Measurements of Top Quark Properties in ATLAS

Jie Yu

On behalf of the ATLAS Collaboration

La Thuile (Feb 28, 2013)

Motivation to study top quark properties

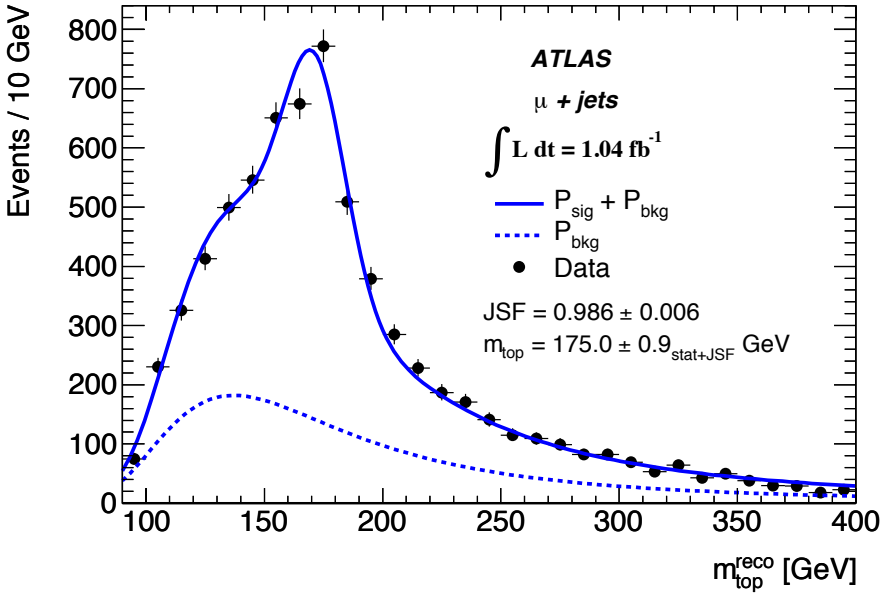
- Precise tests of the Standard Model and verification of NP QCD calculations:
  - Top Mass
  - Top quark polarization
  - Spin Correlation
  - Measurement of $\sigma_{t\bar{t}\gamma}$
  - W helicity
  - Charge asymmetry (*)
- Opens a window to search for new physics
  - Search for FCNC
  - Search for new heavy quark
  - Search for top-jet resonances
  - Search for $t\bar{t}$ + large $E_{\mathrm{T}}^{\mathrm{miss}}$
  - Search for $t\bar{t}$ resonances (*)

Figure: An old Chinese proverb: if one wants to see far away, he needs to stand on the 'top'.

* See talk of *Pier-Olivier DeViveiros*

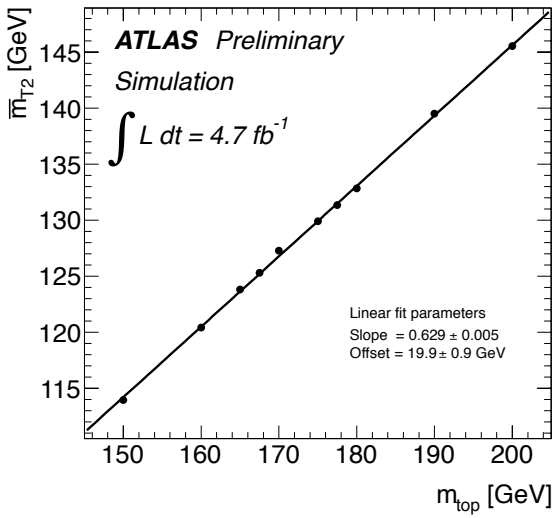
Top Mass

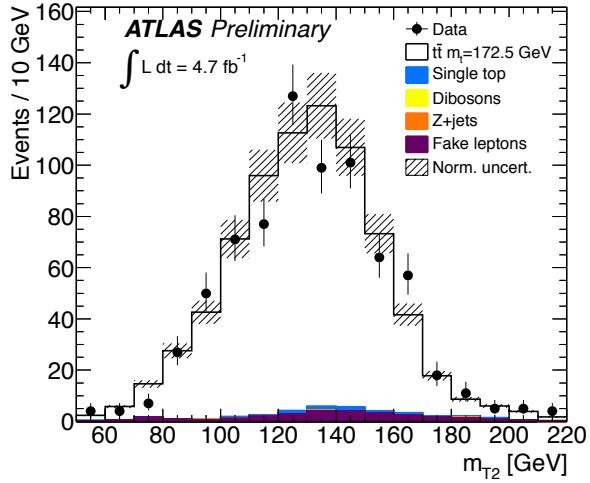
- l+jets (7 TeV, 1.04 fb^{-1}, *Eur.Phys.J. C72 (2012) 2046*)
- di-lepton (7 TeV, 4.7 fb^{-1}, *ATLAS-CONF-2012-082*)



- l+jets: m_{top} and jet energy scale factor (JSF) simultaneously fitted using the m_{top}^{reco} and m_W^{reco} distributions
- $m_{top} = \mathbf{174.5 \pm 0.6(stat) \pm 2.3(syst)}$ GeV
- di-lepton: $M_{T2} \equiv \min_{\vec{p_T}^{\nu 1}, \vec{p_T}^{\nu 2}} \{Max[M_T(m_{lb_1}, \vec{p_T}^{\nu 1}), M_T(m_{lb_2}, \vec{p_T}^{\nu 2})]\}$
- $m_{top} = \mathbf{175.2 \pm 1.6(stat)^{+3.1}_{-2.8}(syst)}$ GeV

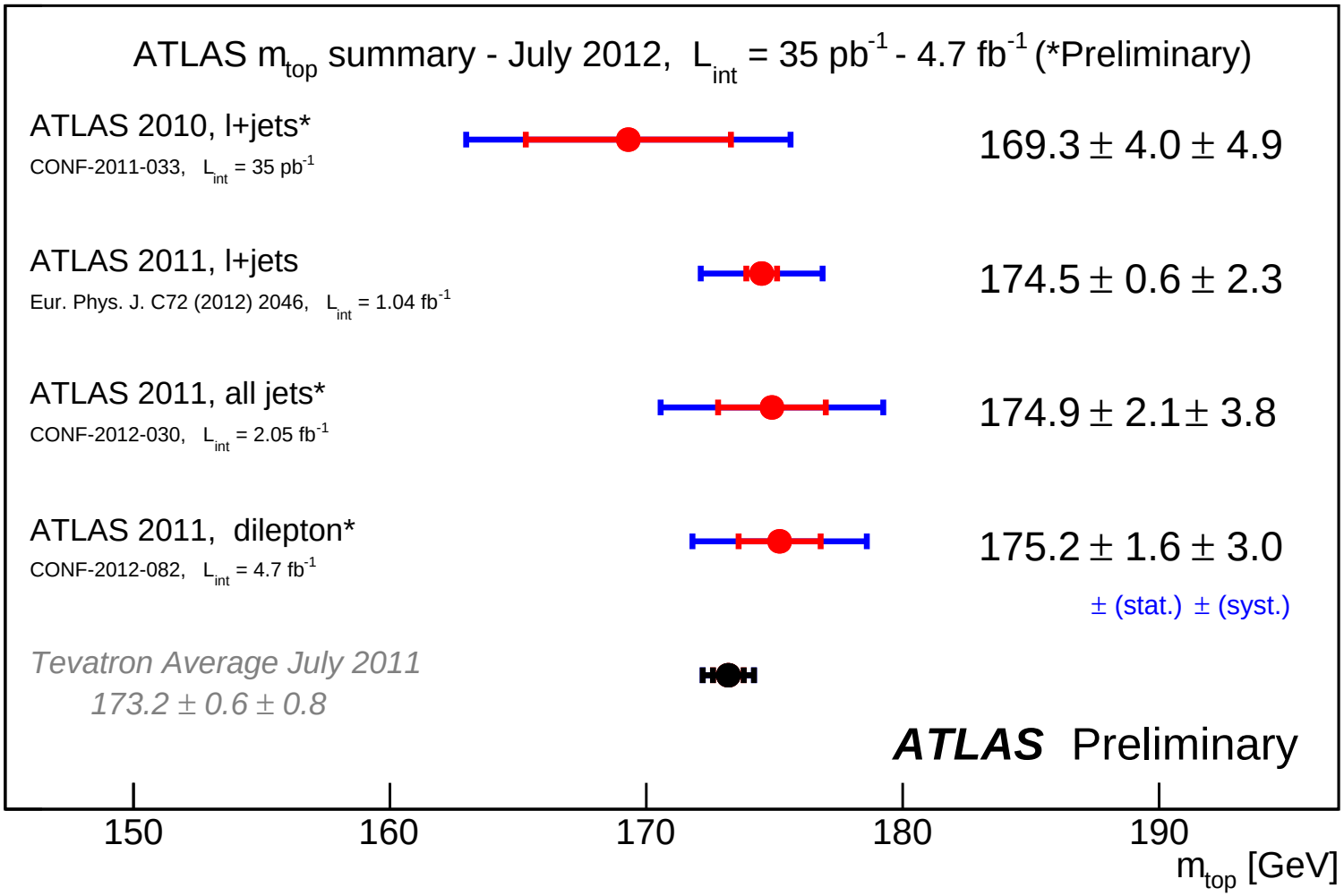
- Calibration curve determined in MC
- Largest systematic uncertainties: Jet Energy Scale (JES), b-jet JES, $t\bar{t}$ modeling





Top Mass: overview

- Measurements have been done in several channels

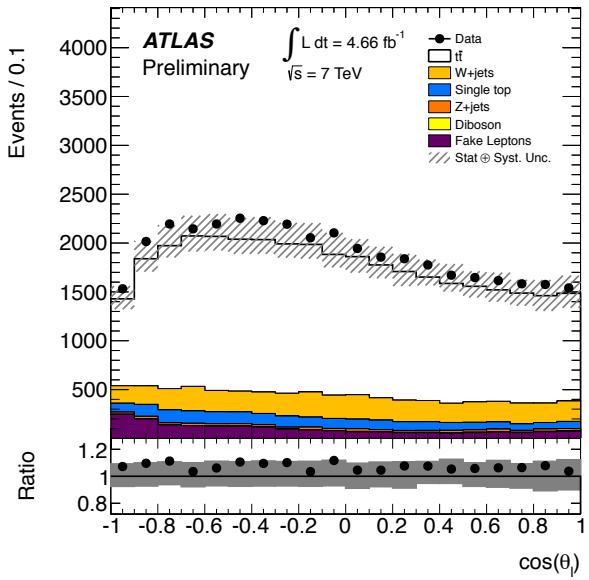


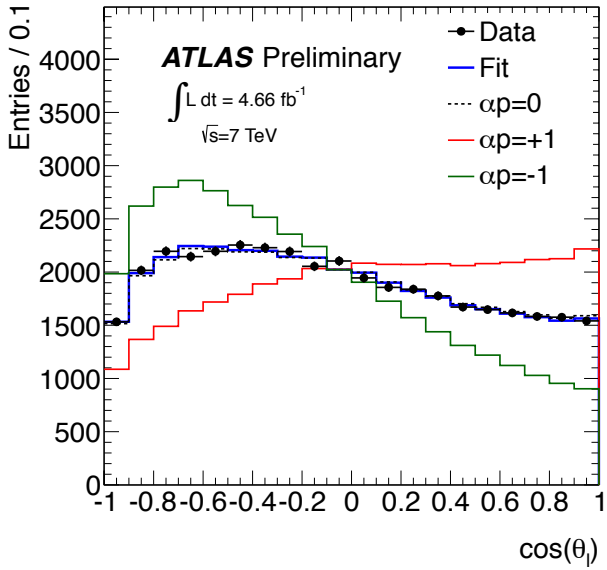
Top quark polarization (7 TeV, 4.66 fb^{-1}, *ATLAS-CONF-2012-133*)

- In SM top quarks are produced almost unpolarized
- In some BSM scenarios, top quarks are produced polarized
- Polarization was measured in l+jets using θ_l, polar angle of the lepton in the top quark rest frame:

$$f = \frac{1}{2} + \frac{N(\cos\theta_l > 0) - N(\cos\theta_l < 0)}{N(\cos\theta_l > 0) + N(\cos\theta_l < 0)}$$

- f is measured using template fit method: fully positively VS. negatively polarized top quarks
- SM expectation: $f_{SM} = 0.5$

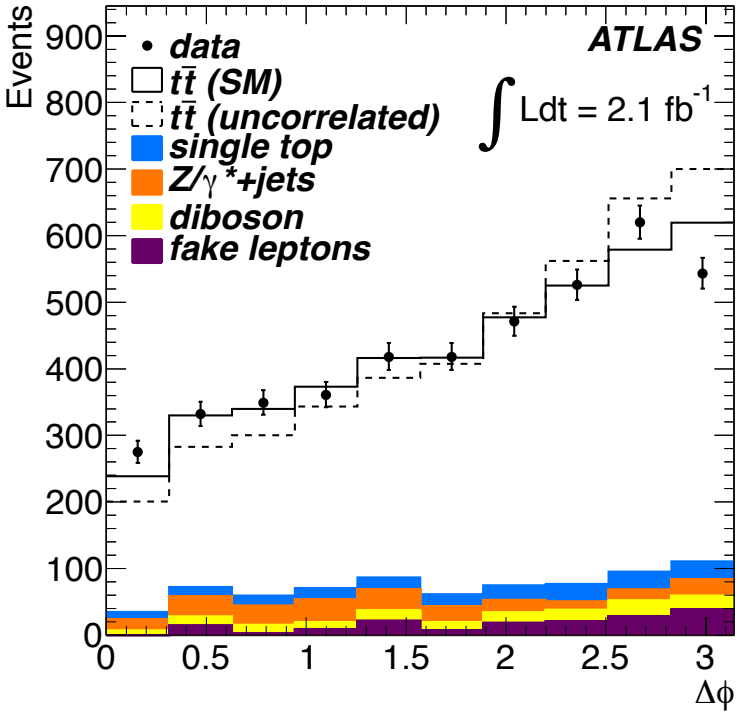




- Results of the fit: $\mathbf{f = 0.470 \pm 0.009(stat)^{+0.023}_{-0.032}(syst)}$

Spin Correlation (7 TeV, 2.1 fb^{-1}, *PRL 108, 212001 (2012)*)

- $t\bar{t} \to l^+\nu b, l^-\bar{\nu}\bar{b}$ produce charged leptons possessing correlations in azimuthal angle, $\Delta\phi$
- The degree of spin correlation of $t\bar{t}$, $A \equiv \frac{N(\uparrow\uparrow)+N(\downarrow\downarrow)-N(\uparrow\downarrow)-N(\downarrow\uparrow)}{N(\uparrow\uparrow)+N(\downarrow\downarrow)+N(\uparrow\downarrow)+N(\downarrow\uparrow)}$



- $A^{measured} = A^{SM} \cdot f^{SM}$
- The fit includes a linear superposition: $f^{SM} \times$ (SM prediction) + $(1 - f^{SM}) \times$ (uncorrelated model)
- The four di-lepton channels fitted simultaneously to get a common f^{SM}

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

$$A^{measured} = \mathbf{0.40 \pm 0.04(stat)^{+0.08}_{-0.07}(syst)}$$

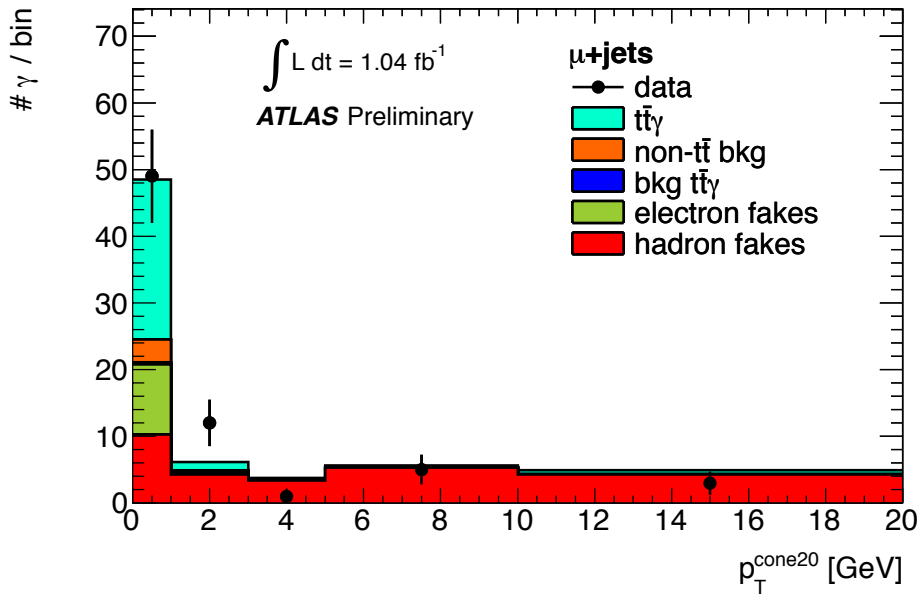
- Zero $t\bar{t}$ spin correlation is excluded with a significance of $\mathbf{5.1\sigma}$
- *DØ* Collaboration reported the evidence with a significance of 3.1σ

Measurement of $t\bar{t}\gamma$ cross section (7 TeV, 1.04 fb^{-1}, *ATLAS-CONF-2011-153*)

- Electroweak couplings of the top quark: investigating $t\bar{t}$ with an additional gauge boson, e.g. $t\bar{t}\gamma$ and $t\bar{t}Z$
- $t\bar{t}\gamma$ cross section measurement: based on a template fit using p_{T}^{cone20} distributions of photon candidates

(p_{T}^{cone20}: $\Sigma p_{\mathrm{T}}^{track}$ in a cone with $R < 0.2$)

fit parameter	e+jets	μ+jets
hadron fakes	21 ± 6	28 ± 8
e fake γ from $t\bar{t}$	7.4 ± 1.7	10.9 ± 2.2
$t\bar{t}\gamma$ background	0.2	0.4
non-$t\bar{t}$	6.7	3.8
total background	78 ± 14	
total signal	46 ± 12	

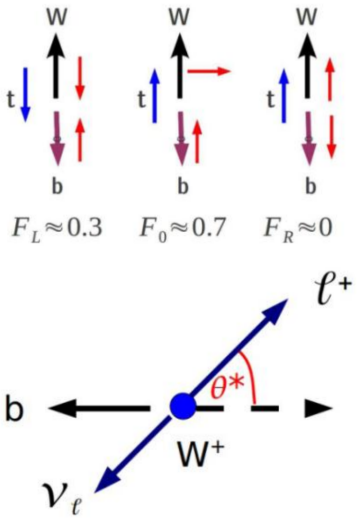


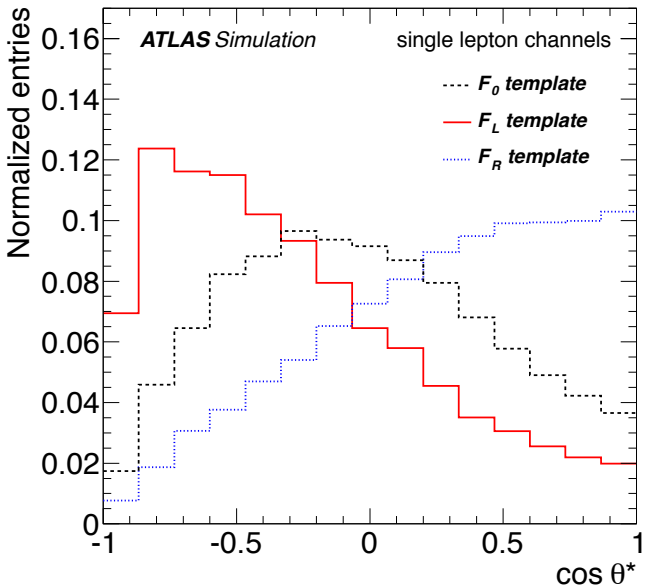
- $\boxed{\sigma_{t\bar{t}\gamma} \cdot BR = \mathbf{2.0 \pm 0.5(stat) \pm 0.7(syst) \pm 0.08(lumi)}\ pb}$
- Consistent with the SM prediction: $2.1 \pm 0.4 pb$ (arxiv:1102.1967)

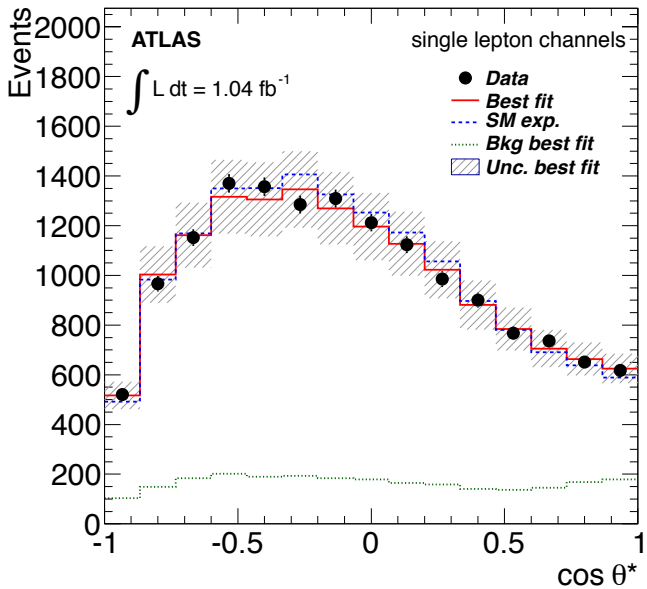
∗ Search for $t\bar{t}Z$ production: ATLAS-CONF-2012-126

W helicity: template fit (7 TeV, 1.04 fb^{-1}, *JHEP 1206 (2012) 088*)

- In $t \to Wb$, W polarization can be longitudinal, left or right-handed
- The angular distribution is:
  $\frac{1}{\sigma}\frac{d\sigma}{dcos(\theta^*)} = \frac{3}{4}(1-cos^2\theta^*)F_0 + \frac{3}{8}(1-cos\theta^*)^2F_L + \frac{3}{8}(1+cos\theta^*)^2F_R$
- Method 1: comparing the observed $cos\theta^*$ distribution with templates for W boson helicity states obtained from simulation







W polarization fraction	longitudinal (F_0)	left-handed (F_L)	right-handed (F_R)
SM prediction	0.687 ± 0.005	0.311 ± 0.005	0.0017 ± 0.0001
Measurement	**$0.66 \pm 0.06 \pm 0.07$**	**$0.33 \pm 0.03 \pm 0.03$**	**$0.01 \pm 0.03 \pm 0.06$**

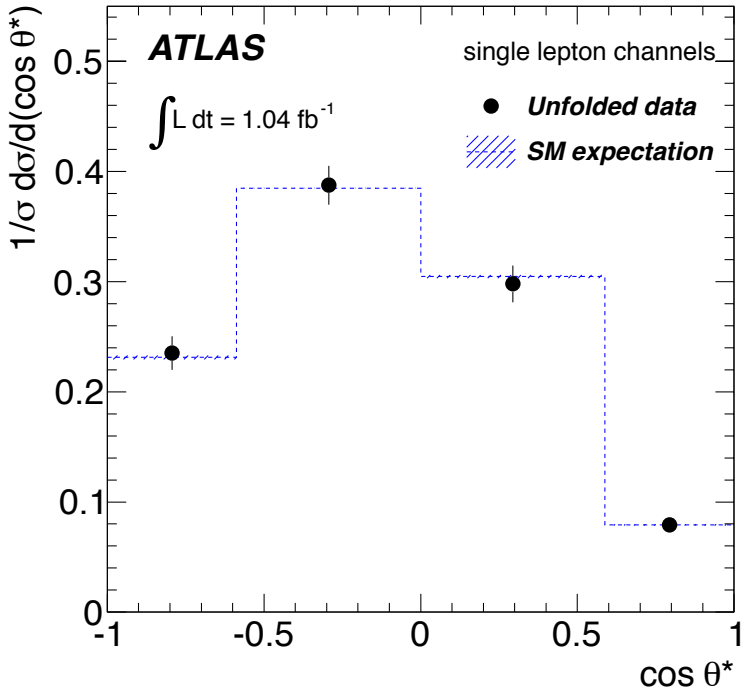
W helicity: angular asymmetry (7 TeV, 1.04 fb^{-1}, *JHEP 1206 (2012) 088*)

- Method 2: polarization of the W bosons can also be obtained through angular asymmetry:

$$A_{\pm} = \frac{N(cos\theta^* > z_{\pm}) - N(cos\theta^* < z_{\pm})}{N(cos\theta^* > z_{\pm}) + N(cos\theta^* < z_{\pm})}; \quad z_{\pm} = \pm(1 - 2^{2/3})$$

- Iterative unfolding procedure until the method converges, backgrounds are subtracted before that

- In l+jets:
  - $A_+ = 0.52 \pm 0.02(stat.) \pm 0.03(syst.)$
  - $A_- = -0.84 \pm 0.01(stat.) \pm 0.02(syst.)$
- In dilepton:
  - $A_+ = 0.56 \pm 0.02(stat.) \pm 0.04(syst.)$
  - $A_- = -0.84 \pm 0.02(stat.) \pm 0.04(syst.)$
- Systematic: lepton misidentification, jet energy scale, MC modeling



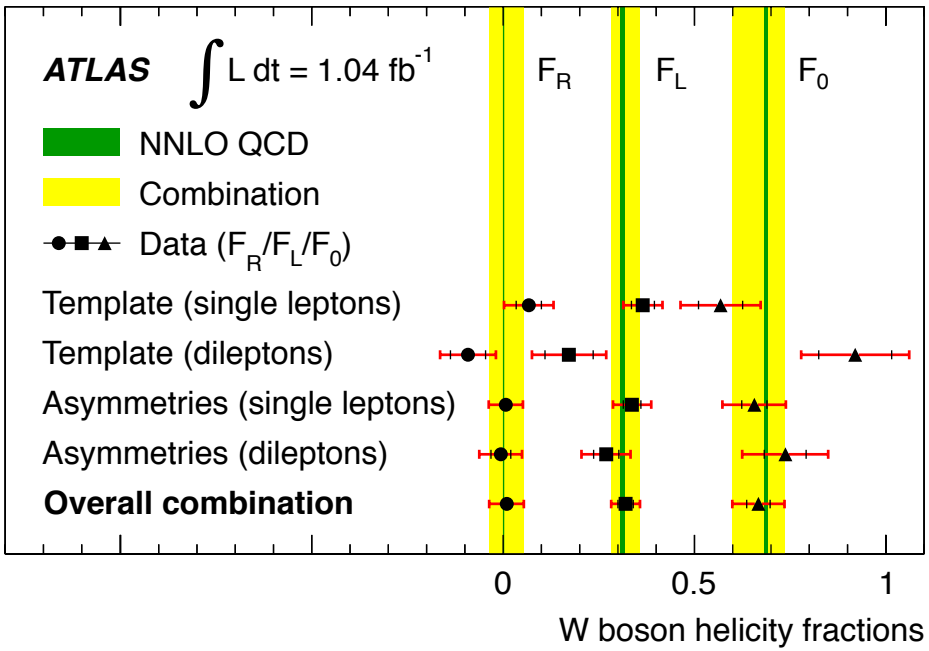
- Combining both channels:

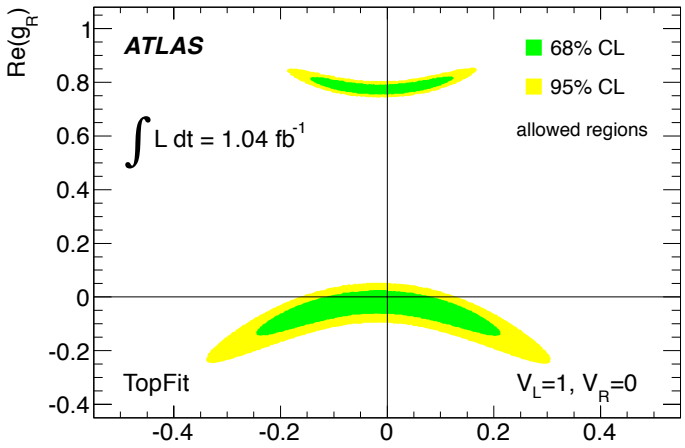
$$F_0 = \mathbf{0.67 \pm 0.04 \pm 0.07},\ F_L = \mathbf{0.32 \pm 0.04 \pm 0.02},\ F_R = \mathbf{0.01 \pm 0.02 \pm 0.04}$$

- At the same precision level as Tevatron combination and CMS result

W helicity: overview and anomalous Wtb limit

- An overall combination of both measurements is done using the 'best linear unbiased estimator' (*BLUE*) method.





$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\,\gamma^{\mu}\left(\mathbf{V}_{\mathrm{L}}P_{\mathrm{L}} + \mathbf{V}_{\mathrm{R}}P_{\mathrm{R}}\right)t\;W_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\,\frac{i\sigma^{\mu\nu}q_{\nu}}{M_{W}}\left(\mathbf{g}_{\mathrm{L}}P_{\mathrm{L}} + \mathbf{g}_{\mathrm{R}}P_{\mathrm{R}}\right)t\;W_{\mu}^{-} + \mathrm{h.c.},$$

- ▷ V_{L} is modified V_{tb} with contribution from new physics
- ▷ V_{R}, g_{L}, g_{R} are purely due to the possible presence of new phenomena
- ▷ P_{L} and P_{R} are chirality operators

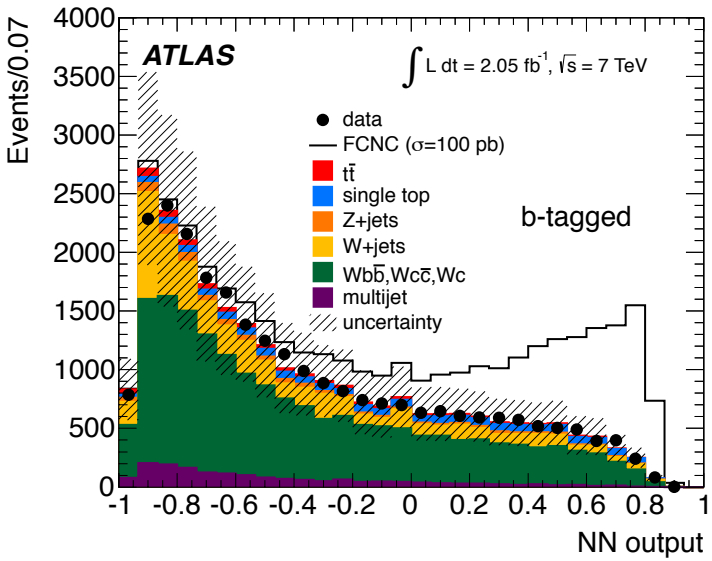
Do we know what we don't know?

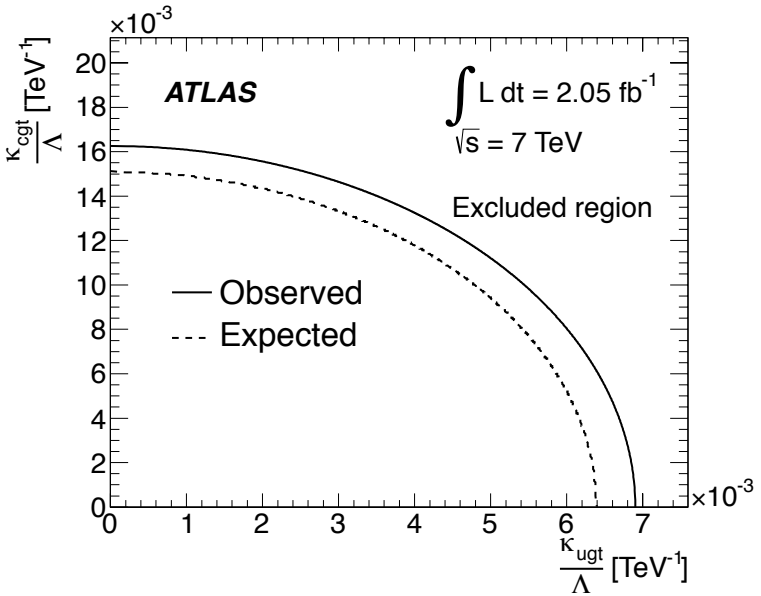
- Top quark was born in the family of particles and an 'ID' is licensed for it.
- How is it connecting to the 'universe' outside of the family?

- Let's go further and see !!

Search for FCNC single top production (7 TeV, 2.05 fb^{-1}, *PLB 712 (2012) 351-369*)

- In SM, flavour-changing neutral-current (FCNC) processes are forbidden at tree level and suppressed at higher orders
- BSM with new sources of flavour predict higher rates for FCNCs
- A single top production search: $qg \to t \to W(\to l\nu)b$, where $q = u, c$



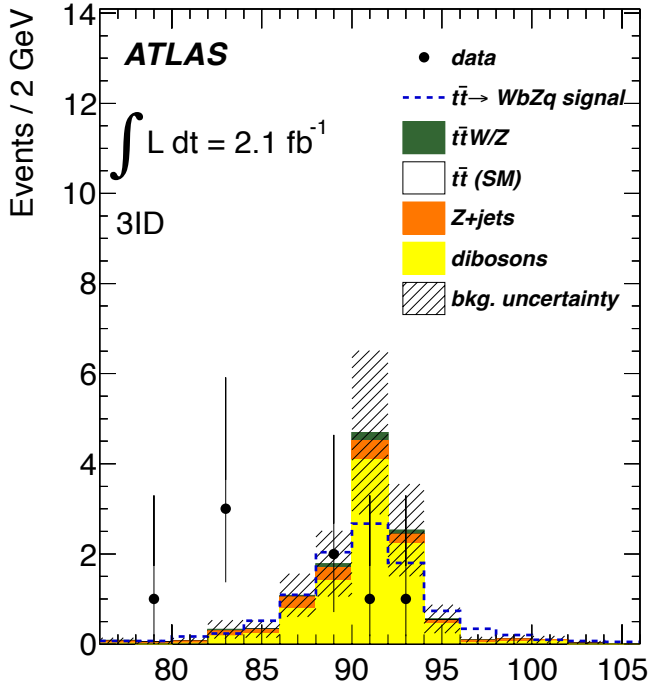


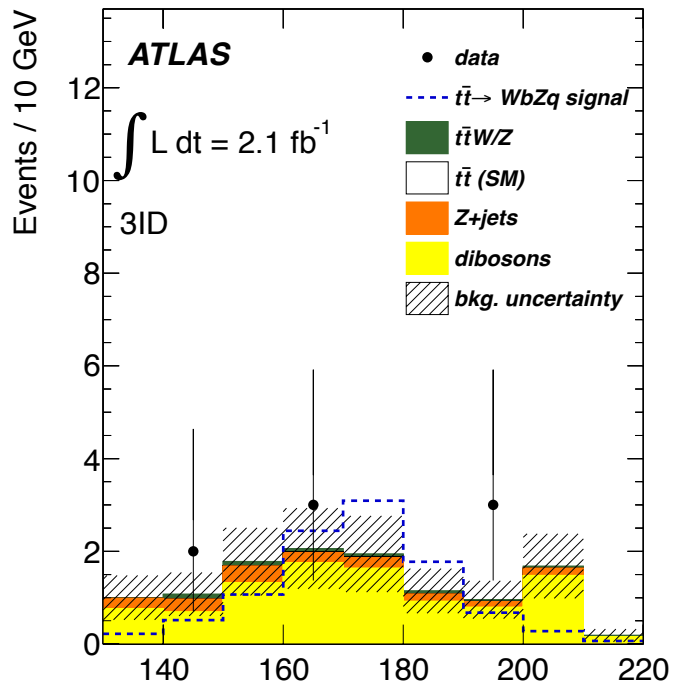
- First measurement of FCNC with top production at LHC, most stringent upper limits on the coupling constants and branching fractions

- $\kappa_{ugt}/\Lambda < \mathbf{6.9}\cdot10^{-3}$ TeV^{-1}
- $\kappa_{cgt}/\Lambda < \mathbf{1.6}\cdot10^{-2}$ TeV^{-1}
- $\mathcal{B}(t \to ug) < \mathbf{5.7}\cdot10^{-5}$
- $\mathcal{B}(t \to cg) < \mathbf{2.7}\cdot10^{-4}$

Search for FCNC in top decays (7 TeV, 2.05 fb^{-1}, *JHEP 09 (2012) 139*)

- The top-quark FCNC decay BR in several SM extensions is typically many orders of magnitude larger than the SM BR
- Searching for $t\bar{t} \to \mathbf{Zq}Wb \to \mathbf{llq}l\nu b$: events selected with '3ID' (3 identified leptons) or '2ID+TL' (2 identified leptons + 1 track lepton)
- The expected and observed 95% C.L. upper limits on the FCNC top quark decay $t \to Zq$ BR.

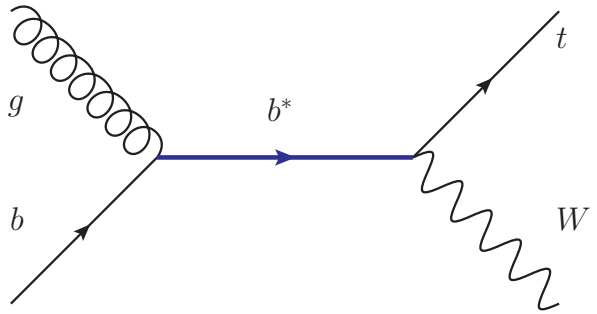


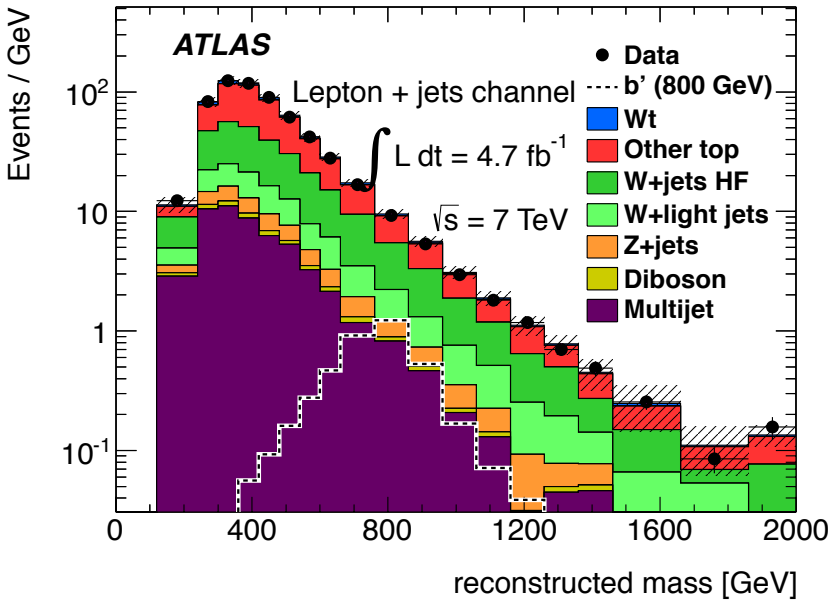


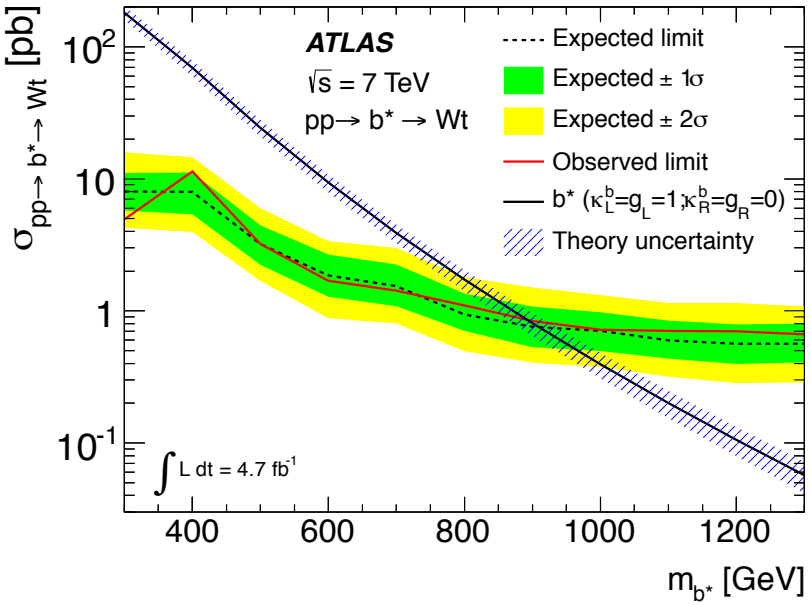
channel	observed	(-1σ)	expected	$(+1\sigma)$
3ID	0.81%	0.63%	0.95%	1.4%
2ID+TL	3.2%	2.15%	3.31%	4.9%
Combine	**0.73%**	0.61%	0.93%	1.4%

Search for new heavy quarks (7 TeV, 4.7 fb^{-1}, *arXiv:1301.1583*)

- First search for excited-quarks coupling to the third generation of SM quarks, complementary to the first generation coupling search
- Search for $b^* \rightarrow Wt$ in l+jets and di-lepton



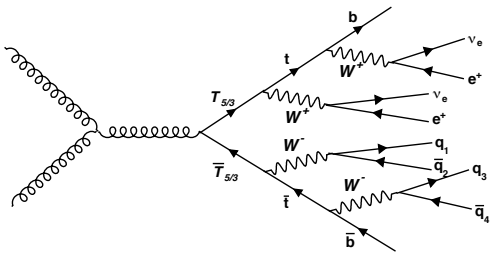




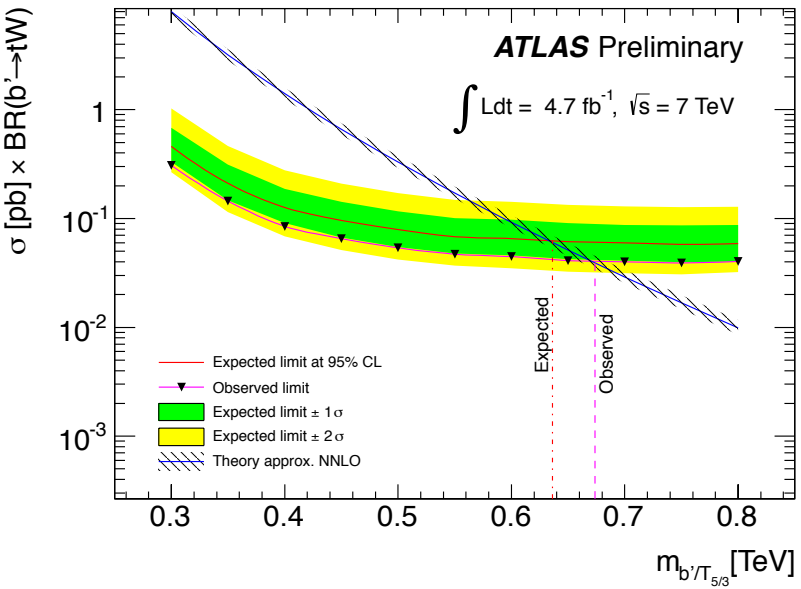
- The search is general, three specific b^*-quark coupling scenarios are considered to extract b^*-quark coupling and mass limits
- Limits shown for purely left-handed couplings and unit strength chromomagnetic coupling, **lower limit of 870 GeV**

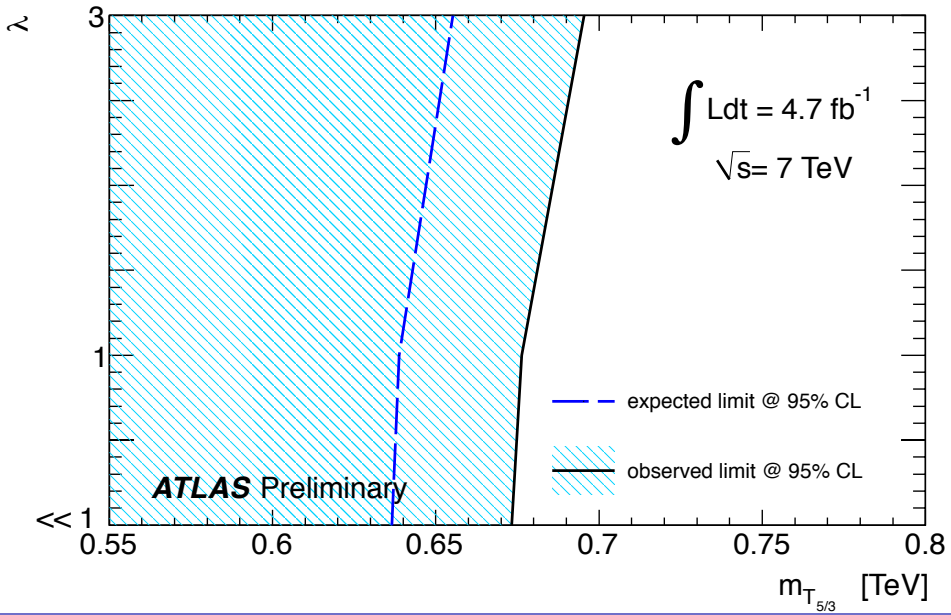
Search for new heavy quarks (7 TeV, 4.7 fb^{-1}, *ATLAS-CONF-2012-130*)

- Covers broad spectrum of BSM scenarios: pair production of down type heavy quarks (b'), single and pair production of $T_{5/3}$ (with charge $\pm\frac{5}{3}$), and four top quarks final state
  - Counting experiment performed in same charge ee, $e\mu$, $\mu\mu$ channels
  - Main backgrounds: charge mis-identification, lepton mis-reconstruction, diboson and $t\bar{t}$



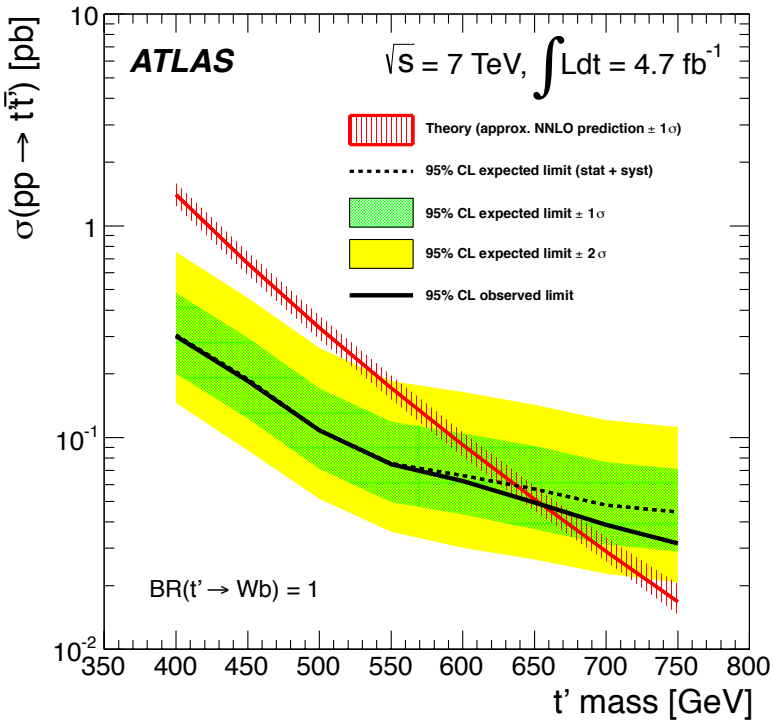
- Lower limit on b' and $T_{5/3}$ mass: **$>$0.67 TeV at 95% C.L.**, on the four top quarks production cross section: **$<$61fb at 95% C.L.**

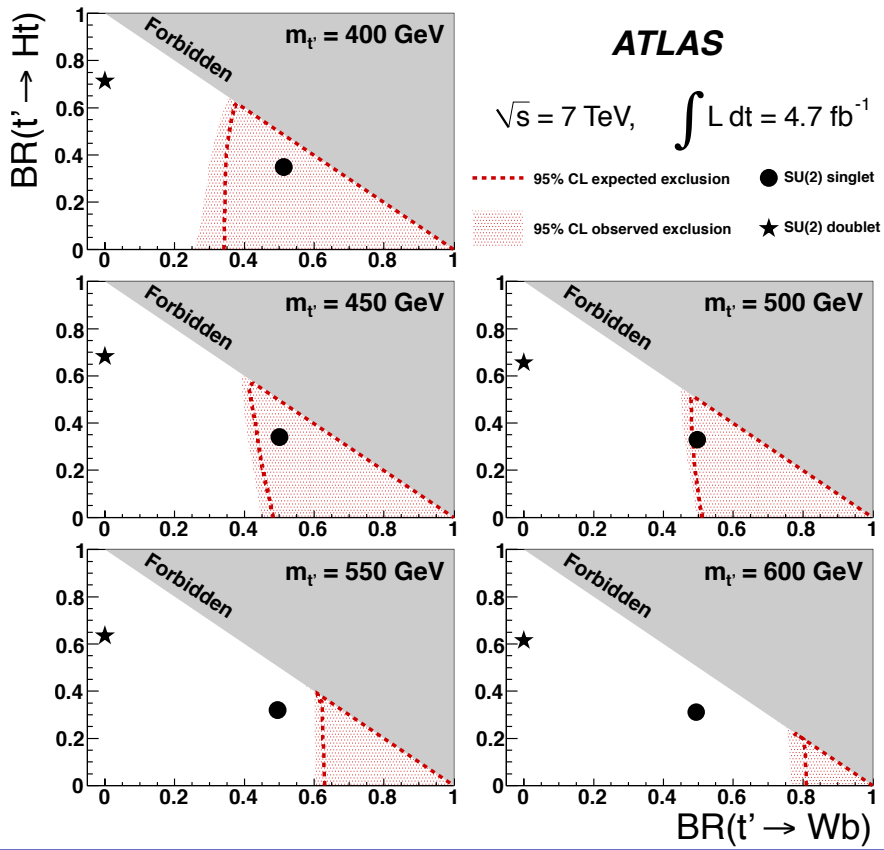




Search for new heavy quarks (7 TeV, 1.04 fb^{-1}, *PLB 718 (2013) 1284-1302*)

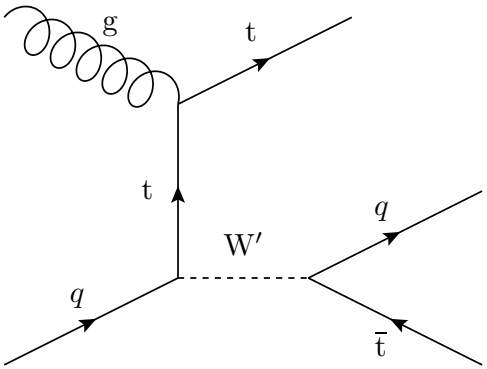
- Heavier fourth generation quarks often present in new physics models
- Generically assuming vector-like quarks coupling to the third family without a specific model (specific BR's)
- Search was done in l+jets channel and optimized for $t' \to Wb$ decay
- Most stringent limit up to date: $m_{t'} > \mathbf{656}$ GeV **@ 95% CL**





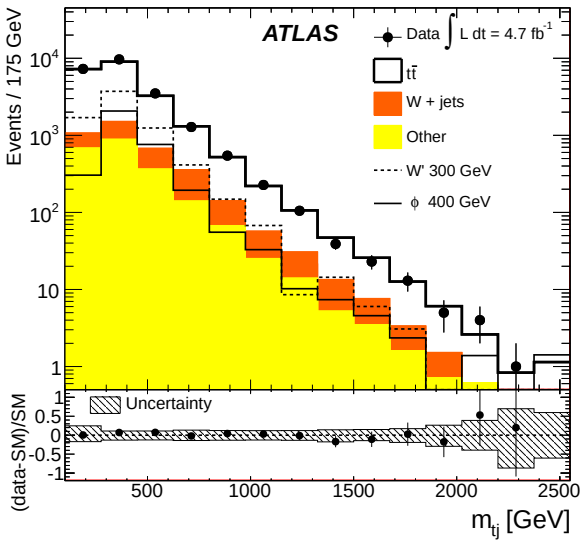
Search for top-jet resonances (7 TeV, 4.7 fb^{-1}, *PRD 86, 091103 (2012)*)

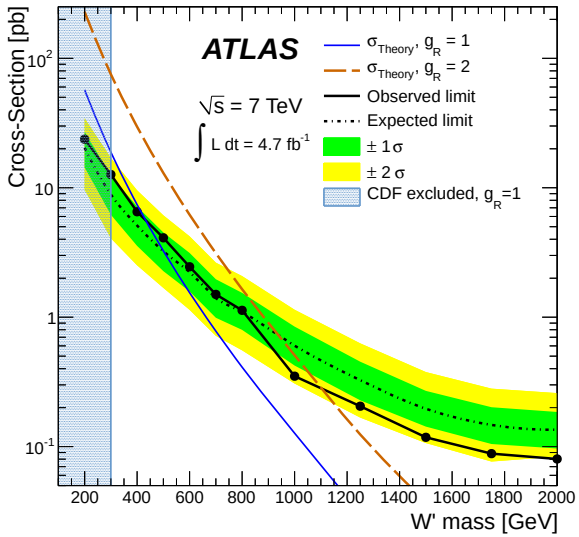
- In the models beyond SM, a new heavy particle, W' or ϕ can be produced at the LHC in association with a top or anti-top

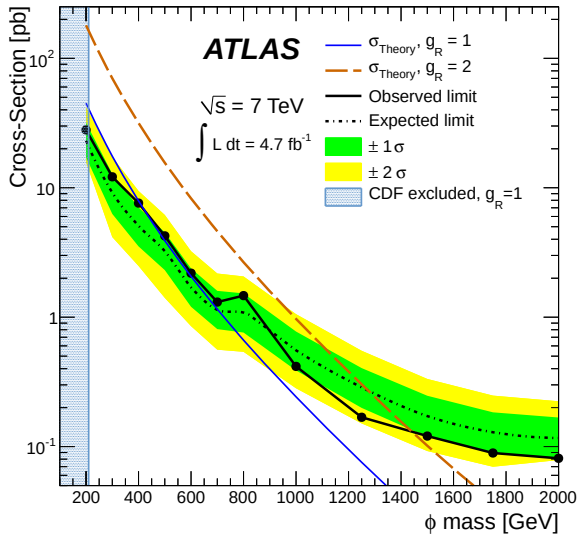


  - m_{tj} and $m_{\bar{t}j}$ are formed with an additional jet, which gives largest mass
  - Assuming unit coupling, the expected 95% C.L. lower limit on the mass of the new particle is 500 (700) GeV in the W' (ϕ) model

- **Lower limits of 430 GeV** are observed for W' and ϕ models.



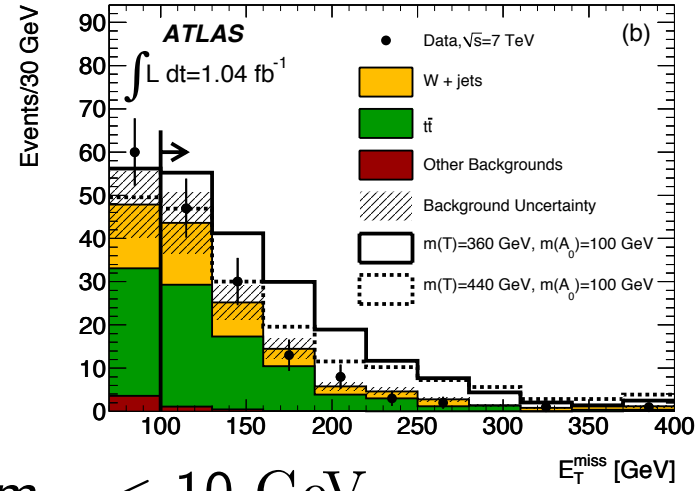




* Search for *tb* resonances (*PRL 109 (2012) 081801*)

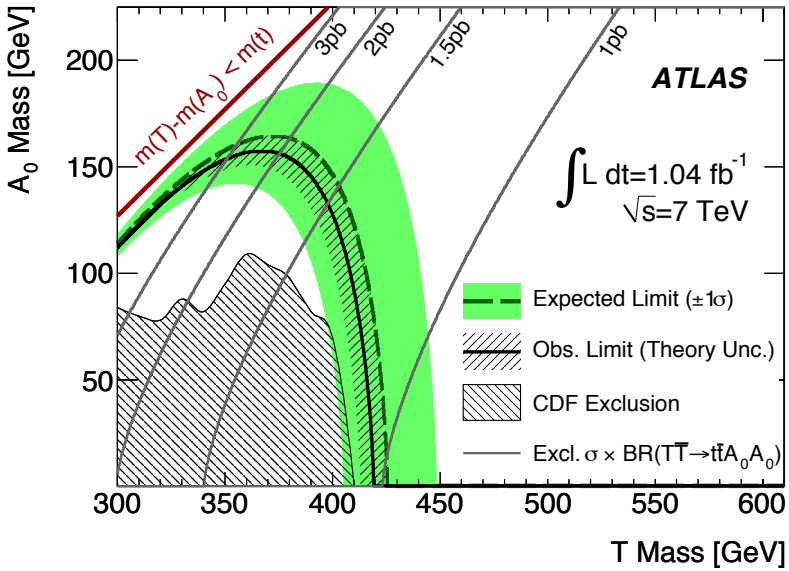
Search for $t\bar{t}$+large $E_{\mathrm{T}}^{\mathrm{miss}}$ (7 TeV, 1.04 fb^{-1}, *PRL 108 (2012) 041805*)

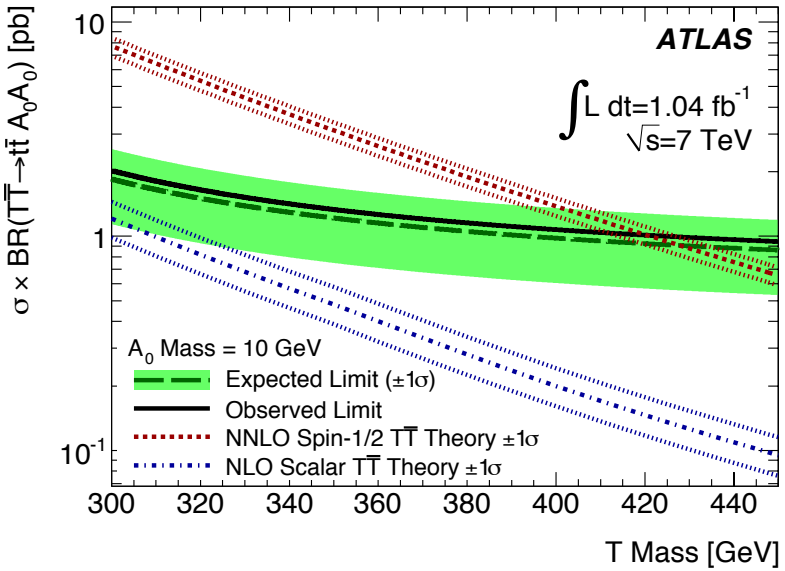
- Exotic top partners can decay:
  $T\bar{T} \to t\bar{t}A_0A_0$ (identical to $t\bar{t}$ final state, with large $E_{\mathrm{T}}^{\mathrm{miss}}$ from A_0 pair)
- $t\bar{t} \to l\nu b, qqb$, $\geq$4 jets, $E_{\mathrm{T}}^{\mathrm{miss}} > 100$ GeV, $m_T(l, E_{\mathrm{T}}^{\mathrm{miss}}) > 150$ GeV



Exclusion limits at the 95% C.L. :

- ▷ **T mass up to 420 GeV** excluded for $m_{A_0} < 10$ GeV
- ▷ **330 $<$ T mass $<$ 390 GeV** for $m_{A_0} < 140$ GeV





Summary

- LHC has been running successfully at 7 TeV and 8 TeV. ATLAS has recorded $>$90% good quality data.
- Top quark measurements are now entering the precision era at LHC
- Besides, an effort is made to search for new physics in the top sector
- Topics covered in this presentation:
  - Top mass measurement
  - Top quark polarization
  - Spin correlation
  - Measurement of $\sigma_{t\bar{t}\gamma}$
  - W helicity
  - Search for FCNC
  - Search for new heavy quark
  - Search for top-jet resonances
  - Search for $t\bar{t}$ + large $E_{\mathrm{T}}^{\mathrm{miss}}$

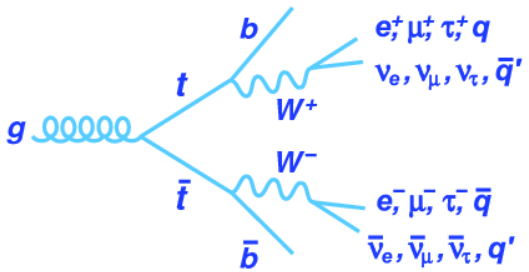
- Additional results can be found at ATLAS top group public results web page.
- More results are coming with data collected in 2012 at 8 TeV, as well as the results at 7 TeV


THANK YOU

Back up

Object definition and event selection

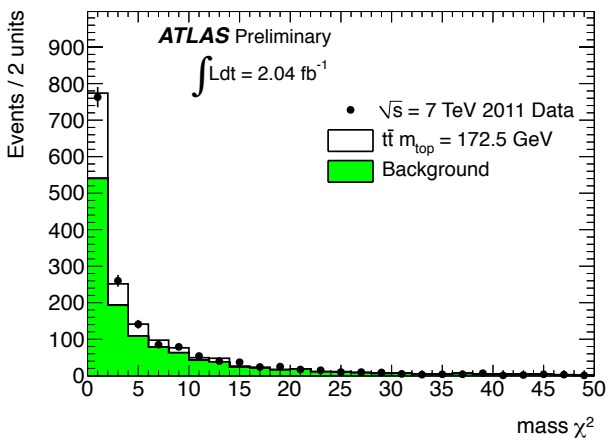
- Electrons:
  - EM cluster with track matched
  - Isolation in tracker and calorimeter
  - $E_T > 25$ GeV, $|\eta| < 1.37$ or $1.52 < |\eta| < 2.47$
- Muon:
  - Tracks in inner detector and muon spectrometer
  - Isolation in tracker and calorimeter
  - $p_{\mathrm{T}} > 20$ GeV, $|\eta| < 2.5$
- Jet:
  - Reconstructed from topological clusters using the anti-kt algorithm ($R = 0.4$)
  - $p_{\mathrm{T}} > 25$ GeV, $|\eta| < 2.5$
- Missing transverse energy $E_{\mathrm{T}}^{\mathrm{miss}}$
  - Vector sum of energy deposits in calorimeter
  - Corrected for identified objects
- b-tagging:
  - Neural network based b-tagging algorithm MV1 with average b-tagging efficiency of $\sim$70% and light jet rejection factor $\sim$140

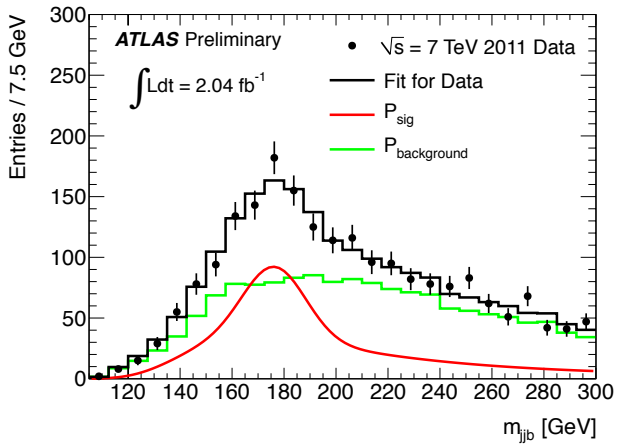


- Event selection:
  - lepton+jets: lepton trigger, exactly one lepton, $\geq$3 or 4 jets, b-tagged jets, $E_{\mathrm{T}}^{\mathrm{miss}}$
  - di-lepton: lepton trigger, two opposite charge leptons, $\geq$2 jets, b-tagged jets, $E_{\mathrm{T}}^{\mathrm{miss}}$, Z veto
  - full hadronic: mixed jet triggers, $\geq$5 jets, b-tagged jets

Top Mass: full hadronic (7 TeV, 2.04 fb^{-1})

- Preliminary: *ATLAS-CONF-2012-030*
- Event selection: 5 jets with p_{T} >55 GeV, 6th jet with p_{T} >30 GeV
- $\chi^2(m_W, m_{top}) = \frac{(m_{j_1,j_2} - m_W)^2}{\sigma_W^2} + \frac{(m_{j_1,j_2,b1} - m_{top})^2}{\sigma_{top}^2} + \frac{(m_{j_3,j_4} - m_W)^2}{\sigma_W^2} + \frac{(m_{j_3,j_4,b2} - m_{top})^2}{\sigma_{top}^2}$
- From MC: $\sigma_W = 10.2$ GeV and $\sigma_{top} = 17.4$ GeV
- Minimizing χ^2 to find the best combination





- Using the calibration curve and data:
  $m_{top} = 174.9 \pm 2.1(stat.) \pm 3.8(syst.)$ GeV
- Largest systematic uncertainties: 4j+2b or 5j+1b mixing; matching criteria for leading p_{T} jet; background modeling