Measurement of the W-Helicity in Top-Quark Decays with the ATLAS Experiment

Cora Fischer[1], Andrea Knue[2], Kevin Kröninger[1], Arnulf Quadt[1], Elizaveta Shabalina[1], Philipp Stolte[1]

[1]Georg-August-Universität Göttingen
II. Physikalisches Insitut
[2]Glasgow University

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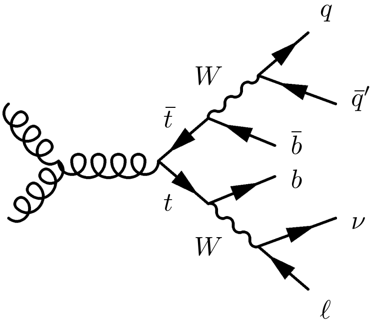
Outline

Top-Quark Pair Production at the LHC

Strong production of $t\bar{t}$ pairs in pp collisions:

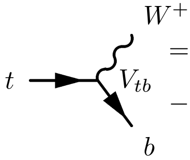


- $\mathcal{B}(t \rightarrow Wb) \approx 100\%$
- top-quark decays before hadronization

  $\rightarrow$ excellent test area of SM
- 3 final states: dileptonic, ℓ+jets, fully-hadronic

- example: decay in ℓ+jets channel
- in Göttingen: studies in this channel; event selection requires at least 4 jets and 1 b-tag
- full 2011 data set ($\sqrt{s}$ =7 TeV, $\mathcal{L}$=4.7 fb^{-1})

W-Helicity Measurement in Top-Quark Decays



$$= -\frac{ig_W}{\sqrt{2}}\bar{b}\gamma^\mu(V_L P_L + V_R P_R)tW^-_\mu - \frac{ig_W}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_\nu}{m_W}(g_L P_L + g_R P_R)tW^-_\mu$$

red=0 in SM

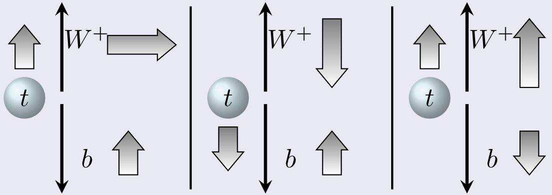
- SM predicts V-A structure of Wtb vertex
  → affects possible polarizations of W-boson

helicity fractions:

$$F_0 = \frac{\Gamma(t\to W_0+b)}{\Gamma}$$

$$F_L = \frac{\Gamma(t\to W_L+b)}{\Gamma}$$

$$F_R = \frac{\Gamma(t\to W_R+b)}{\Gamma}$$



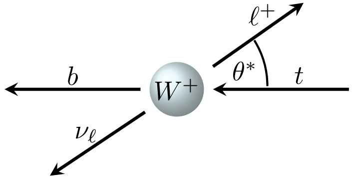
⇒ SM expectation: $F_0 \approx 0.7$ $F_L \approx 0.3$ $F_R \approx 0$

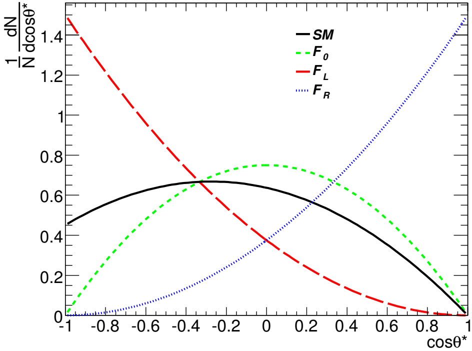
⇒ precision measurement of these quantities tests theory of weak coupling in SM

↪ deviations from expectations would hint to new physics

How to measure the W-helicity fractions?

- spin analyser of the W-boson: $\cos\theta^*$



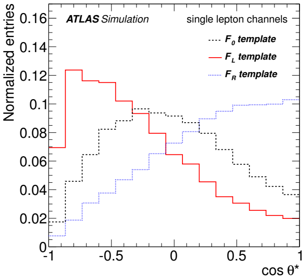


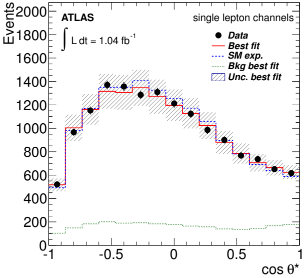
$$\frac{1}{N}\frac{\mathrm{d}N}{\mathrm{d}\cos\theta^*} = \frac{3}{8}\left(1-\cos\theta^*\right)^2 F_L + \frac{3}{4}\sin^2\theta^* F_0 + \frac{3}{8}\left(1+\cos\theta^*\right)^2 F_R$$

The Template Method

- determination of helicity fractions F_0, F_L and F_R via template-fit to data in $\cos\theta^*$ distribution
- get templates from MC and data driven estimates
- 3 signal templates and

  3 background templates
- perform likelihood fit to data
- Gauss Prior on normalization of background templates with corresponding uncertainty as width





Plots from JHEP06(2012)088

Evaluation of Systematic Uncertainties

Two ways of estimating systematic uncertainties:

- evaluation via ensemble tests
- evaluation via profile likelihood fit

Ensemble Tests:

- perform ensemble tests with systematic varied samples ($\pm 1\sigma$)
- look at means of parameter distributions from fit
- take difference of means as systematic uncertainty due to the particular source

- consider ensemble tests for identifying dominant systematic uncertainties
- then: perform profile likelihood analysis in order to decrease uncertainties

Profile Likelihood Fit

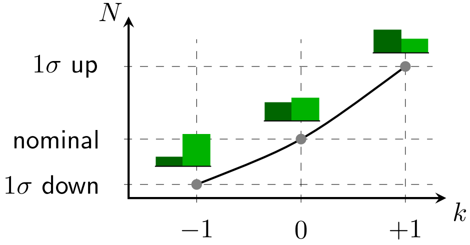
- Profiling: template fit with additional nuisance parameters k
  $\hookrightarrow$ minimization of:

$$-2\ln(\mathcal{P}) = 2\sum_{m=1}^{N_{\text{bins}}}(N_m - d_m \cdot \ln(N_m)) + \sum_{i=1}^{N_{\text{bkg}}} \frac{(N_{B,i} - N_{B,\text{exp},i})^2}{\sigma^2_{N_{B,\text{exp},i}}} + \sum_{j=1}^{N_{\text{prof}}} k_j^2$$

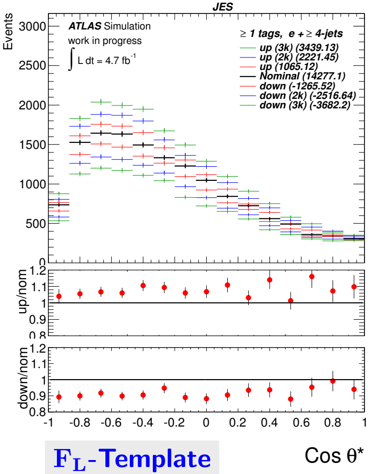
- need to describe "template morphing":
  $\rightarrow$ number of entries N for each bin and each template as function of k

- use quadratic fit for interpolation curves

- only able to profile continuous systematics



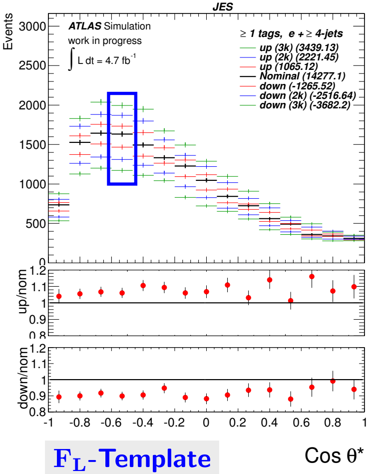
- use information of $\pm1\sigma, \pm2\sigma, \pm3\sigma$ syst. varied samples
- variation of jet energy scale:



F_L-Template

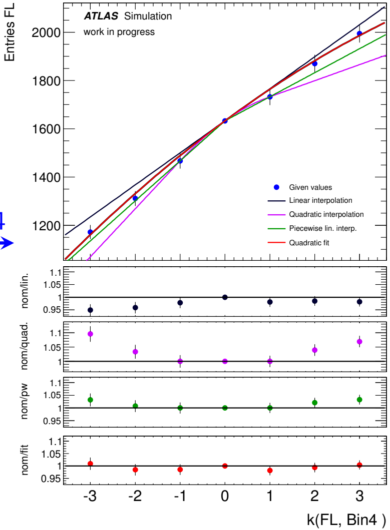
Example: Jet Energy Scale

- use information of $\pm 1\sigma, \pm 2\sigma, \pm 3\sigma$ syst. varied samples
- variation of jet energy scale:



F_L-Template

bin 4 →



Dominant Uncertainties

Dominant uncertainties of the analysis:

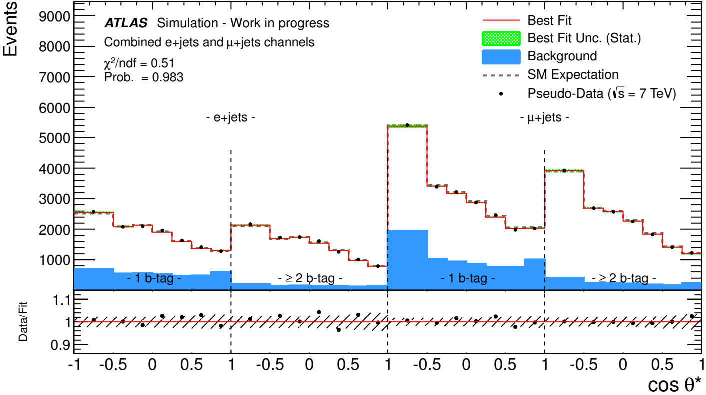
- statistical uncertainty
- Jet Energy Scale (JES)
- method uncertainties: limited template statistic of pure helicity states
- signal modelling uncertainties: choice of MC generator
- background modelling
  (W+jets shape, heavy flavor content, multijet background shape)

Reducing the Statistical Uncertainty

- study effect of combined fit in several channels:

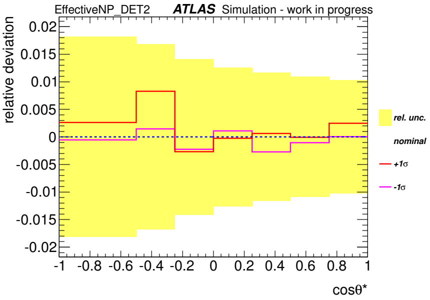
  ↪ statistical uncertainty can be reduced by splitting into different b-tag bins
  → constrains backgrounds

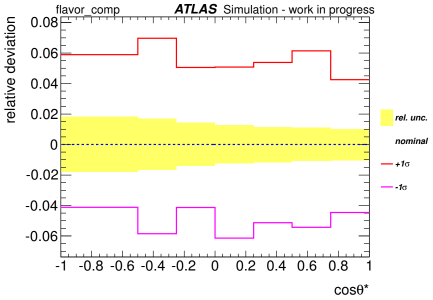
- currently chosen fit setup: combined fit in 4 channels:
  e+jets, μ+jets, 1 exclusive and 2 inclusive b-tags:



Profiling: Identifying Shape Uncertainties

F_R template, e+jets, 1 excl. b-tags:





Components that do not contribute to shape uncertainty as defined above:

- 'profile acceptance':

  ⇒ use nominal templates and scale with integral of systematic varied templates

  ⇒ expect only influence on uncertainty (shape is the nominal one)

Profile Fit to Pseudo-Data

- Currently JES components and b-tagging SF components implemented in profile fit (8 nuisance parameters + 22 'acceptance' components):

  Expected stat. + JES + b-tag SF uncertainty (from 2000 ensemble tests):

	Profiling	Ensemble Test
$\sigma(F_0)$	0.0253	0.0463
$\sigma(F_L)$	0.0152	0.0231
$\sigma(F_R)$	0.0134	0.0279

- expected uncertainties lower for profiling!
- next: include other systematics in profile fit

Current Status

Evaluated uncertainties:

- statistical
- JES, b-tagging
- signal modelling
- ISR/FSR
- template statistic

Conservative estimate of total uncertainty:

- last publication: JHEP06(2012)088 ($\sqrt{s} = 7$ TeV, $\mathcal{L}$=1.04 fb^{-1}), combination of 4 measurements
  (ℓ+jets and dilepton channel of $t\bar{t}$, template method and asymmetry method)
- current precision of single measurement as good as combination in JHEP06(2012)088

Summary/Outlook

Summary:

- analysis framework completely set up and running
- identified relevant JES and b-tagging uncertainties
- expected uncertainty from these sources shown
- up to now: signal modelling uncertainty is dominant (largest single unc., evaluated via ensemble tests)
- consideration of different fit setups (e. g.: 6 channels via inclusion of 0 excl. b-tag regions in e and μ+jets channels)

Outlook:

- add more systematic uncertainties as nuisance parameters in profile fit
- next step: evaluation of background modelling uncertainties
- goal is to publish results in a paper $\sim$ fall this year

BACK UP

Standard $t\bar{t}$ Event Selection

Requirements:

- exactly one isolated lepton
- at least 4 Jets, p_T(jet)>25 GeV, $|\eta| < 2.5$
- jet vertex fraction |JVF| >0.75
- at least one b-tagged jet

muon channel:

- $p_T(\mu)$ >20 GeV
- $|\eta(\mu)|$ <2.5
- $\not{E}_T$ >20 GeV
- $\not{E}_T + m_T(W)$ >60 GeV

electron channel

- $p_T(e)$ >25 GeV
- $|\eta(e)|$ <2.47 and outside 1.37< $|\eta|$ <1.52
- $\not{E}_T$ >30 GeV
- $m_T(W)$ >30 GeV

- used b-tagger: MV1 (neural network), 70% efficiency, 1/134 mist-tag rate
- reconstruction with KLFitter: m_t=172.5 GeV, use b-tag weight

The Template Method

- determine W-helicity fractions F_0, F_L and F_R via **template fit** to $\cos\theta^*$ distribution in data
- number of entries in bin j:

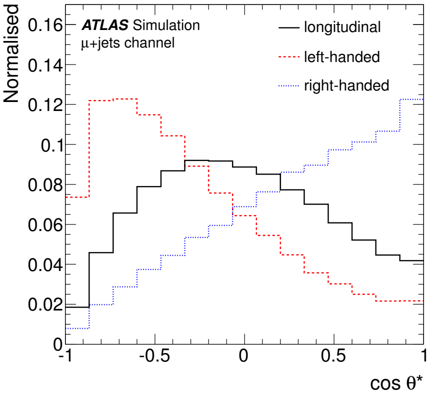
$$N_j = \sum_{i=0,L,R} N_i^p \cdot \epsilon_i \int_{\Delta x_j} f_i(x)\mathrm{d}x + \sum_{i=\mathrm{bkg}} N_i^p \cdot \int_{\Delta x_j} f_i(x)\mathrm{d}x$$

- 3 signal templates F_0, F_L, F_R and
- 3 background templates: W+jets, multijet, 'remaining background'
- maximize the likelihood:

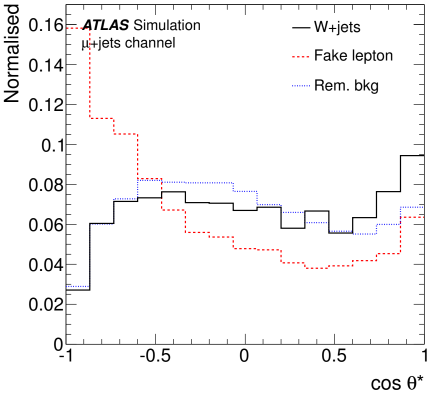
$$\mathcal{P}\left(\vec{N}\right) = \underbrace{\prod_{i=1}^{n_b} \frac{N_i^{d_i}}{d_i!} \cdot \mathrm{e}^{-N_i}}_{\text{Poisson terms}} \cdot \underbrace{\prod_{j=1}^{n_{\mathrm{bkg}}} \frac{1}{\sqrt{2\pi}\sigma_{\mathrm{B,exp},j}} \exp\left(\frac{(N_{\mathrm{B},j} - N_{\mathrm{B,exp},j})^2}{2\sigma^2_{\mathrm{B,exp},j}}\right)}_{\text{Gauss constraint on background}}$$

Signal and Background Templates

Templates μ+jets channel:



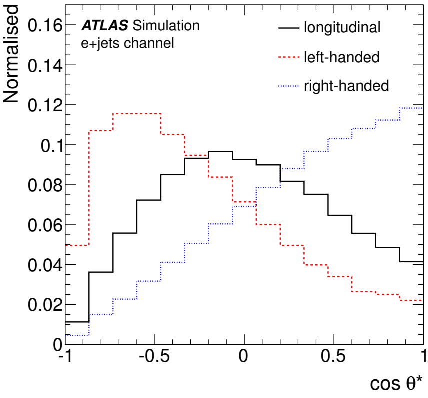
Signal



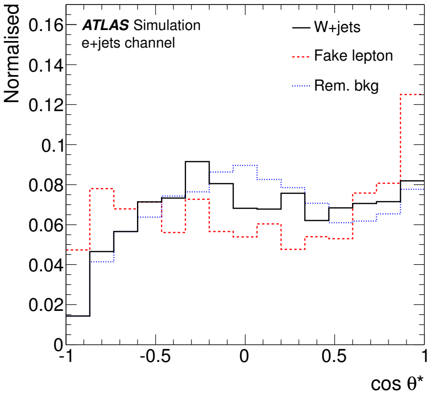
Background

Signal and Background Templates

Templates e+jets channel:



Signal

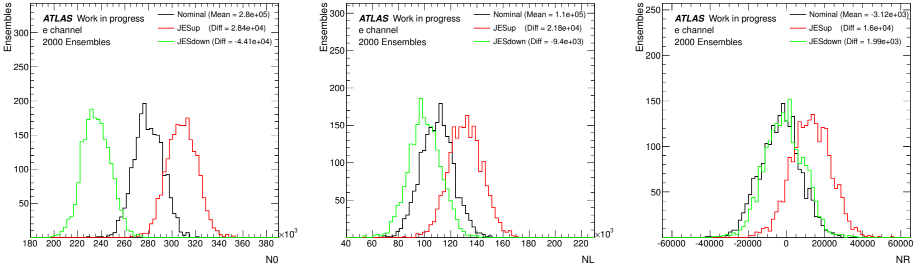


Background

Ensemble Tests

- create pseudo-data sets for each systematic source
- use samples varied by systematic source 1σ up and 1σ down
- create ensembles from pseudo-data:
  $\rightarrow$ fluctuate bin contents with Poisson probability
- perform fit to ensembles, obtain parameter distributions:

Example systematic source: jet energy scale (JES), 2000 ensembles:



Ensemble Tests

- create pseudo-data sets for each systematic source
- use samples varied by systematic source 1σ up and 1σ down
- create ensembles from pseudo-data:
  $\rightarrow$ fluctuate bin contents with Poisson probability
- perform fit to ensembles, obtain parameter distributions:

use means of parameter distributions:

$$F_i = \frac{\langle N_i \rangle}{\langle N_0 \rangle + \langle N_L \rangle + \langle N_R \rangle}, \quad \text{for} \quad i = 0, L, R$$

$\Rightarrow$ differences to nominal ensembles are taken as systematic uncertainty

Template Fit with Different Setups

Statistical uncertainties in template fit to pseudo-data, from 2000 ensembles:

ATLAS Simulation - work in progress

Uncertainty	e-μ, 1incl b-tags	e-μ, 1excl, 2incl b-tags	e-μ, 0, 1excl, 2incl b-tags
fixed background			
σ_{F_0}	0.02111	0.02032	0.02019
σ_{F_L}	0.01340	0.01295	0.01286
σ_{F_R}	0.01009	0.00968	0.00962
fitted background			
σ_{F_0}	0.03363	0.02226	0.02220
σ_{F_L}	0.01784	0.01430	0.01419
σ_{F_R}	0.01910	0.01063	0.01037
number of templates:	7	9	11

Profiling: Things to Consider

Binning of $\cos\theta^*$ distribution:

- ensure reasonably small rel. stat. uncertainty per bin:

  $\hookrightarrow$ do not want to profile statistical fluctuations!

- modified binning: trade-off value of 5% rel. stat. uncertainty per bin for 7 bins in total

- loss of sensitivity to shape investigated: statistical uncertainty only slightly increased ($\sim 0.001 \hat{=} 5\%$)

For all systematic sources:

- identify uncertainties that contribute shape uncertainties

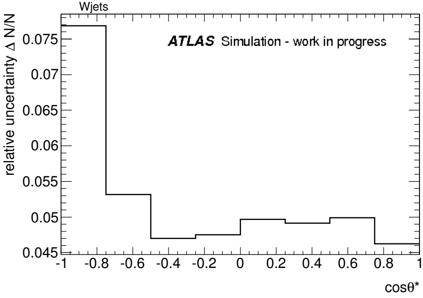
  $$\text{relative deviation} = \frac{\text{bin entry(syst)} - \text{bin entry(nominal)}}{\text{bin entry(nominal)}}$$

- criterion for profiling: more than 20% of bins have larger rel. deviation than rel. stat. uncertainty

Modified Binning of $\cos\theta^*$ Distribution

- find trade-off for rel. stat. uncertainty that is undershoot in each bin in each template
- adjust binning such that the chosen trade-off criterion is matched by each template
- first: take $\sim$ half as many bins $\rightarrow$ 8 bins with equal bin width

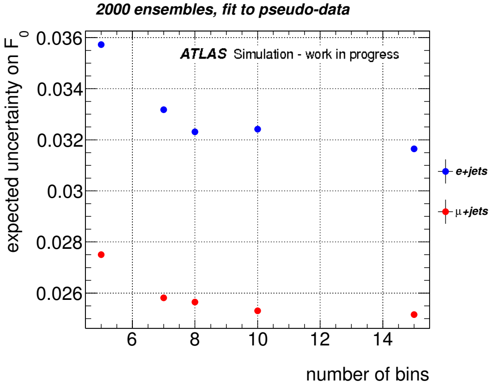
- limiting factor: W+jets template in e+jets channel
- idea: merge first two bins into one larger bin



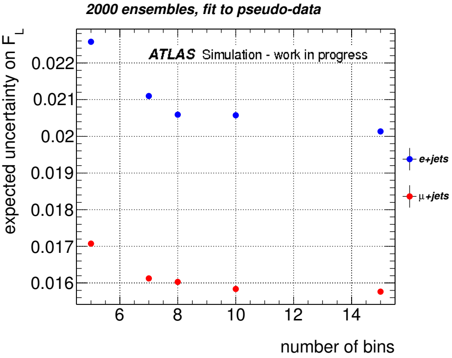
Influence of Binning on Template Fit

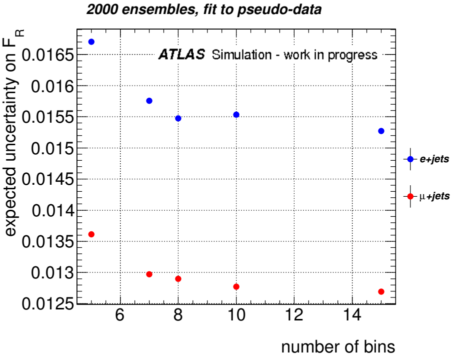
- perform template fit to pseudo-data using different number of bins (equal bin width)
- look at statistical uncertainties of fractions F_i

- loss of sensitivity with less bins: stat. unc. increases with lower bin number
- may use binning shown on previous slide: uncertainties not dramatically increased



Stat. Uncertainty as Function of number of Bins





Template Fit to Pseudo-Data

Compare 2 setups:

four channels: e+jets, μ+jets, 1 excl. and 2 incl. b-tags

six channels: add 0 excl. b-tag control region to above

$\hookrightarrow$ expect better constraint on b-tag systematic

Template fit to pseudo-data (Protos SM prediction), 0 nuisance parameters, expected uncertainty (2000 ensembles):

	four channels	six channels
$\sigma(F_0)$	0.0228	0.0227
$\sigma(F_L)$	0.0146	0.0145
$\sigma(F_R)$	0.0110	0.0106

$\Rightarrow$ expected statistical uncertainty on helicity fractions

Profile Fit to Pseudo-Data

Currently JES components and b-tagging SF components implemented in profile fit (8 nuisance parameters)

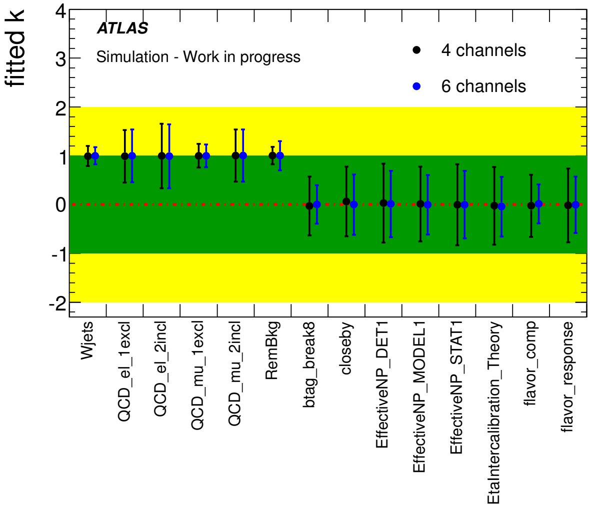
Expected uncertainties on helicity fractions from 2000 ensembles:

	four channels	six channels
$\sigma(F_0)$	0.0253	0.0241
$\sigma(F_L)$	0.0152	0.0151
$\sigma(F_R)$	0.0134	0.0117

$\Rightarrow$ including acceptance parameters does not change uncertainties (30 nuisance parameters)

Profile fit with 8 NP to Pseudo-Data

Nuisance parameter values of profile fit including relevant b-tag and JES components (2000 ensembles):



$\Rightarrow$ nuisance parameters close to zero, uncertainties decreased below one

(background parameters: fit result/input value shown)

Status: Uncertainty Evaluation

Systematic sources that are evaluated/to be evaluated:

Source of unc.	$\sigma(F_0)$	$\sigma(F_L)$	$\sigma(F_R)$
Statistical	0.0228	0.0146	0.0110
JES (shape)		✓	
JES (acc.)		✓	
b-tag SF (shape)		✓	
b-tag SF (acc.)		✓	
PDF		?	
Modelling	0.0306	0.0119	0.0190
Template Stat.	0.0106	0.0065	0.0054
Jet Reco		?	
Lepton Reco		?	
ISR/FSR	0.0028	0.0024	0.0005
QCD, W+jets shape		?	
top mass		?	
$\not{E}_T$, HF		?	

HF: heavy flavour content of W+jets

Estimation of Total Uncertainty

Latest publication of W-helicity measurement in $t\bar{t}$ events:

- JHEP06(2012)088, $\sqrt{s} = 7$ TeV, $\mathcal{L}$=1.04 fb^{-1}
- combination of 4 measurements: ℓ+jets and dilepton channel of $t\bar{t}$, template method and asymmetry method

Conservative estimate of total uncertainty for current analysis:

- take uncertainties that are not already evaluated from JHEP06(2012)088 (only template method, ℓ+jets channel)
- add in quadrature to already evaluated uncertainties

Comparison of precision:

	$\sigma(F_0)$	$\sigma(F_L)$	$\sigma(F_R)$
current, conservative estimate:	0.068	0.033	0.042
results from combination in JHEP06(2012)088:	0.07	0.04	0.05