Recent Top quark properties measurements (excluding mass and asymmetries)

On Behalf of LHC and Tevatron

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Outline

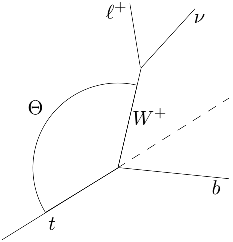
- Top Quark Production Properties
  - Spin Correlation
  - Top Polarization
- Top Quark Decay Properties
  - W-Boson Helicity
- Top width

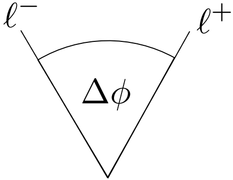
Spin Correlations

- Top lifetime is less than the timescale of QCD interaction
    - Top spin at production is conserved through to the decay

$$\frac{1}{N}\frac{d^2N}{d\cos\theta_1 d\cos\theta_2} = \frac{1}{4}(1 + B_1\cos\theta_1 + B_2\cos\theta_2 + C_{\text{helicity}}\cos\theta_1\cdot\cos\theta_2)$$

- $C_{\text{helicitiy}} = -A_{\text{helicity}}\alpha_1\alpha_2$
- α Spin analyzing power: $\alpha_{\ell^+} = +0.998$, $\alpha_d = -0.966$, $\alpha_b = -0.393$
- $A_{\text{helicity}} = \frac{N_{\text{like}} - N_{\text{unlike}}}{N_{\text{like}} + N_{\text{unlike}}}$
- NLO QCD Prediction $A = 0.31$ (dilepton)
- Sensitivity also through $\Delta\phi$ between leptons





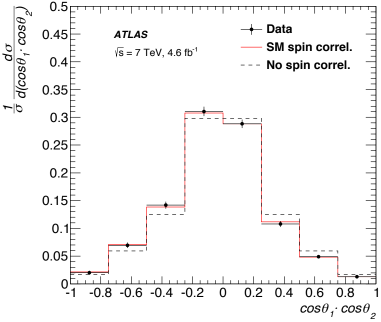
ATLAS: Dilepton $t\bar{t}$ final states at $\sqrt{s} = 7\,\text{TeV}$

Phys. Rev. D 93, 012002 (2016)

- Reconstruction of $t\bar{t}$ event in dilepton using kinematic constraints
- Angular distribution is unfolded to parton level
- Extract C_{helicity} and therefore also A_{helicity}:

$$C_{\text{helicitiy}} = -A_{\text{helicity}}\alpha_1\alpha_2$$

$$A_{\text{helicity}} = 0.315 \pm 0.061(\text{stat.}) \pm 0.049(\text{syst.})$$

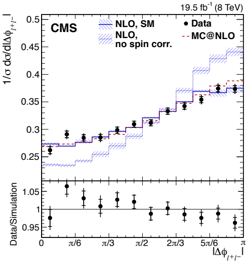


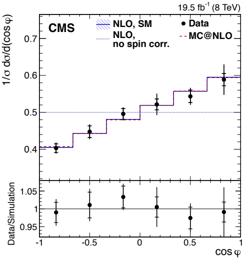
CMS: Dilepton final states at $\sqrt{s} = 8\,\text{TeV}$

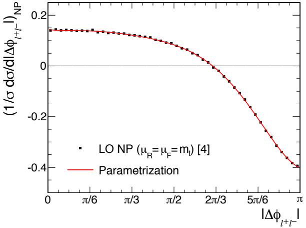
PRD 93, 052007 (2016)

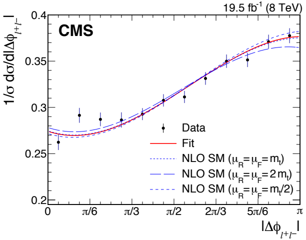
Dilepton Topolgies

- $\Delta\Phi_{\ell^+\ell^-}$ sensitive to top polarization
  $\Rightarrow$no need of full reconstruction of $t\bar{t}$ system
- ϕ directly sensitive to spin correlations









Variable	$f_{SM} \pm \text{(stat)} \pm \text{(syst)} \pm \text{(theor)}$	Total uncertainty
$A_{\Delta\phi}$	$1.14 \pm 0.06 \pm 0.13\,^{+0.08}_{-0.11}$	$^{+0.16}_{-0.18}$
$A_{\cos\varphi}$	$0.90 \pm 0.09 \pm 0.10 \pm 0.05$	± 0.15
$A_{c_1c_2}$	$0.87 \pm 0.17 \pm 0.21 \pm 0.04$	± 0.27
$A_{\Delta\phi}$ (vs. $M_{t\bar{t}}$)	$1.12 \pm 0.06 \pm 0.08\,^{+0.08}_{-0.11}$	$^{+0.12}_{-0.15}$

ATLAS: Spin correlation at 8TeV in Dilepton

Phys Rev Lett 114, 142001 (2015)

Fit to $\Delta\Phi$ Distribution:

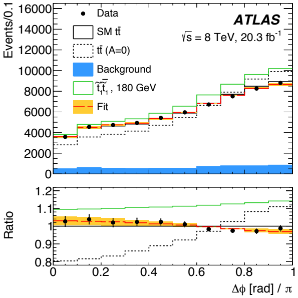
$$\Delta\Phi = f_{SM} \cdot SM + (1 - f_{SM}) \cdot no\ corr.$$

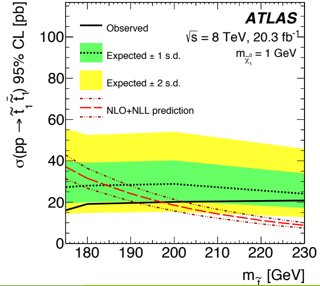
Final Result:

$$f_{SM} = 1.20 \pm 0.05(\text{stat.}) \pm 0.18(\text{syst.})$$
$$A_{\text{helicity}} = 0.38 \pm 0.04$$

Search for stops with $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$

Assuming $BR(\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0) = 100\%$: top squark masses are excluded between top mass and 191 GeV at 95%C.L.

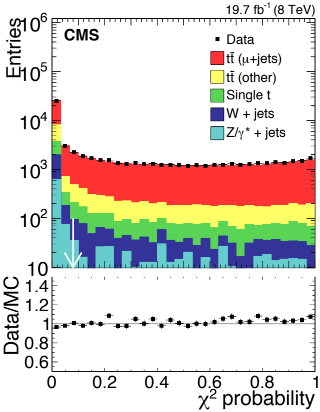




CMS: Muon + jets final state at $\sqrt{s} = 8\,\mathrm{TeV}$

PLB 758, 321 (2016)

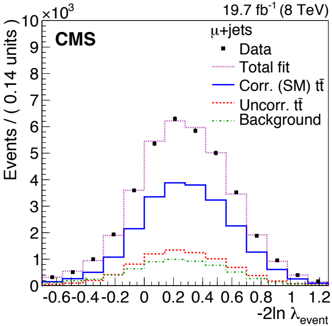
- Muon + jets final state
- Using kinematic fit to reduce background

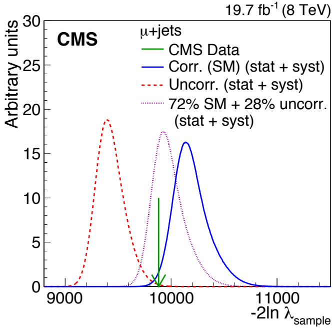


- Evaluate jet-quark permutations
- Can apply additional quality criteria
- $\chi^2/\mathrm{ndof} < 5$ and χ^2 probability larger than 0.08

CMS: Muon+Jets final state at $\sqrt{s} = 8\,\text{TeV}$

PLB 758, 321 (2016)





Spin Correlation With Matrix Element Method

$$f = 0.72 \pm 0.08(\text{stat.})^{+0.15}_{0.13}(\text{syst.})$$

$$A_{\text{hel}}^{\text{measured}} = 0.23 \pm 0.03(\text{stat.})^{+0.05}_{-0.04}(\text{syst.})$$

D0: Dilepton and lepton + jets at $\sqrt{s} = 1.96\,\text{TeV}$

PLB 757 (2016) 199

Spin Correlation Factor

- Use matrix method
- Spin correlation factor in the off-diagonal basis:

$$O_{\text{off}} = 0.89 \pm 0.16(\text{stat.}) \pm 0.15(\text{syst.})$$

- Main systematic uncertainty: Signal modelling ± 0.135

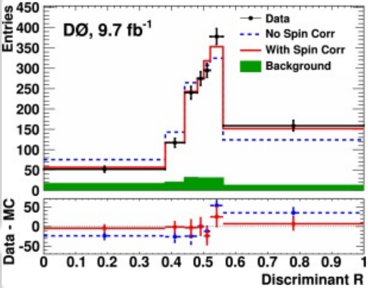
Event Fraction f_{gg}

Fraction of $t\bar{t}$ events produced by gluon fusion:

$$f_{gg} = 0.08 \pm 0.12(\text{stat.}) \pm 0.11(\text{syst.})$$

Is in agreement with SM prediction at NLO

Tevatron and LHC measurement are complementary



Spin Correlation Discriminant

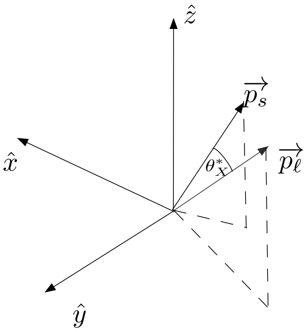
$$R(x) = \frac{P_{t\bar{t}}(x, \text{SM})}{P_{t\bar{t}}(x, \text{SM}) + P_{t\bar{t}}(x, \text{null})}$$

Top Quark Polarization

- Single-top: $V - A$ structure of the SM predicts large polarization P, along the direction of the momentum of the spectator quark in the top rest frame
- $t\bar{t}$: Measure Polarisation in Beam, Helicity or transverse base

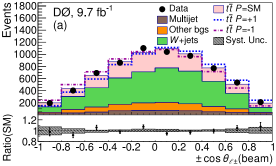
- $\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^*_X} = \left(\frac{1}{2} + A_X \cos\theta^*_X\right)$
- Here is $A_X = \frac{1}{2}P_t\alpha_X$
- Top quark polarization can be potentionally determined by measuring θ^*_X distribution
- Also it can be measured through asymmetries:

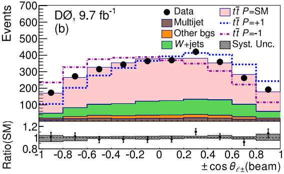
$$A_X = \frac{1}{2}P_t\alpha_X = \frac{N(\uparrow) - N(\downarrow)}{N(\uparrow) + N(\downarrow)}$$

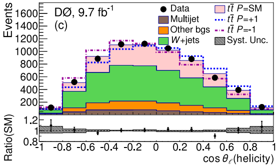


D0: $t\bar{t}$ lepton + jets at $\sqrt{s} = 1.96\,\text{TeV}$

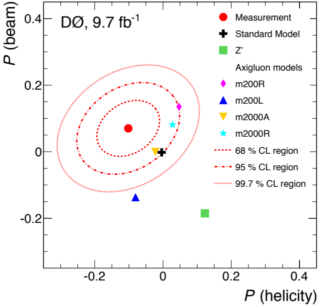
arXiv:1607.07627, subm. to PRL







Axis	Measured polarization	SM prediction
Beam	$+0.070 \pm 0.055$	-0.002
Beam - D0 comb.	$+0.081 \pm 0.048$	-0.002
Helicity	-0.102 ± 0.061	-0.004
Transverse	$+0.040 \pm 0.034$	$+0.011$

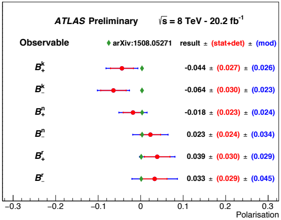


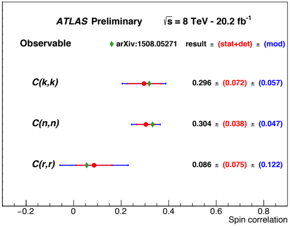
Polarizations are consistant with SM predictions

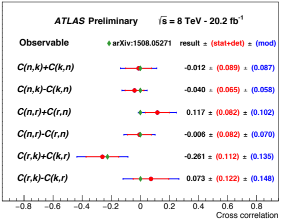
ATLAS: Measurement of the spin density matrix in dilepton final states at $\sqrt{s} = 8\,\text{TeV}$

ATLAS-CONF-2016-099

Fully bayesian unfolding to extract spin correlatian matrix elements







$$B^k_+ = -0.044 \pm 0.038[\pm 0.027(\text{mass})]$$

$$B^k_- = -0.064 \pm 0.040[\pm 0.027(\text{mass})]$$

$$C(k,k) = 0.296 \pm 0.093[\pm 0.037(\text{mass})]$$

k refers to helicity basis

In agreement with NLO SM predictions $B^k_+ = 0.0030 \pm 0.0010$, $B^k_- = 0.0034 \pm 0.0010, C(k,k) = 0.318 \pm 0.003$

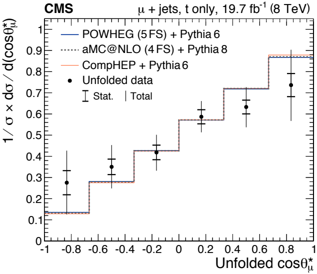
CMS: Polarization in t-channel single top quark production at $\sqrt{s} = 8\,\text{TeV}$

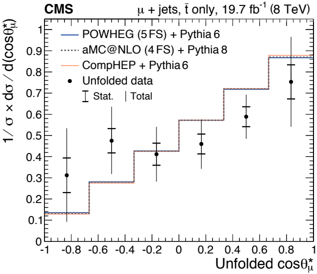
JHEP 04 (2016) 073

- μ + Jets final state
- Use Boosted Decision Tree to separate signal and background
- Extract asymmetries from normalised angular distributions via unfolding

$$A_\mu(t) = 0.29 \pm 0.03(stat) \pm 0.10(syst) = 0.29 \pm 0.11,$$
$$A_\mu(\bar{t}) = 0.21 \pm 0.05(stat) \pm 0.13(syst) = 0.21 \pm 0.14,$$
$$A_\mu(t+\bar{t}) = 0.26 \pm 0.03(stat) \pm 0.10(syst) = 0.26 \pm 0.11,$$

- Measurement is compatible with a *p*-value of 4.6%





W-Boson Helicity and Anomalous Couplings

W-Boson Helicity

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

$F_0 = 0.687 \pm 0.005$ $F_L = 0.311 \pm 0.005$ $F_R = 0.0017 \pm 0.0001$
at NNLO in SM including electroweak effects for $m_{\text{top}} = 172.8 \pm 1.3\,\text{GeV}$
[Phys Rev D 81 (2010) 111503]

Anomalous Couplings

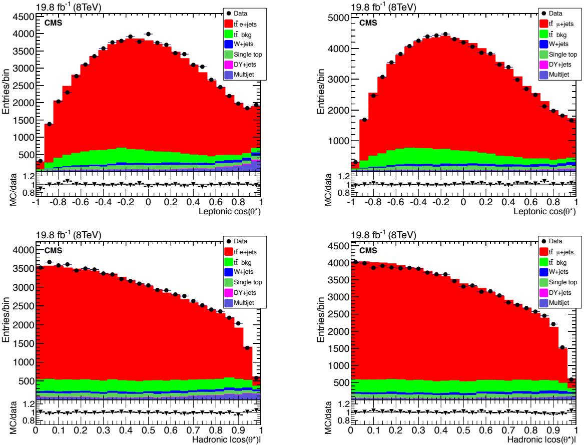
$$L_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^\mu(V_L P_L + V_R P_R)tW_\mu^- - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_\nu}{m_W}(g_L P_L + g_R P_R)tW_\mu^- + h.c.$$

- In SM: $V_L = V_{tb}$, $V_R = g_L = g_R = 0$
- Deviations would hint to physics beyond the standard model
- Dedicated talk tomorrow

CMS: lepton + jets channel at $\sqrt{s} = 8\,TeV$

PLB 762 (2016) 512-534

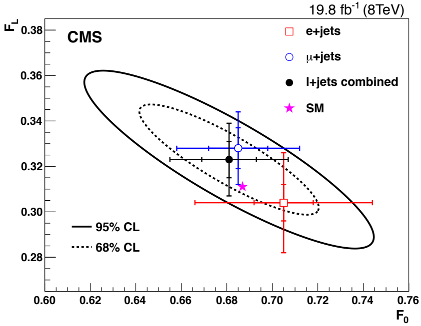
- Full event reconstruction by using t mass and W mass
- Using constrained likelihood fit to improve determination of p_{ν}^{z}
- Only using leptonic branch
- Extract helicity fractions from angular distributions

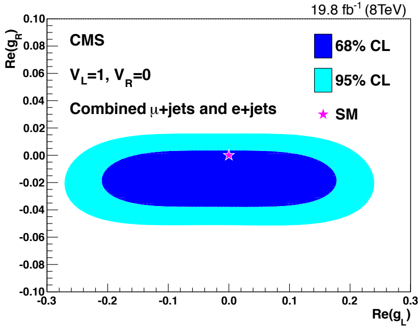


CMS: lepton + jets channel at $\sqrt{s} = 8\,TeV$

PLB 762 (2016) 512-534

$F_0 = 0.681 \pm 0.012(\text{stat.}) \pm 0.023(\text{syst}),$
$F_L = 0.323 \pm 0.008(\text{stat.}) \pm 0.014(\text{syst.}),$
and $F_R = -0.004 \pm 0.005(\text{stat.}) \pm 0.014(\text{syst.})$
correlation coefficient between F_0 and F_L: -0.87

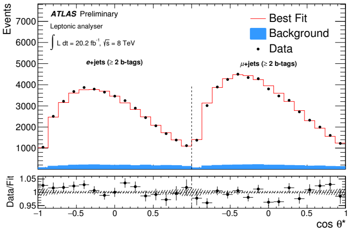




ATLAS: lepton + jets Channel at $\sqrt{s} = 8\,\text{TeV}$

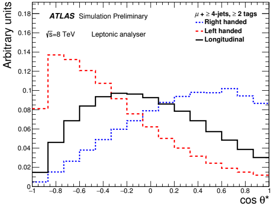
Paper in Preparation

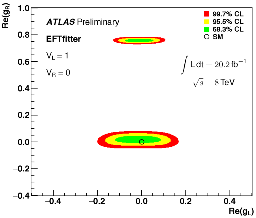
- Using Leptonic Branch

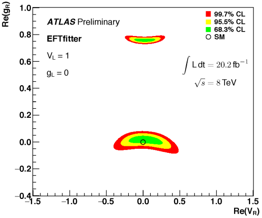


$$F_0 = 0.709 \pm 0.012(\text{stat. + bkg. norm}) \pm 0.015(\text{syst.})$$
$$F_R = 0.299 \pm 0.008(\text{stat. + bkg. norm.}) \pm 0.013(\text{syst})$$
$$F_L = -0.008 \pm 0.006(\text{stat + bkg. norm.}) \pm 0.012(\text{syst})$$

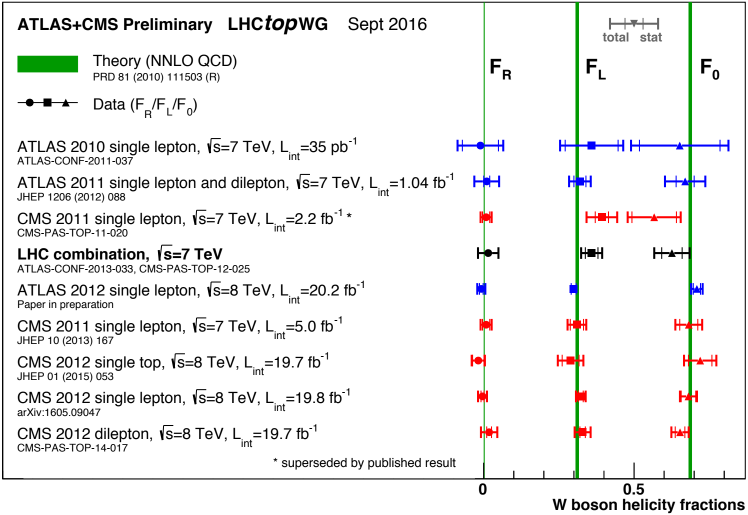
- Most sensitive measurement so far.







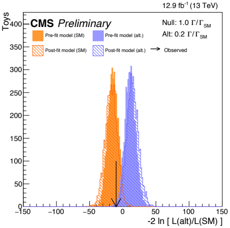
Summary *W*-Boson Helicity

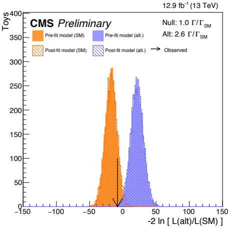


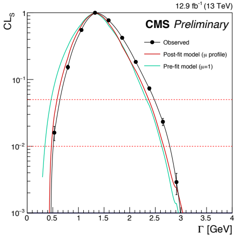
CMS: Measurement of the top width at $\sqrt{s} = 8\,\text{TeV}$

CMS-TOP-16-019

- Using $t\bar{t}$ and tW decay events with 2 charged leptons
- Reconstruct $M_{\ell b}$ distribution and use for hypothesis tests
- $N_{\text{signal}} = \mu[(1 - x) \cdot N_{\text{SM}} + x \cdot N_{\text{alt}}]$
- Measure hypthesis seperation with CL_s criterium







- Binary hypothesis test: $0.6 \leq \Gamma_t \leq 2.5\,\text{GeV}$ at the 95 % C.L., with expected bounds of $0.6 \leq \Gamma_t \leq 2.4\,\text{GeV}$ with $m_t = 172.5\,\text{GeV}$
- First direct measurement at LHC and most precise direct bound on top width

Conclusions

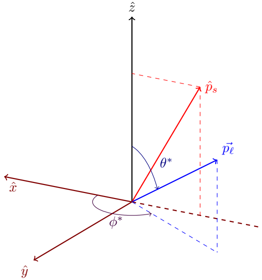
- New spin correlation measurements have been presented from both LHC and Tevatron experimentes
- Top polarization measurements show no deviation from Standard Model prediction
- Measurement of W-Helicity provides probe of Wtb vertex
- Direct searches to probe Wtb vertex and its CP nature
- First measurment of top width with LHC

All measurements getting more precise and the search for the boundaries of the Standard Model continues!

Back Up

ATLAS: Anomalous couplings in the Wtb vertex with single top quarks at $\sqrt{s} = 7\,\mathrm{GeV}$

JHEP 04 (2016) 023



Normalized double differential angular measurement in θ^* and ϕ^*

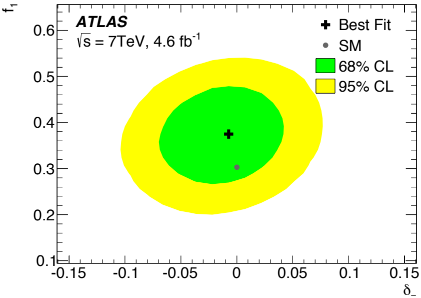
- θ^* defined relative to the W boson direction in top rest frame
- ϕ^* defined relative to plane containing spectator quark and W

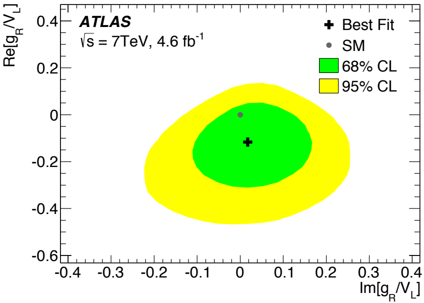
- f_1: fraction of W-Bosons with transverse polarization
- δ_-: phase between amplitudes for long. and trans. W-Bosons produced with left-handed b-quarks
- Simultaneous parameter extraction:
  $f_1 = 0.37 \pm 0.05(\text{stat.}) \pm 0.05(\text{syst.})$
  $\delta_- = -0.014\pi \pm 0.023\pi(\text{stat.}) \pm 0.028\pi(\text{syst.})$
- Main uncertainties: Statistics, MC event generator and Jet Energy Scale

ATLAS: Anomalous couplings in the Wtb vertex with single top quarks at $\sqrt{s} = 7\,\text{GeV}$

JHEP 04 (2016) 023

Assumption: $V_R = g_L = 0$





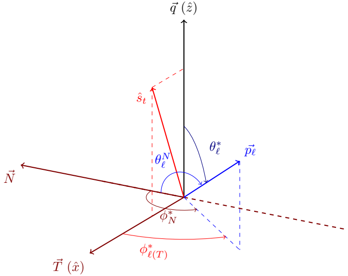
Limits at 95% C.L:
$Re[g_R/V_L] \in [-0.36, 0.10]$, $Im[g_R, V_L] \in [-0.17, 0.23]$,
$\rho(Re[g_R/V_L], Im[g_R/V_L]) = 0.11$

ATLAS: Probing the *Wtb* vertex structure with t-channel single top quarks at $\sqrt{s} = 8$ TeV

ATLAS-CONF-2016-096

- Using various angular distributions of top decays to extract top and *W* polarization observables

Asymmetry	Angular observable	Polarisation observable	SM prediction
A_{FB}^{ℓ}	$\cos\theta_\ell$	$\frac{1}{2}\alpha_\ell P$	0.45
A_{FB}^{tW}	$\cos\theta_W \cos\theta_\ell^*$	$\frac{3}{8}P\,(F_{\mathrm{R}} + F_{\mathrm{L}})$	0.10
A_{FB}	$\cos\theta_\ell^*$	$\frac{3}{4}\langle S_3\rangle = \frac{3}{4}\,(F_{\mathrm{R}} - F_{\mathrm{L}})$	-0.23
A_{EC}	$\cos\theta_\ell^*$	$\frac{3}{8}\sqrt{\frac{3}{2}}\langle T_0\rangle = \frac{3}{16}\,(1 - 3F_0)$	-0.20
A_{FB}^{T}	$\cos\theta_\ell^T$	$\frac{3}{4}\langle S_1\rangle$	0.34
A_{FB}^{N}	$\cos\theta_\ell^N$	$-\frac{3}{4}\langle S_2\rangle$	0
$A_{\mathrm{FB}}^{T,\phi}$	$\cos\theta_\ell^* \cos\phi_T^*$	$-\frac{2}{\pi}\langle A_1\rangle$	-0.14
$A_{\mathrm{FB}}^{N,\phi}$	$\cos\theta_\ell^* \cos\phi_N^*$	$\frac{2}{\pi}\langle A_2\rangle$	0

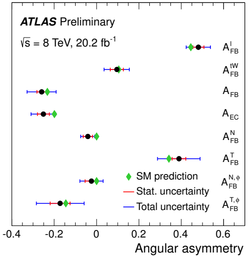


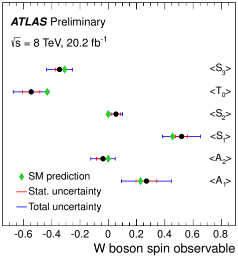
- 4 enrichment cuts $|\eta(j)| > 2$, $\Delta\eta(j,b) > 1.5$, $130\,\mathrm{GeV} < m(l\nu b) < 200\,\mathrm{GeV}$ and $H_T(\ell, j, E_T^{\mathrm{miss}}) > 195\,\mathrm{GeV}$ to improve S/B

ATLAS: Probing the *Wtb* vertex structure with t-channel single top quarks at $\sqrt{s} = 8$ TeV

ATLAS-CONF-2016-096

- Measured angular distributions are unfolded to parton level (after background substraction)
  - Iterative bayesian unfolding for A_{FB}^{N} and SM bayesian unfolding for other
- Angular asymmetries extracted from the unfolded distributions
- Results in agreement with Standard Model Prediction
  - Dominant sources of uncertainty: data statistics, modelling of t-channel and $t\bar{t}$, Jet Energy Scale
- Limit on $Im(g_R)$ extracted by using A_{FB}^{N} and A_{FB}^{l} distributions





$$Im(g_R) \in [-0.17, 0.06]$$

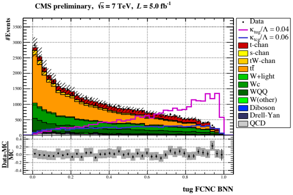
(Assumption: $V_L = 1$, $V_R = g_L = 0$)

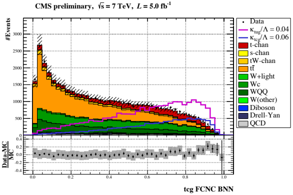
CMS: *Wtb* couplings and FCNC in t-channel single top at $\sqrt{s} = 7\,\text{GeV}$

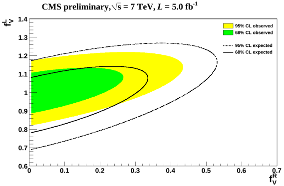
CMS-PAS-TOP-14-007

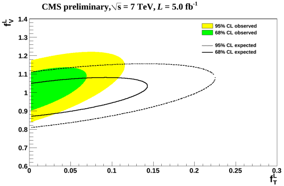
- Final states with μ + jets channel
- After preselection use 3 Bayesian Neural Network for anomalous *Wtb* couplings
- Observed exclusion limits at 95 % C.L.:

$f|^R_V| > 0.34$, $|f^L_T < 0.09$









Limits on Branching Ratios:

$Br(t \to u + g) < 3.55 \times 10^{-4}$,

$Br(t \to c + g) < 3.44 \times 10^{-3}$