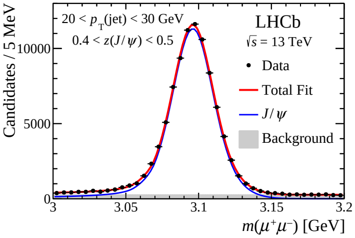
Large double parton scattering contribution favoured

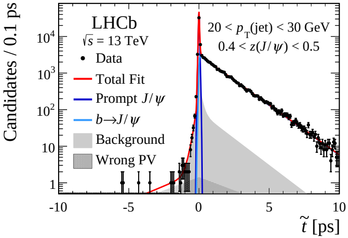




- For $2 < y < 4.5$ & $p_T < 10\,\mathrm{GeV}$, find $\sigma(\mathrm{pp} \to \mathrm{J/\psi\,J/\psi}\,X) = 13.5 \pm 0.9 \pm 0.8\,\mathrm{nb}$.
- Total cross section depends strongly on J/ψ polarisation, shape of differential cross sections less so.
- No single model describes the data adequately.
- Fit with DPS + SPS models yields DPS fraction in the region ∼85 %.

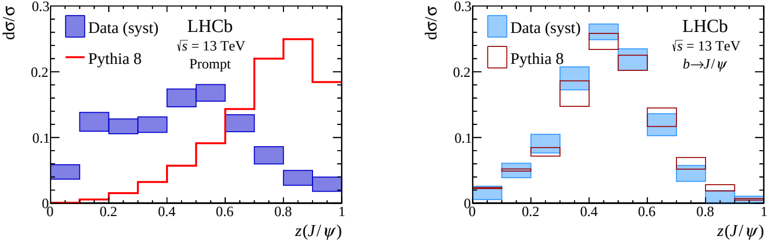
J/ψ isolation also discriminates models





- Use $297 \pm 11\,\mathrm{pb}^{-1}$ data at 13 TeV.
- Select $J/\psi \to \mu^+\mu^-$ candidates & build jets around them.
- Fit J/ψ mass to discriminate combinatorial background & projection of J/ψ decay time onto beam line ($\tilde{t}$) to distinguish prompt J/ψ from those from B decays.
- Measure cross sections in bins of $z(J/\psi) \equiv p_T(J/\psi)/p_T(\mathrm{jet})$.
- Direct production model favours large $z(J/\psi)$ while parton shower model favours smaller $z(J/\psi)$.

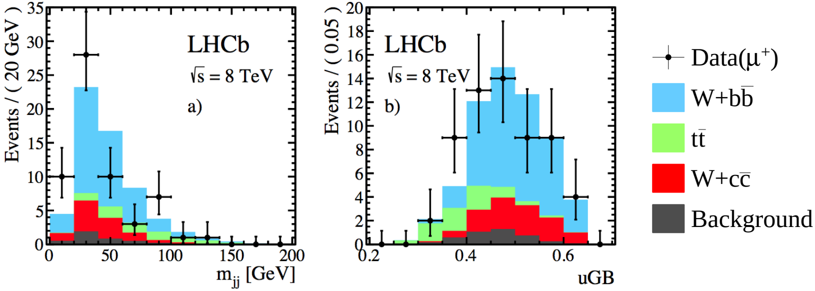
Prompt J/ψ isolation disagrees with direct production model



- J/ψ from B well modelled in Pythia 8.
- Prompt J/ψ disagrees with direct production model in Pythia 8.
- May relate to long standing discrepancy with polarisation predictions - direct production predicts large polarisation while little is found in experimental data.

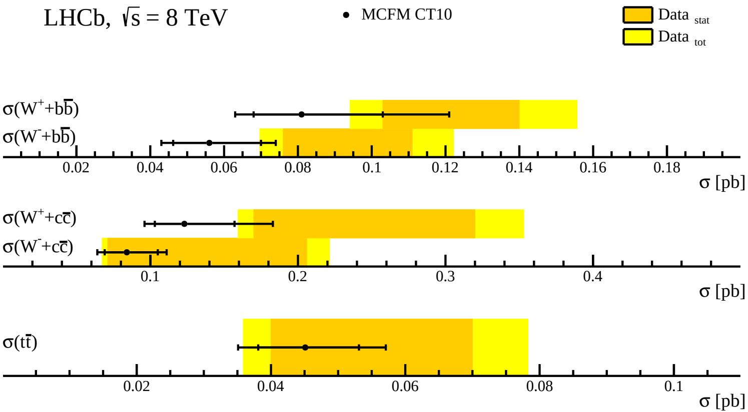
Outline

Heavy flavour jets test pQCD



- Use $1.98 \pm 0.02\,\text{fb}^{-1}$ at 8 TeV.
- Select events with two heavy flavour tagged jets & a high momentum, isolated lepton.
- Train MVAs to discriminate $t\bar{t}$ events from W + $b\bar{b}$ (uGB), & b jets from c jets.
- Fit dijet mass distribution (m_{jj}) & MVA responses to discriminate backgrounds (mainly Z & QCD multi-jet), & three classes of signal.
- Sensitive to PDFs at high & low Bjorken x.

Cross sections agree with predictions



- Signal significances 4.9 σ for $t\bar{t}$, 7.1 σ for $\mathrm{W}^+ + b\bar{b}$, 5.6 σ for $\mathrm{W}^- + b\bar{b}$, 4.7 σ for $\mathrm{W}^+ + c\bar{c}$, 2.5 σ for $\mathrm{W}^- + c\bar{c}$.
- Study of $\mathrm{W} + c\bar{c}$ first of its kind.

Outline

Conclusions

- Rich production measurement programme at LHCb.
- Many confirmations of theory predictions; some intriguing discrepancies.
- More B production measurements coming soon ($\mathrm{B}^{+} \to \mathrm{J}/\psi\, \mathrm{K}^{+}$).
- J/ψ pair production favours large double parton scattering contribution.
- Prompt J/ψ isolation disfavours direct production mechanism.
- First measurement of $\mathrm{W} + c\bar{c}$ cross sections.
- Great scope for further investigation at LHCb.


Thanks!

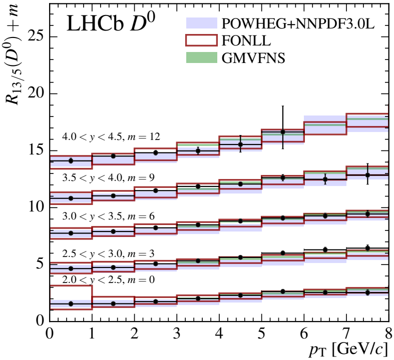
Backup

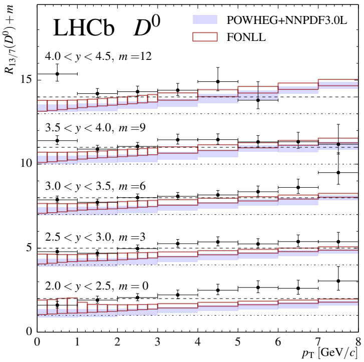
Charm cross section systematics at 5 TeV

Table 2: Systematic uncertainties expressed as fractions of the cross-section measurements, in percent. Uncertainties that are computed bin-by-bin are expressed as ranges giving the minimum to maximum values. Ranges for the correlations between p_T-y bins and between modes are also given, expressed in percent.

	Uncertainties (%)				Correlations (%)	
	D^0	D^+	D_s^+	D^{*+}	Bins	Modes
Luminosity	3.9				100	100
Tracking	3–5	5–17	4–18	5–20	90–100	90–100
Branching fractions	1.2	2.1	5.8	1.5	100	0–95
Simulation sample size	2–24	4–55	3–55	2–21	-	-
Simulation modelling	2	1	1	1	-	-
PID sample size	0–2	0–1	0–2	0–1	0–100	0–100
PID binning	0–44	0–10	0–20	0-15	100	100
PDF shapes	1–6	1–5	1–2	1–2	-	-

Charm cross section ratio





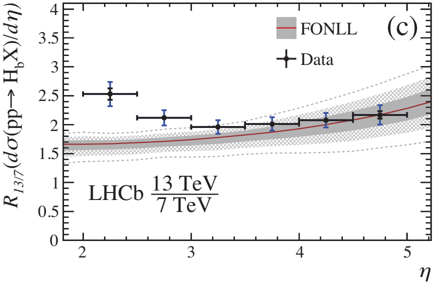
- Some experimental & theory uncertainties cancel.
- Ratio of cross sections at 13 TeV to 5 TeV (left) agree better with predictions than previously measured ratios of 13 TeV to 7 TeV (right), which are consistently high.

B cross section systematics

Table 4: Systematic uncertainties independent of η on the $pp \to H_b X$ cross-sections at 7 and 13 TeV and their ratio.

Source	7 TeV	13 TeV	Ratio 13/7
Luminosity	1.7%	3.9%	3.8%
Tracking efficiency	3.8%	4.3%	2.5%
b semileptonic $\mathcal{B}$	2.1%	2.1%	0
Charm hadron $\mathcal{B}$	2.6%	2.6%	0
b decay cocktail	1.0%	1.0%	0
Ignoring b cross-feeds	1.0%	1.0%	0
Background	0.2%	0.3%	0
$b \to u$ decays	0.3%	0.3%	0
δ	2.0%	2.0%	0.2%
Total	5.9%	7.1%	4.6%

B differential cross section ratio



Discrepancy at low η under investigation.

J/ψ pair production systematics

Table 1: Summary of the systematic uncertainties on the measurement of the J/ψ pair production cross-section.

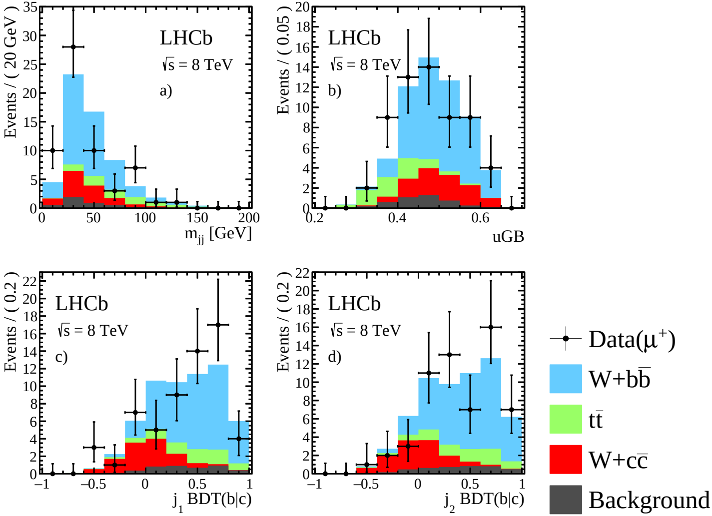
Source	Uncertainty[%]
Signal shape	1.8
Data/simulation difference	1.0
Tracking efficiency	0.8×4
Muon PID efficiency	2.3
Trigger efficiency	1.1
Fraction of J/ψ from b-hadron candidates	1.0
$\mathcal{B}(J/\psi \to \mu^+\mu^-)$	1.1
Luminosity	3.9
Total	6.2

J/ψ jet production systematics

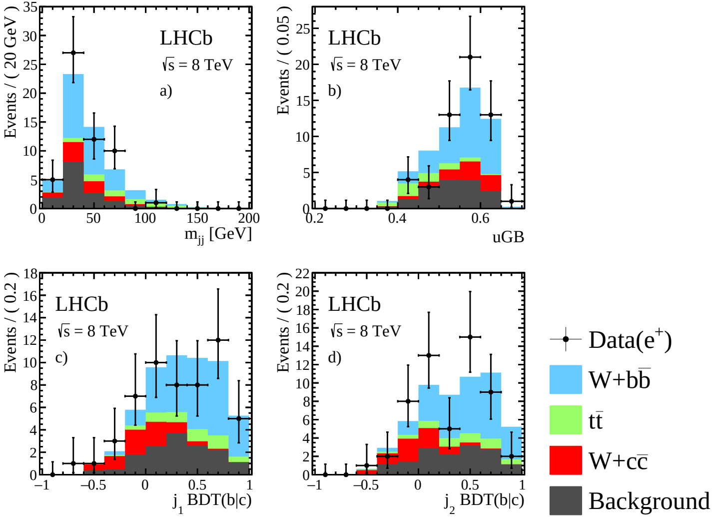
Source	Systematic
Reconstruction efficiency	2 %
Trigger efficiency	2-5 %
Offline selection efficiency	0-2 %
Mass fit model	1 %
$\tilde{t}$ fit model	1 %
Background model	-
PV misassociation	-
Detector response	0.001-0.014 (absolute)
Detector response unfolding	0.01 (absolute)
Fragmentation model	-
Total	0.010-0.015 (absolute)

Reconstruction efficiency includes unknown J/ψ polarisation.

All fit variables for μ^+



All fit variables for e^+



$t\bar{t}$, $\mathrm{W} + b\bar{b}$ & $\mathrm{W} + c\bar{c}$ production systematics

Source	Systematic
Luminosity	1.16 %
Event selection efficiency	2 %
Reconstruction & trigger efficiencies	1.0-5.0 %
Lepton kinematic efficiency	-
Heavy flavour tagging efficiency	5-10 %
Flavour dependence of jet energy scale	2 %
Effect of ghost tracks (jet energy scale)	1.2 %
Momentum resolution (jet energy scale)	1 %
Data/MC differences (jet energy scale)	1 %
Jet reconstruction & selection efficiency	2 %
Background normalisation predictions	3-10 %
Finite MC sample size	1-7 %
Correlations in fit variables	10 %