GEORG-AUGUST-UNIVERSITÄT
GÖTTINGEN

Measurements of *W*-boson helicity, top-quark polarization and spin correlation in top-quark pairs

Kevin Kröninger – University of Göttingen

on behalf of the ATLAS, CDF, CMS and D0 Collaborations

Top2013, Durbach, September 14-19 2013

W-boson polarization

Physics case

- Top quark (mostly) decays into bottom quark and *real W* boson
- Massive spin-1 *W* boson has three polarization (helicity) states
- SM predictions of *helicity fractions*:

$$F_0 = \frac{m_{top}^2}{m_{top}^2 + 2m_W^2} \approx 0.70 \quad (\text{LO}) \rightarrow 0.687 \pm 0.005 \quad (\text{NNLO})$$

$$F_L = \frac{2m_W^2}{m_{top}^2 + 2m_W^2} \approx 0.30 \quad (\text{LO}) \rightarrow 0.311 \pm 0.005 \quad (\text{NNLO})$$

$$F_R = 0^{*} \quad (\text{LO}) \rightarrow 0.0017 \pm 0.0001 \quad (\text{NNLO})$$

Phys. Rev. D 81 (2010) 111503

* assuming m_b=0 GeV

- Helicity fractions are defined by *Wtb* vertex
- Sensitive to BSM effects, e.g.
  - Anomalous couplings, e.g. (V + A) admixture in charged weak current
  - Additional particles, e.g. charged Higgs, top squark, ...

(see backup for interpretations)

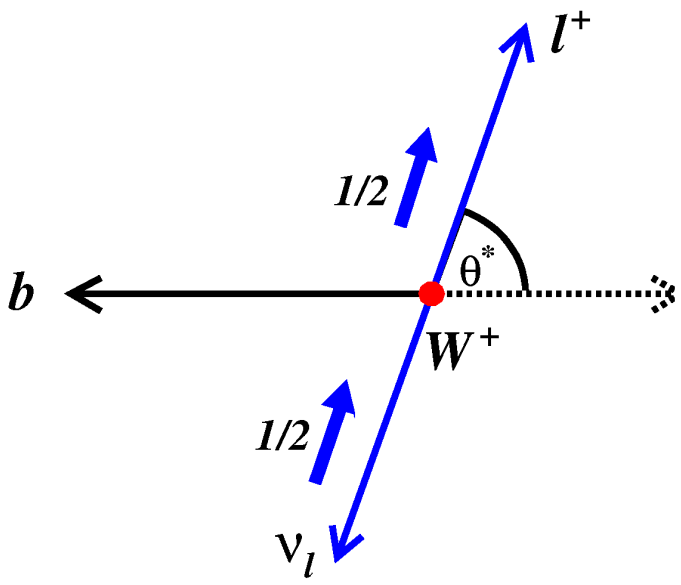
W-boson polarization

Observables

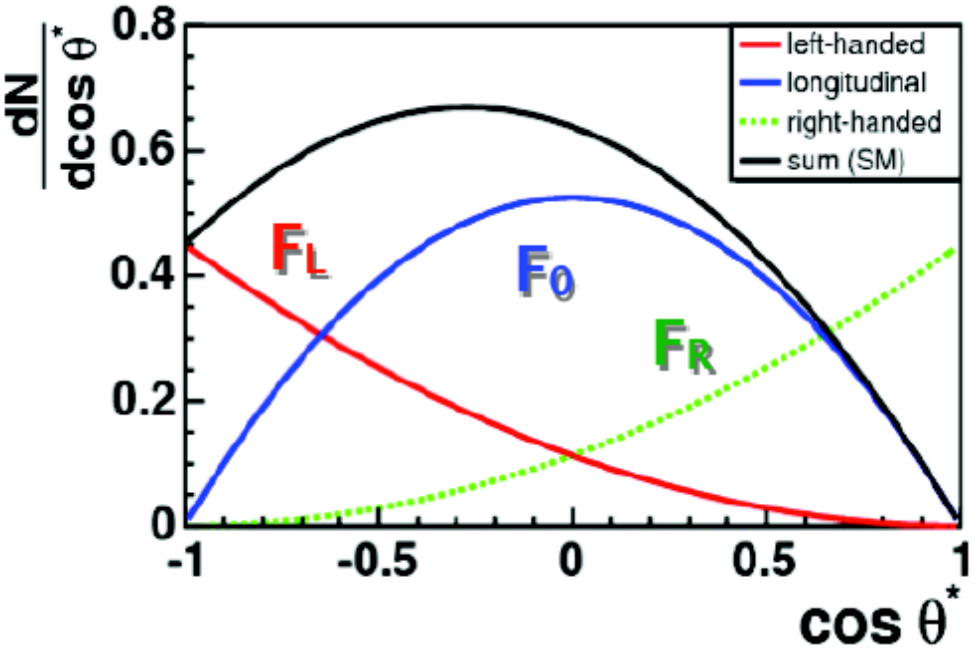
- Information about *W*-boson polarization from angular distributions of its decay products

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

SM prediction: ~0% ~31% ~69%



Reverse momentum of top quark

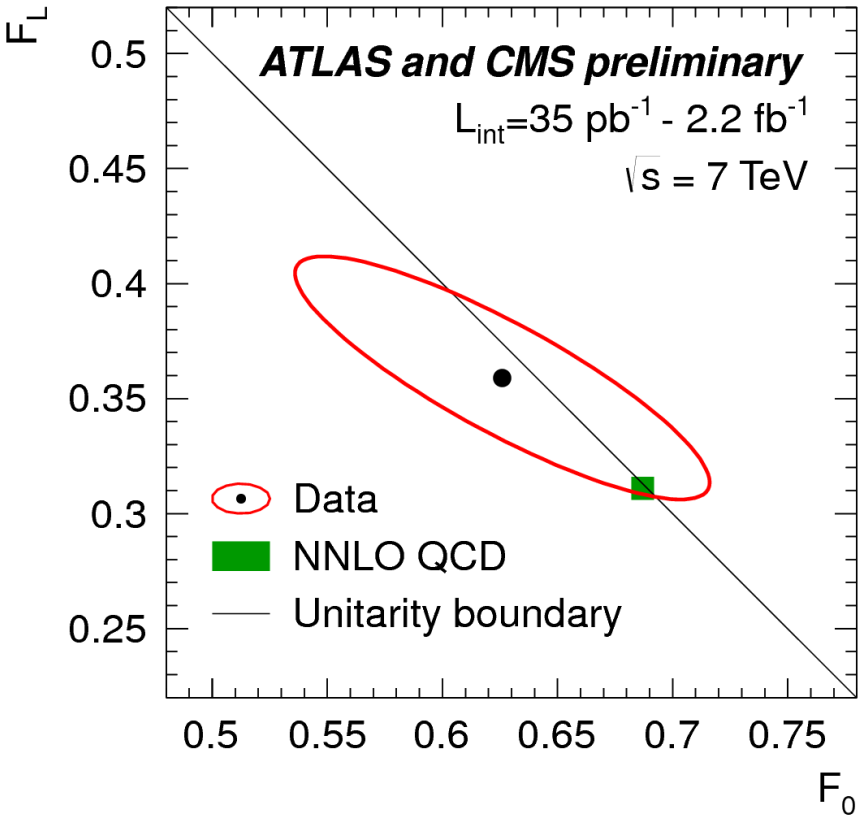


W-boson polarization

Status of combined measurements

- LHC combination (03/2013)

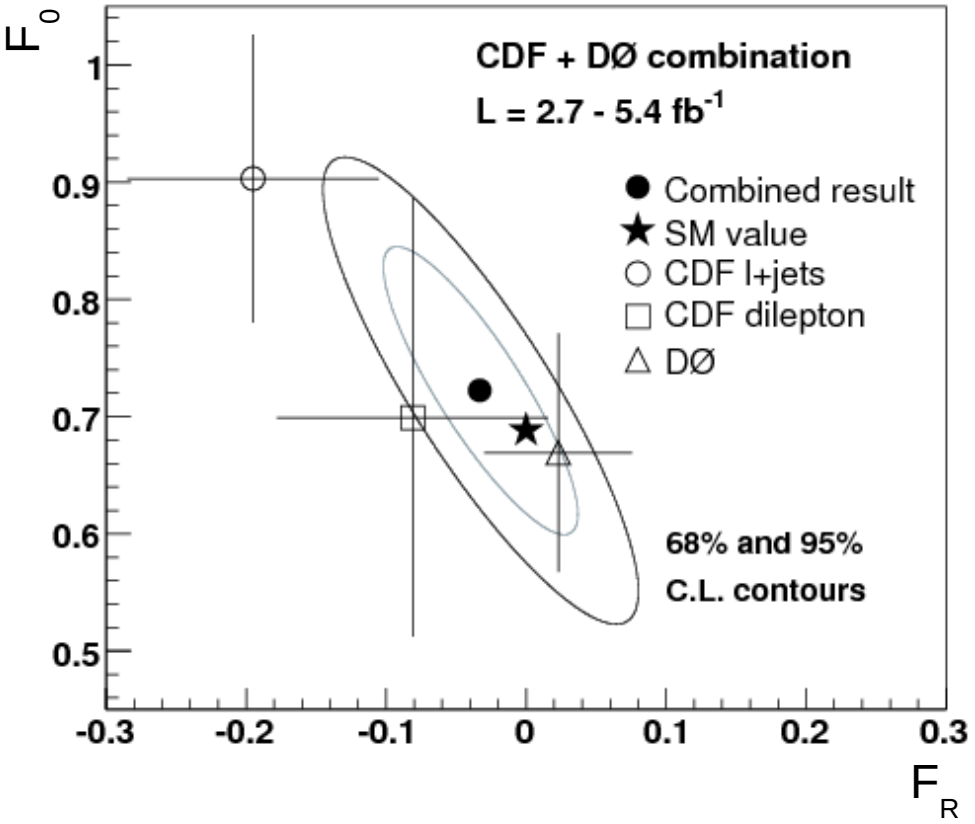
ATLAS-CONF-2013-033
CMS PAS TOP-12-025



Compare: ΔF_0 = 5.9%

Tevatron combination (02/2012)

Phys. Rev. D 85 (2012) 071106

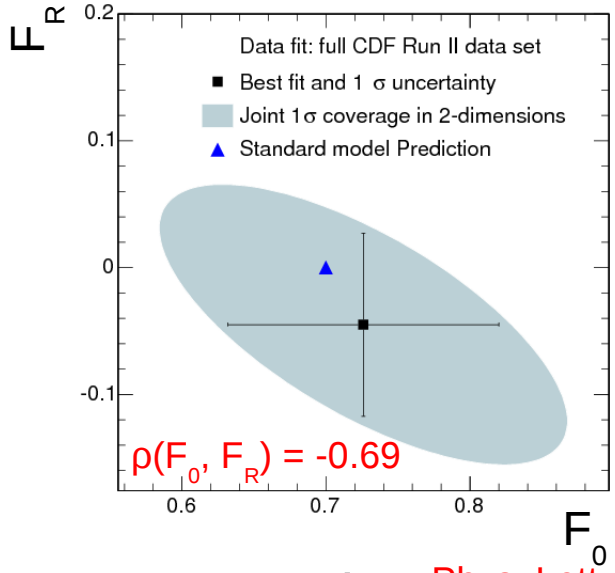


Compare: ΔF_0 = 8.1%

W-boson polarization

CDF updates

- Single-lepton analysis Phys. Rev. D 87 (2013) 031104(R)
  - Using full Run-II data set (8.7 fb^{-1})
  - Fit F_0 and F_R using *matrix-element method*
  - Systematic uncertainties dominated by modeling



- Dilepton analysis Phys. Lett. B 722 (2013) 48

D0 updates

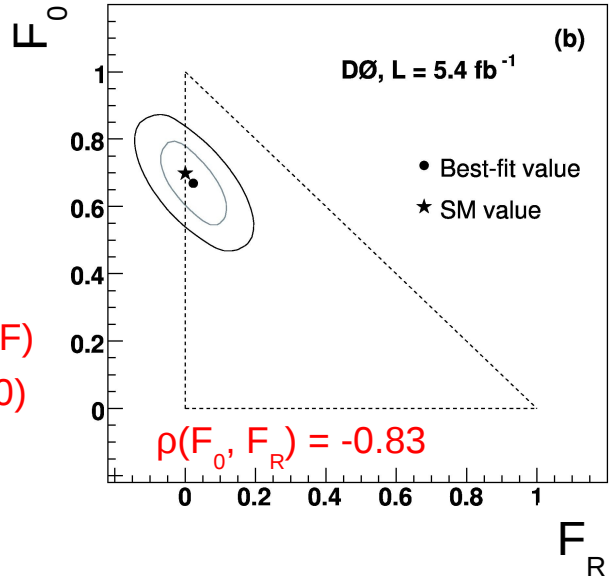
Phys. Rev. D 83 (2011) 032009

- D0 single-lepton and dilepton analysis
  - Using 5.4 fb^{-1} of data
  - Fit F_0 and F_R using template method
  - Systematic uncertainties dominated by modeling

Note the swapped axes

Compare: ΔF_0 = 9.4% (CDF)

Compare: ΔF_0 = 10.2% (D0)



W-boson polarization

New CMS measurement

arXiv:1308.3879, submitted to JHEP
See poster by Annik Olbrechts for details

- Single lepton selection with at least two *b*-tags (5.0 fb^{-1})
- Data-driven estimate of W/Z+jets and DY+jets, other sources estimated using simulation
- Signal simulated using MadGraph with PYTHIA, background with MadGraph, POWHEG and PYTHIA
- Reconstruction of final state using a χ^2-based kinematic fit (16% loss due to unphysical/no solution)
- Calculation of angle θ* for the lept. and hadr. decaying top quark
- Fit strategy: reweighting events on parton level based on helicity fractions

NEW

$$W(\cos(\theta^*);F_R,F_L,F_0)=\frac{\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma(F_R,F_L,F_0)}{\mathrm{d}\cos(\theta^*)}}{\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma(F_R^{\mathrm{SM}},F_L^{\mathrm{SM}},F_0^{\mathrm{SM}})}{\mathrm{d}\cos(\theta^*)}}$$

W-boson polarization

New CMS measurement

NEW

arXiv:1308.3879, submitted to JHEP
See poster by Annik Olbrechts for details

- Binned likelihood fit to the data:
  - "3D" fit: Signal normalization F_{tt}, F_0 and F_L
  - "2D" fit: Signal normalization F_{tt} and F_0 (assume F_R = 0, include hadr. side)
- Results:

$$F_0 = 0.682 \pm 0.030\,(\text{stat}) \pm 0.033\,(\text{syst})$$
$$F_L = 0.310 \pm 0.022\,(\text{stat}) \pm 0.022\,(\text{syst})$$
$$F_R = 0.008 \pm 0.012\,(\text{stat}) \pm 0.014\,(\text{syst})$$
$$\rho_{0L} = -0.95$$

$$F_0 = 0.685 \pm 0.017\,(\text{stat}) \pm 0.021\,(\text{syst})$$
$$F_L = 0.315 \pm 0.017\,(\text{stat}) \pm 0.021\,(\text{syst})$$

- Important sources of syst. uncertainty for F_0 (F_L):
  - MC statistics ~ 0.016 (0.012)
  - Top-quark mass ~ 0.016 (0.011)
  - Signal modeling ~ 0.014 (0.013)

W-boson polarization

New CMS preliminary result

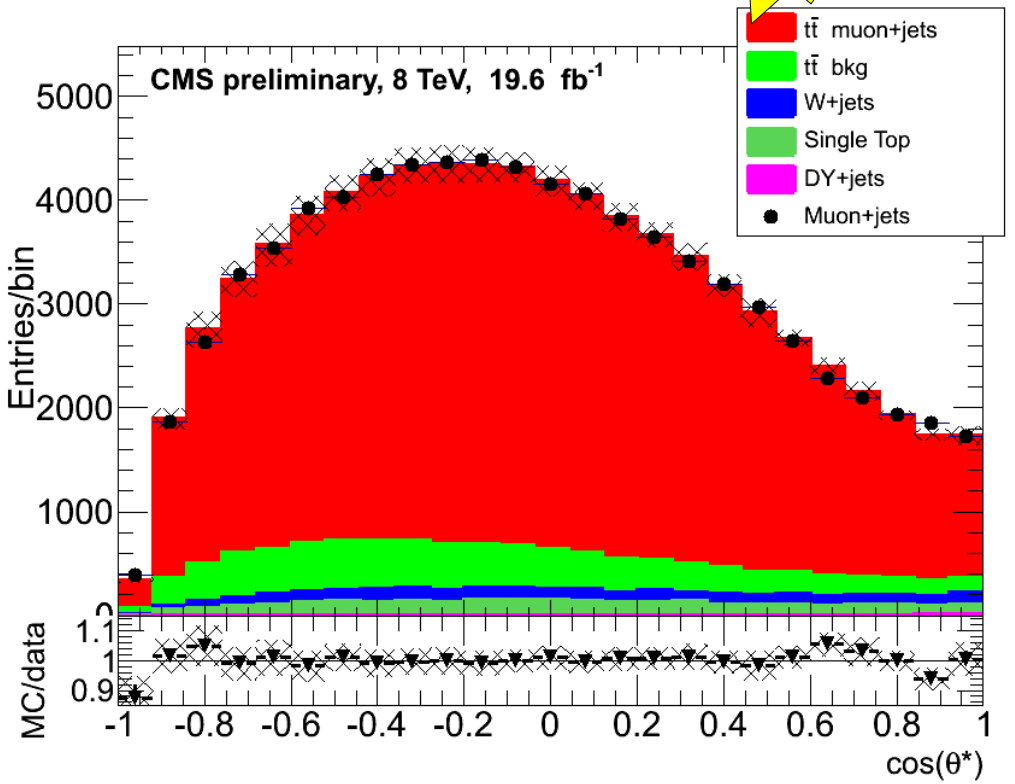
CMS PAS TOP-13-008

- Repeat analysis on 8 TeV data (19.6 fb^{-1}) with single-muon selection and tighter requirements on jets and leptons
- Use leptonic side and "3D" fit
- Results:

$$F_0 = 0.659 \pm 0.015\,(\text{stat}) \pm 0.023\,(\text{syst})$$
$$F_L = 0.350 \pm 0.010\,(\text{stat}) \pm 0.024\,(\text{syst})$$
$$F_R = -0.009 \pm 0.006\,(\text{stat}) \pm 0.020\,(\text{syst})$$
$$\rho_{0L} = -0.95$$

- Important sources of syst. uncertainty for F_0 (F_L):
  - Signal modeling ~ 0.017 (0.014)
  - Top-quark mass ~ 0.012 (0.008)
  - E_T^{miss} shape ~ 0.004 (0.018)

NEW



Top-quark spin and correlation

Physics case

- Large top-quark mass leads to very short lifetime

$$\tau_{top} = \frac{1}{\Gamma_{top}} \approx 5 \cdot 10^{-25}\ \text{s} < \tau_{had} \approx \frac{1}{\Lambda_{QCD}} \approx 3 \cdot 10^{-24}\ \text{s}$$

- No bound states including top quarks (toponium, top-hadrons)
- Spin information (polarization and spin correlation) are passed on to decay products and not diluted by hadronization effects.
- Angular distributions of final-state particles reveal information about the top-quark spin and correlation
- Expect negligible top-quark polarization and finite spin correlation in the SM
- The amount of spin correlation is sensitive to the production mechanism
- Deviations from SM predictions can be caused by BSM models, e.g., models including axigluons, W' bosons, extra right-handed top-quark couplings, etc.

Top-quark spin and correlation

Observables

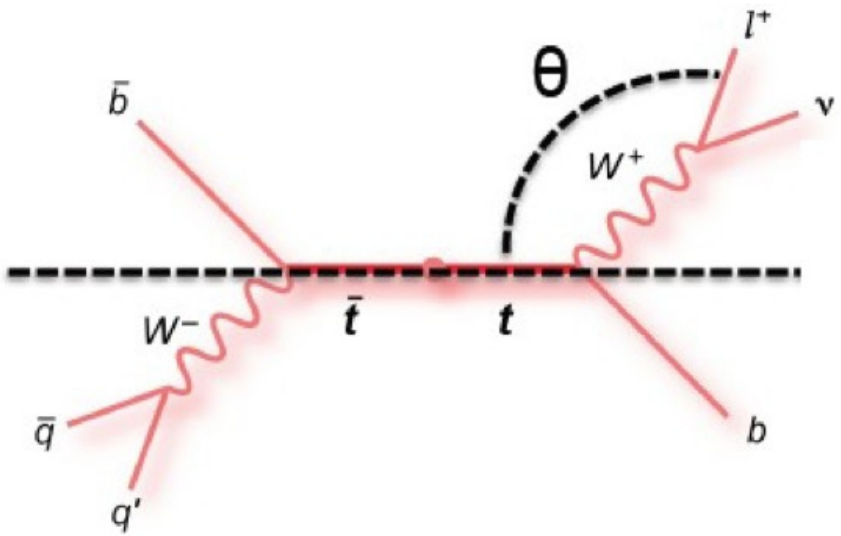
- Information about top-quark polarization and spin correlation from angular distributions of the decay products

$$\frac{1}{\sigma}\frac{\mathrm{d}^2\sigma}{\mathrm{d}\cos(\theta_i)\,\mathrm{d}\cos(\theta_j)} = \frac{1}{4}\left(1 + B_i\cos(\theta_i) + B_j\cos(\theta_j) + C\cos(\theta_i)\cos(\theta_j)\right)$$

Top-quark polarization — Antitop-quark polarization — Spin correlation

- Angle θ_i between momentum direction of particle *i* in the (anti-)top-quark rest frame and a reference axis, e.g., beam (Tevatron) or helicity axis (LHC)

See presentation by Oliver Maria Kind on single-top polarization



Top-quark polarization

Observables and predictions

- Information about top-quark polarization can be obtained from differential cross section

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\cos(\theta_i)} = \frac{1}{2}\left(1+(2)\alpha_i P\cos(\theta_i)\right)$$

B_i in previous formula
CMS uses a “2”

- *P* is the *degree of polarization*
- α_i is the *spin analyzing power* of the final-state particle:
  - α = 1.0 for charged lepton and down-type quark
  - α = -0.4 for the bottom quark
  - α = -0.3 for the neutrino and the up-type quark
- LHC analyses use charged leptons and the helicity axis
- SM prediction:

$$P \approx 0.003$$

Driven by weak corrections
arXiv:1305.2066

See poster by Kamil Augsten
for ‘work-in-progress’ D0 studies

Top-quark polarization

CMS preliminary result

CMS PAS TOP-12-016

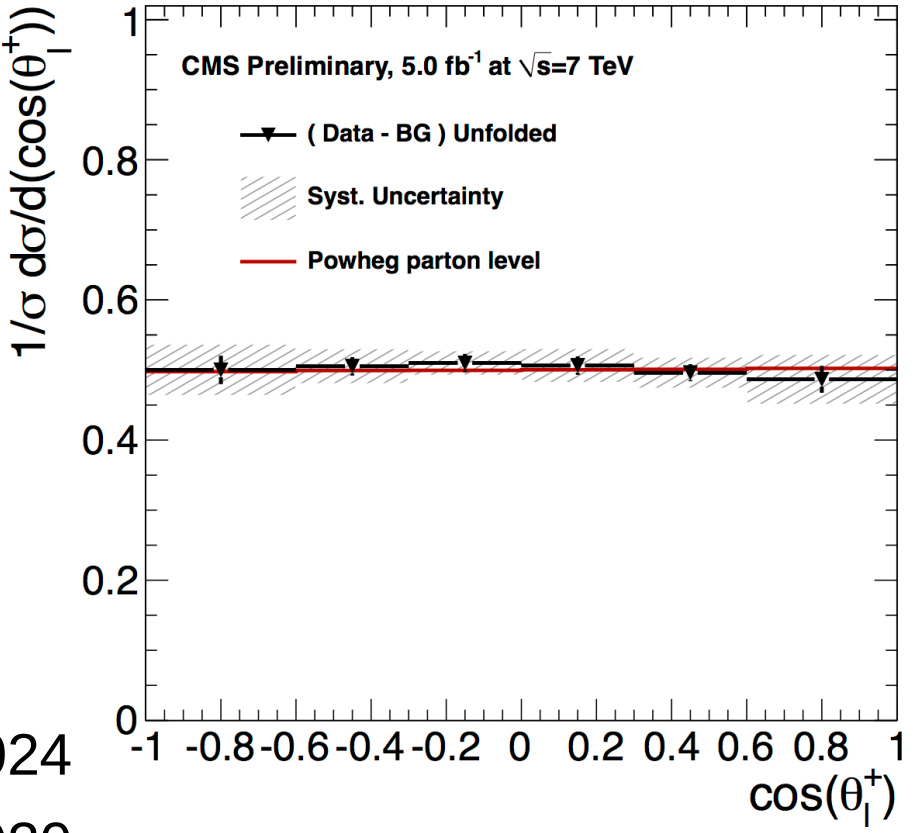
- Background subtraction and *regularized unfolding using SVD*
- Dilepton selection (5.0 fb^{-1})
- Observable is asymmetry variable

$$P = \frac{N(\cos(\theta^+) > 0) - N(\cos(\theta^+) < 0)}{N(\cos(\theta^+) > 0) + N(\cos(\theta^+) < 0)}$$

- Results (mind factor of 2):

$$P = -0.009 \pm 0.029\ (\text{stat}) \pm 0.041\ (\text{syst})$$

- Important sources of syst. uncertainty:
  - Reconstruction (“Mt scan range”) ~ 0.024
  - Jet energy scale ~ 0.020
  - Top-quark mass ~ 0.019

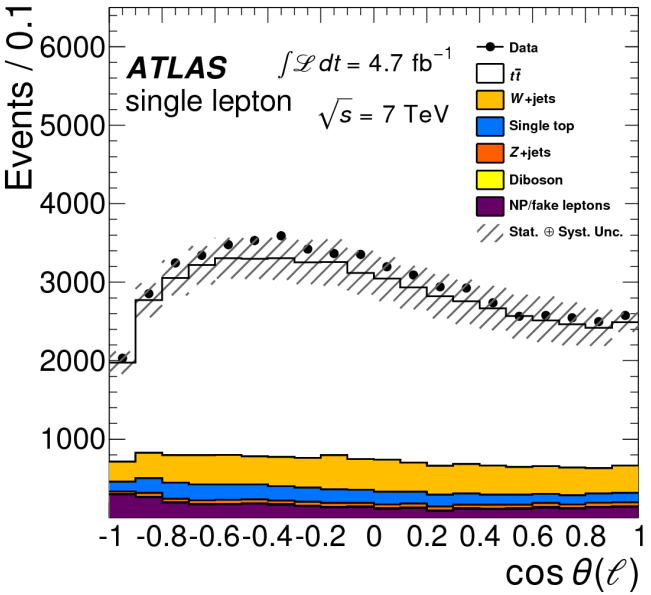


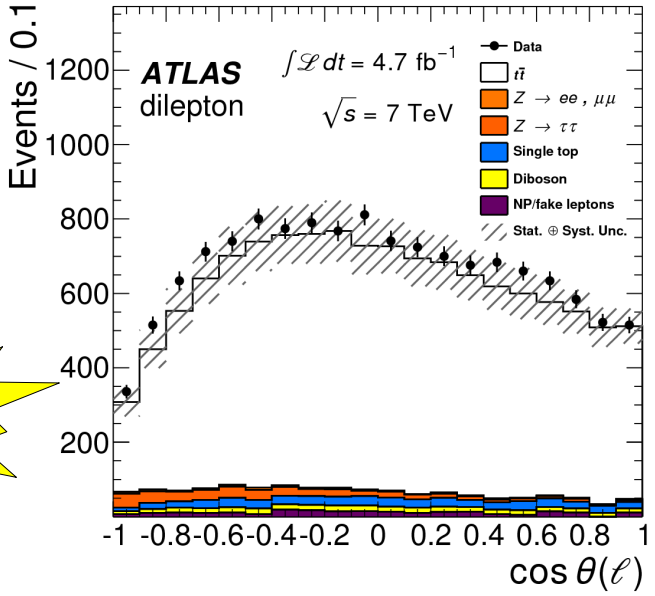
Only consider top-quark polarization, antitop-quark polarization as cross-check

Top-quark polarization

New ATLAS measurement

- Single lepton (at least one *b*-tag) and dilepton (no *b*-tag) selection using 4.7 fb^{-1} data
- Data-driven estimate of W/Z+jets and non-prompt / misidentified leptons, other sources estimated using simulation
- Signal simulated using MC@NLO with HERWIG, background with MC@NLO, AcerMC, ALPGEN and HERWIG
- Reconstruction of final state using a likelihood-based kinematic fit or neutrino weighting (15% loss due to unphysical/no solution)
- Calculation of angle θ^+ (top quark) and θ^- (antitop-quark)





NEW

arXiv:1307.6511, submitted to PRL

See posters by R. Schäfer and S. Hamilton for details

Top-quark polarization

New ATLAS measurement

NEW

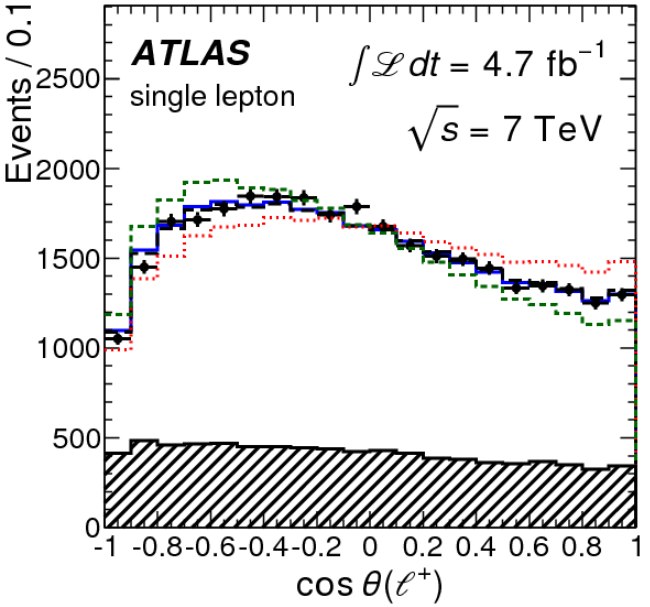
arXiv:1307.6511, submitted to PRL

See posters by R. Schäfer and S. Hamilton for details

- Template fit to reconstructed spectra
- Templates are obtained by reweighting the samples according to differential cross-section. Consistently done so as to conserve spin correlations.
- Two assumptions:
  - CP conserving process: top and antitop quark have same polarization
  - CP violating process: top and antitop quark have opposite polarization
- Results:

$$\alpha_l P_{CPC} = -0.035 \pm 0.014\ (\text{stat}) \pm 0.037\ (\text{syst})$$
$$\alpha_l P_{CPV} = 0.020 \pm 0.016\ (\text{stat})^{+0.013}_{-0.017}\ (\text{syst})$$

- Important sources of syst. unc. for CPC (CPV):
  - Jet reconstruction ~ 0.031 ($^{+0.009}_{-0.005}$)
  - Modeling ~ 0.015 ($^{+0.005}_{-0.013}$)



Observables and predictions

- Information from angular distributions of decay products

$$\frac{1}{\sigma}\frac{\mathrm{d}^2\sigma}{\mathrm{d}\cos(\theta_i)\,\mathrm{d}\cos(\theta_j)} = \frac{1}{4}\left(1 + A\,\alpha_i\alpha_j\cos(\theta_i)\cos(\theta_j)\right)$$

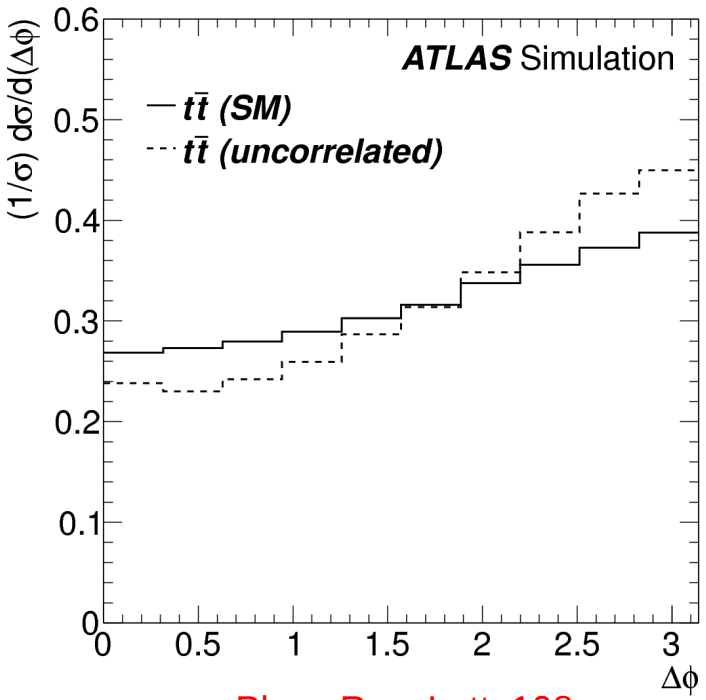
Assuming no top-quark polarization

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

C in previous formula

Also: $\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\Delta\phi}$

Phys. Rev. D 81 (2010) 074024



Phys. Rev. Lett. 108 (2012) 212001

- Correlation depends on production mechanism:
  - LHC: gg with (un)like-helicity gluons for low (high) invariant top-quark pair masses
  - Tevatron: unlike-helicity quark pairs

Spin correlation

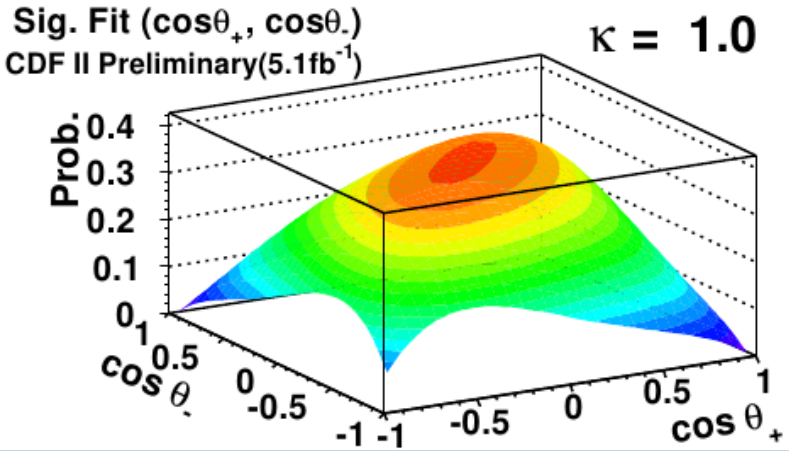
CDF preliminary result

CDF note 10719

- Dilepton analysis
  - Using 5.1 fb^{-1} data
  - Calculate angle Θ for charged lepton and b-jet
  - Fit spin correlation coefficient C using cos Θ·cos Θ distributions
  - Results

$$C = 0.042^{+0.563}_{-0.562}\ (\text{stat} + \text{syst})$$

SM: C ~ 0.8



D0 evidence

Phys. Rev. Lett. 108 (2012) 032004

- Single-lepton analysis
- Using 5.3 fb^{-1} data
- Build discriminant using *matrix-element method*
- Fit fraction *f* of events with SM spin correlation
- Systematic uncertainties dominated by MC statistics
- Combined with dilepton analysis
- Results

Phys. Rev. Lett. 107 (2011) 032001

$$f = 0.85 \pm 0.29\ (\text{stat} + \text{syst})$$

- Establish evidence (3.1 std) for non-zero spin correlation

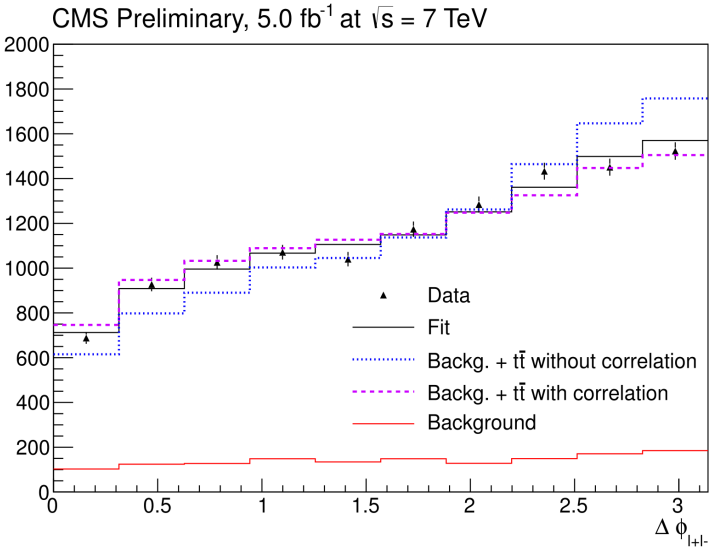
Spin correlation

CMS preliminary results

CMS PAS TOP-12-004

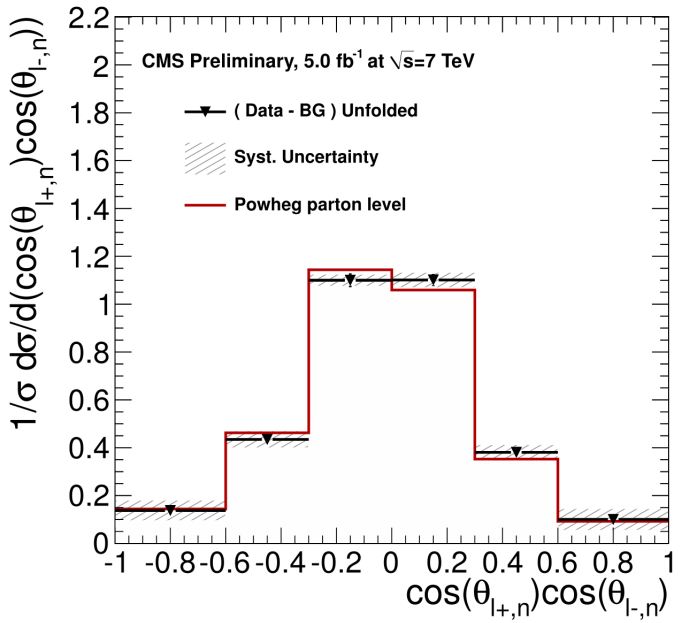
- Dilepton selection with at least one *b*-tag using 5.1 fb^{-1} data
- Template fit to ΔΦ distribution with normalization parameters and fraction *f* of events with spin correlation
- Results:

$$f = 0.74 \pm 0.08\ (\text{stat}) \pm 0.24\ (\text{syst})$$



- Background subtraction and *regularized unfolding using SVD*
- Results:

$$A_{\Delta\phi} = -0.097 \pm 0.015\ (\text{stat}) \pm 0.036\ (\text{syst})$$
$$A_{\Delta cc} = -0.015 \pm 0.037\ (\text{stat}) \pm 0.055\ (\text{syst})$$



Spin correlation

New ATLAS preliminary results

NEW

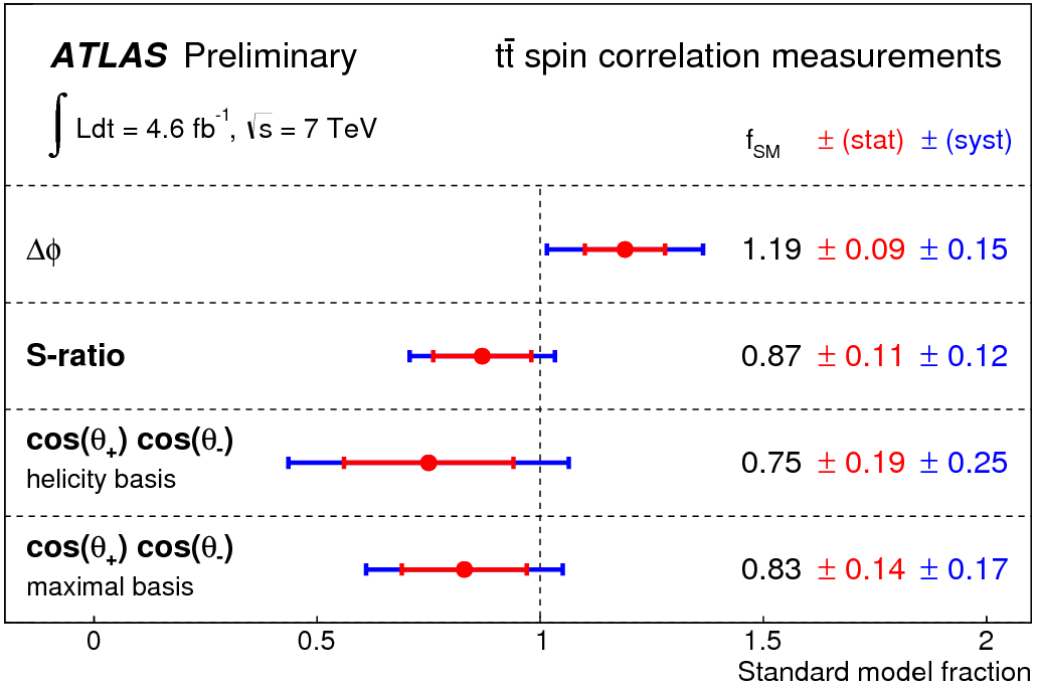
ATLAS-CONF-2013-101

- Dilepton selection using 4.7 fb^{-1} data
- Reconstruction of final state using neutrino weighting
- Template fit to several distributions with normalization parameters and fraction *f* of events with spin correlation
- New Observable: *S-ratio*

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

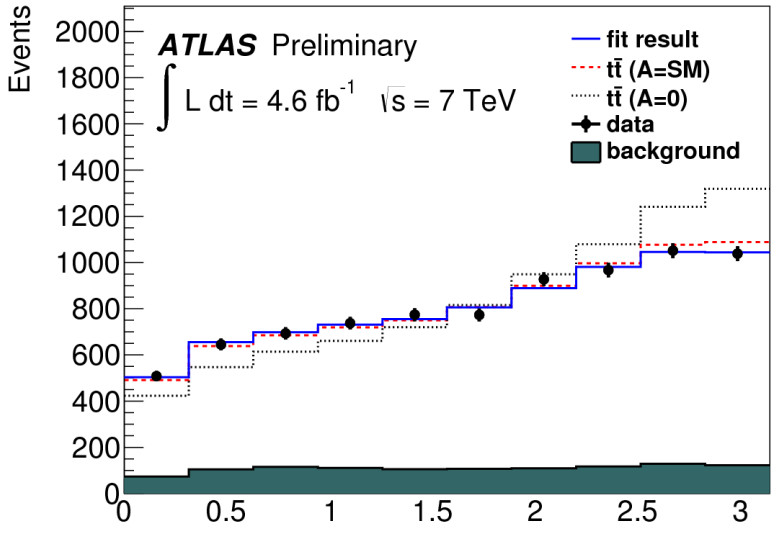
- Important sources of syst. unc.
  - Signal modeling up to ~0.09
  - Jet reconstruction up to ~0.12

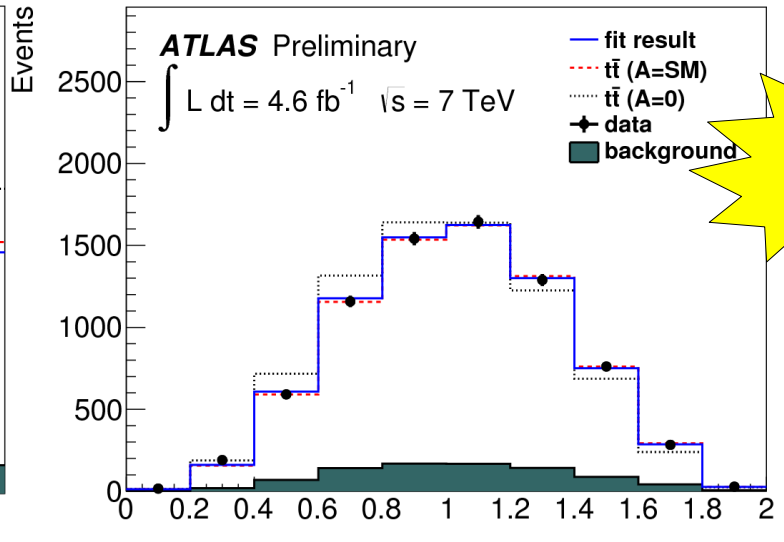
Results:

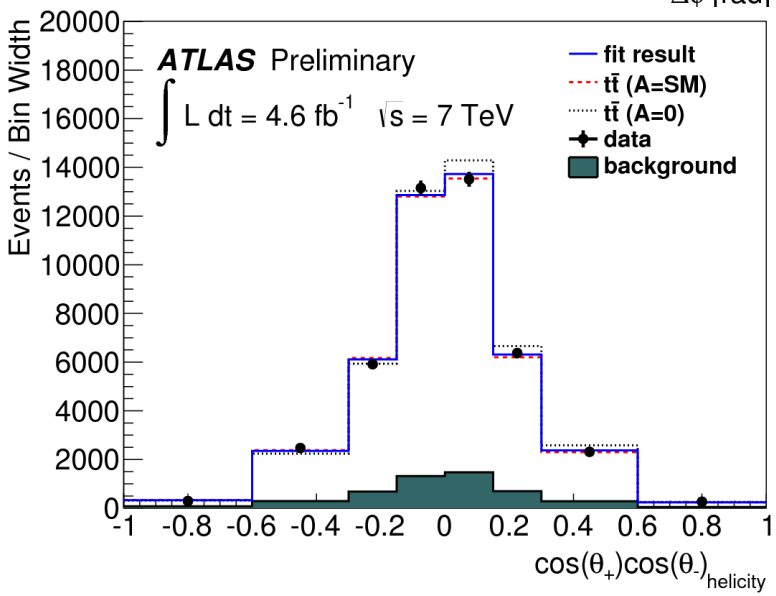


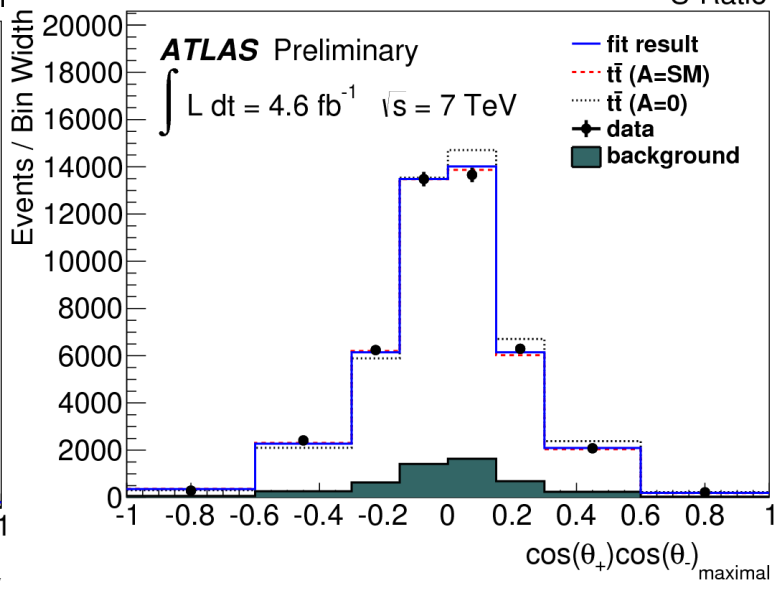
New ATLAS preliminary results

ATLAS-CONF-2013-101









Summary

- Precision measurements of angular distributions are
  - good observables for testing SM predictions,
  - sensitive to BSM contributions
- Measurements show no sign of new physics:
  - *W*-helicity measurements are getting more precise
  - No polarization of top quarks observed in top-quark pair production
  - Spins of top-quark pairs are not uncorrelated
- Most analyses dominated by systematic uncertainties
- Outlook
  - Interpret precision measurements in terms of anomalous couplings
  - Improve understanding of systematic uncertainties, in particular modeling of signal (and background)
  - Plenty of data to be analyzed