

Top Quark Properties Measurements in ATLAS

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on behalf of the ATLAS Collaboration

Overview

Top Quark in the SM:

- Electric charge $+2/3 e$
- Short lifetime $0.5 \times 10^{-24} \text{s}$
- Width: $\sim 1.4 \text{GeV}$
- Branching ratio:
 $\sim 100\%$ decay into $W^+ b$
- Spin correlation of $t\bar{t}$
- Top unpolarized in $pp \rightarrow t\bar{t}$
- W helicity in top decay
- Small charge asymmetry
- Large coupling to Higgs



Free parameter in the SM:

- Top mass

Other things we can learn from top events:

- CPT violation:
- Top-Antitop mass difference
- $t\bar{t} + V$

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Other things we can learn from top events:

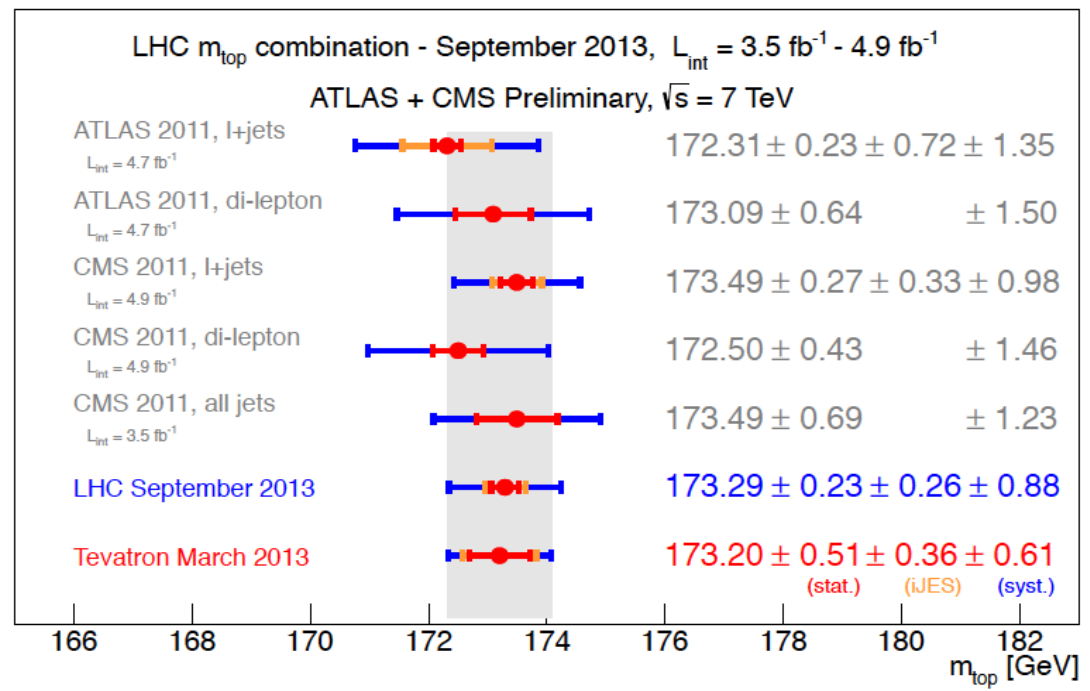
- **FCNC Search**
- **CP violation**
- **CPT violation:**
- **Top-Antitop mass difference**
- **$t\bar{t} + V$**



Top Quark Mass

- Motivation:
 - Not predicted by the SM
 - Together with Higgs: check consistency
- Several measurements by LHC and Tevatron collaborations
 - In various channels, using various methods

■ LHC combination:

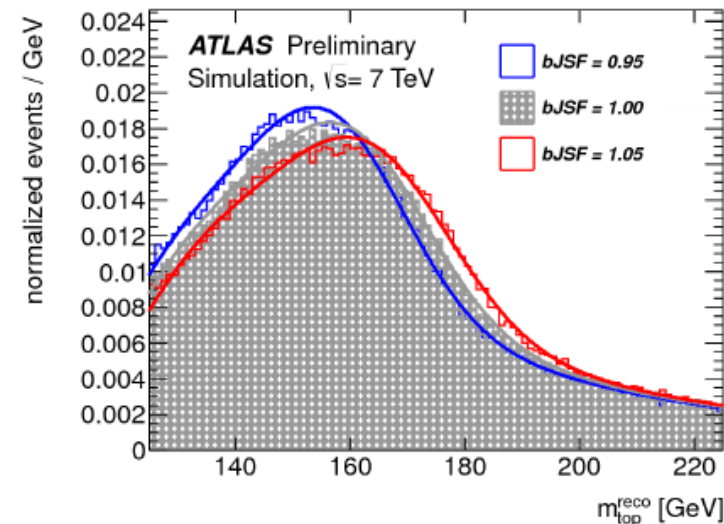


ATLAS-CONF-2013-102
CMS PAS TOP-13-005

Top Quark Mass

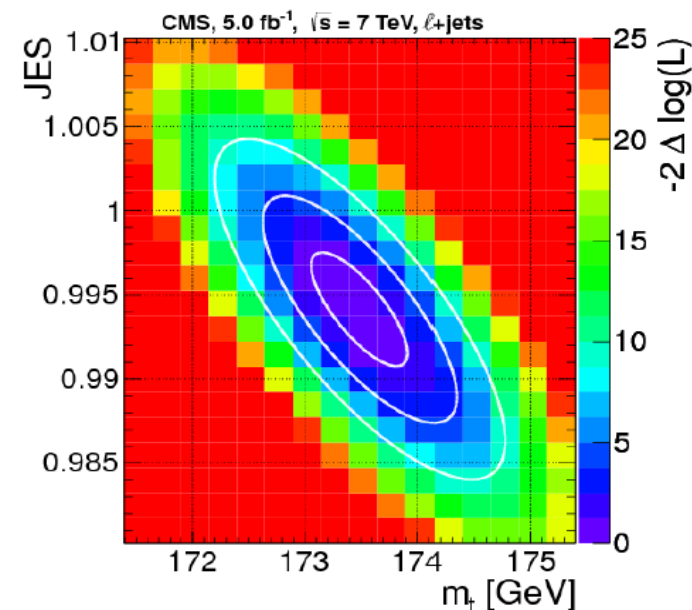
■ ATLAS inputs:

- ATLAS: l+jets and dilepton final state with template method
- l+jets: 3D method:
fit top mass, JES and b-JES



■ CMS inputs:

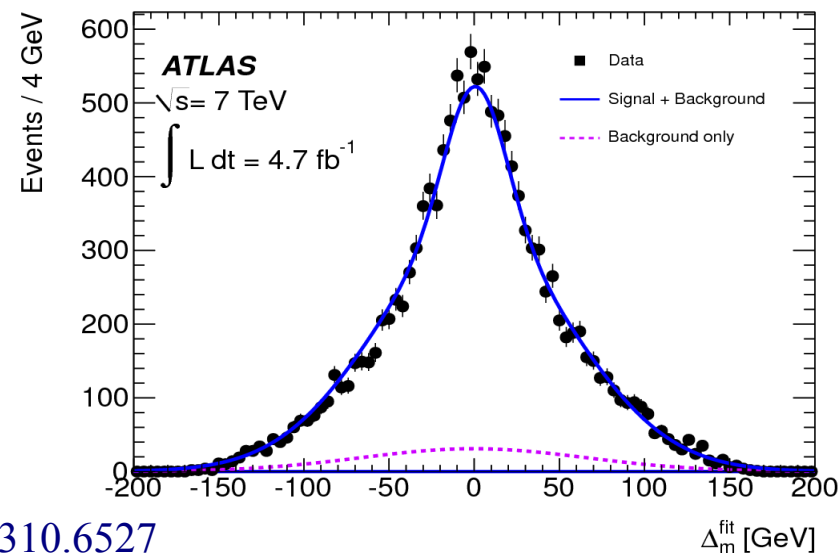
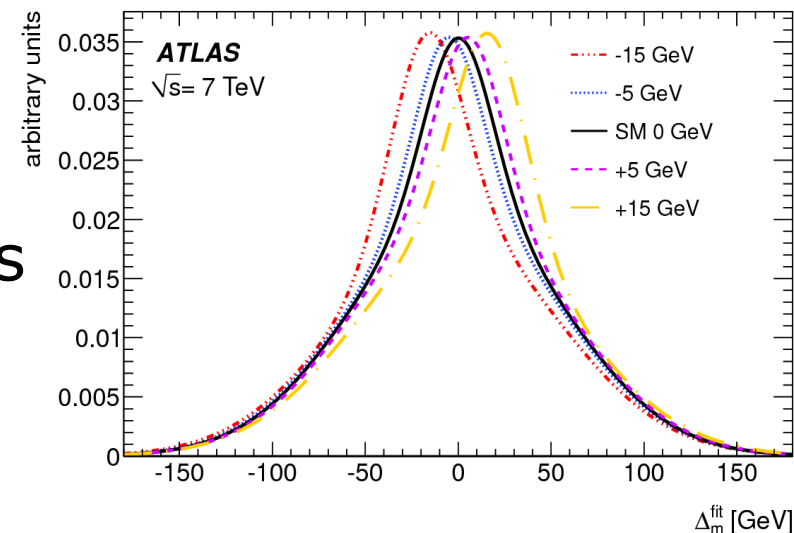
- CMS: l+jets, dilepton and all-hadronic
 - l+jets and all-hadronic: ideogram method
 - Dilepton: template method



Top-Antitop Mass Difference

- Do top and anti-top have equal mass?
 - If not: CPT violation!
- Using template technique in $l+jets$ events
 - Kinematic fit of $t\bar{t}$ events, with top antitop mass difference as free parameter in each event
 - Assume average top mass of 172.5 GeV
- Result:

$$m_t - m_{\bar{t}} = 0.67 \pm 0.61(\text{stat}) \pm 0.41(\text{syst}) \text{ GeV}$$
- Still statistics limited
- Good agreement with the SM!



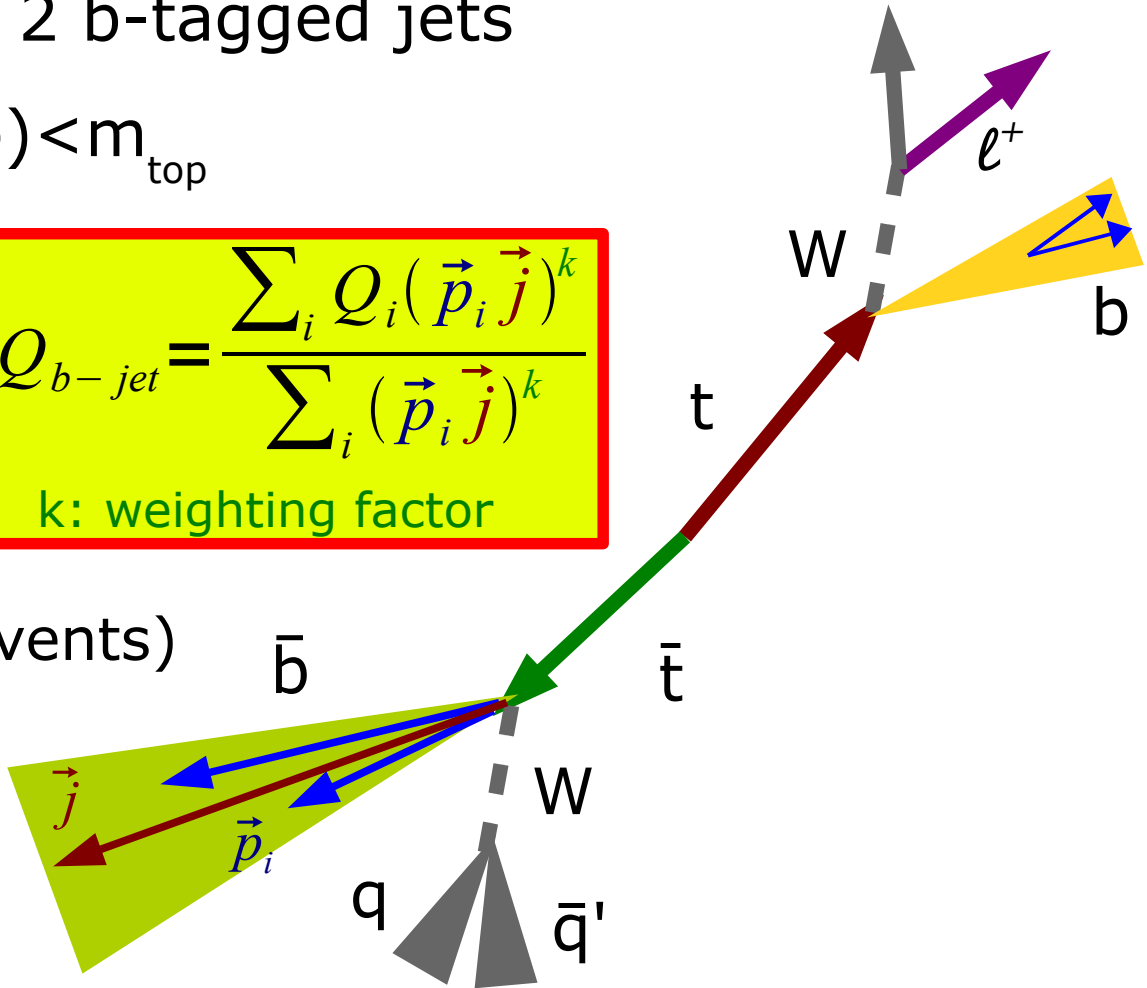
arXiv:1310.6527

Top Quark Charge

- Exotic model with top charge $-4/3 e$ could be possible (SM: $+2/3e$)
- Use l+jets events with at least 2 b-tagged jets
- **Lepton-b pairing**: Expect $m(l,b) < m_{top}$
 → use for choice of pairing
- b-jet charge: weighting technique
 - Use up to 10 tracks in jet
 - k set to 0.5 (optimized on $t\bar{t}$ events)
- Determine top charge from
 - Lepton from W
 - b-jet charge

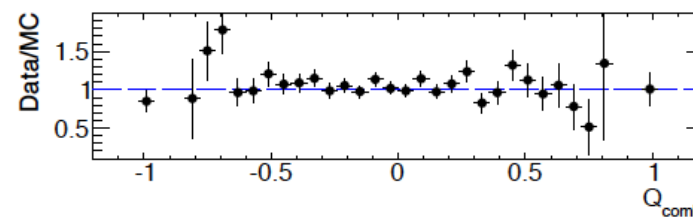
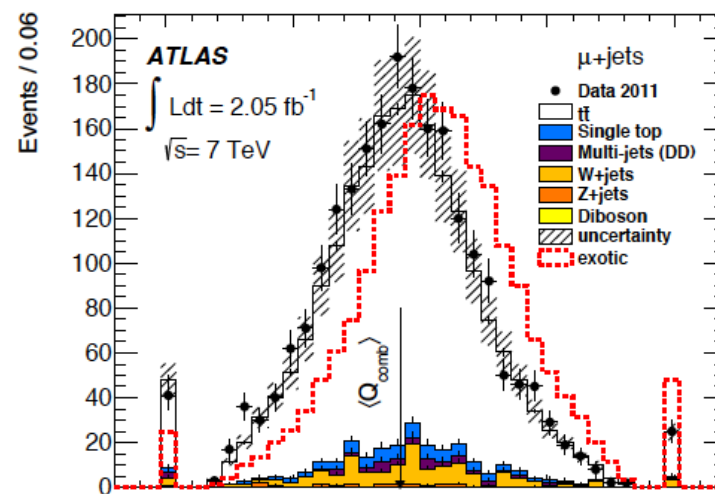
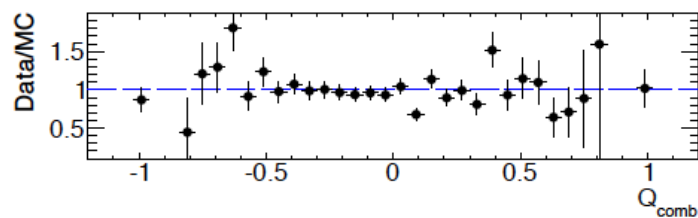
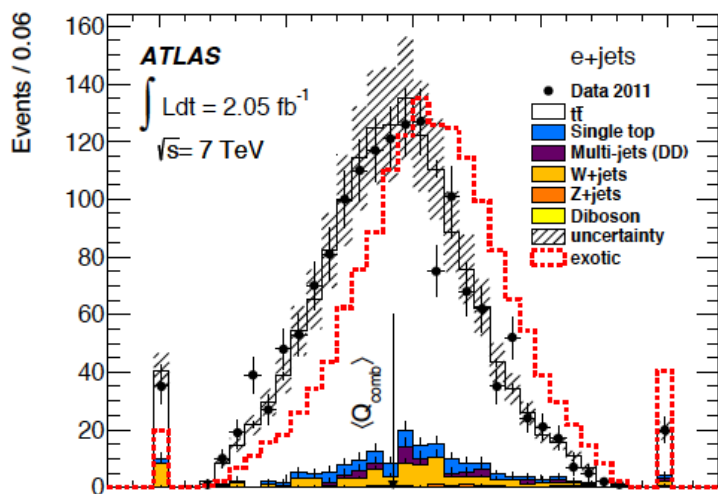
$$Q_{b-jet} = \frac{\sum_i Q_i (\vec{p}_i \cdot \vec{j})^k}{\sum_i (\vec{p}_i \cdot \vec{j})^k}$$

k: weighting factor



Top Quark Charge

- Calculate charge and build templates of $Q_{\text{comb}} = Q_{b\text{-jet}}^l \cdot Q_l$.



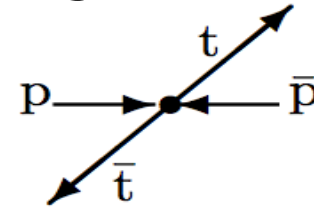
arxiv: 1307.4568

Exclude exotic top charge of $-4/3 e$ with more than 8 sigma!

Asymmetry: Idea

- NLO QCD: Interference between $q\bar{q}$ diagrams \rightarrow causes $t\bar{t}$ asymmetry

- Top quarks more likely to go into direction of incoming quark

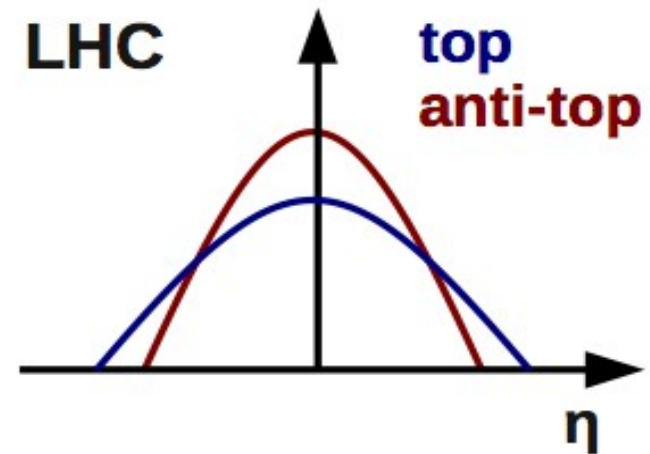


- At Tevatron: asymmetry measured somewhat higher than SM prediction
- LHC: Quarks are valence quarks, antiquark always are from the sea \rightarrow antitop less boosted and more central than top in case of asymmetry
- Measure charge asymmetry at LHC

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

$$|y| = |y_t| - |y_{\bar{t}}|$$

$$y = \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right)$$





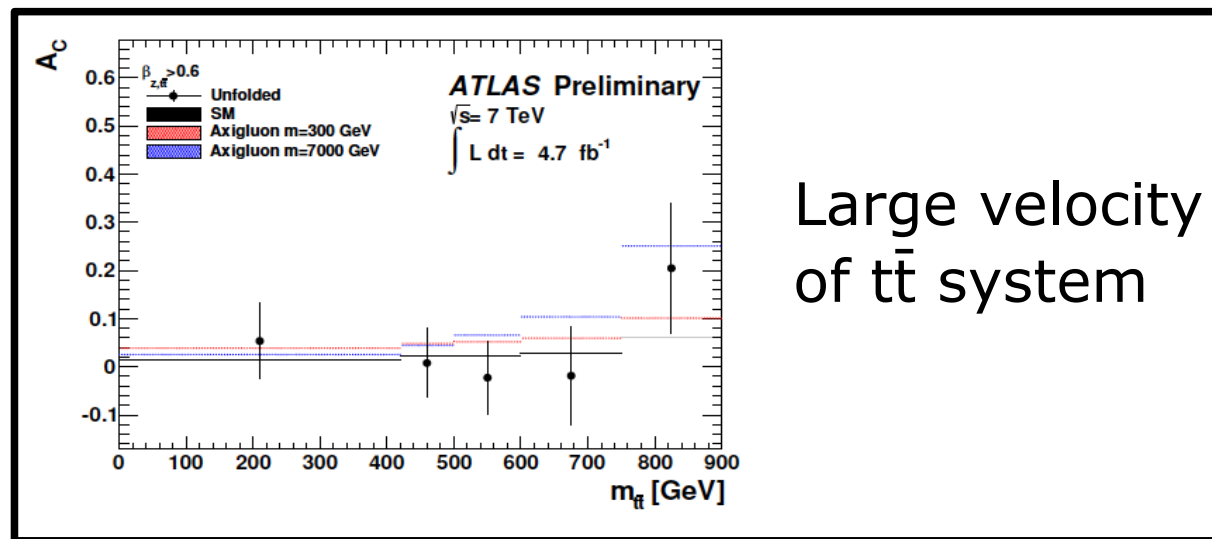
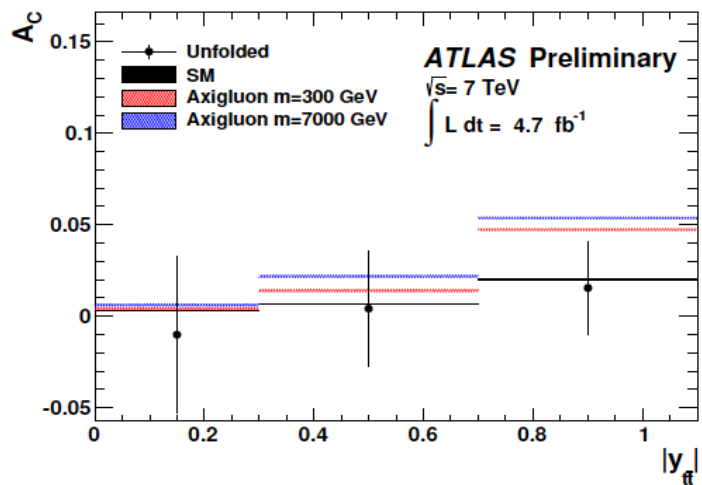
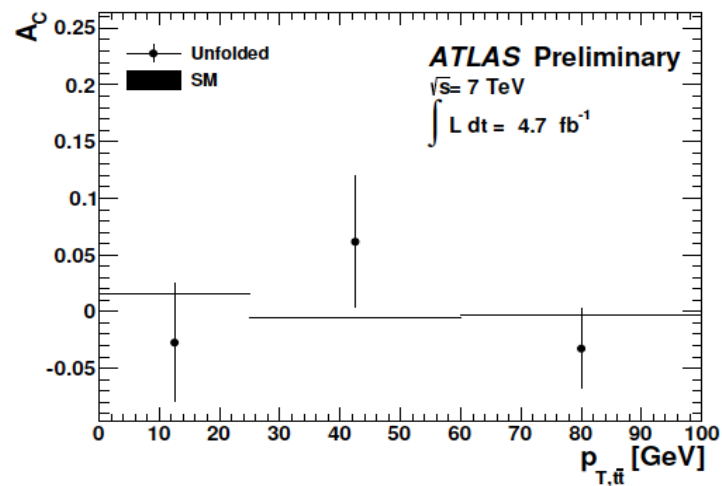
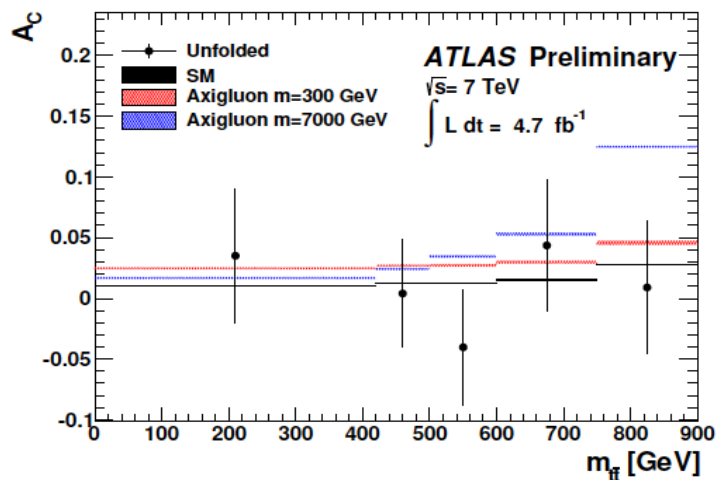
Charge Asymmetry: $l+jets$

- Charge asymmetry in $l+jets$ events
 - Inclusive, differential and for highly boosted $t\bar{t}$ events
 - Enhancement of sensitivity to BSM effects
 - Corrected of detector and acceptance effects: **Full Bayesian unfolding**
- **Inclusive:** $A_C = -0.006 \pm 0.010$ (stat+syst)
 - Compatible with SM prediction of 0.0123 ± 0.0005
- **Differential** wrt. several variables:
 - $p_T^{t\bar{t}}$ sensitive to ratio of negative and positive contributions to overall asymmetry
 - $m_{t\bar{t}}$ dependence as $q\bar{q}$ process enhanced for larger $m_{t\bar{t}}$
 - gg-fusion dominant in central **rapidity** region, $q\bar{q}$ process contributes more for forward rapidity region

Bernreuther, Si, PRD 86, 034026 (2012)

ATLAS-CONF-2013-078

Charge Asymmetry: $l+jets$



Large velocity
of $t\bar{t}$ system

- No deviation from SM expectation seen

ATLAS-CONF-2013-078

Charge Asymmetry: Dilepton

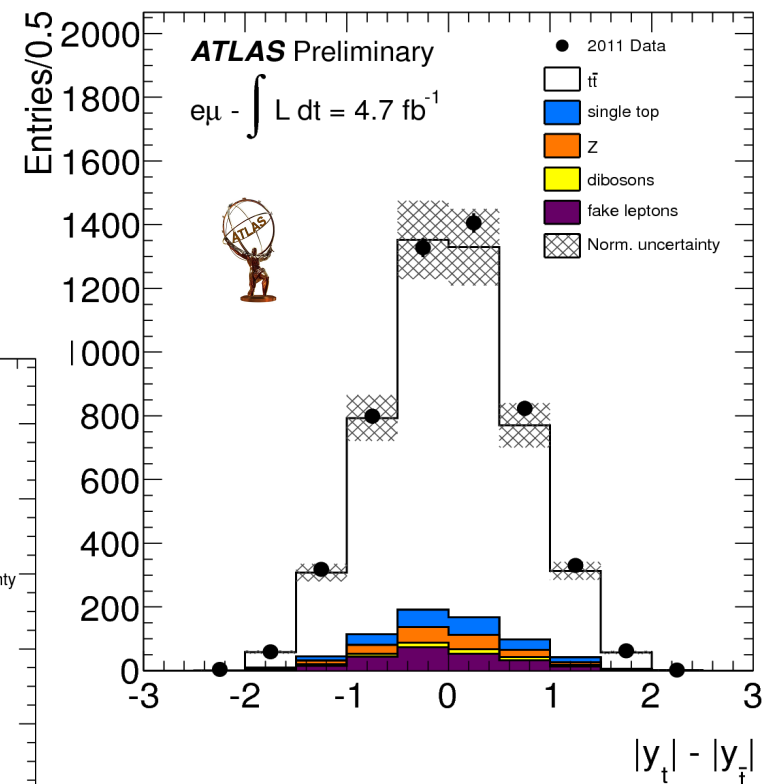
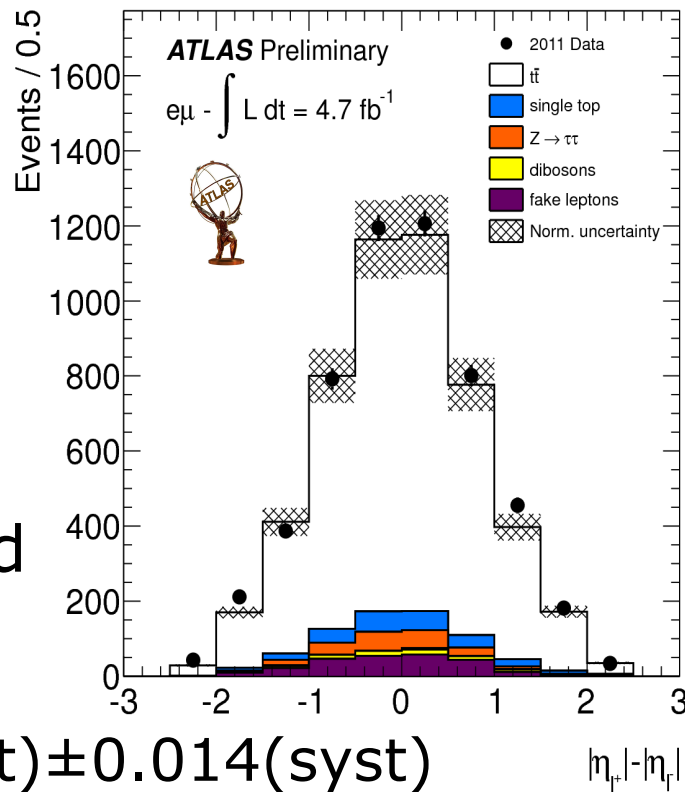
Inclusive measurements:

- $A_c^{ll} = 0.023 \pm 0.012(\text{stat}) \pm 0.008(\text{syst})$
 - MC@NLO prediction: 0.004 ± 0.001
- $A_c = 0.057 \pm 0.024(\text{stat}) \pm 0.015(\text{syst})$

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

Combination of ATLAS A_c results in l+jets and dilepton final state

- $A_c = 0.029 \pm 0.018(\text{stat}) \pm 0.014(\text{syst})$



ATLAS-CONF-2012-057

Polarization



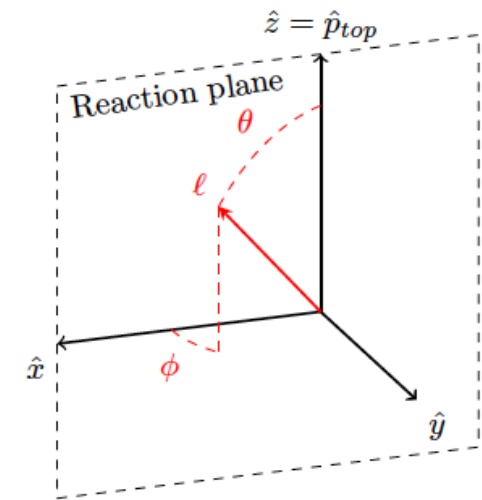
- Motivation: some models predicting larger asymmetry at Tevatron also induce top polarization

- Predicted to be ~ 0 in SM

- Doubly differential distribution:

$$d\sigma \propto 1 \pm (\alpha P)_1 \cos \theta_1 \pm (\alpha P)_2 \cos \theta_2 - C \cos \theta_1 \cos \theta_2$$

P_n : polarization; C: spin correlation; K_i : spin analyzing power of decay product i; θ_i : direction of daughter wrt. chosen axis



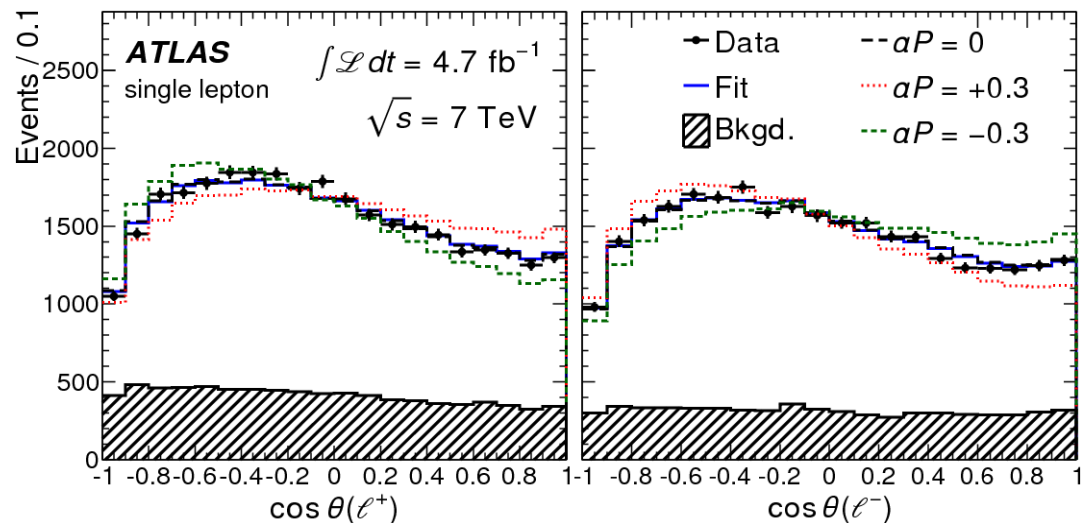
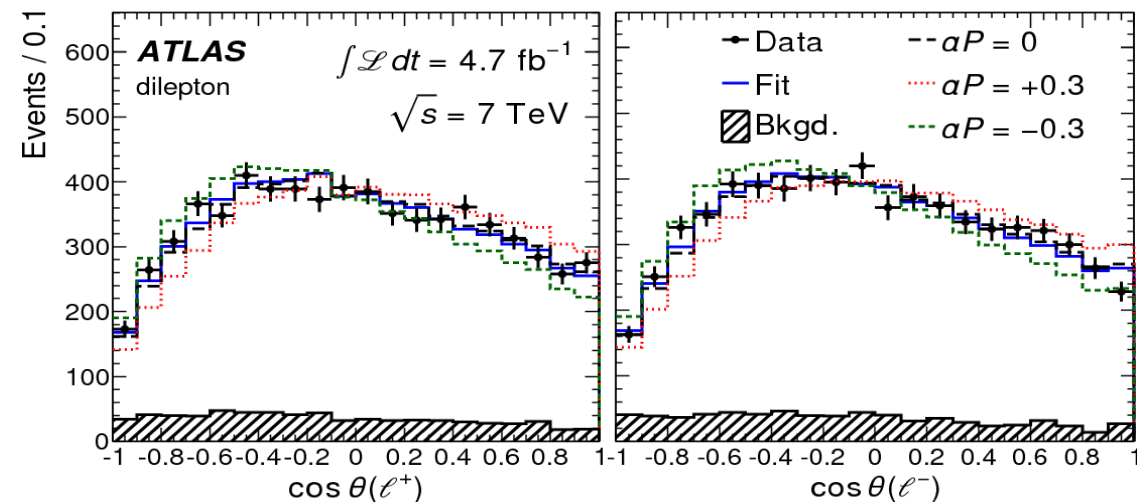
- Measurement in dilepton and l+jets final state: use $\cos \theta$ templates

- Reconstruction of full $t\bar{t}$ event required
 - Template fit for two scenarios:
 - CP conserving: $(\alpha P)_1 = (\alpha P)_2$
 - CP violating: $(\alpha P)_1 = -(\alpha P)_2$

Polarization

■ CP conserving:

CP violating:



■ Results:

$$\alpha_l P_{CPC} = -0.035 \pm 0.014 (stat) \pm 0.037 (syst)$$

$$\alpha_l P_{CPV} = 0.020 \pm 0.016 (stat)_{-0.017}^{+0.013} (syst)$$

■ Consistent with SM prediction

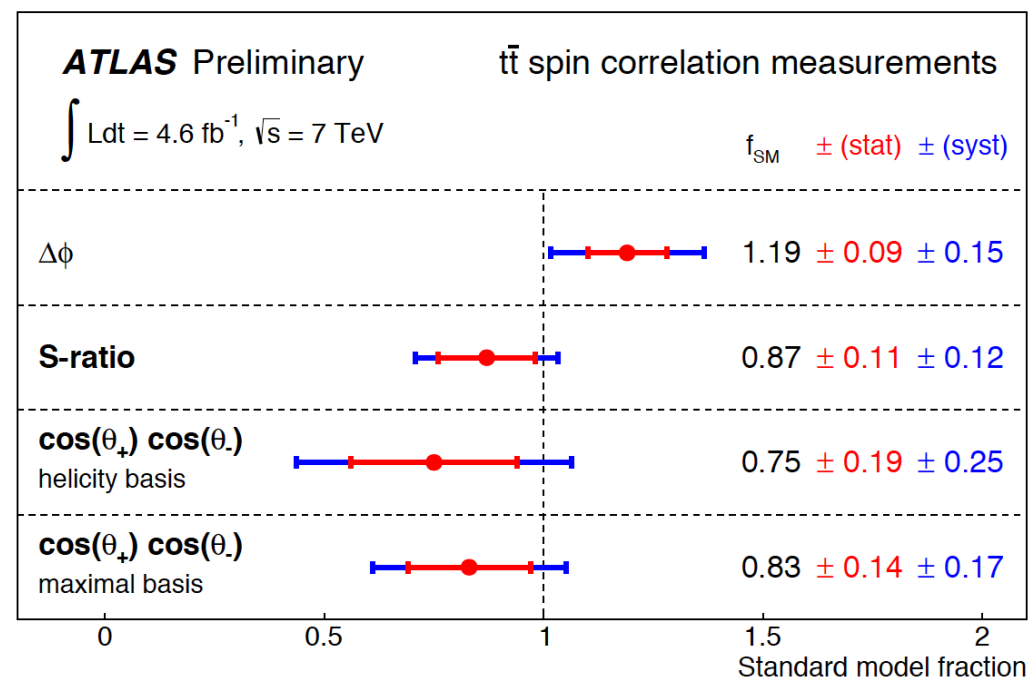
$t\bar{t}$ Spin Correlations

- Test full chain from production to decay!
- LHC: $\sim 85\%$ $gg \rightarrow t\bar{t}$: dominated by **like helicity gluons** at low \sqrt{s}
- Three sets of variables with complementary information:
 - Simple azimuthal angle: $\Delta\phi = |\phi_{l^+} - \phi_{l^-}|$

- No kinematic reconstruction needed!

- Angles θ_1 (θ_2) between decay products and quantization axis
- **Ratio of matrix elements** between correlated and uncorrelated hypothesis

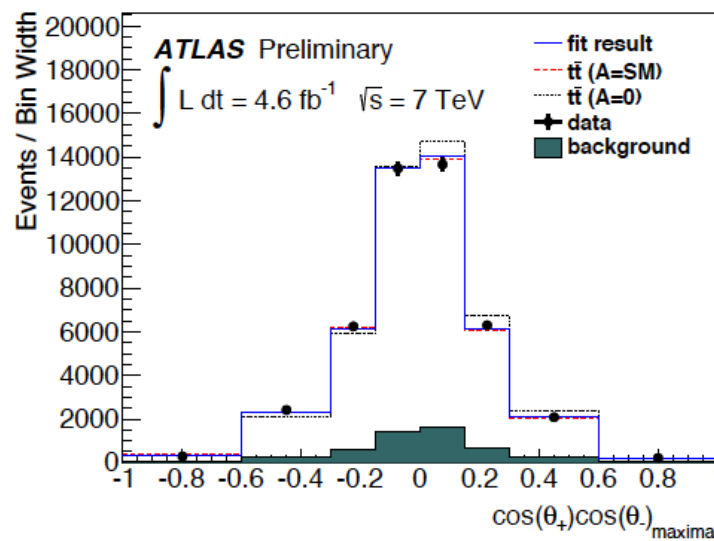
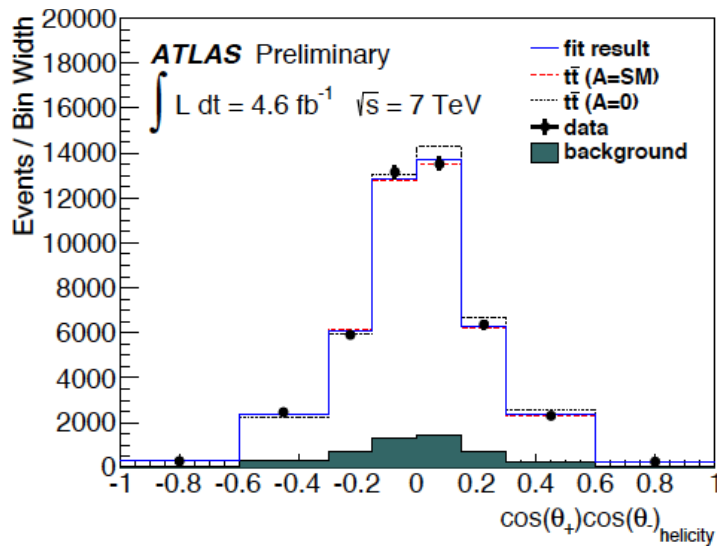
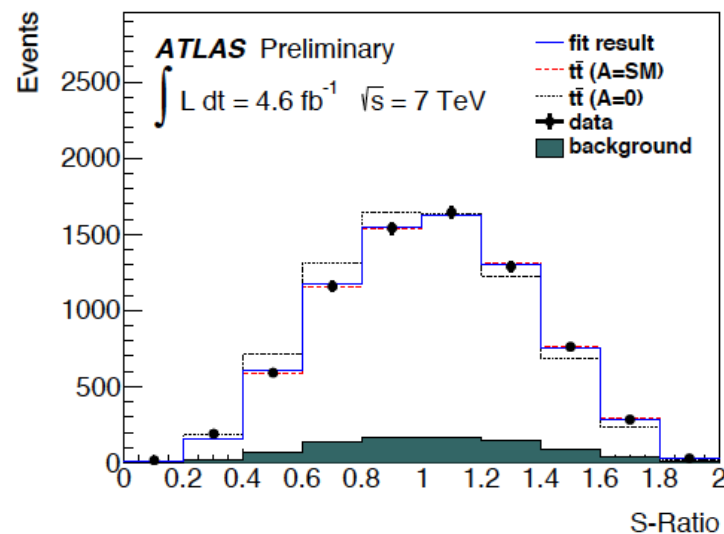
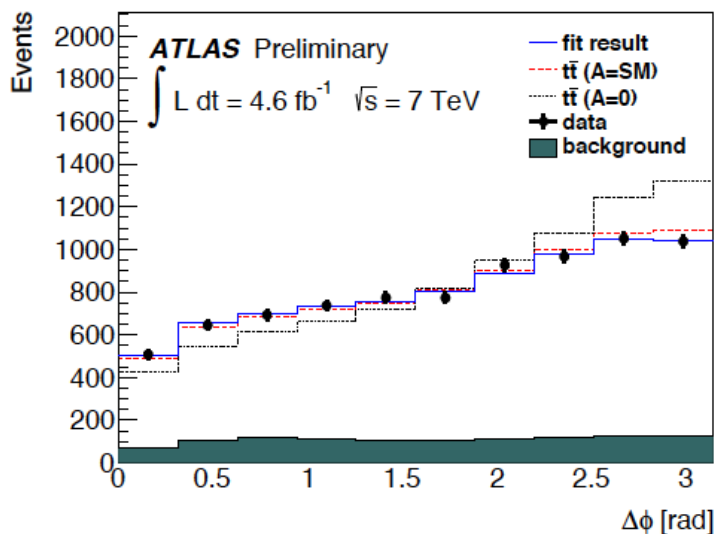
$$S = \frac{(|\mathcal{M}|_{RR}^2 + |\mathcal{M}|_{LL}^2)_{\text{corr}}}{(|\mathcal{M}|_{RR}^2 + |\mathcal{M}|_{LL}^2)_{\text{uncorr}}}$$



- Measurement performed in dilepton channel

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$t\bar{t}$ Spin Correlations

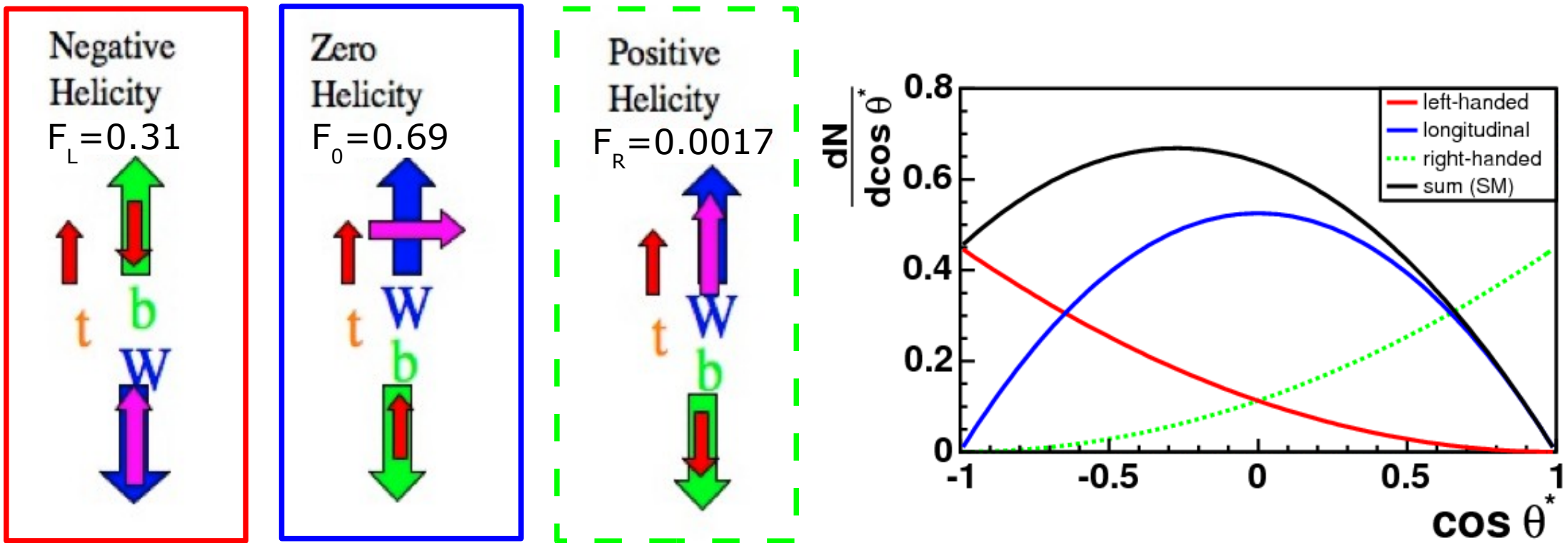


■ Measurements compatible with SM prediction

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W Helicity

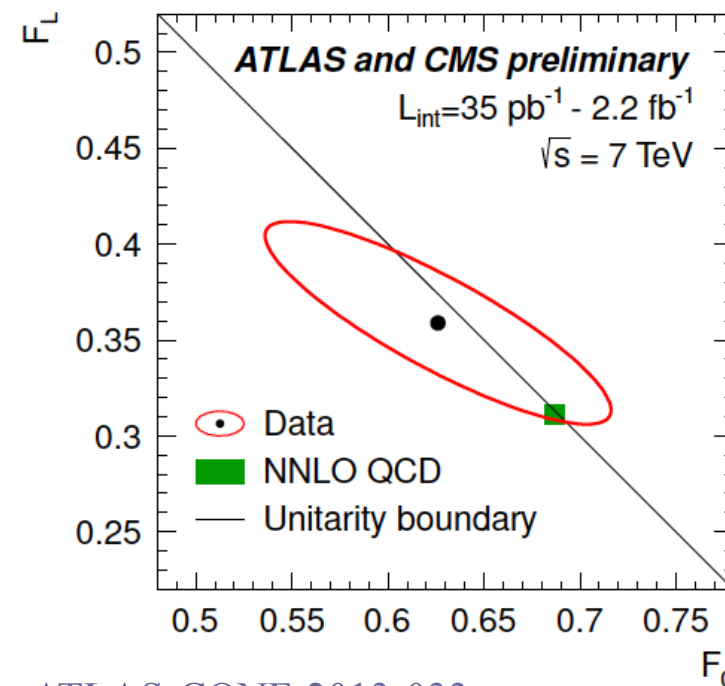
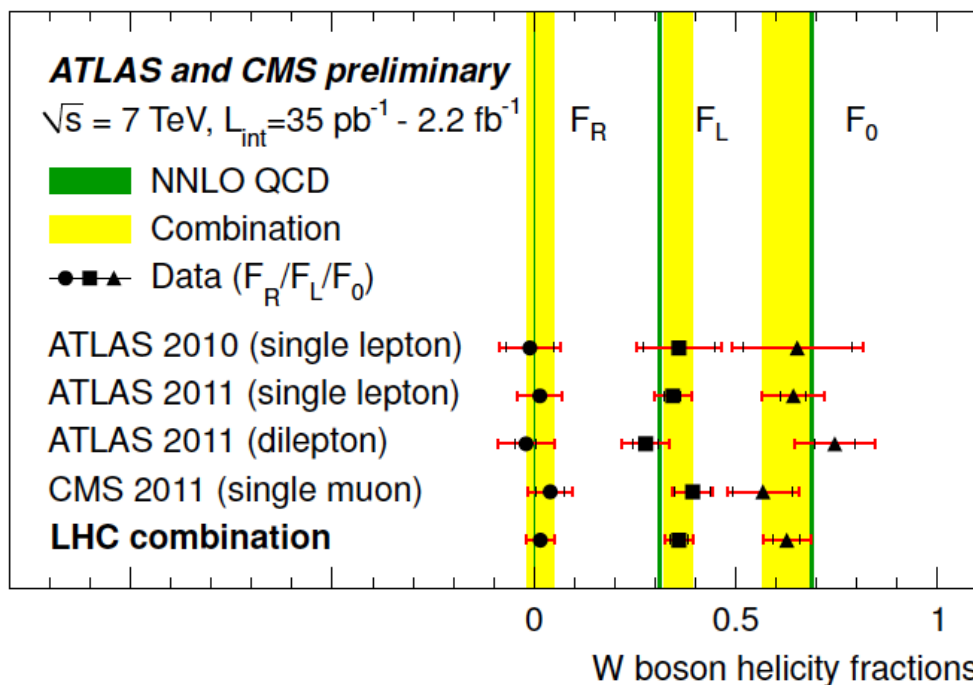
- Left handed coupling of W-boson to fermions:
Not every combination of spin for W and b-quark is allowed



- Measure angle θ^* between down-type decay product and reversed direction of the top quark in the W rest frame

W Helicity

- LHC combination using ATLAS & CMS measurements
 - Dilepton and l+jets
 - Template fit and asymmetry measurement in $\cos \theta^*$
 - Combination done using BLUE



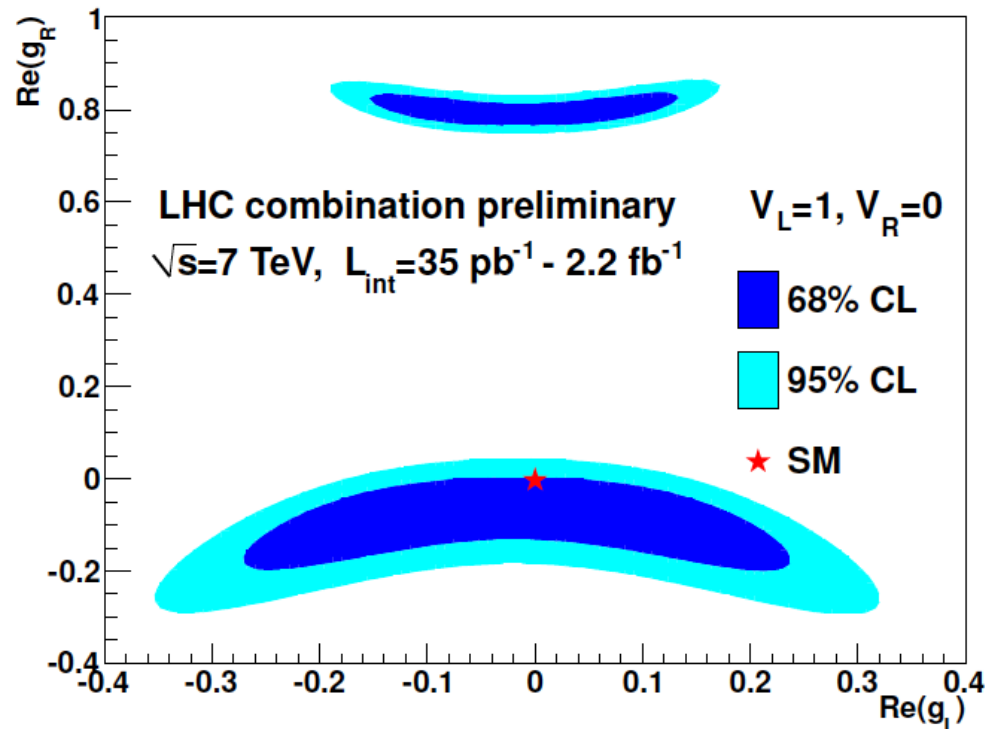
- Good agreement with SM prediction

ATLAS-CONF-2013-033
 CMS PAS TOP-12-025

Anomalous Couplings

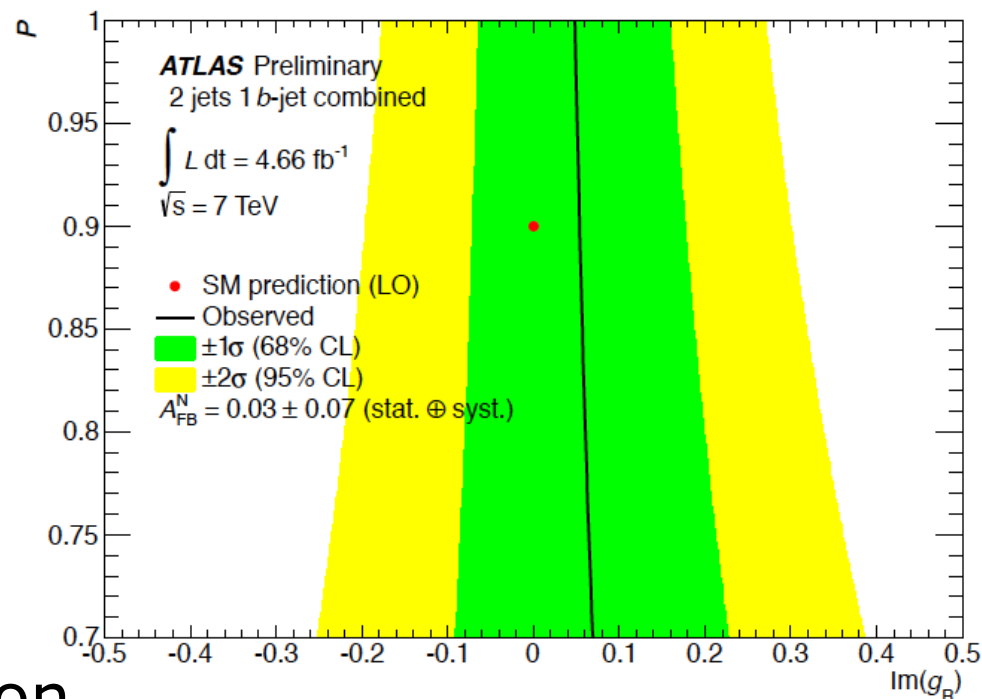
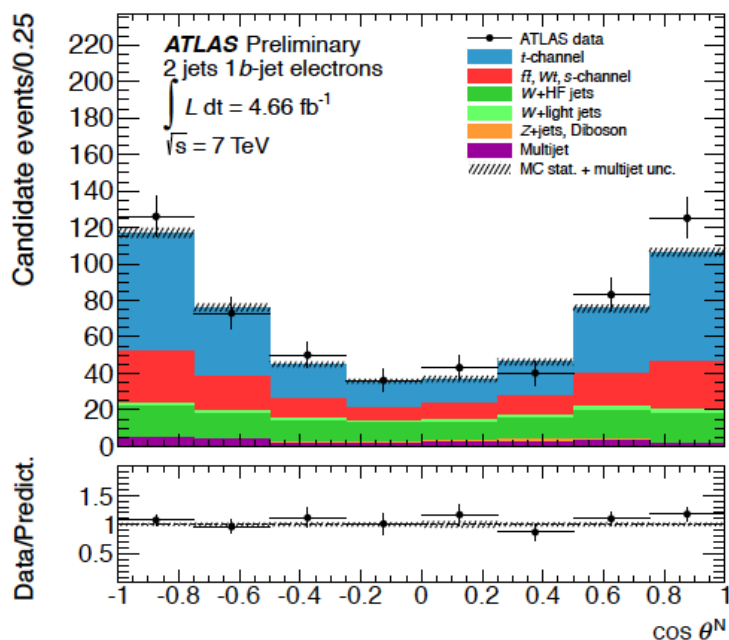
- Using effective field theory: translate helicity fractions into couplings → set limits on anomalous couplings

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



CP Violation

- Test anomalous couplings in t-channel single top \rightarrow probe $\text{Im}(g_r)$
- Events with 2 jets, one identified as b-jet, 1 lepton, missing ET
 - Asymmetry in $\cos \theta^N$
 - θ^N : between direction of lepton in W rest frame and W in top rest frame

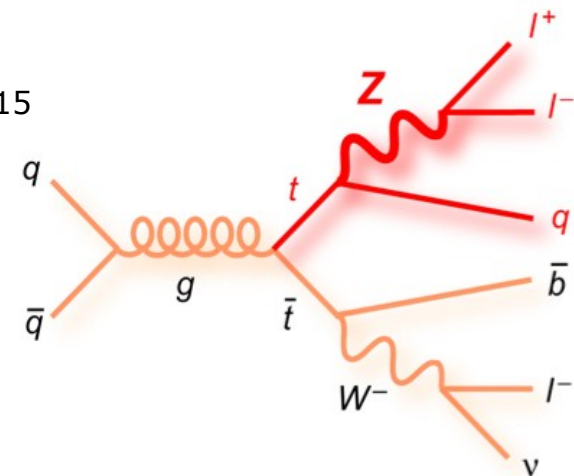


- Limit consistent with SM prediction

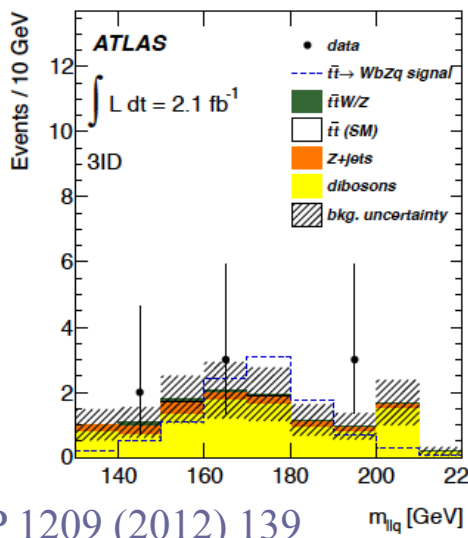
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FCNC

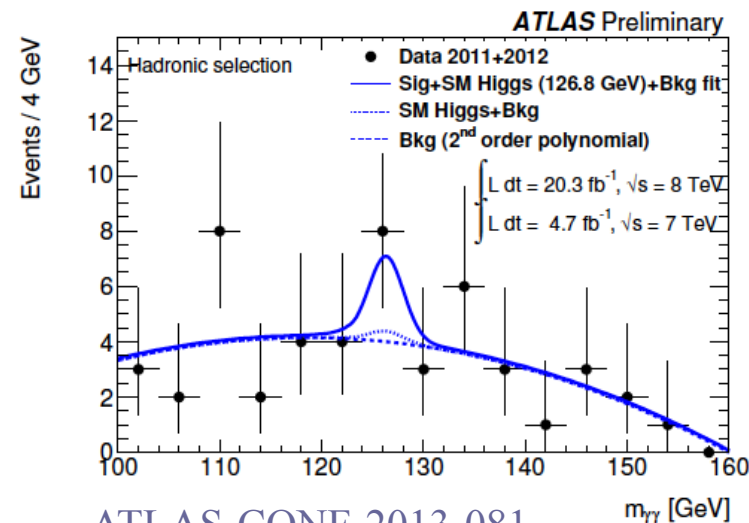
- Many beyond SM models predict FCNC
 - Suppressed in SM: $\text{Br}(t \rightarrow Zq) \sim 10^{-14}$, $\text{Br}(t \rightarrow Hc) \sim 3 \times 10^{-15}$
- Search for $t \rightarrow Zq$ in tripletonic $t\bar{t}$ events and $t \rightarrow Hc$ in $l + \text{jets}$ and all-hadronic events with $H \rightarrow \gamma\gamma$
- $t \rightarrow Zq$: Require events with 3 leptons
 - Kinematically consistent with $t\bar{t} \rightarrow WbZq$: χ^2 minimization
- $t \rightarrow Hc$: Reconstruct $\gamma\gamma$ invariant mass
- No evidence for FCNC found \rightarrow set upper limits



$\text{Br}(t \rightarrow Zq) < 0.73\% @ 95\% \text{ CL}$
 $\text{Br}(t \rightarrow Hc) < 0.83\% @ 95\% \text{ CL}$



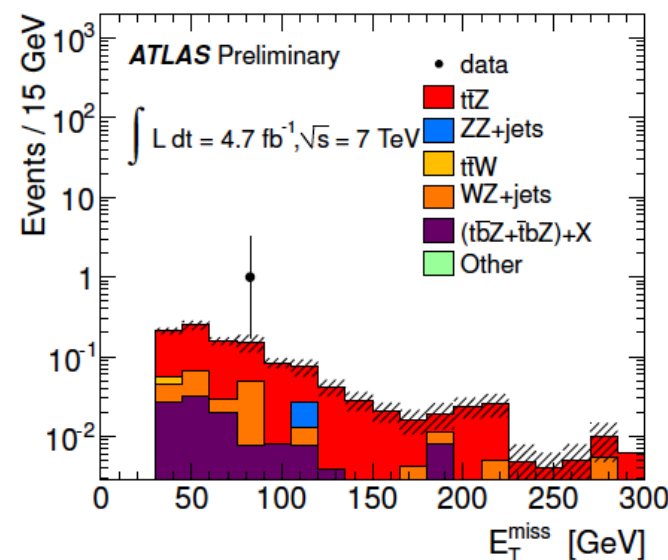
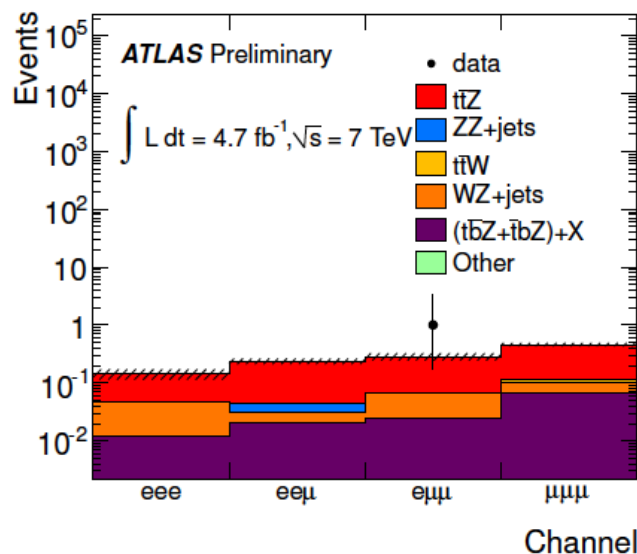
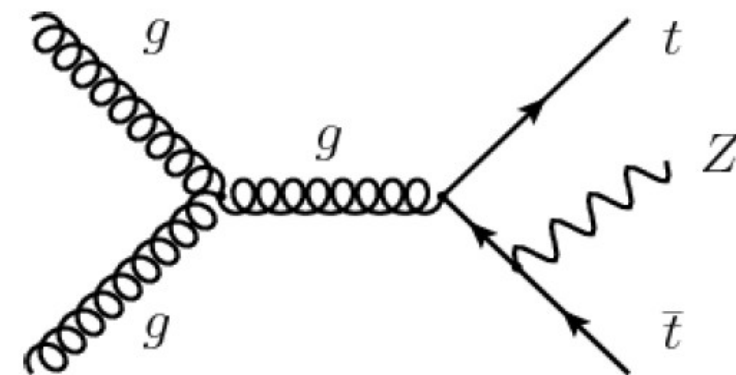
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ATLAS-CONF-2013-081

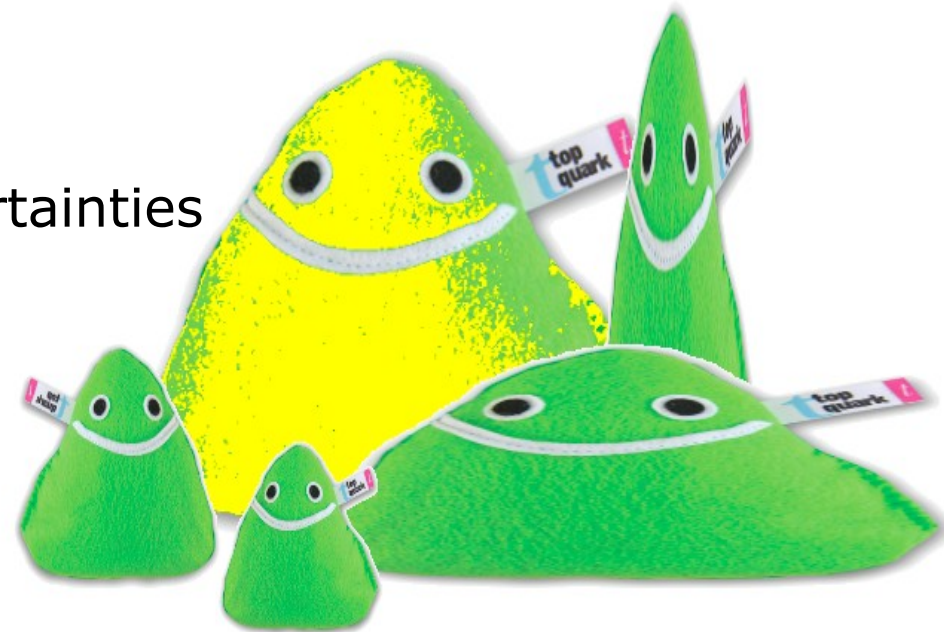
$t\bar{t}+Z$

- Coupling of top to Z boson: measure $t\bar{t}Z$ cross section
 - Events with 3 leptons, where $Z \rightarrow ll$
- One candidate event observed
 - Expected from SM: 0.85 events + 0.28 events from background
 - Upper 95% CL limit: $\sigma_{t\bar{t}Z} < 0.71 \text{ pb}$ (0.74 pb expected)



Summary

- Many interesting top quark properties measurements performed at ATLAS
 - Precision measurements
 - many dominated by systematic uncertainties
 - Sensitive searches for new physics
- All compatible with SM so far
- More info and analyses:
<https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults>
- All presented analyses using 7 TeV data sample from 2011
- 8 TeV sample currently being analyzed



Stay Tuned!

BACKUP



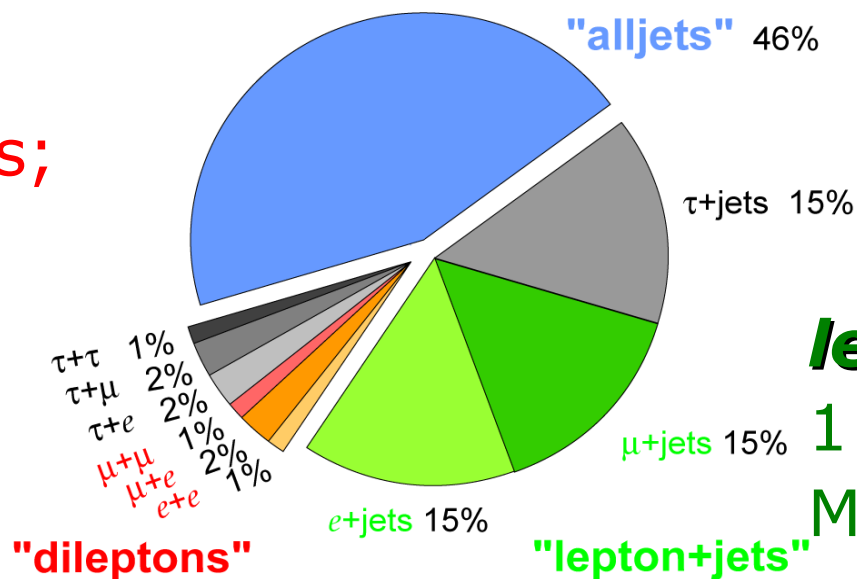
$t\bar{t}$ Final States

$t\bar{t}$ $W^+bW^-\bar{b}$: Final states are classified according to W decay

$$B(t \rightarrow W^+b) = 100\%$$

pure hadronic:
 ≥ 6 jets (2 b-jets)

Top Pair Branching Fractions



dilepton:

2 isolated leptons;
High missing E_T
from neutrinos;
2 b-jets

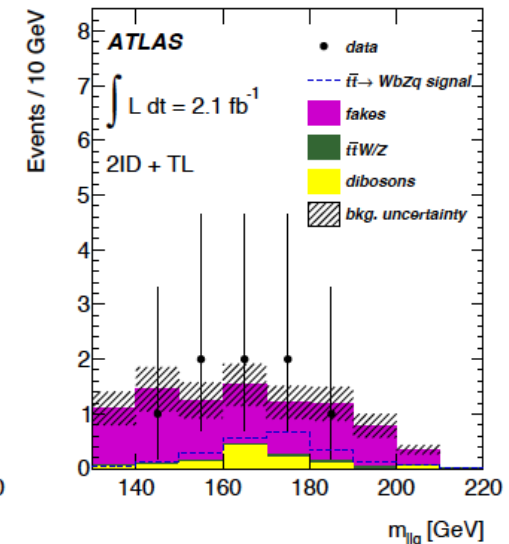
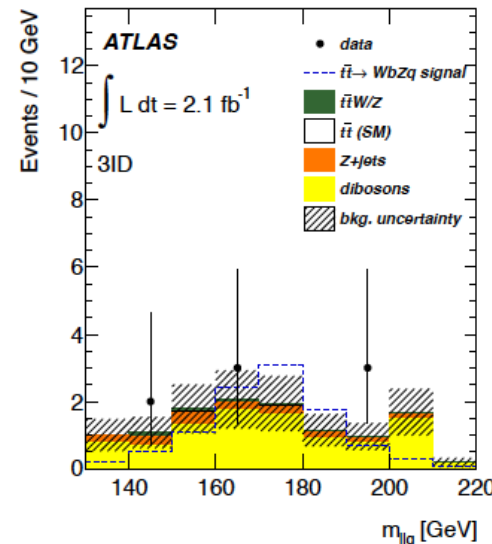
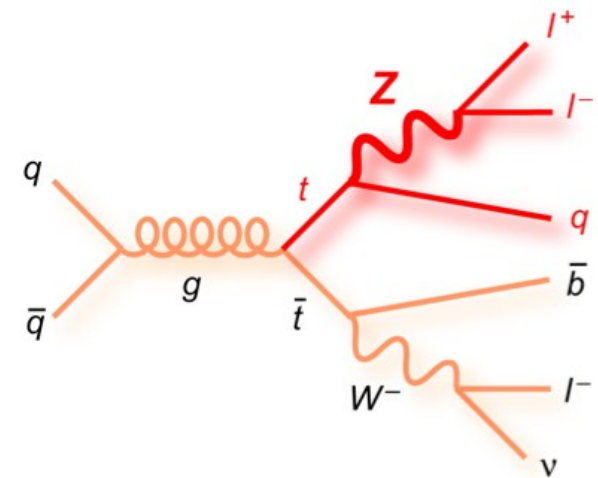
lepton+jets:

1 isolated lepton;
Missing E_T from neutrino;
 ≥ 4 jets (2 b-jets)

FCNC

- Many beyond SM models predict FCNC
 - Suppressed in SM: $\text{Br}(t \rightarrow Zq) \sim 10^{-14}$
- Search for $t \rightarrow Zq$ in trileptonic $t\bar{t}$ events
- Require events with 3 leptons
 - Kinematically consistent with $t\bar{t} \rightarrow WbZq$: χ^2 minimization
- No evidence for FCNC found
→ set upper limit

$\text{Br}(t \rightarrow Zq) < 0.73\% \text{ @ } 95\% \text{ CL}$



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Jet Energy Scale

