Measurements of Top Quark Properties at the LHC
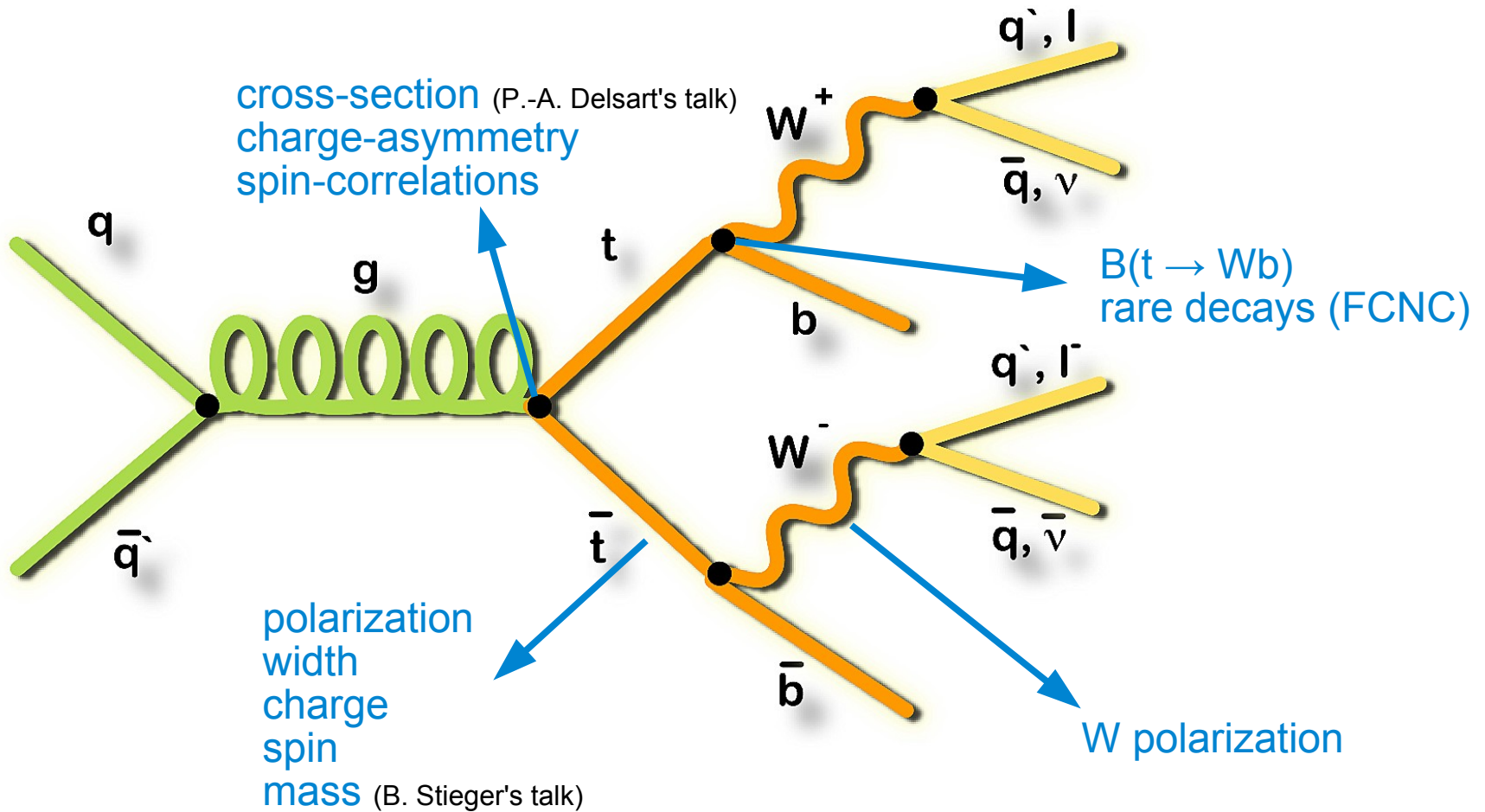
Roman Lysák
Institute of Physics, Prague

on behalf of the ATLAS and CMS collaborations
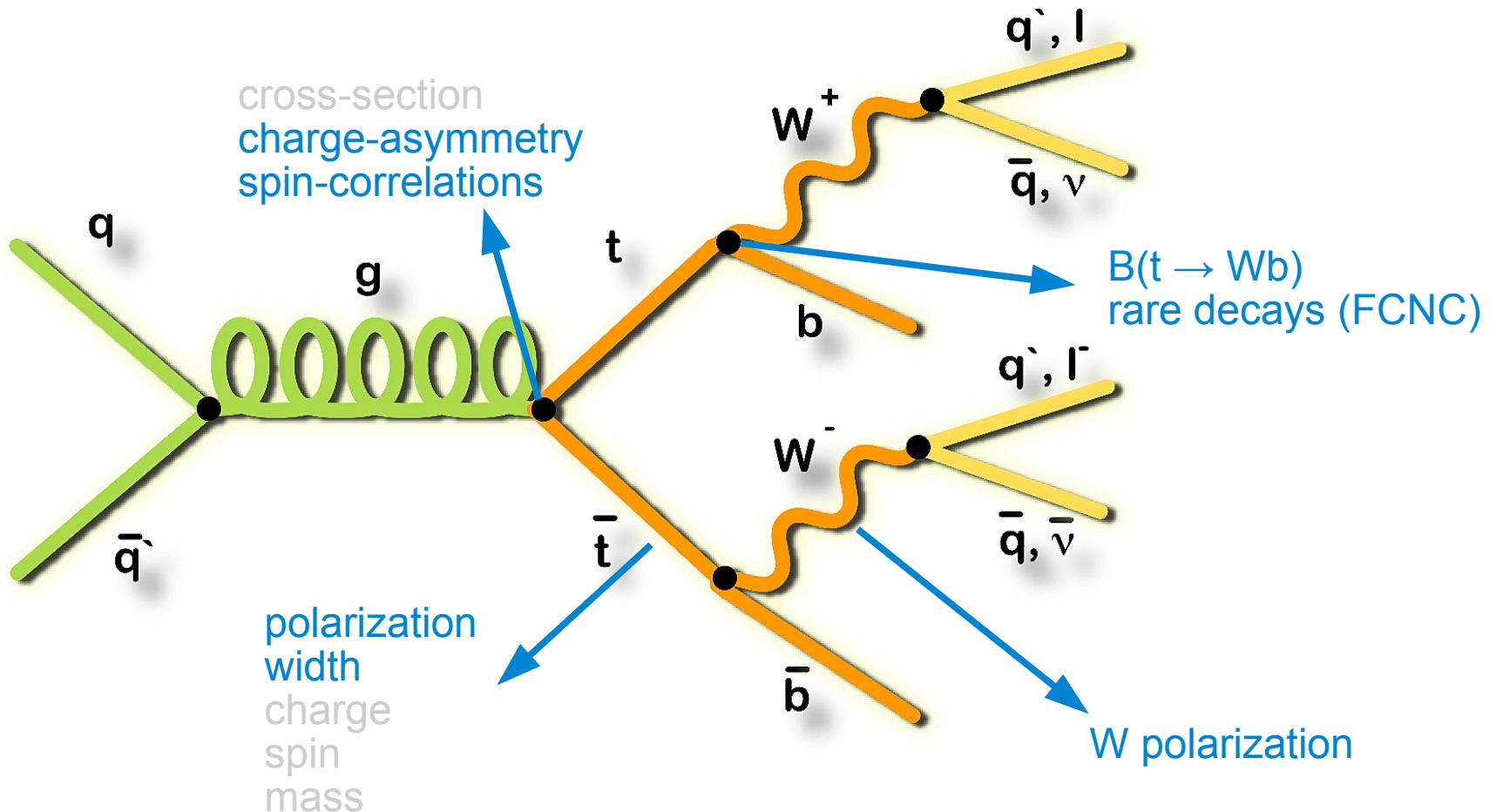
Blois 2014

Motivation

- ATLAS/CMS: ~6 millions of t$\bar{\text{t}}$ events produced per experiment
 - → era of precise, differential top quark physics

Motivation

- ATLAS/CMS: ~6 millions of $t\bar{t}$ events produced per experiment

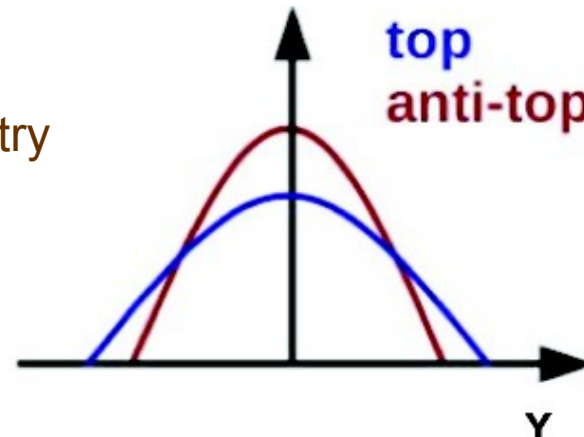 → era of precise, differential top quark physics

Top quark charge asymmetry

Top quark charge asymmetry

arXiv1405.0421
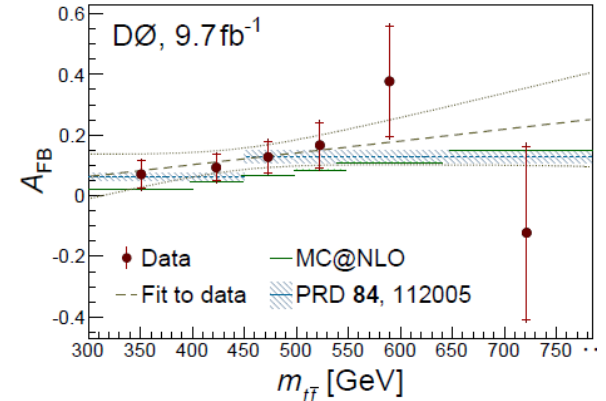
- Tevatron experiments: tension between Standard Model prediction and their results at ~2-3 sigma → measure asymmetry at LHC too !

- In Standard Model (SM), asymmetry in $t\bar{t}$ pair production at NLO
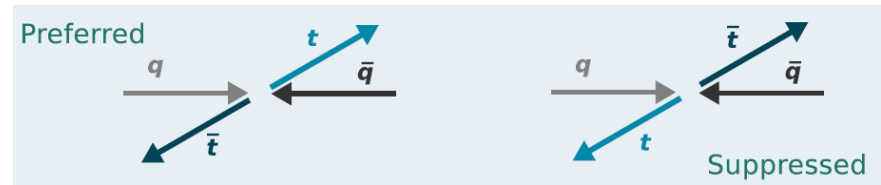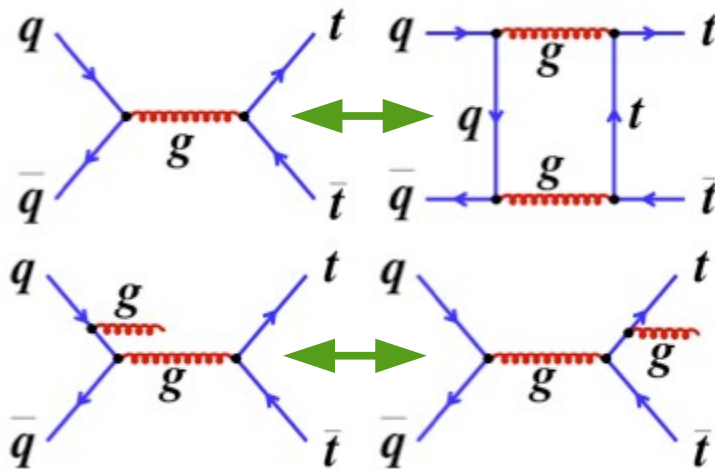
- LHC (p-p collider)
  → central – forward/backward asymmetry

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Asymmetry observables

- Two complementary observables:

$t\bar{t}$ based:

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

$$\Delta|y| = |y_{top}| - |y_{antitop}|$$

Advantages:

– Direct probe

lepton based:

$$A_{ll} = \frac{N\left(\Delta|\eta|>0\right) - N\left(\Delta|\eta|<0\right)}{N\left(\Delta|\eta|>0\right) + N\left(\Delta|\eta|<0\right)}$$

$$\Delta|\eta| = |\eta_{l+}| - |\eta_{l-}|$$

– influenced by top polarization, decay
– no need for kinematic reconstruction

- SM predictions for LHC: ~ 1 %

PRD 86 (2012) 034026

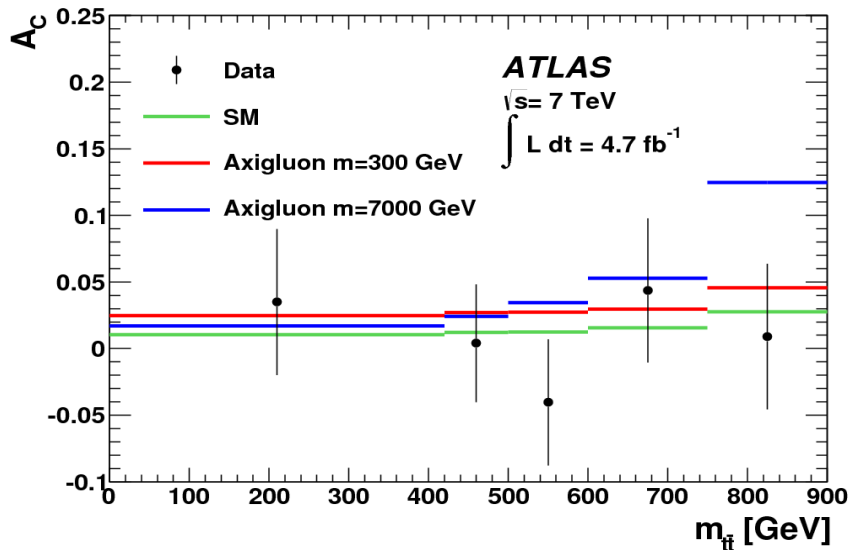|	A_C	A_{ll}
7 TeV	1.23 %	0.70 %
8 TeV	1.11 %	0.64 %

- All measurements unfold their results to parton level

Charge asymmetry at ATLAS

4.7/fb @ 7 TeV

lepton+jet channel:

- Differential measurements in p_T, mass and rapidity of $t\bar{t}$ pair

- A_C also measured for events with large velocity of $t\bar{t}$
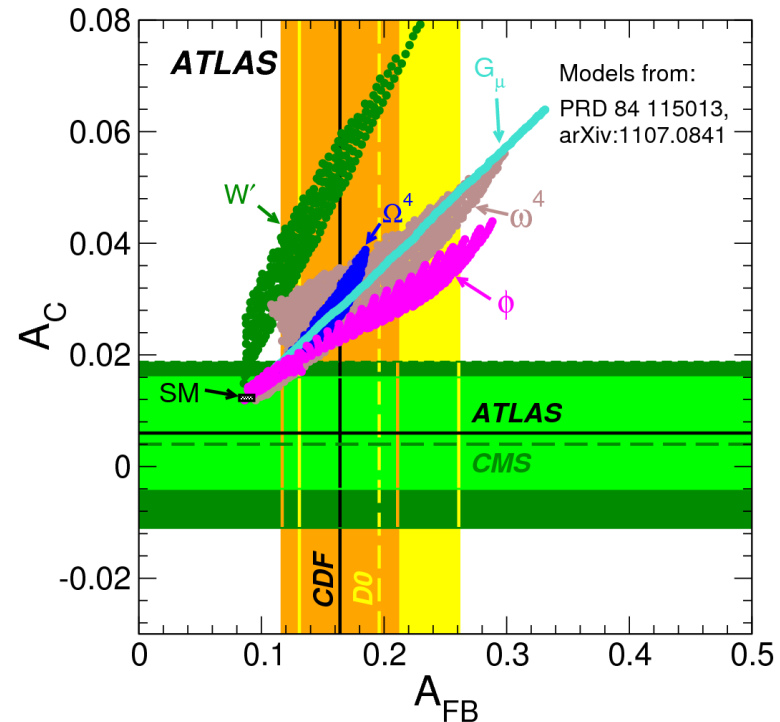
  A_C = 0.6 ± 1.0 (stat+syst) %

dilepton channel:

- Inclusive only measurement

- Dominant syst. (A_C): MC generator

  A_C = 5.7 ± 2.4 (stat) ± 1.5 (syst) %
  A_{ll} = 2.3 ± 1.2 (stat) ± 0.8 (syst) %

Charge asymmetry at CMS
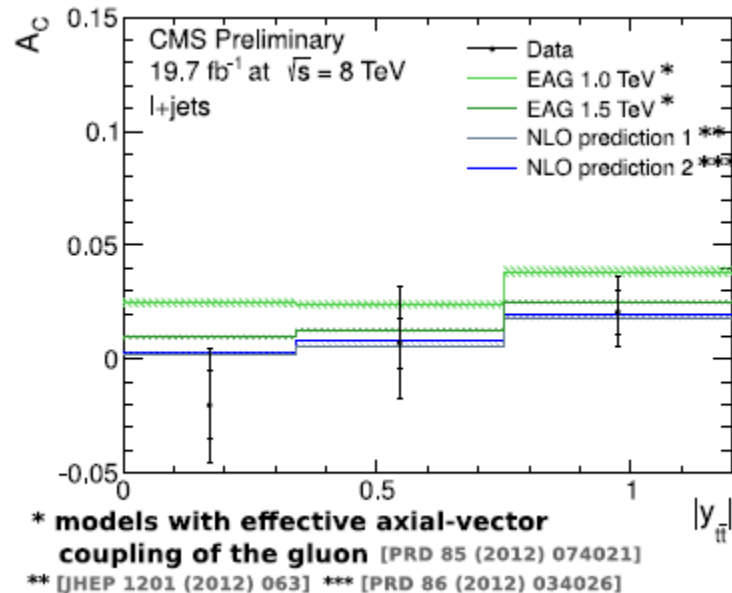

lepton+jet channel (19.7/fb @ 8 TeV):

- Differential measurements in p_T, mass and rapidity of $t\bar{t}$ pair

- Dominant syst.: Q^2 scale, generator

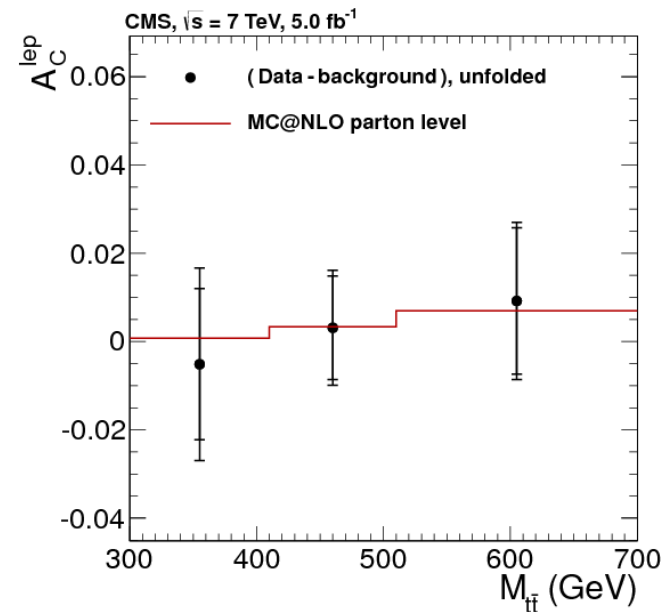$A_C = 0.5 \pm 0.7 \text{ (stat.)} \pm 0.6 \text{ (syst) \%}$

dilepton channel (5.0/fb @ 7 TeV):

- A_{ll} also differential in p_T, mass and rapidity of $t\bar{t}$ pair

- Dominant syst.: Q^2 scale, unfolding

$A_C = 1.0 \pm 1.7 \text{ (stat)} \pm 0.8 \text{ (syst) \%}$
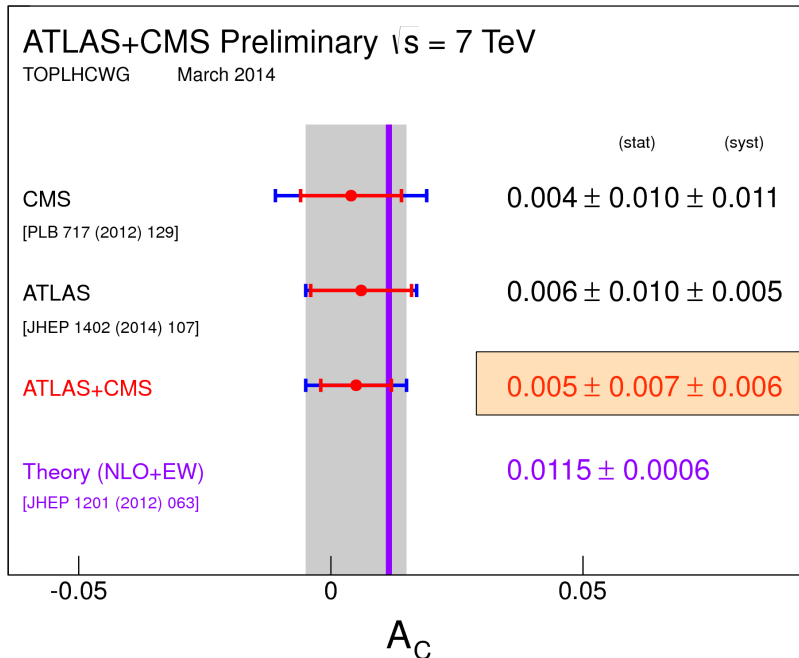$A_{ll} = 0.9 \pm 1.0 \text{ (stat)} \pm 0.6 \text{ (syst) \%}$

* models with effective axial-vector coupling of the gluon [PRD 85 (2012) 074021]
** [JHEP 1201 (2012) 063] *** [PRD 86 (2012) 034026]

LHC combination of charge asymmetry

5.0/fb @ 7 TeV

- First LHC A_C combination
- Inputs: published 7 TeV measurements from lepton + jet channel
- Best Linear Unbiased Estimate (BLUE) method used
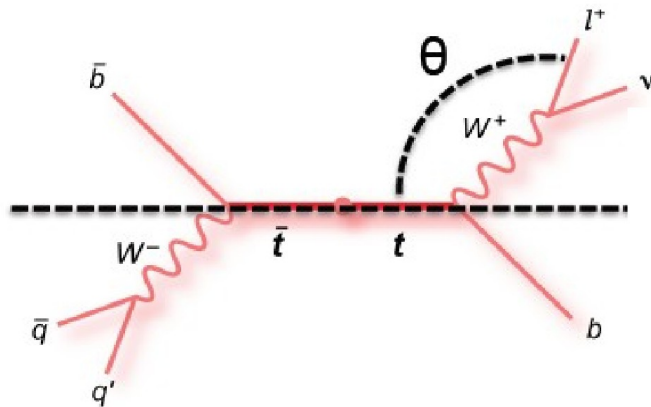- Groundwork for future combinations

ATLAS+CMS Preliminary $\sqrt{s}$ = 7 TeV
TOPLHCWG   March 2014

	(stat)	(syst)
CMS [PLB 717 (2012) 129]	$0.004 \pm 0.010 \pm 0.011$	
ATLAS [JHEP 1402 (2014) 107]	$0.006 \pm 0.010 \pm 0.005$	
ATLAS+CMS	$0.005 \pm 0.007 \pm 0.006$	
Theory (NLO+EW) [JHEP 1201 (2012) 063]	0.0115 ± 0.0006	

A_C

	ATLAS	CMS	Comb.	Corr.
A_C	0.006	0.004	0.005	0.058
Statistical	0.010	0.010	0.007	0
Detector response model	0.004	0.007	0.004	0
Signal model	< 0.001	0.002	0.001	1
W+jets model	0.002	0.004	0.003	0.5
QCD model	< 0.001	0.001	0.000	0
Pileup+MET	0.002	< 0.001	0.001	0
PDF	0.001	0.002	0.001	1
MC statistics	0.002	0.002	0.001	0
Model dependence				
Specific physics models	< 0.001	*	0.000	0
General simplified models	*	0.007	0.002	0
Systematic uncertainty	0.005	0.011	0.006	
Total uncertainty	0.011	0.015	0.009	

Uncertainties

$t\bar{t}$ spin correlations and top polarization

t̄t spin correlations and top polarization

- At LHC, top quarks are produced almost un-polarized
- There is correlation between top and anti-top spin
- Top quark short lifetime → the spin properties are transferred to decay products
- The correlation and polarization is expressed by (in a given quantization axis):

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_+ \, d\cos\theta_-} = \frac{1}{4}\left(1 + \alpha_+ P_+ \cos\theta_+ + \alpha_- P_- \cos\theta_- + A\,\alpha_+\alpha_- \cos\theta_+ \cos\theta_-\right)$$

	b	ℓ	d	u
α (NLO)	-0.39	0.998	0.93	-0.31

- measurables of interest:
  - $P_{+/-}$ – top/anti-top polarization (SM @ 7/8 TeV: 0.003)
  - A – spin correlation strength
    - SM @ 7 TeV: $A_{maximal} = 0.44$, $A_{helicity} = 0.31$

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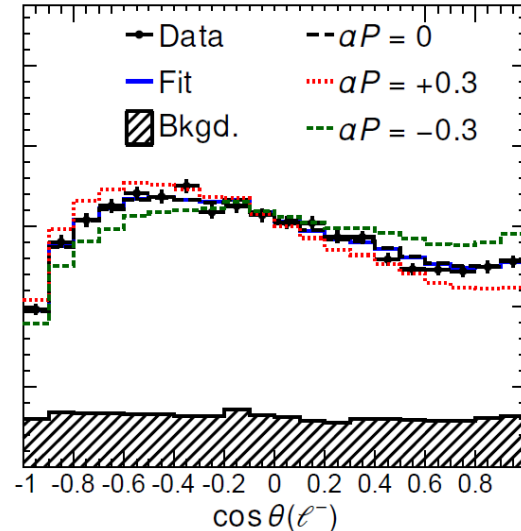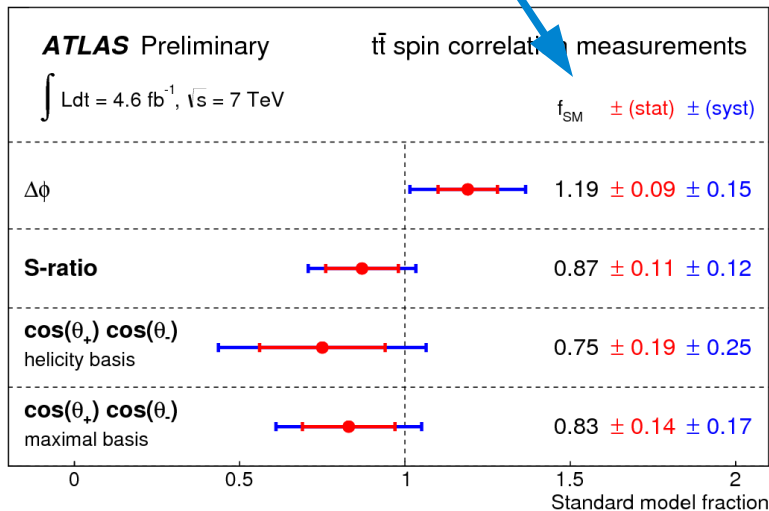# Spin Correlations and polarization at ATLAS

4.6/fb @ 7 TeV, dilepton channel

- 4 sensitive observables

- SM corr. and no-correlation templates

- Dominant systematic uncertainties:

  Q^2 scale & jet energy scale

$$f_{SM} = N_{A=SM} / (N_{A=SM} + N_{A=0})$$

4.7/fb @ 7 TeV

- single-lepton and dilepton channels

- positive and negative polariz. templates

- Testing CP conserving ($P_+ = P_-$)
  and CP violating ($P_+ = -P_-$) scenario

- Dominant systematics: jet energy scale

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

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

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# Spin correlations and top polarization at CMS

- 5.0/fb @ 7 TeV, dilepton channel
- Unfolding to parton level
- Dominant systematics:
  top p_T reweighting, unfolding

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

$$A_{\Delta\Phi} = \frac{N(\Delta\Phi_{l_+ l_-} > \pi/2) - N(\Delta\Phi_{l_+ l_-} < \pi/2)}{N(\Delta\Phi_{l_+ l_-} > \pi/2) + N(\Delta\Phi_{l_+ l_-} < \pi/2)}$$

$$A_{c_1 c_2} = \frac{N(\cos\theta_1 \cos\theta_2 > 0) - N(\cos\theta_1 \cos\theta_2 < 0)}{N(\cos\theta_1 \cos\theta_2 > 0) + N(\cos\theta_1 \cos\theta_2 < 0)}$$

Asymmetry	Data (unfolded)	MC@NLO	NLO (SM, correlated)	NLO (uncorrelated)
$A_{\Delta\phi}$	$0.113 \pm 0.010 \pm 0.007 \pm 0.012$	0.110 ± 0.001	$0.115^{+0.014}_{-0.016}$	$0.210^{+0.013}_{-0.008}$
$A_{c_1 c_2}$	$-0.021 \pm 0.023 \pm 0.027 \pm 0.010$	-0.078 ± 0.001	-0.078 ± 0.006	0
A_P	$0.005 \pm 0.013 \pm 0.020 \pm 0.008$	0.000 ± 0.001	N/A	N/A
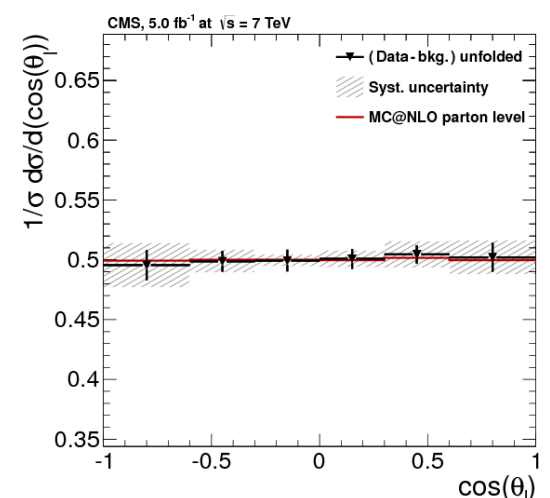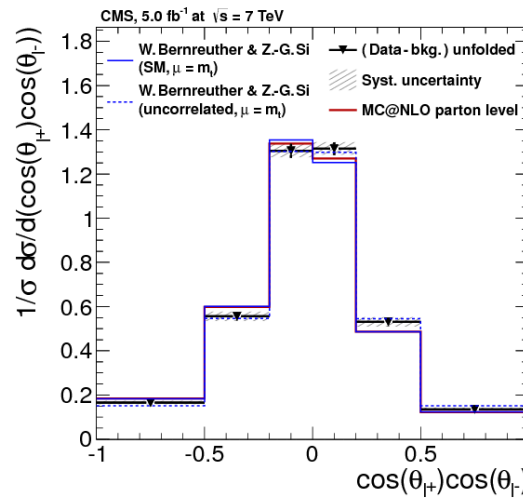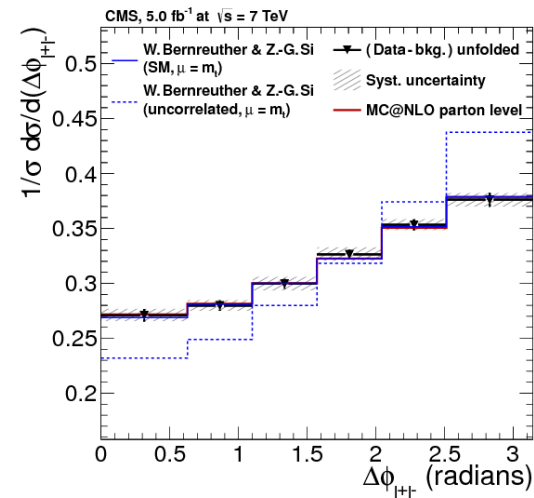
B(t → Wb)/B(t → Wq) ratio

Measurement of R = B(t → Wb)/B(t → Wq)

- SM: BR(t → Wb) ~ 1.0 (assuming 3 quark generations)
- CMS measurement (19.7/fb @ 8 TeV)
  - dilepton channel
- Fitting b-tagged jet multiplicity
- Dominant systematics: b-tagging efficiency

  R = 1.014 ± 0.003 (stat) ± 0.032 (syst)

  R > 0.955 @ 95% C.L.
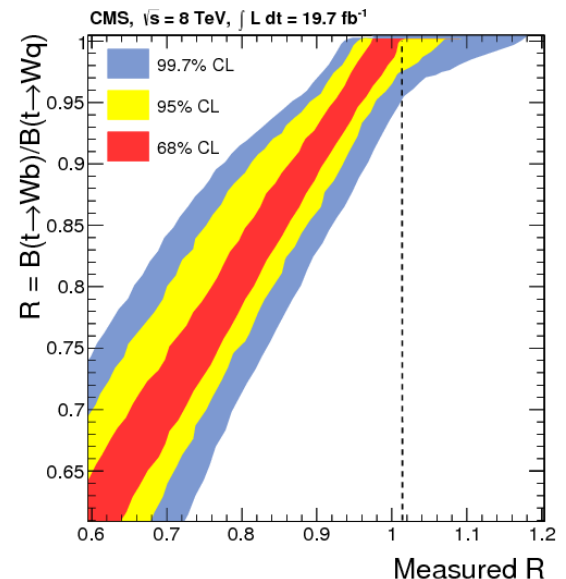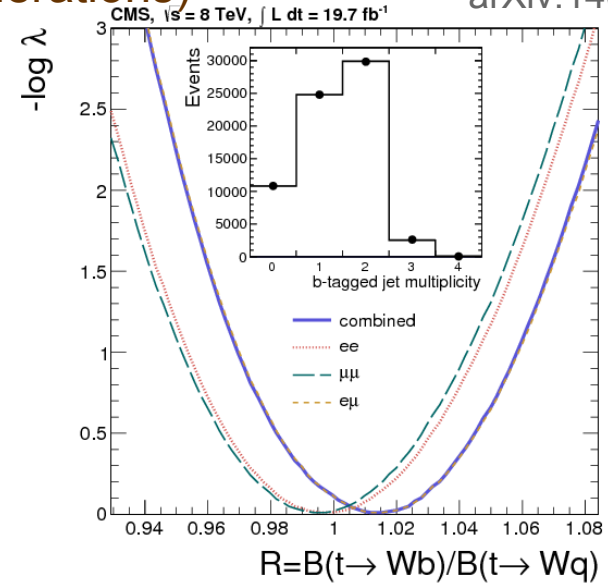
- Indirect determination (assuming 3 quark generations)
  - V_{tb}: R = $|V_{tb}|^2$

    $|V_{tb}|$ > 0.975 @ 95% C.L.

  - top width (combining with single top t-channel cross-section):

$$\Gamma_t = \frac{\sigma_{t-channel}}{BR(t \to Wb)} \frac{\Gamma(t \to Wb)}{\sigma_{t-channel}^{theory}}$$

Γ_t = 1.36 ± 0.02 (stat) $^{+0.14}_{-0.11}$ (syst) GeV

arXiv:1404.2292

CMS, √s = 8 TeV, ∫ L dt = 19.7 fb⁻¹

-log λ

Events

b-tagged jet multiplicity

— combined
····· ee
– – μμ
– – eμ

R=B(t→ Wb)/B(t→ Wq)

CMS, √s = 8 TeV, ∫ L dt = 19.7 fb⁻¹

R = B(t→Wb)/B(t→Wq)

99.7% CL
95% CL
68% CL

Measured R

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Flavor changing neutral currents (FCNC)

Limits on t → Zq, t → gq and t → γq

- SM: FCNC highly suppressed due to GIM mechanism, BR ~ $O(10^{-14})$

- Various BSM: enhancement up to $O(10^{-4} – 10^{-5})$

PRL 112 171802

CMS (19.7/fb @ 8 TeV):

- tt → Zq + Wb

    BR(t → Zq) < 0.05 %

CMS TOP-14- 003

CMS (19.1/fb @ 8 TeV):

- Single-top topology

- BDT output

    BR(t → uγ) < 0.016 %

    BR(t → cγ) < 0.182 %

ATLAS-CONF-2013-063

ATLAS (14.2/fb @ 8 TeV):

- Single-top topology

BR (t → ug) < $5.7*10^{-5}$, BR(t → cq) > $2.7*10^{-4}$
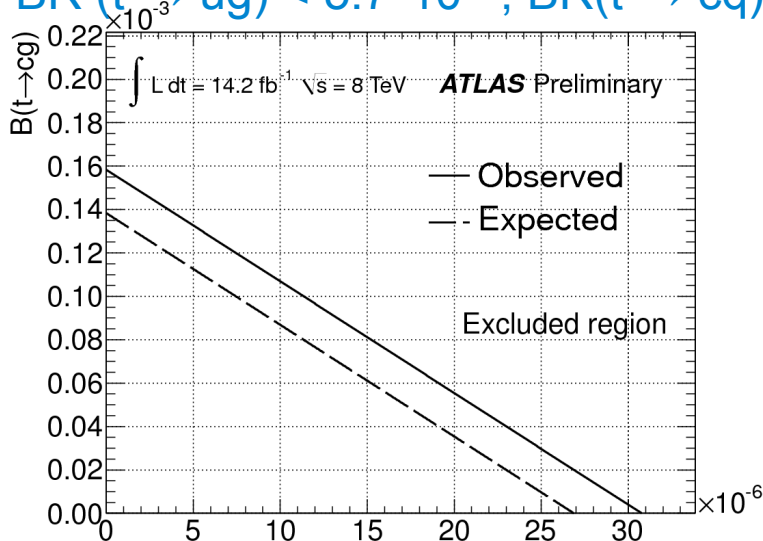
All limits are at 95 % C.L.
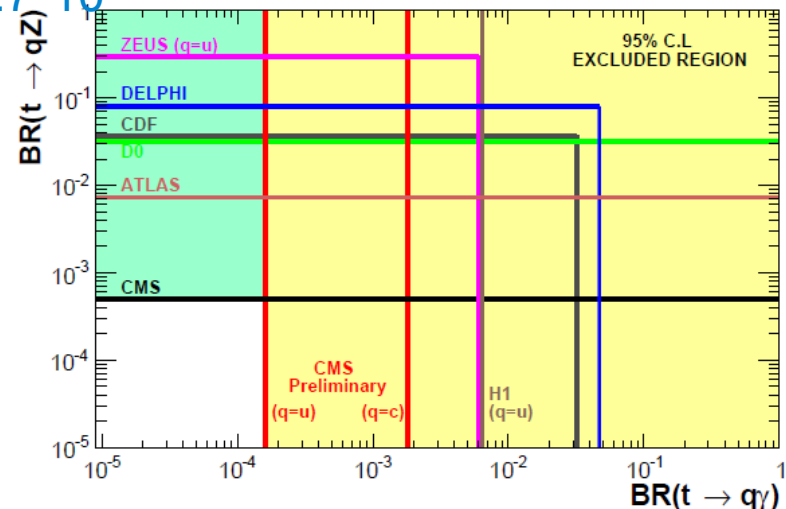
limits will be further reduced by 1-2 orders of magnitude at LHC14

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Limits on t → Hq

arXiv:1403.6293

ATLAS (20.3/fb @ 8 TeV + 4.7/fb @ 7 TeV):

- tt → qH (→ γγ) + Wb

- Leptonic/hadronic W decays considered

- BR(t → qH) < 0.79 %

- Higgs Yukawa coupling:

$$\sqrt{\lambda_{tcH}^2 + \lambda_{tuH}^2} < 0.17$$
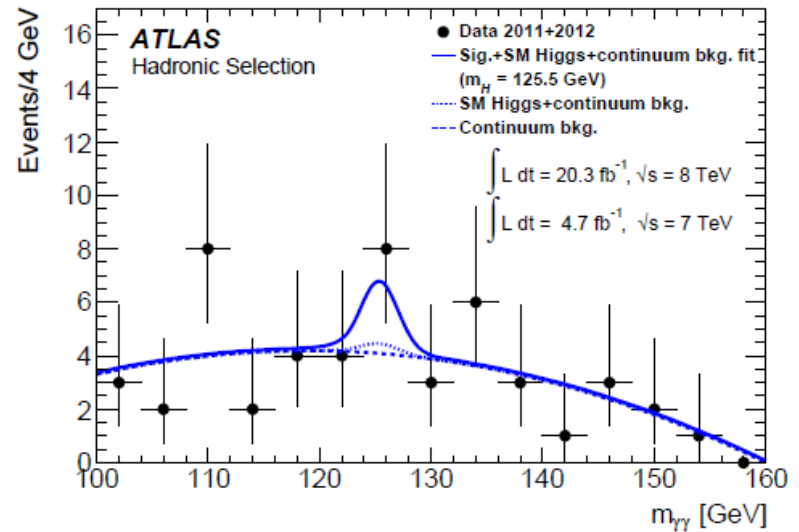
CMS SUS-13-002

CMS (19.5/fb @ 8 TeV):

- generic search for ≥ 3 lepton events

  (≤ 1 hadronic tau)

- Various SUSY interpretations

- BR(t → cH) < 1.28 %
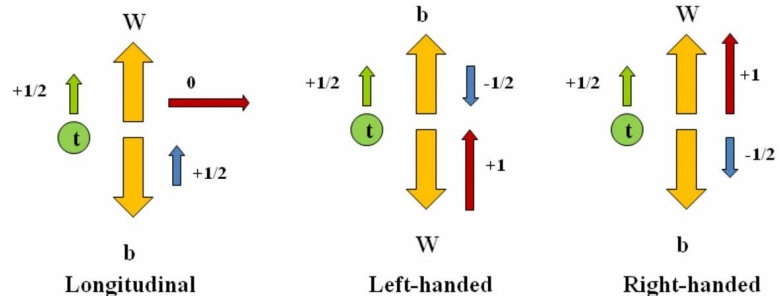
$$\sqrt{|\lambda_{tc}^h|^2 + |\lambda_{ct}^h|^2} < 0.21$$

Higgs Decay Mode		obs	exp	1σ range
$h \to WW^*$	(BR = 23.1 %)	1.58 %	1.57 %	(1.02–2.22) %
$h \to \tau\tau$	(BR = 6.15 %)	7.01 %	4.99 %	(3.53–7.74) %
$h \to ZZ^*$	(BR = 2.89 %)	5.31 %	4.11 %	(2.85–6.45) %
combined		1.28 %	1.17 %	(0.85–1.73) %

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PRL 112 171802   All limits are at 95 % C.L.

W boson polarization in top quark decay

W polarization at CMS

- SM: V-A nature of EWK interactions + low b-quark mass
  → almost no right-handed W^+ boson in top quark decay
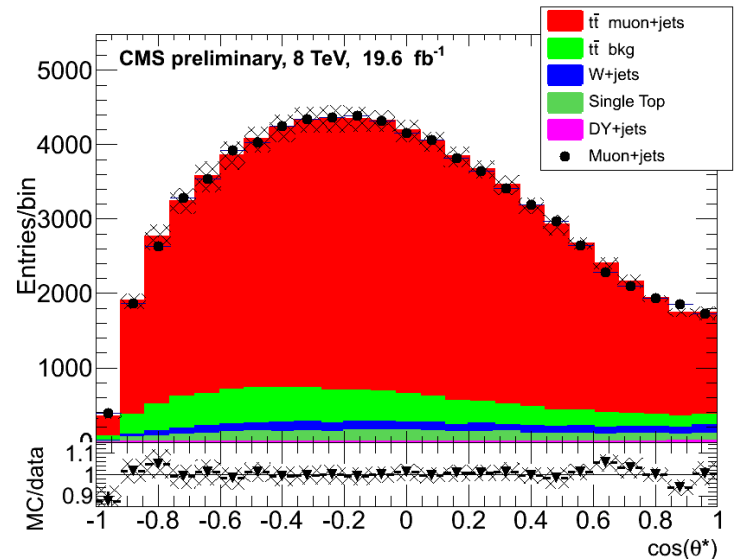

SM fractions: $F_0 = 0.687$ $F_L = 0.311$ $F_R = 0.0017$

- 19.6/fb @ 8 TeV, muon + jets
  - Fit to $\cos\theta^*$
  - Dominant syst.: Q^2 scale, top mass

$F_0 = 0.659 \pm 0.015 \,(\text{stat}) \pm 0.023 \,(\text{syst})$

$F_L = 0.350 \pm 0.010 \,(\text{stat}) \pm 0.024 \,(\text{syst})$

$F_R = -0.009 \pm 0.006 \,(\text{stat}) \pm 0.020 \,(\text{syst})$

Conclusions

- Precise measurements of top quark properties at LHC
  - most of the inclusive ones systematically dominated already

- No hints of new physics in top quark properties measurements yet

- Lots of 8 TeV studies still in progress
- At 13 TeV: measure properties more differentially, reduce systematics, explore new observables

All results on public web pages:
  - ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults
  - CMS: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults

BACKUP

Top charge in ATLAS

- 2.05/fb @ 7 TeV, lepton +jets channel
- Distinguish t(+2/3e) vs. t(–4/3e)
- Charge of the b-jet from track weighting
- Lepton and b-tagged jet associated using m_{lb}
- t(– 4/3e) scenario excluded at 8 sigma
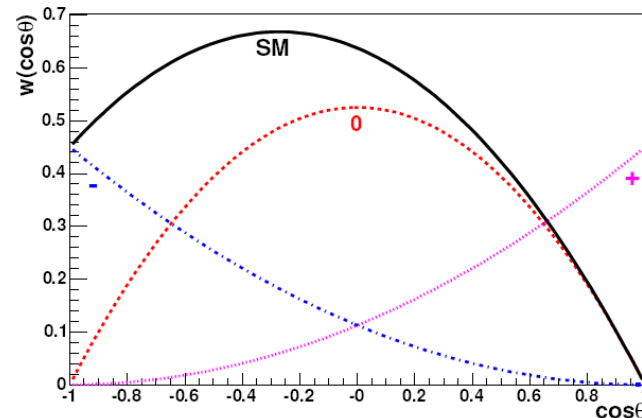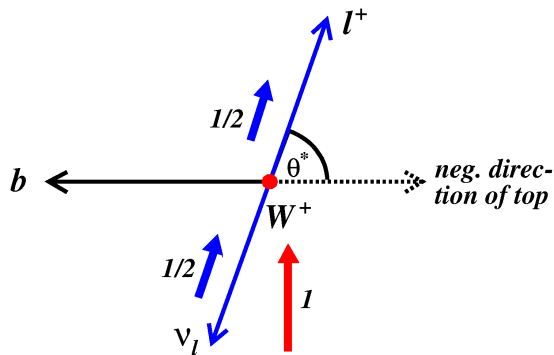

Q_{top} = 0.64 ± 0.02 (stat) ± 0.08 (syst)
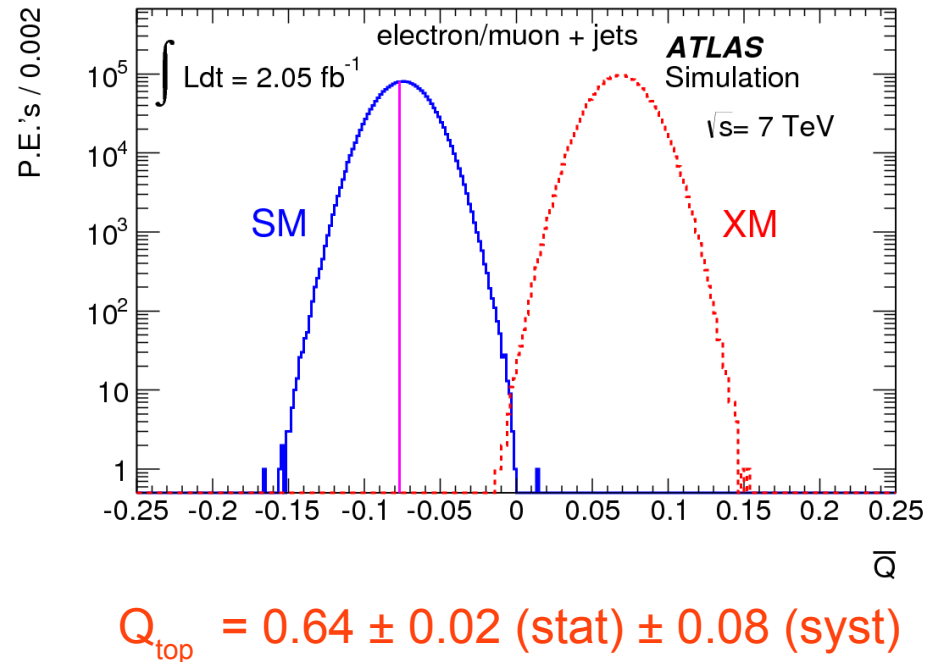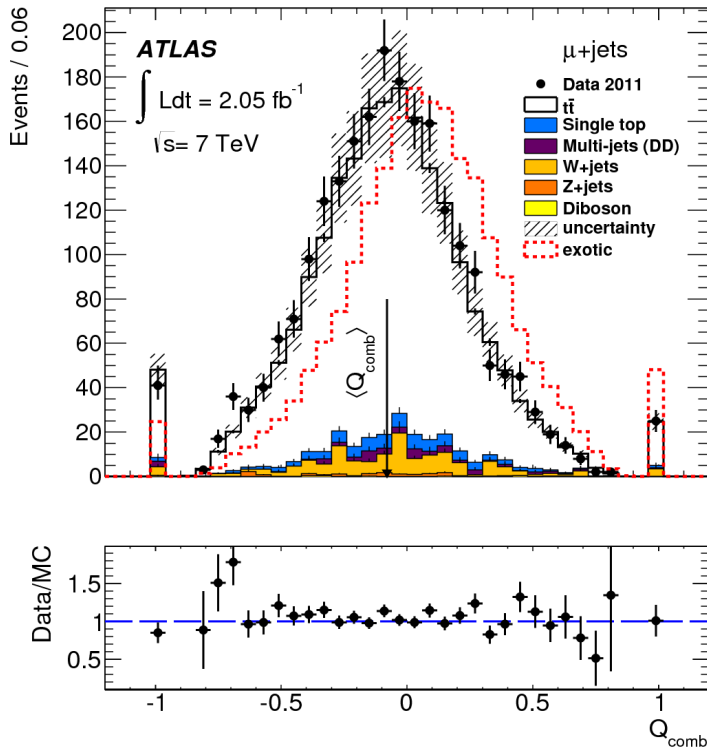
W boson polarization in top quark decay

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SM fractions: $F_0 = 0.687$ $F_L = 0.311$ $F_R = 0.0017$
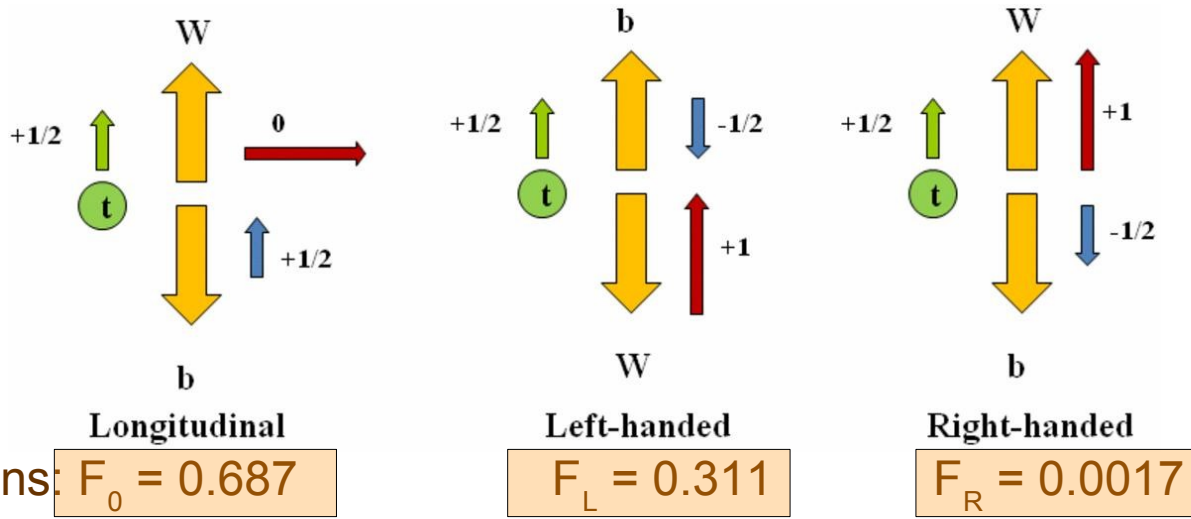
- Measurements: fit of cos θ* using left-/right-/longitudinal templates

LHC combination of W helicity measurements

- 7 TeV, up to 2.2/fb

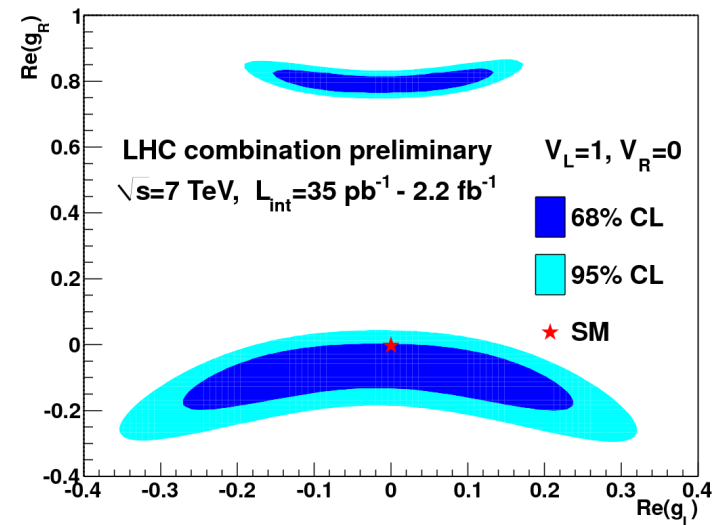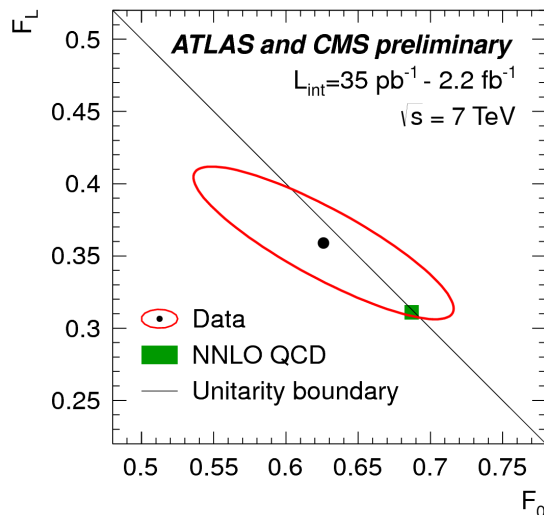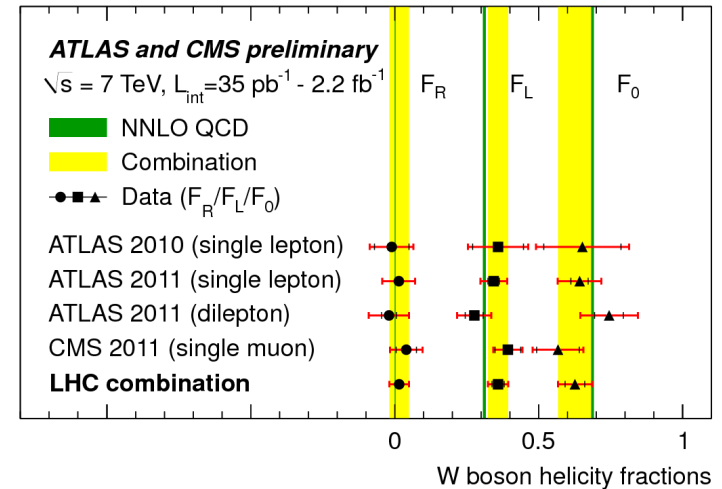$F_0 = 0.626 \pm 0.034$ (stat) ± 0.048 (syst)

$F_L = 0.359 \pm 0.021$ (stat) ± 0.028 (syst)

$F_R = 0.015 \pm 0.034$ (stat+syst)

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Spin Correlations at ATLAS

4.6/fb @ 7 TeV, dilepton channel

- 4 observables sensitive to different sources of new physics in $t\bar{t}$ production
- Templates for SM correlation and no-correlation
- Dominant systematic uncertainties:

    signal modeling (renormalization / factorization scale) & jet energy scale

$$S = \frac{(|M|^2_{RR}+|M|^2_{LL})_{CORR}}{(|M|^2_{RR}+|M|^2_{LL})_{UNCORR}}$$
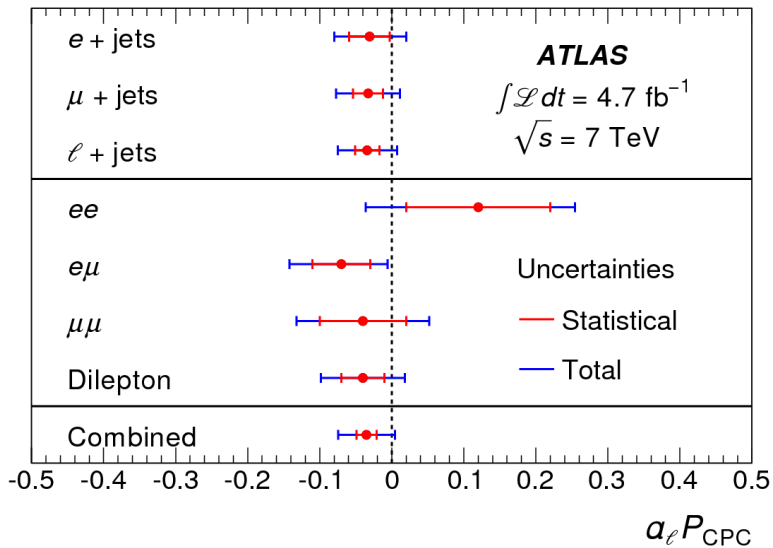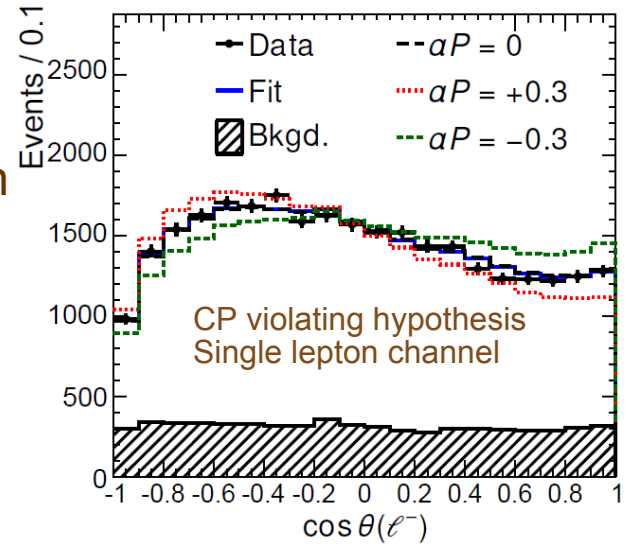
$$f_{SM} = N_{A=SM}/(N_{A=SM}+N_{A=0})$$
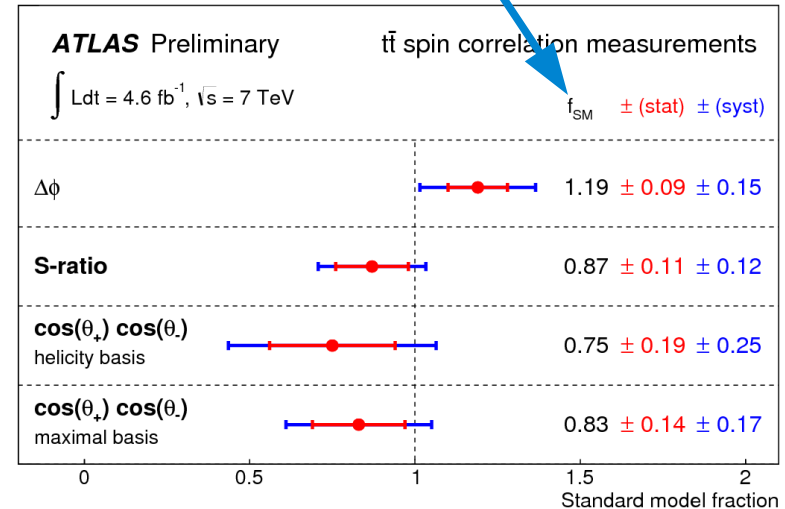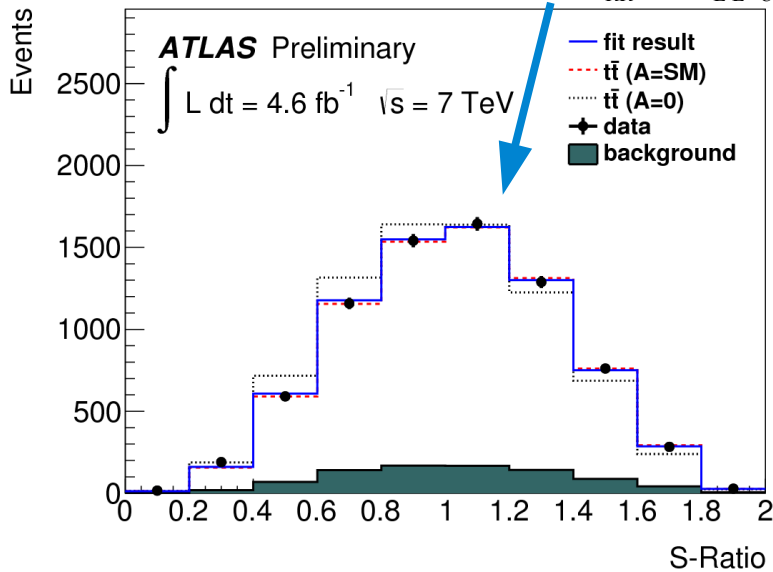
Basis	$\Delta\phi$	S-ratio	$\cos(\theta_+)\cos(\theta_-)_{\text{helicity}}$	$\cos(\theta_+)\cos(\theta_-)_{\text{maximal}}$
$A^{\text{measured}}_{\text{helicity}}$	$0.37 \pm 0.03 \pm 0.05$	$0.27 \pm 0.03 \pm 0.04$	$0.23 \pm 0.06 \pm 0.10$	—
$A^{\text{measured}}_{\text{maximal}}$	$0.52 \pm 0.04 \pm 0.07$	$0.38 \pm 0.05 \pm 0.06$	—	$0.36 \pm 0.06 \pm 0.09$

Top polarization at ATLAS
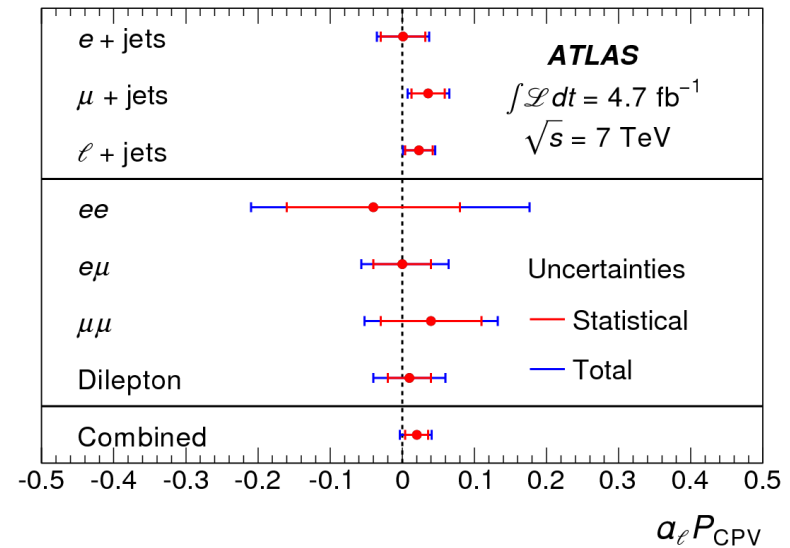
4.7/fb @ 7 TeV

- single-lepton and dilepton channels
- Templates for positive and negative polarization
- Testing both CP conserving ($P_+ = P_-$) and CP violating ($P_+ = -P_-$) scenario
- Dominant systematics: jet energy scale

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

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

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