Measurement of top quark properties at the ATLAS experiment

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Physics at the LHC 2012

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FSP 101 ATLAS

GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN

Outline

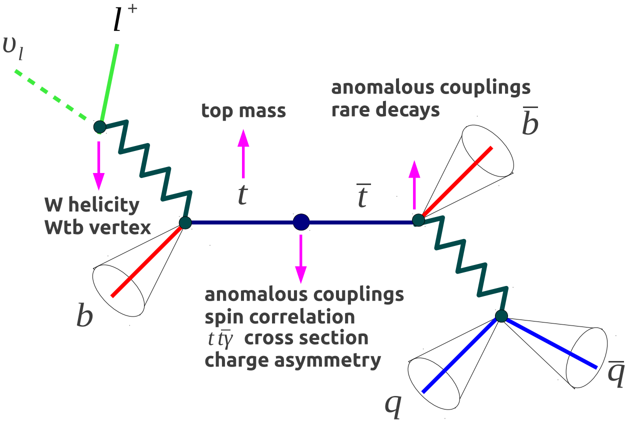
The top quark and its properties

Why is the top quark special?

- heaviest quark ($m_{top} = 173.2 \pm 0.9$ GeV)
- Yukawa coupling ~ 1
- decays before forming bound states

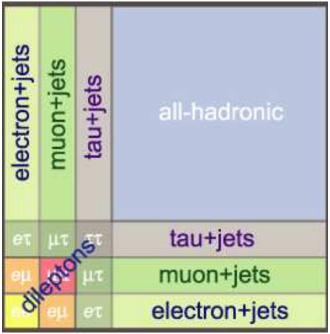
Why study its properties?

- top mass is a fundamental parameter
- test SM predictions
- look for new physics



Overview of analyses

Top mass
Wtb vertex
Charge asymmetry
$t\bar{t}\gamma$



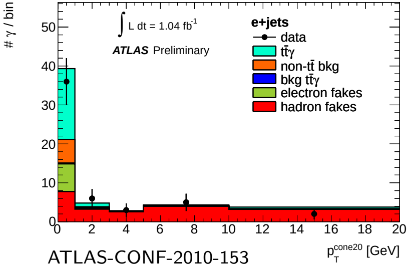
→ Top mass

Wtb vertex
Spin correlation
Charge asymmetry

- → + FCNC in $t\bar{t}$ decays, FCNC in single top production
- → all analyses: only **leptonically decaying taus** considered in signal

$t\bar{t}\gamma$ cross section

- test EM coupling to the top quark
- search for $t\bar{t}$ + prompt photon: $E_{T,\gamma} > 15$ GeV
  - → measure cross section
- prompt photons: isolated
  - → distinguish from hadron fakes
- data driven bkg estimates



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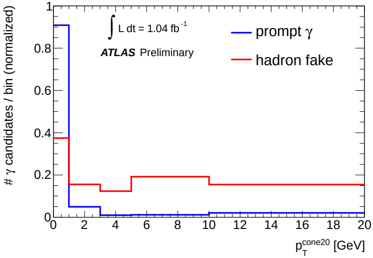


Main systematics:

ISR/FSR, JES, Photon ID eff: $\sim$ 0.3 pb

Result:

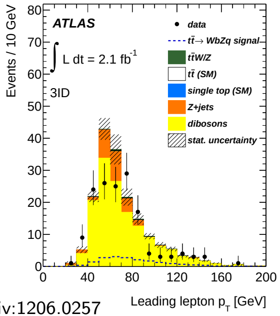
$$\sigma_{t\bar{t}\gamma} = 2.0 \pm 0.50\,(\text{stat.}) \pm 0.70\,(\text{syst.}) \pm 0.08\,(\text{lumi})\ \text{pb}$$

→ **significance: 2.7 σ**

FCNC in $t\bar{t} \to$ WbZq $\to l^+l^-l'\nu_{l'}qb$

- SM BR($t \to qZ$): $\sim 10^{-14}$ (hep-ph/0409342)
- deviation from SM: new physics
  → e.g. quark singlet model (hep-ph/0210112)
- 3 identified leptons (3ID)
- or: 2ID + track lepton (TL)
  → 22 % increase in signal acc.

	3ID	2ID+TL
ZZ and WZ	9.5 ± 4.4	1.0 $\pm^{0.5}_{0.6}$
$t\bar{t}W$ and $t\bar{t}Z$	0.51 ± 0.14	0.25 ± 0.05
$t\bar{t}$, WW	0.07 ± 0.02	7.6 ± 2.2
Z+jets	1.7 ± 0.7	
Single top	0.01 ± 0.01	
2+3 fake leptons	0.0 $\pm^{0.2}_{0.0}$	
Expected background	11.8 ± 4.4	8.9 ± 2.3
Data	8	8
Signal efficiency	(0.205 ± 0.024)%	(0.045 ± 0.007)%



arXiv:1206.0257

Main systematics:

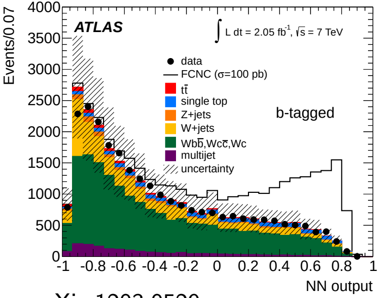
- 3ID: ZZ+WZ gen., $\sigma_{t\bar{t}}$, JES
- 2ID+1TL: $\sigma_{t\bar{t}}$, fake leptons, ISR/FSR

No evidence found, set limit (comb.):

BR($t \to qZ$) $<$ 0.73 % (2.1 fb^{-1})

FCNC in single top production

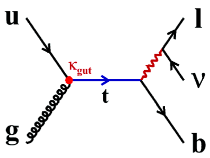
- in SM: BR($t \to qg$) $\sim 10^{-13}$
- search for non-SM processes
- difficult to separate from multijet bkg:
  ➔ look at single top **production**
- $qg \to t \to W(\to l\nu)b$



arXiv:1203.0529

Most significant variables for NN:

- p_T^W
- ΔR(bjet,lepton)
- Lepton charge

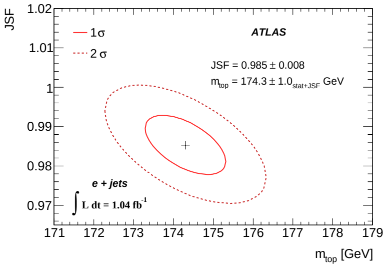


No evidence found, set limit:

- $\sigma < 3.9$ pb @ 95 % CL
- BR($t \to ug$) $< 5.7 \cdot 10^{-5}$
- BR($t \to cg$) $< 2.7 \cdot 10^{-4}$

Top mass: lepton+jets

- ➜ 2D template fit
- ➜ hadronically decaying W: constrain JES
- ➜ simultaneous measurement of m_{top} and JSF via LH fit to data (templates from MC)

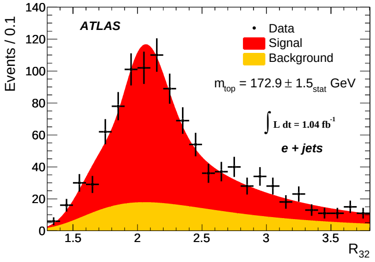


arXiv:1203.5755

Mass in lepton+jets channel:

$$m_{top} = 174.5 \pm 0.6 \text{ (stat.)} \pm 2.3 \text{ (syst.) GeV}$$

- ➜ 1D template fit with $R_{32} = \frac{m_{top}^{reco}}{m_{W}^{reco}}$ (developed at ATLAS)
- ➜ helps to reduce JES

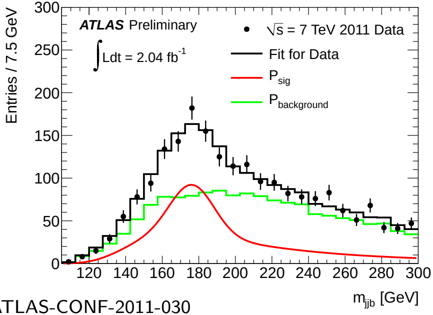


Mass for 1D method:

$$m_{top} = 174.4 \pm 0.9 \text{ (stat.)} \pm 2.5 \text{ (syst.) GeV}$$

Top mass: all hadronic

- at least 6 jets with $p_T > 30$ GeV
- at least 5 jets with $p_T > 55$ GeV
- 2 b-tags
- reconstruction via χ^2 fit
- rescale light jets with m_W/m_W^{reco}
- f_{Sig} and m_{top} are free parameters



ATLAS-CONF-2011-030

Main systematics:

- ISR/FSR: 1.7 GeV
- Bkg model: 1.9 GeV
- JES: 2.1 GeV
- b-JES: 1.4 GeV

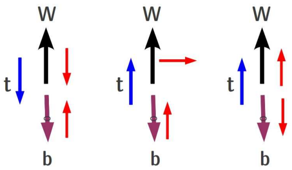
Final result:

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

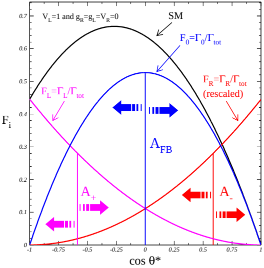
→ in agreement with result from lepton+jets channel

Wtb vertex

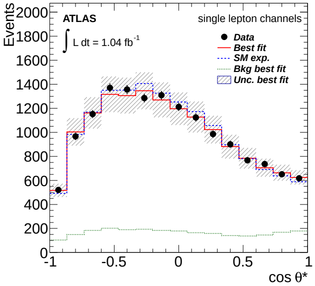
Three polarisation states:



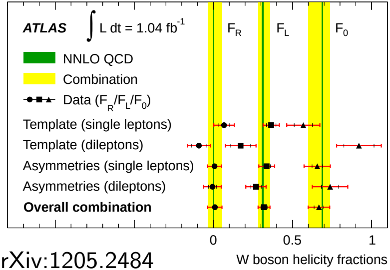
$F_L \approx 0.3$ $F_0 \approx 0.7$ $F_R \approx 0$



- lepton+jets/dilepton
- observable: angular distribution of charged lepton in rest frame of W boson
- two sets of observables:
  - helicity fractions (template fit)
  - angular asymmetries (count events)



Wtb vertex



arXiv:1205.2484

Final result:

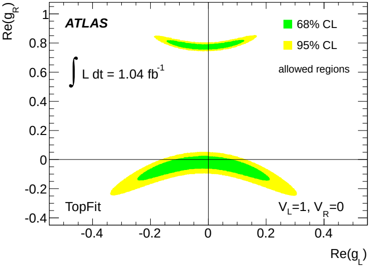
$$F_0 = 0.67 \pm 0.07$$
$$F_L = 0.32 \pm 0.04$$
$$F_R = 0.01 \pm 0.05$$

- dominated by JES, fake lept., ISR/FSR
- agrees with SM expectations
- **most precise measurement**

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}(V_L P_L + V_R P_R)\, t\, W_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}(g_L P_L + g_R P_R)\, t\, W_{\mu}^{-} + \mathrm{h.c.}$$

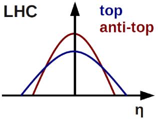
More limits (backup):

- set all but one coupling to zero
- set $F_R = 0$

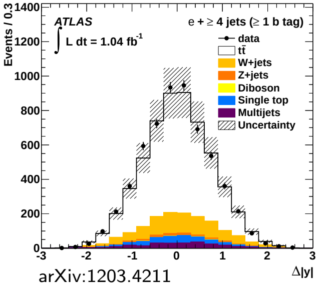


Charge asymmetry: lepton+jets

- expect small asymmetry:
  - ➔ g radiation from IS or FS
  - ➔ interference of Feynman diagr.



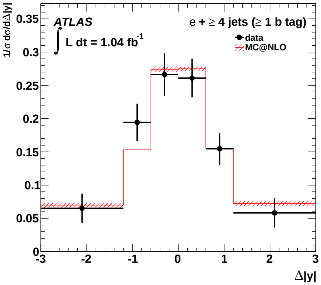
- $A_C = \frac{N(\Delta|y|>0) - N(\Delta|y|<0)}{N(\Delta|y|>0) + N(\Delta|y|<0)}$



arXiv:1203.4211

subtract bkg

Bayesian unfolding



Main systematics:

➔ ISR/FSR, JES, Signal model $\sim$ 0.010

Final result:

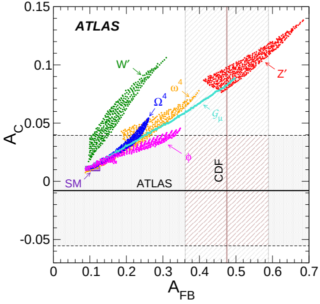
A_C = -0.018 $\pm$ 0.028 (stat.) $\pm$ 0.023 (syst.)

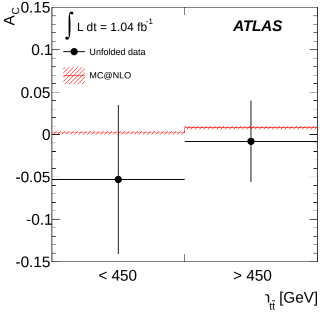
(MC@NLO: 0.006 $\pm$ 0.002)

Charge asymmetry: mass dependence

CDF result:

- measured A_{FB} for $m_{ttbar} > 450$ GeV: significance: 3.4 σ (arXiv:1101.0034v1)
- possible explanations: flavour changing Z'





Conclusion:

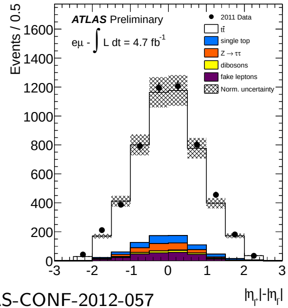
- ATLAS measurement of A_C is in agreement with SM
- disfavours a model with flavour changing Z'

→ new CDF result: still large asymmetry, but with lower significance (CDF Note 10807)

Charge asymmetry: dilepton → New for PLHC!

Two observables:

- measure $A_C^{t\bar{t}}$ as in lepton+jets
- measure $A_C^{ll} = \frac{N(\Delta|\eta|>0)-N(\Delta|\eta|<0)}{N(\Delta|\eta|>0)+N(\Delta|\eta|<0)}$
- $\Delta|\eta| = |\eta_{l+}| - |\eta_{l-}|$
- SM prediction: $A_C^{t\bar{t}} = 0.006 \pm 0.002$
  $A_C^{ll} = 0.004 \pm 0.001$



ATLAS-CONF-2012-057

- reconstruct full event using the $gg \to t\bar{t}$ matrix element
- subtract background
- correct distribution with calibration curves
- main Systematics: ISR/FSR, Signal modelling, fake lepton

Lepton based asymmetry:

$A_C^{ll} = 0.023 \pm 0.012\ (\text{stat.}) \pm 0.008\ (\text{syst.})$

Top based asymmetry:

$A_C^{t\bar{t}} = 0.057 \pm 0.024\ (\text{stat.}) \pm 0.015\ (\text{syst.})$

Combination with lepton+jets result:

$A_C^{t\bar{t}} = 0.029 \pm 0.018\ (\text{stat.}) \pm 0.014\ (\text{syst.})$

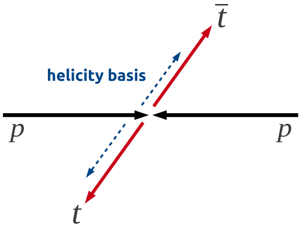
→ No deviation from SM has been found.

Spin correlation

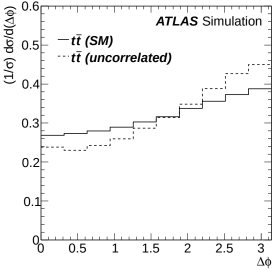
- tops decay before hadronization
- spins of tops are correlated:

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

- depends on quark/gluon fraction ($\sqrt{s}$)



Parton level distribution:



→ measure A in helicity and in max. basis

SM: $A_{\mathrm{hel}} = 0.31$, $A_{\mathrm{max}} = 0.44$

Observable:

→ $\Delta\phi$(lepton,lepton)

→ no full event reconstruction

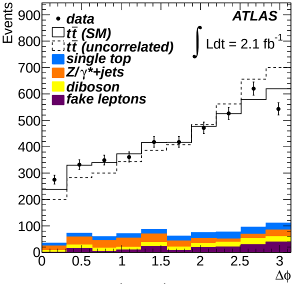
Spin correlation

$A^{\mathrm{meas}}_{\mathrm{basis}} = A^{\mathrm{SM}}_{\mathrm{basis}} \cdot f^{\mathrm{SM}}$

- $f^{\mathrm{SM}} < 0$: anti-correlation
- $f^{\mathrm{SM}} = 0$: no correlation
- $f^{\mathrm{SM}} > 1$: correlation > SM prediction
- SM: $A_{\mathrm{hel}} = 0.31$, $A_{\mathrm{max}} = 0.44$

Dominating uncertainties:

- Statistics: 0.14
- JES/JER: 0.12
- Fake lepton: +0.16/-0.07
- Signal modelling: 0.11



PRL 108, 212001 (2012)

Results:

$$f^{\mathrm{SM}} = 1.30 \pm 0.14\ (\mathrm{stat.})\ ^{+0.27}_{-0.22}\ (\mathrm{syst.})$$

↓

$$A^{meas}_{\mathrm{hel}} = 0.40 \pm 0.04\ (\mathrm{stat.})\ ^{+0.08}_{-0.07}\ (\mathrm{syst.})$$

$$A^{meas}_{\mathrm{max}} = 0.57 \pm 0.06\ (\mathrm{stat.})\ ^{+0.12}_{-0.10}\ (\mathrm{syst.})$$

→ **First observation of spin correlation: 5.1 σ**

More on searches for BSM physics in top events

- $t\bar{t}$ events with large E_T^{miss}($1.04\ fb^{-1}$):
  - Phys.Rev.Lett. 108 (2012) 041805
- $t\bar{t}$ resonances
  - lepton+jets ($2.05\ fb^{-1}$): arXiv:1205.5371v1
  - dilepton ($2.04\ fb^{-1}$): ATLAS-CONF-2011-123

→ Poster from Michele Petteni

→ Talk by Till Eifert (Friday, 12:35 pm)

- Search for down-type fourth generation quarks
  - $1.04\ fb^{-1}$: arXiv:1202.6540
  - $1.04\ fb^{-1}$: JHEP 04 (2012) 069

→ Poster from Dennis Wendland

→ Talk by Till Eifert (Friday, 12:35 pm)

Summary

- thousands of top quarks have been produced at the LHC

  ➔ precision measurements of top properties
- most analyses are limited by systematics

  ➔ crucial to understand and reduce them
- all measurements are consistent with the SM predictions
- most precise measurement of W-helicity fractions
- **First observation of spin correlation!**

Backup slides

Event selection

E_T^{miss}:

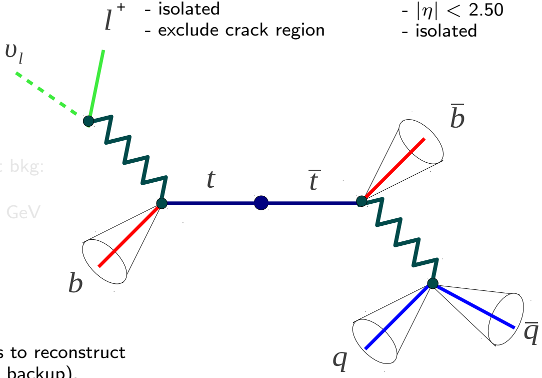
e: $E_T^{miss} > 35$ GeV
μ: $E_T^{miss} > 20$ GeV

Electrons:

- $E_T > 25$ GeV
- $|\eta| < 2.47$
- isolated
- exclude crack region

Muons:

- combined Muons (tracker+spectrometer)
- $p_T > 20$ GeV
- $|\eta| < 2.50$
- isolated



transverse W mass:

used to reduce multijet bkg:
e: $m_{W,T} > 35$ GeV
μ: $m_{W,T} + E_T^{miss} > 60$ GeV

Jets:

- AntiKt jets (R = 0.4)
- $p_T > 25$ GeV
- $|\eta| < 2.5$
- at least four jets

b-Jets:

Used different methods to reconstruct secondary vertices (see backup).
→ require at least one tagged jet

For dilepton analyses:

- ≥ 2 jets
- cuts to reduce Z+jets bkg
- larger E_T^{miss} cut

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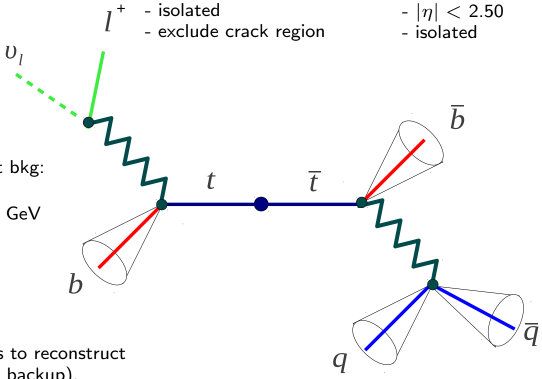

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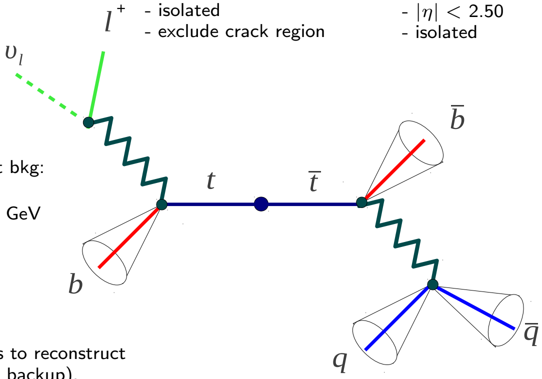

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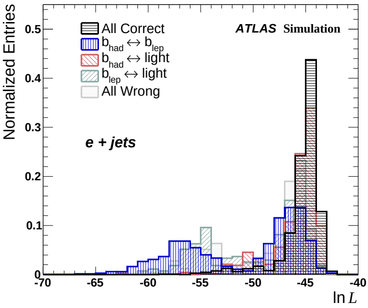
Top reconstruction

Kinematic likelihood fit

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



Reco via a χ^2 fit (example: hadronic top mass)

$$\chi^2 = \frac{(m_{j1,j2} - m_W)^2}{\sigma_W^2} + \frac{(m_{j1,j2,b1} - m_t)^2}{\sigma_t^2} + \frac{(m_{j3,j4} - m_W)^2}{\sigma_W^2} + \frac{(m_{j3,j4,b2} - m_t)^2}{\sigma_t^2}$$

with $\sigma_W = 10.2$ GeV, $\sigma_t = 17.4$ GeV

Event reconstr. (dilepton channel, charge asymm)

Problem:

- ➔ have final state with two neutrinos
- ➔ need to fully reconstruct event
- ➔ 16 equations to solve
- ➔ 22 unknowns to determine

Idea:

- ➔ vary 4 momentum of objects (width, resolution)
- ➔ transfer functions for b-jets: priors
- ➔ if solution: calculate weight:
- ➔ $\frac{(2\pi)^4}{\epsilon_1 \epsilon_2 s} d\epsilon_1 d\epsilon_2 f_{PDF}(\epsilon 1) f_{PDF}(\epsilon_2) |\mathcal{M}(y)|^2 W(x,y) d\Phi_n$

What do we know?

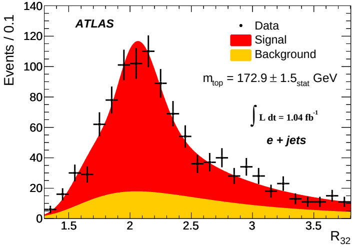
- ➔ have 16 measured quantities
- ➔ fix W and top mass to WA
- ➔ add equations:
  - MET balance in transverse plane
  - $t\bar{t}$-p_T

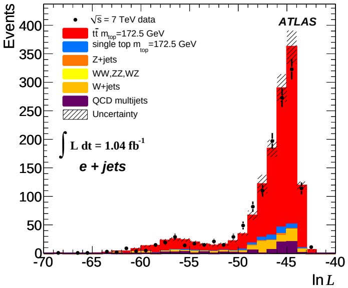
Finally:

- ➔ for each permutation of jets: phase space sampling (10^4-10^5 points, use Vegas)
- ➔ each point: calculate number of solutions
- ➔ calculate weight $y^k = \frac{\sum_{j=1}^{N^{sampl}} \sum_{i=1}^{N_j^{sol}} (w_{ij}^k y_{ij}^k)}{\sum_{j=1}^{N^{sampl}} \sum_{i=1}^{N_j^{sol}} w_{ij}^k}$
- ➔ ϵ_{reco} for highest weight: 47 % (rdm: 30 %)

Top mass: 1D template fit

- $R_{32} = \frac{m_{top}^{reco}}{m_{W}^{reco}}$
- less sensitive to JES
- jets for hadronic top: $p_T > 40$ GeV
- ln L > -50
- reconstruction: kinematic likelihood
- template fit





Main systematics:

- ISR/FSR: 1.42 GeV
- JES: 1.23 GeV
- b-JES: 1.16 GeV

Final result:

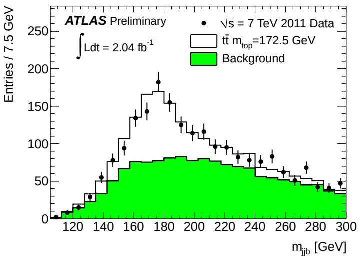
$m_{top} = 174.4 \pm 0.9$ (stat.) ± 2.5 (syst.) GeV

$\rightarrow$ in agreement with result from 2D method

Top mass: all hadronic

- ATLAS-CONF-2011-030
- calculate m_{jjb}
- perform template fit

Reconstructed distribution:



Jet selection:

- $\geq$ 6(5) jets with $p_T >$ 30(55) GeV
- $|\eta(\mathrm{jet})| <$ 4.5, Δ R(jet$_i$, jet$_j$) $>$ 0.6
- 2 b-tags: $p_T >$ 55 GeV, $|\eta| <$ 2.5
- Δ R(b_1, b_2) $>$ 1.2

Procedure:

- data driven estimate for multijet bkg
- reconstruction via χ^2 fit
- in reconstruction: $m_{jj} \in$ [50,110] GeV
- rescale light jets with m_W / m_W^{reco}

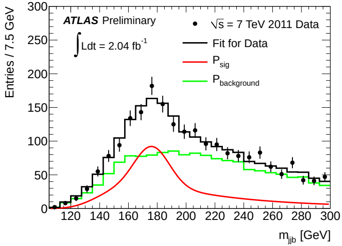
Top mass: all hadronic

- fit with five templates
- binned likelihood
- f_{Sig} and m_{top} are free parameters
- use pseudo data for systematics

Systematic uncertainties:

Source	Uncertainty [GeV]
Method	0.4
Template statistics	0.9
MC generator	0.5
ISR/FSR	1.7
PDF	0.6
Background modelling	1.9
Jet energy scale	2.1
b-jet energy scale	1.4
b-tag efficiency scale factors	0.3
Jet energy resolution	0.3
Jet reconstruction efficiency	0.2
Total systematic uncertainty	3.8

Fit to data:



Final result:

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

$\rightarrow$ in agreement with world average
and result from lepton+jets channel

Limit on effective operator

New physics processes can be modeled by effective Langrangian [1] :

$$\mathcal{L}_{\text{eff}} = \sum \frac{C_x}{\Lambda^2} O_x + \dots$$

One of the six-dimension operators (C_{uW}^{33}) can alter the helicity fractions:

$$F_0 = \frac{m_t^2}{m_t^2 + 2m_W^2} - \frac{4\sqrt{2}Re(C_{uW}^{33})v^2}{\Lambda^2 V_{tb}} \frac{m_t m_W (m_t^2 - m_W^2)}{(m_t^2 + 2m_W^2)^2}$$

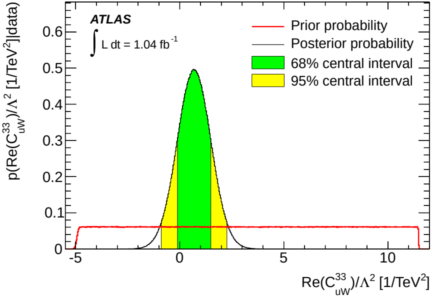
$$F_L = \frac{2m_W^2}{m_t^2 + 2m_W^2} + \frac{4\sqrt{2}Re(C_{uW}^{33})v^2}{\Lambda^2 V_{tb}} \frac{m_t m_W (m_t^2 - m_W^2)}{(m_t^2 + 2m_W^2)^2}$$

$\rightarrow$ Assumption in model: $F_R = 0$

[1] C. Zhang and S. Willenbrock, Effective-Field-Theory Approach to Top-Quark Production and Decay, Phys. Rev. D83 (2011) 034006; J.A. Aguilar-Saavedra, A minimal set of top anomalous couplings, Nucl. Phys B812 (2009) 181.

Set limit on non-SM coupling (only template method) [2]

2D fit: $F_0 = 0.66 \pm 0.05\,(\mathrm{stat.{+}syst.})$



$$\frac{\mathrm{Re}(C_{uW}^{33})}{\Lambda^2} \in [-0.9,\ 2.3]\ \mathrm{TeV}^{-2}$$

→ No deviation from SM predictions has been found

[2] arXiv:1205.2484

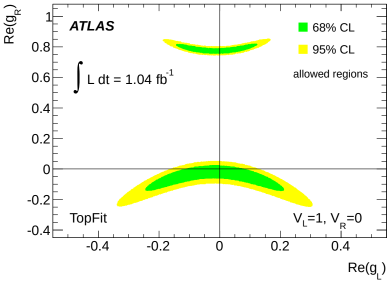
Limit on anomalous couplings [3]

Set limits on g_R and g_L:

- assumption: $V_R = 0$ and $V_L = 1$
- combined angular asymmetries

$$\begin{aligned} A_+ &= 0.53 \pm 0.02 \text{ (stat. + syst.)} \\ A_- &= -0.84 \pm 0.02 \text{ (stat. + syst.)} \end{aligned}$$

- use helicity fractions to calculate anomalous couplings



One dimensional limits on anomalous couplings [4]

Assuming only one non-vanishing coupling:

$$\mathrm{Re}(\mathrm{V_R}) \in [-0.20, 0.23] \rightarrow \frac{\mathrm{Re}(\mathrm{C}^{33}_{\phi\phi})}{\Lambda^2} \in [-6.7, 7.8]\,\mathrm{TeV}^{-2}$$

$$\mathrm{Re}(\mathrm{g_L}) \in [-0.14, 0.11] \rightarrow \frac{\mathrm{Re}(\mathrm{C}^{33}_{\mathrm{dW}})}{\Lambda^2} \in [-1.6, 1.2]\,\mathrm{TeV}^{-2}$$

$$\mathrm{Re}(\mathrm{g_R}) \in [-0.08, 0.04] \rightarrow \frac{\mathrm{Re}(\mathrm{C}^{33}_{\mathrm{uW}})}{\Lambda^2} \in [-1.0, 0.5]\,\mathrm{TeV}^{-2}$$

Conclusion for anomalous couplings:

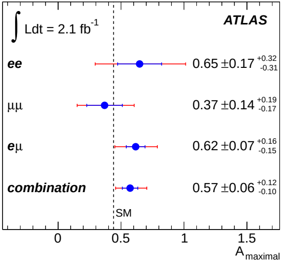
- couplings compatible with zero

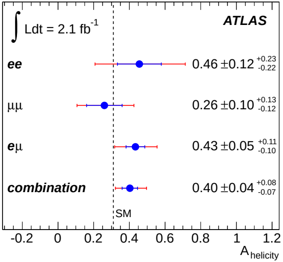
[4] arXiv:1205.2484

Backup: spin correlation

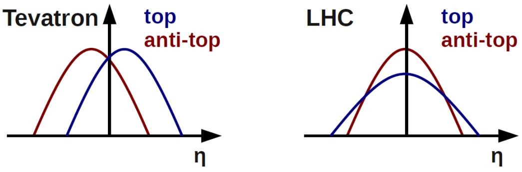
Dilepton selection

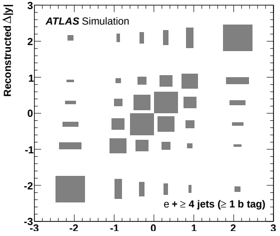
- single lepton trigger
- exactly two leptons, opposite charge
- ee/$\mu\mu$:
  - $m_{ll} > 15$ GeV: remove Υ, J/Ψ
  - $E_T^{miss} > 60$ GeV: remove Z/γ+jets,W+jets
- eμ:
  - $H_T > 130$ GeV
    $\rightarrow$ suppress $Z/\gamma \rightarrow \tau\tau$



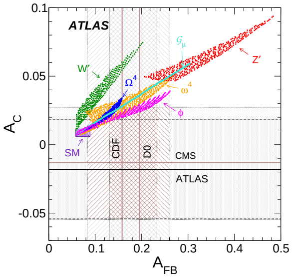


Backup: Charge asymmetry





- at Tevatron: can measure A_{FB}
- LHC is symmetric: can measure A_C
- at LHC: much more gg-fusion
  ➔ expect only small asymmetry

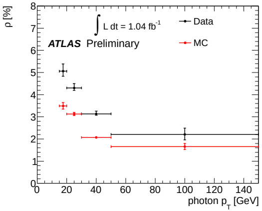


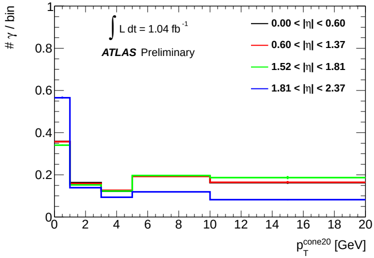
Backup: $t\bar{t}\gamma$ cross section

Templates

- signal (from $Z \rightarrow ee$)
- hadron fakes
- electron fakes (from $Z \rightarrow ee$)
- non-$t\bar{t}$ bkg
- bkg $t\bar{t}\gamma$

Fake rate $e \rightarrow \gamma$





fit parameter	fit value with statistical uncertainty		
hadron fakes in the e+jets channel	21	± 6	events
hadron fakes in the μ+jets channel	28	± 8	events
electrons faking photons from $t\bar{t}$ in the e+jets channel	7.4	± 1.7	events
electrons faking photons from $t\bar{t}$ in the μ+jets channel	10.9	± 2.2	events
$t\bar{t}\gamma$ background in the e+jets channel	0.2		events
$t\bar{t}\gamma$ background in the μ+jets channel	0.4		events
non-$t\bar{t}$ background in the e+jets channel	6.7		events
non-$t\bar{t}$ background in the μ+jets channel	3.8		events
total number of background events	78	± 14	events
total number of signal events	46	± 12	events
$t\bar{t}\gamma$ signal (before selection and acceptance cuts)	2100	± 500	events

Backup: FCNC $t \to qZ$

Theoretical values for BR for SM and beyond SM scenarios

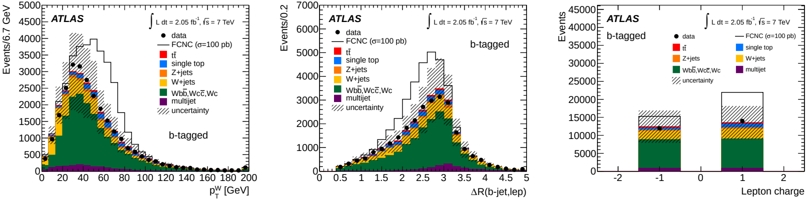
Process	SM	QS	2HDM	FC 2HDM	MSSM	$\not R$ SUSY	TC2	RS
$t \to u\gamma$	3.7×10^{-16}	7.5×10^{-9}	—	—	2×10^{-6}	1×10^{-6}	—	$\sim 10^{-11}$
$t \to uZ$	8×10^{-17}	1.1×10^{-4}	—	—	2×10^{-6}	3×10^{-5}	—	$\sim 10^{-9}$
$t \to ug$	3.7×10^{-14}	1.5×10^{-7}	—	—	8×10^{-5}	2×10^{-4}	—	$\sim 10^{-11}$
$t \to c\gamma$	4.6×10^{-14}	7.5×10^{-9}	$\sim 10^{-6}$	$\sim 10^{-9}$	2×10^{-6}	1×10^{-6}	$\sim 10^{-6}$	$\sim 10^{-9}$
$t \to cZ$	1×10^{-14}	1.1×10^{-4}	$\sim 10^{-7}$	$\sim 10^{-10}$	2×10^{-6}	3×10^{-5}	$\sim 10^{-4}$	$\sim 10^{-5}$
$t \to cg$	4.6×10^{-12}	1.5×10^{-7}	$\sim 10^{-4}$	$\sim 10^{-8}$	8×10^{-5}	2×10^{-4}	$\sim 10^{-4}$	$\sim 10^{-9}$

Experimental limits on BR @ 95 % C.L. (without CMS result)

	LEP	HERA	Tevatron
$BR(t \to q\gamma)$	2.4% [25–29]	0.64% ($tu\gamma$) [30]	3.2% [31]
$BR(t \to qZ)$	7.8% [25–29]	49% (tuZ) [32]	3.2% [33]
$BR(t \to qg)$	17% [34]	13% [32, 35, 36]	2.0×10^{-4} (tug), 3.9×10^{-3} (tcg) [37]

Backup: FCNC in single top production

Most significant variables for neural network



Process	Expected events		
SM single top	1460	±	150
$t\bar{t}$	660	±	70
W+light jets	4700	±	1100
$Wb\bar{b}/Wc\bar{c}$+jets	2700	±	1500
Wc + jets	12100	±	6700
Z+jets/diboson	700	±	170
Multijet	1600	±	800
Total background	24000	±	7000
Observed	26223		

Further variables:

- m_{top}, m_{bjet}, η_{bjet}
- $\Delta\Phi$(W,bjet), p_T^{lep}, p_T^{bjet}
- $\cos\Theta^*$, ΔR(W,bjet)

Reconstruction:

- exactly one jet
- neutrino p_z from constraint on m_W
- two results: take smallest value

Reducing ISR/FSR uncertainties

How was it evaluated in 2011 analyses?

- user AcerMC+Pythia, using Perugia HARD/SOFT tunes for ISR/FSR
  $\rightarrow$ **not based on LHC data**
- six samples: ISR up/down, FSR up/down, ISR & FSR up, ISR & FSR down
- take half of the largest difference between two samples

What was changed for 2012 (2011 data)?

- now: set ISR/FSR parameters **based on LHC data**
- ISR: constrain variation using jet gap fraction info in dil. events
- FSR: tune parameters $\rightarrow$ describe jet shapes in QCD events
- have two samples with more/less parton shower activity (AcerMC+Pythia)