Top quark properties at ATLAS

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SUSY 2012, August 2012, Peking University, Beijing, China

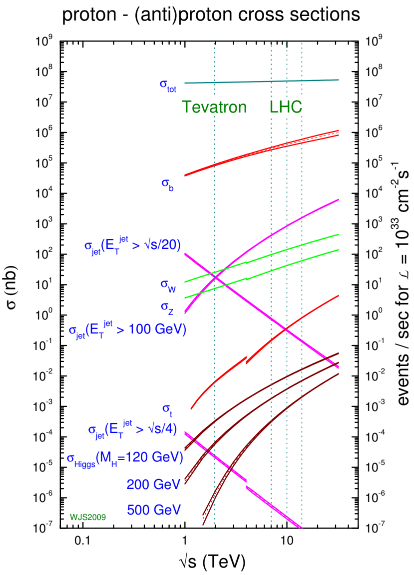
Introduction

The top quark:

- ✍ The heaviest elementary particle observed, $m_{\text{top}} \sim 173$ GeV
- ✍ Yukawa coupling ~ 1
- ✍ Decays before forming bound states
- ✍ Dominant decay $t \to Wb$ with BR($t \to Wb$) ~ 1

Why studying its properties:

- ☞ m_{top} a free parameter in the Standard Model (SM)
- ☞ Test the SM predictions
- ☞ Search for new physics



Outline

- Charge asymmetry, A_C
  - lepton+jets: Eur. Phys. J. C72 (2012) 2039 (1.04 fb^{-1})
  - di-lepton: ATLAS-CONF-2012-057 (4.7 fb^{-1})
- Top-quark mass, m_{top}
  - lepton+jets: Eur. Phys. J. C72 (2012) 2046 (1.04 fb^{-1})
  - all jets: ATLAS-CONF-2012-030 (2.05 fb^{-1})
  - di-lepton: ATLAS-CONF-2012-082 (4.7 fb^{-1})
- Differential cross-section
  - $t\bar{t}$+jets: ATLAS-CONF-2012-083 (4.7 fb^{-1})
  - $d\sigma/dm_{t\bar{t}}, d\sigma/dp_{\text{T},t\bar{t}}, d\sigma/dy_{t\bar{t}}$: arXiv:1207.5644[hep-ex] (2.05 fb^{-1})
- FCNC
  - $t \rightarrow qZ$: arXiv:1206.0257[hep-ex] (2.05 fb^{-1})
- Summary

General object and event selection

b-tagging

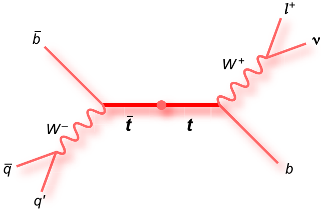
- JetFitter: fit decay chain of b/c
- IP3D + SV1: track impact parameter (IP) + secondary vertex (SV)
- MV1: combination with NN

Jet

- Topological clusters
- Anti-k_t ($R = 0.4$)
- $p_T > 25$ GeV, $|\eta| < 2.5$

Electron

- EM calo object, track-matched
- Calo and track isolation
- $E_T > 25$ GeV, $|\eta| < 2.47$ excluding $[1.37, 1.52]$



Muon

- Segments in inner tracking/muon detectors
- Calo and track isolation
- $p_T > 20$ GeV, $|\eta| < 2.5$

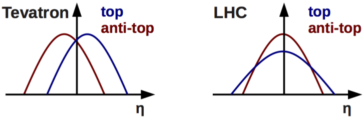
E_T^{miss}

- Vector sum of calo energy deposits
- Corrected for identified objects

Event categorization ($W \to qq', \ell\nu$) and selections:

- lepton+jets: exactly one high p_T lepton (trigger), $\geq$3(4) jets, b-tagged jet(s), large E_T^{miss}
- di-lepton: single-lepton trigger, two opposite-charged leptons, $\geq$2 jets, b-tagged jet(s), large E_T^{miss}, Z event veto (same flavor)
- all jets: mixed jet triggers, $\geq$5 high p_T jets, 2 b-tagged jets

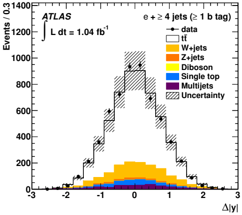
Charge asymmetry, A_C

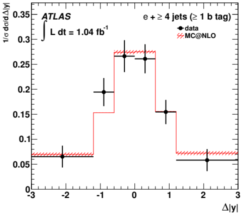


$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

SM prediction: $A_C = 0.006 \pm 0.002$ (MC@NLO)

Measured and unfolded $\Delta|y| \equiv |y_t| - |y_{\bar{t}}|$ distributions:

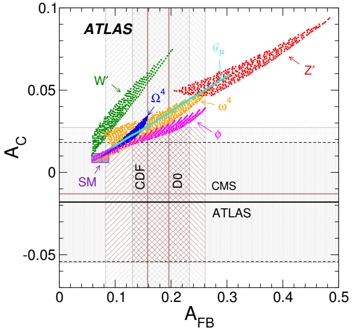




Largest uncertainties: signal modeling, initial state radiation (ISR)/ final state radiation (FSR), JES

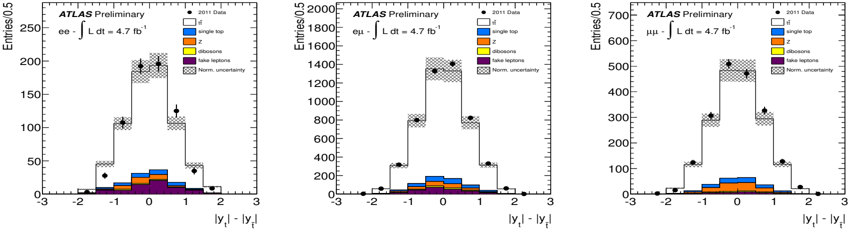
Unfolded charge asymmetry (Bayesian):
$A_C = -0.019 \pm 0.028(\text{stat}) \pm 0.024(\text{syst})$

Charge asymmetry separated in $m_{t\bar{t}}$:
$A_C = -0.052 \pm 0.070(\text{stat}) \pm 0.054(\text{syst})$
for $m_{t\bar{t}} < 450$ GeV
$A_C = -0.008 \pm 0.035(\text{stat}) \pm 0.032(\text{syst})$
for $m_{t\bar{t}} > 450$ GeV



Charge asymmetry: di-lepton

Measured $\Delta|y|$ distributions:



ee, $e\mu$ and $\mu\mu$ combination (after background subtraction and efficiency/acceptance corrections):
$A_C^{t\bar{t}} = 0.057 \pm 0.024(\text{stat}) \pm 0.015(\text{syst})$

Combination with lepton+jets:
$A_C^{t\bar{t}} = 0.029 \pm 0.018(\text{stat}) \pm 0.014(\text{syst})$
consistent with the SM prediction

$t\bar{t}$ asymmetry transmitted to leptons
$\rightarrow$ lepton based asymmetry $A_C^{\ell\ell}$

$$A_C^{\ell\ell} = \frac{N(\Delta|\eta| > 0) - N(\Delta|\eta| < 0)}{N(\Delta|\eta| > 0) + N(\Delta|\eta| < 0)}$$

ee, $e\mu$ and $\mu\mu$ combination:
$A_C^{\ell\ell} = 0.023 \pm 0.012(\text{stat.}) \pm 0.008(\text{syst.})$

Largest uncertainties: signal generator, ISR/FSR, JES, and QCD multijet estimation

Top quark mass, $m_{\mathbf{top}}$

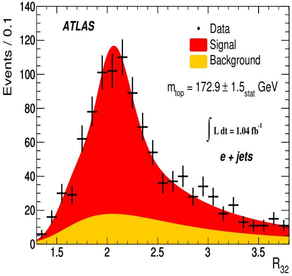
Top mass: lepton+jets

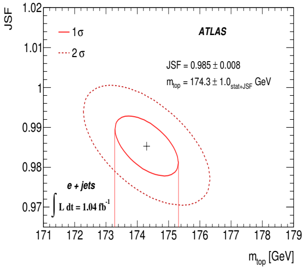
Two template methods employed:

- 1d-analysis: reconstructed mass ratio $R_{32} \equiv \frac{m_{top}^{reco}}{m_W^{reco}}$
  - Additional cuts: $\ln L > -50$, $p_T^{jet} > 40$ GeV (jet triplet assigned to the hadronic top decay), $60 < m_W^{reco} < 100$ GeV
  - Signal templates from m_{top} dependent MC samples, parameterized R_{32} templates
- 2d-analysis: simultaneous fit to derive m_{top} and jet energy scale factor (JSF)
  - Light jet pair with $50 < m_{jj} < 110$ GeV considered for kinematic fit of the hadronic W decay candidates
  - In-situ constraint of m_W^{reco}

$m_{top} = 174.4 \pm 0.9(\text{stat}) \pm 2.5(\text{syst})$ GeV (1d-analysis)
$m_{top} = 174.5 \pm 0.6(\text{stat}) \pm 2.3(\text{syst})$ GeV (2d-analysis)

Largest uncertainties: JES, b-JES and ISR/FSR





Top mass: di-lepton

Very low background after selection but need to handle the two neutrinos, define m_{T2} (stransverse mass, a lower bound of the parent particle mass) as:

$$m_{T2}(m_{invis}) = \min_{\vec{p}_T^{(1)}, \vec{p}_T^{(2)}} \left\{ \max \left[m_T(m_{invis}, \vec{p}_T^{(1)}), m_T(m_{invis}, \vec{p}_T^{(2)}) \right] \right\}$$

where $\vec{p}_T^{(1)}$ and $\vec{p}_T^{(2)}$ represent the values of the invisible particles' transverse momenta, and

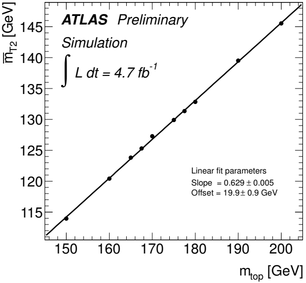
$$m_T(m_{invis}, \vec{p}_T^{(i)}) = \sqrt{m_{vis}^2 + m_{invis}^2 + 2(E_T^{vis} E_T^{invis} - \vec{p}_T^{vis} \cdot \vec{p}_T^{(i)})}$$

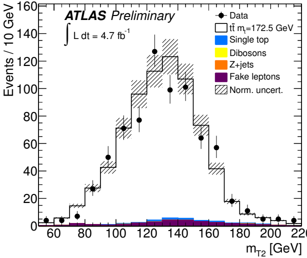
$$\vec{p}_T^{(1)} + \vec{p}_T^{(2)} = \vec{p}_T^{miss}, \qquad \vec{p}_{vis}^{(i)} = \vec{p}_{lepton}^{(i)} + \vec{p}_{b-jet}^{(i)}$$

Calibration curve to map $\overline{m}_{T2}$ (mean value of m_{T2} distribution) to m_{top} using MC simulation samples with varied input top mass.

$m_{top} = 175.2 \pm 1.6(\text{stat})^{+3.1}_{-2.8}(\text{syst})$ GeV

Largest uncertainties: JES, b-JES, signal generator, parton shower and color reconnection





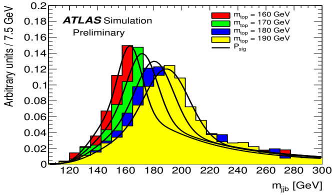
Top mass: all jets

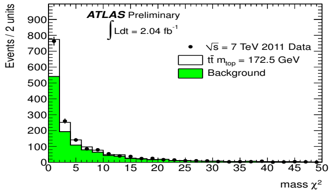
- QCD multijet background ← suppressed by requiring double b-tagging
- $b\bar{b}$ background ← reduced by requiring m_{jj} consistent with W mass
- Signal templates of m_{jjb} from MC simulation (varied input m_t) and background shape constructed from data
- Full event reconstruction via kinematic fit ($\chi^2 > 8$ to enhance the S/B)

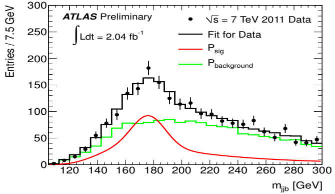
$$\chi^2 = \frac{(m_{j_1,j_2} - m_W)^2}{\sigma_W^2} + \frac{(m_{j_1,j_2,b_1} - m_t)^2}{\sigma_t^2} + \frac{(m_{j_3,j_4} - m_W)^2}{\sigma_W^2} + \frac{(m_{j_3,j_4,b_2} - m_t)^2}{\sigma_t^2}$$

$m_{\text{top}} = 174.9 \pm 2.1(\text{stat}) \pm 3.8(\text{syst})$ GeV

Largest uncertainties: JES, b-JES, ISR/FSR and background modeling

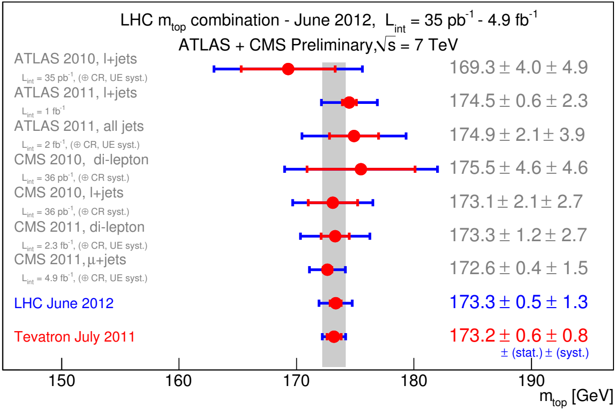






Top mass: LHC combination

ATLAS-CONF-2012-095, CMS PAS TOP-12-001



Differential cross-section

$t\bar{t}$+jets

Definitions of $t\bar{t}j$ events:

Def. 1. $t\bar{t}$ with at least one particle jet not matched to a parton from a top quark

Def. 2. $t\bar{t}$ with ≥5 particle jets (model-independent)

$\sigma_{t\bar{t}(j)}$ measured with template fit to data based on the likelihood discriminant constructed from two input variables, charged-lepton pseudorapidity and Aplanarity

Using Def. 1:

$$\sigma_{t\bar{t}j} = 102 \pm 2(\text{stat})^{+23}_{-26}(\text{syst})\ \text{pb}$$
$$\sigma_{t\bar{t}j}/\sigma^{\text{incl}}_{t\bar{t}} = 0.54 \pm 0.01(\text{stat})^{+0.05}_{-0.08}(\text{syst})$$

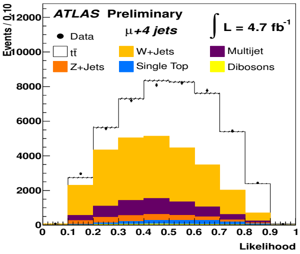
$\sigma_{t\bar{t}j}$ in fiducial regions (within detector acceptance):

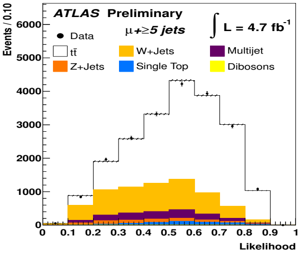
$$\sigma^{\text{fiducial}}_{t\bar{t}j\to e+\text{jets}} = 2.59 \pm 0.09(\text{stat})^{+0.26}_{-0.46}(\text{syst})\ \text{pb}$$
$$\sigma^{\text{fiducial}}_{t\bar{t}j\to \mu+\text{jets}} = 3.48 \pm 0.08(\text{stat})^{+0.43}_{-0.61}(\text{syst})\ \text{pb}$$

Using Def. 2:

$$\sigma^{\text{fiducial}}_{t\bar{t}X\to e+\geq 5\text{jets}} = 4.09 \pm 0.18(\text{stat})^{+0.62}_{-0.85}(\text{syst})\ \text{pb}$$
$$\sigma^{\text{fiducial}}_{t\bar{t}X\to \mu+\geq 5\text{jets}} = 5.27 \pm 0.16(\text{stat})^{+1.04}_{-1.20}(\text{syst})\ \text{pb}$$

Largest uncertainties: signal modeling, JES





Relative differential cross-sections

$1/d\sigma_{t\bar{t}}\ d\sigma/dm_{t\bar{t}}$, $1/d\sigma_{t\bar{t}}\ d\sigma/dp_{\mathrm{T},t\bar{t}}$, $1/d\sigma_{t\bar{t}}\ d\sigma/dy_{t\bar{t}}$

Full kinematic reconstruction of the $t\bar{t}$ events:

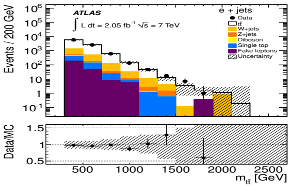
- Likelihood approach, linking the reconstructed objects to the $t\bar{t}$ decay products
- Cut on $\ln L$ to enhance the S/B ratio

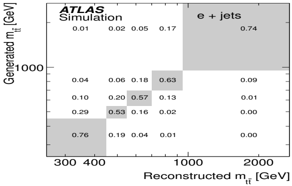
Unfolded relative differential cross-sections:

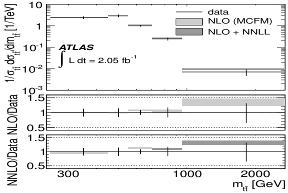
- Response matrix inversion
- Unfolding performed separately in the electron and muon channels, then results combined
- Compared with NLO (+NNLL), MCFM, ALPGEN and MC@NLO predictions

No significant deviations from the SM predictions

Largest uncertainties: JES, signal and background modeling







FCNC

Flavor Changing Neutral Current (FCNC) process :

$$t \to Zq \; (q = u, c)$$

highly suppressed in SM, $BR \sim 10^{-14}$, higher BR predicted by several SM extensions

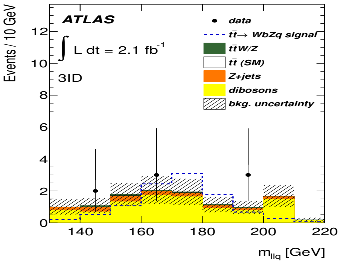
- 3ID: 3 leptons (e/μ), one opposite-sign, same-flavor pair with $m_{\ell^+\ell^-}$ consistent with Z
- 2ID+TL: 2 leptons (e/μ) and 1 isolated track lepton (22% increase in acceptance)

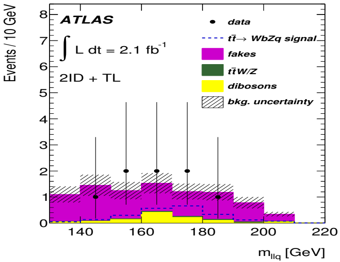
Full reconstruction of $t\bar{t} \to WbZq$ via kinematic fit:

$$\chi^2 = \frac{(m^{\text{reco}}_{j_a\ell_a\ell_b} - m_t)^2}{\sigma_t^2} + \frac{(m^{\text{reco}}_{j_a\ell_c\nu} - m_t)^2}{\sigma_t^2} + \frac{(m^{\text{reco}}_{\ell_c\nu} - m_W)^2}{\sigma_W^2} + \frac{(m^{\text{reco}}_{\ell_a\ell_b} - m_Z)^2}{\sigma_Z^2}$$

$BR(t \to Zq) < 0.73\%$ at 95% C.L.

Largest uncertainties: lepton reconstruction/identification efficiency, JES and ZZ/WZ shape





Summary

- Presented measurements of top-quark properties: charge asymmetry, top quark mass, differential cross-section and FCNC search.
- Not covered:
  - Spin correlation: Phys. Rev. Lett. 108, 212001 (2012) (2.1 fb^{-1})
  - W helicity: JHEP 1206 (2012) 088 (1.04 fb^{-1})
  - $t\bar{t}$ resonances: arXiv:1207.2409[hep-ex] (lepton+jets, boosted, 2.05 fb^{-1}), Eur.Phys.J. C72 (2012) 2083 (lepton+jets and di-lepton, 2.05 fb^{-1}), ATLAS-CONF-2012-102 (all jets, 4.7 fb^{-1})
  - $t\bar{t}\gamma$: ATLAS-CONF-2010-153 (1.04 fb^{-1})
  - Link to the ATLAS top public results
- More measurements with the 2012 data (8 TeV) coming soon

Thank you!

Backup

Background estimation: QCD multijet

Data-driven methods (pre-tagged and tagged samples):

- ✍ Anti-electron: shape from the electron-like objects but failing some of the identification cuts, extrapolating from side band to signal regions (e.g. from low $E_{\mathrm{T}}^{\mathrm{miss}}$ to high $E_{\mathrm{T}}^{\mathrm{miss}}$ region)
- ✍ Matrix method: selecting two categories of events using loose and tight lepton selection requirements, efficiencies of real and fake leptons measured with $Z \to \ell\ell$ and QCD enriched sample
- ✍ Jet-electron: likelihood fit the signal region with shapes of processes containing real electrons from MC and the shapes of the QCD multijet from jets with a high EM fraction (similar idea can be applied to fake muon estimation)

Background estimation: W+jets

Main background for lepton+jets analyses:

Total normalization of W+jets in the signal region ($\geq$4 jets) by exploiting the W charge asymmetry

$$W_{\geq 4,\text{pretag}} = N_{W^+} + N_{W^-} = \left(\frac{r_{MC}+1}{r_{MC}-1}\right)(D^+ - D^-)$$

where $r_{MC} \equiv \frac{N(pp\to W^+ + X)}{N(pp\to W^1 + X)}$ (well predicted in theory).

Extrapolating to tagged sample

$$W_{\geq 4,\text{tagged}} = W_{\geq 4,\text{pretag}} \cdot f_{2,\text{tagged}} \cdot k_{2\to\geq 4}$$

Event likelihood in $t\bar{t}$

$$
\begin{aligned}
L = & \mathcal{T}\left(E_{\mathrm{jet}_1}|\hat{E}_{b_{\mathrm{had}}}\right)\cdot\mathcal{T}\left(E_{\mathrm{jet}_2}|\hat{E}_{b_\ell}\right)\cdot\mathcal{T}\left(E_{\mathrm{jet}_3}|\hat{E}_{q_1}\right)\cdot \\
& \mathcal{T}\left(E_{\mathrm{jet}_4}|\hat{E}_{q_2}\right)\cdot\mathcal{T}\left(E_x^{\mathrm{miss}}|\hat{p}_{x,\nu}\right)\cdot\mathcal{T}\left(E_y^{\mathrm{miss}}|\hat{p}_{y\nu}\right)\cdot \\
& \left\{\begin{array}{cc} \mathcal{T}\left(E_e|\hat{E}_e\right) & e+\mathrm{jets} \\ \mathcal{T}\left(p_{\mathrm{T},\mu}|\hat{p}_{\mathrm{T},\mu}\right) & \mu+\mathrm{jets} \end{array}\right\}\cdot \\
& \mathcal{B}\left[m(q_1q_2)|m_W,\Gamma_W\right]\cdot\mathcal{B}\left[m(\ell\nu)|m_W,\Gamma_W\right]\cdot \\
& \mathcal{B}\left[m(q_1q_2b_{\mathrm{had}})|m_{\mathrm{top}}^{\mathrm{reco,like}},\Gamma_{\mathrm{top}}\right]\cdot \\
& \mathcal{B}\left[m(\ell\nu b_\ell)|m_{\mathrm{top}}^{\mathrm{reco,like}},\Gamma_{\mathrm{top}}\right]\cdot W_{\mathrm{btag}}
\end{aligned}
$$

The likelihood relates the observed objects to the $t\bar{t}$ decay products (quarks and leptons) predicted by the NLO signal Monte Carlo, albeit in Leading Order (LO) kinematic approach, using $t\bar{t} \to \ell\nu b_\ell q_1 q_2 b_{\mathrm{had}}$.

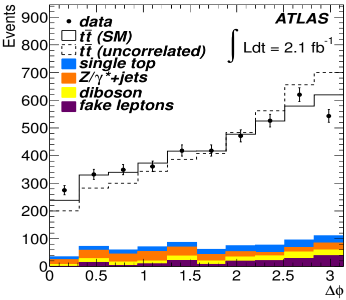
It is defined as a production of transfer functions ($\mathcal{T}$), Breit-Wigner ($\mathcal{B}$) distributions, and a weight W_{brag} accounting for the b-tagging information

Spin correlation in $t\bar{t}$

The top quark decays before hadronization → spin transferred to its decay products ← measured via angular distributions (e.g. $\Delta\phi$ of the two charged leptons).

$$A = \frac{N(\uparrow\uparrow) + N(\downarrow\downarrow) - N(\uparrow\downarrow) - N(\downarrow\uparrow)}{N(\uparrow\uparrow) + N(\downarrow\downarrow) + N(\uparrow\downarrow) + N(\downarrow\uparrow)}$$

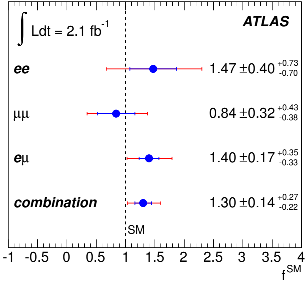
SM predictions: $A^{SM}_{helicity} = 0.31$ (helicity basis) and $A^{SM}_{maximal} = 0.44$ (maximal basis).



Template fit to extract the amount of spin correlation (f^{SM}) from the $\Delta\phi$ distribution

$$f^{SM} = \begin{cases} 0 & \text{uncorrelated spins} \\ 1 & \text{correlated spins (SM prediction)} \\ > 1 & \text{larger spin correlation than SM prediction} \end{cases}$$

$f^{SM} = 1.30 \pm 0.14(\text{stat}) \pm^{+0.27}_{-0.22}$ (syst), $A_{basis} = A^{SM}_{basis} \cdot f^{SM}$



Hypothesis tests (pseudo-experiments with syst. uncert.):
The zero $t\bar{t}$ spin correlation hypothesis excluded with 5.1σ

Largest uncertainties: data/MC statistics, jet energy scale (JES), signal modeling and fake leptons