Top Quark Polarization

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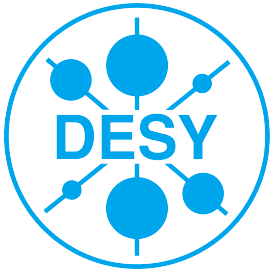
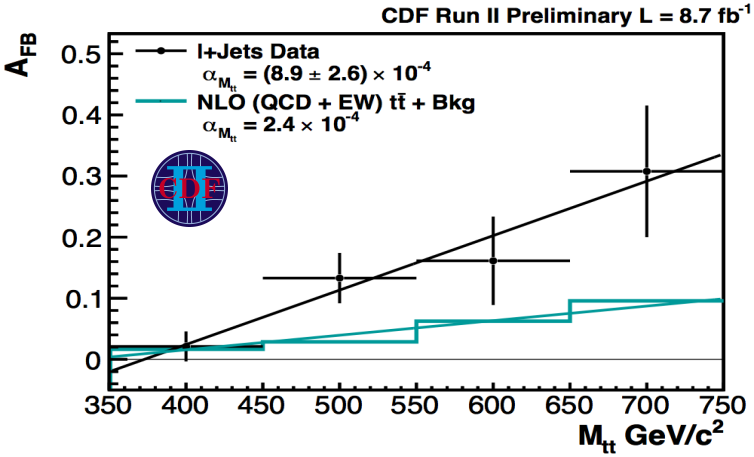


Motivation

- $t\bar{t}$ forward backward asymmetry at Tevatron: larger than SM prediction
  - New physics?
  - Issue: IF new physics, there are constraints from other top precision measurements



- Constraints from b quark coupling from precision flavor observables
  → many models for A_{FB} couple only to right-handed top quarks
  → predict large top polarization!

Krohn et al, arxiv:1105.3743

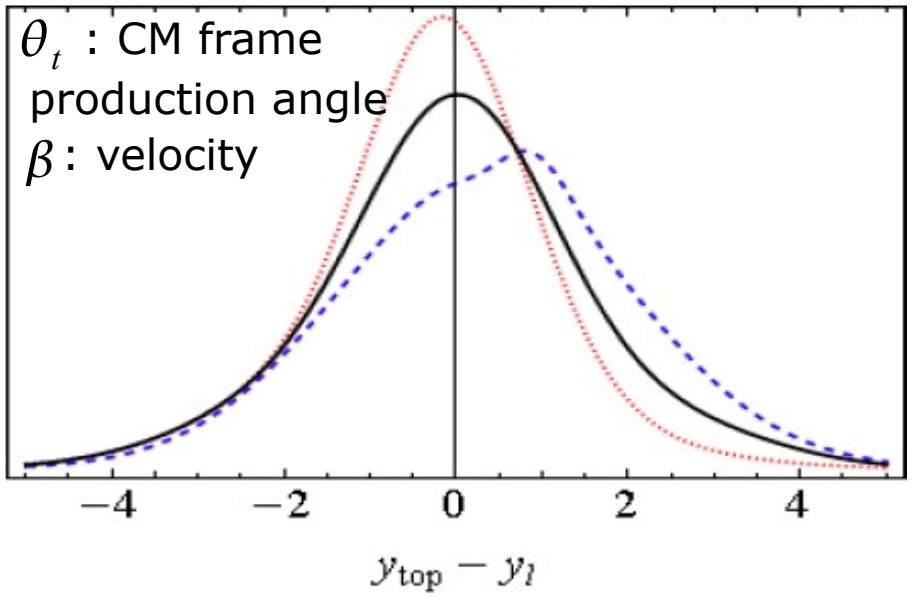
- Top decay in top rest frame:

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{i,n}} = \frac{1}{2}\left(1 + \mathcal{P}_n \kappa_i \cos\theta_{i,n}\right)$$

  - P_n: polarization; κ_i: spin analyzing power of decay product i; θ_i: direction of daughter wrt. chosen axis
    - In ATLAS paper: κ is called α

Motivation

- For example: lepton asymmetry related to top polarization



(a) $\beta_t = 0.5$, $\cos\theta_t = 0.4$

black: unpolarized top
Red: right-handed top
Blue: left-handed top

- Important to measure top polarization

Krohn et al, arxiv:1105.3743

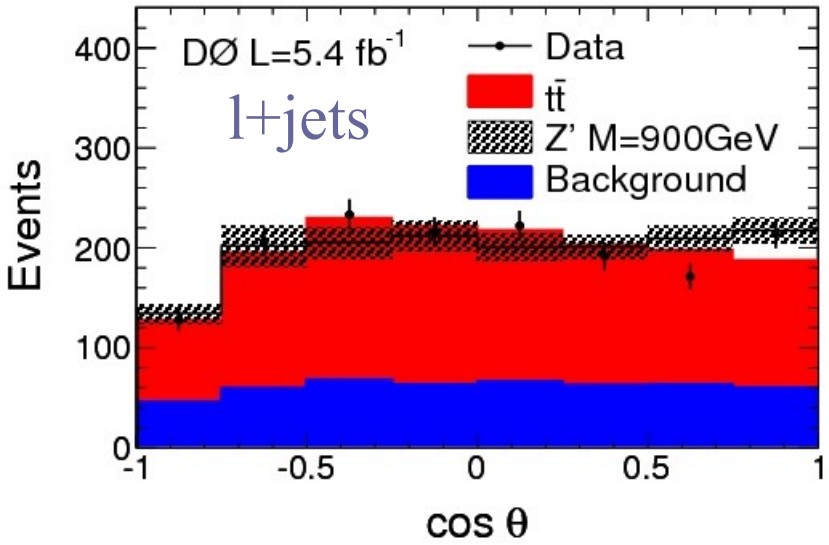
  - In its own right
  - To distinguish models predicting $t\bar{t}$ asymmetry !=SM

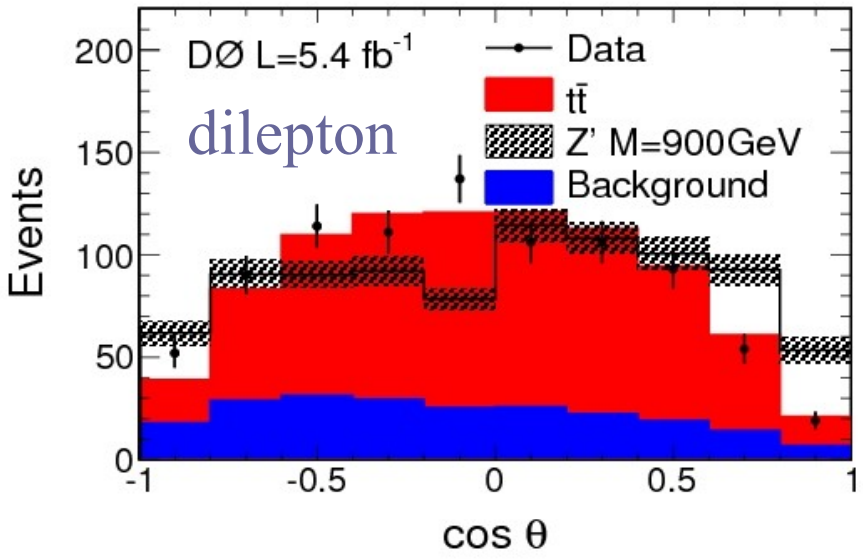
First Top Polarization Study

- First study done by DØ
  - Reconstruction in dilepton: neutrino weighting; in l+jets: kinematic fitter
  - Calculate cos θ distribution
  - Compare prediction of SM MC to data

    → good agreement with SM

PRD 87, 011103 (2013)





Top Polarization Measurements

- Since summer 2012: two measurements of top polarization
  - CMS: dilepton events; 5.0fb^{-1}, 7TeV data
  - ATLAS: dilepton and l+jets events, 4.7fb^{-1}, 7TeV data

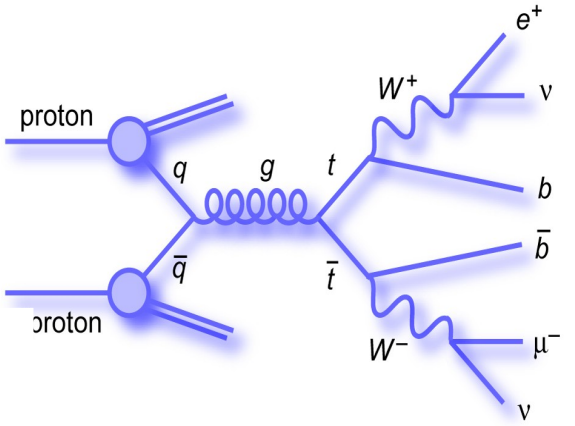
arxiv:1307.6511

- Will go through
  - Measurement procedures
  - Results
  - Systematics

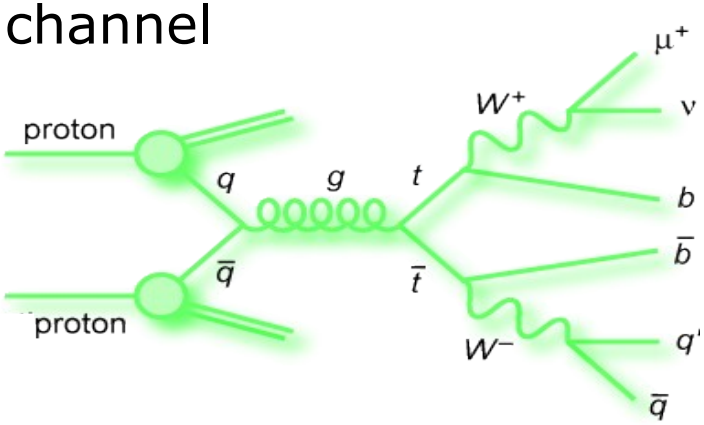
  for both measurements and compare
    - Conclusions are based on my personal opinion!

ATLAS Measurement: Basics

- Calculate cosθ distribution
  - Quantization axis: top quark direction in $t\bar{t}$ rest frame (helicity basis)
- Event selection:
  - Dilepton: standard selection
    - At least 2 jets
    - Two isolated, opposite-sign high p_T leptons (e or μ)
    - Large $\not{E}_T$ for ee and $\mu\mu$ channel, large H_T for eμ channel



  - l+jets: standard selection
    - At least 4 jets, >0 b-tagged
    - Exactly one isolated, high p_T lepton (e or μ)
    - Large $\not{E}_T$ and cut on m_T^W



ATLAS Measurement: Basics

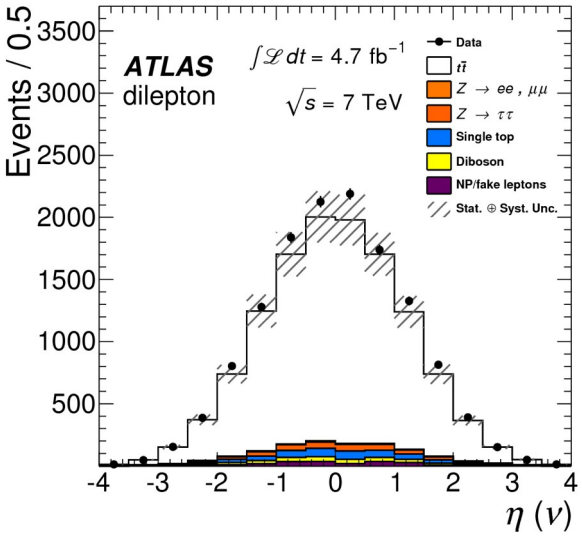
- Sample estimation using MC and data-driven estimations
  - Diboson and single top taken from MC
  - In l+jets:
    - Simulation for Z+jets
    - Charge asymmetry normalization for W+jets (shape from MC)
    - QCD multijet estimated using matrix method
  - In dilepton:
    - Z+jets in ee and $\mu\mu$ channels: estimated with

$$E_{T,rel}^{miss} = E_T^{miss} \times \sin \Delta\phi(E_T^{miss}, closest \quad object)$$

    - Fake estimation using matrix method (mainly W+jets)

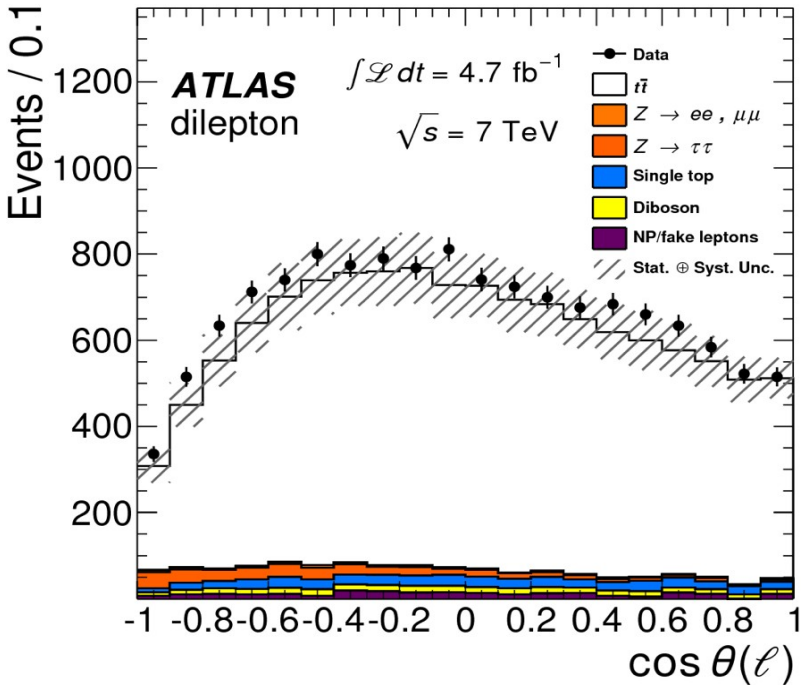
ATLAS Measurement: Procedure

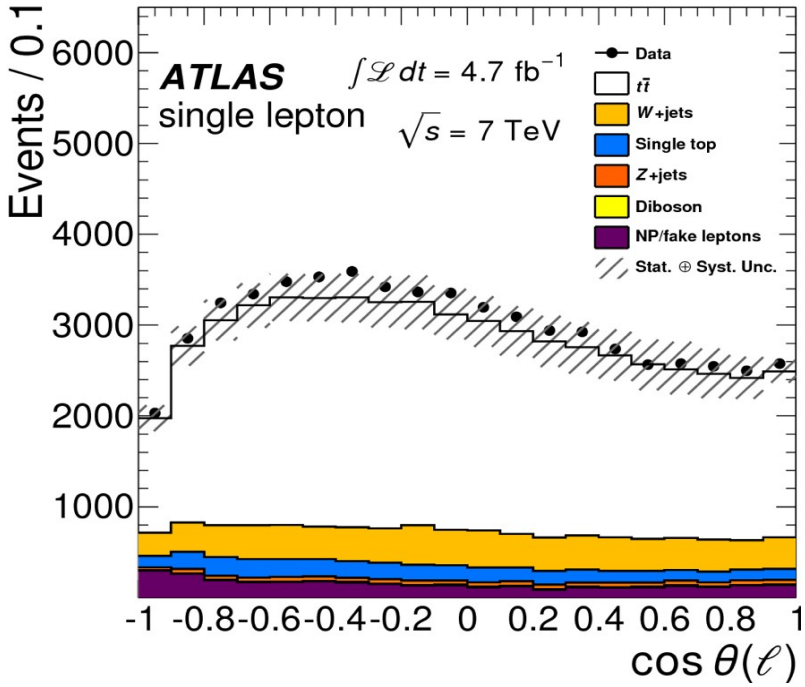
- Reconstruction of $t\bar{t}$ event:
  - l+jets: KLfitter
  - Dilepton: neutrino weighting
    - Assume neutrino ηs
    - solve event kinematics for each assumption
    - Calculate $\not{E}_T$ from neutrino momentum solutions
    - Calculate weight based on the comparison of calculated and measured $\not{E}_T$
    - Neutrino weighting efficiency for signal: ~85%
- Take solution with highest weight
- Use lepton for construction of cos θ



ATLAS Measurement: Procedure

- Cos θ distributions:





- Measurement procedure: template fit
  - Step 1: construct templates with positive and negative polarization

ATLAS Measurement: Procedure

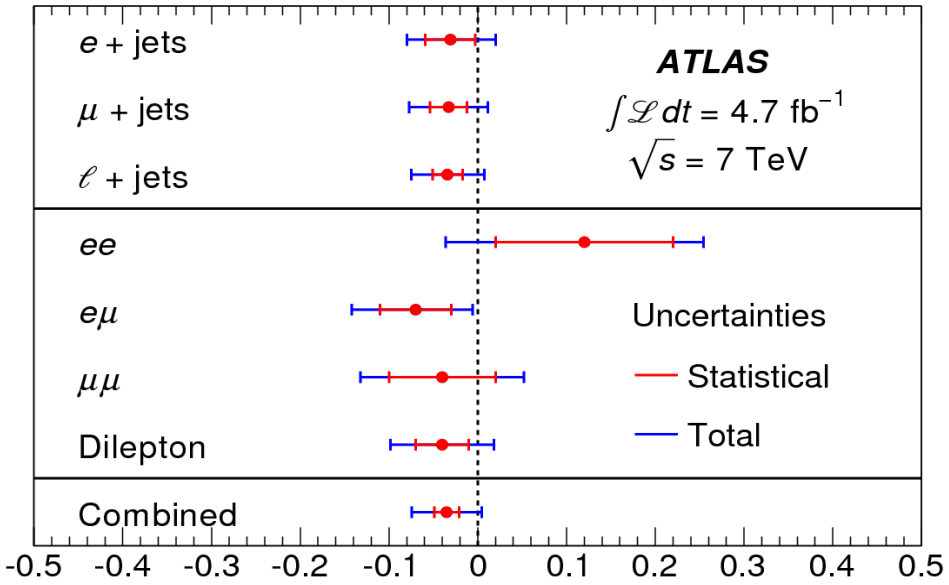
- Consider two scenarios: CP conserving and CP violating
- Reweighting:
  - $t\bar{t}$ MC: MC@NLO with full spin correlation included
  - Use lepton/d-type quark from top and antitop sides:

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

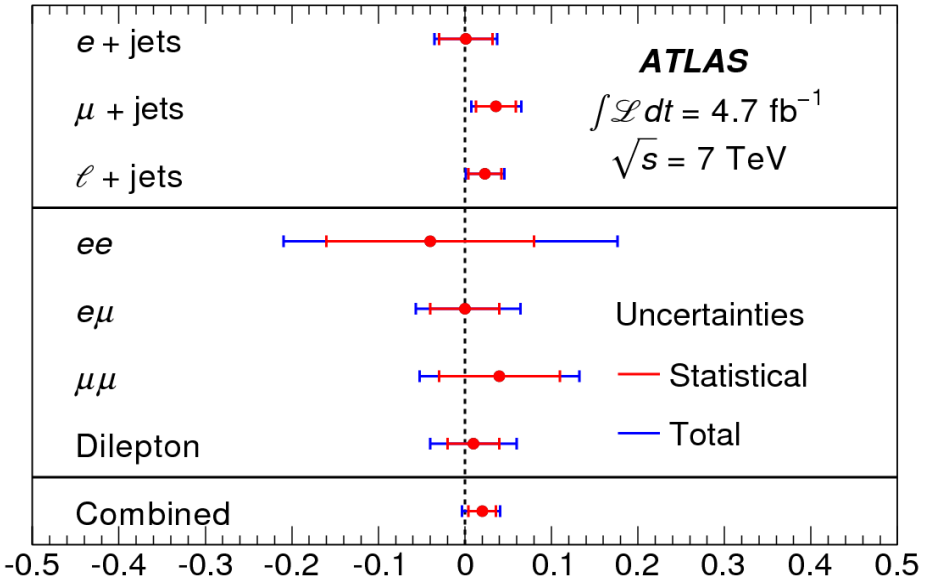
    - For the two scenarios:
      - CP conserving: $(\alpha P)_1 = (\alpha P)_2$
      - CP violating: $(\alpha P)_1 = -(\alpha P)_2$
    - C: spin correlation; use value from MC truth
    - Reweight templates to ±0.3 for polarization of templates
      → to not run into bias
- α for leptons: 1 in LO; close to 1 in NLO

ATLAS Measurement: Fit

- Binned maximum likelihood fit of templates
  - Signal and background templates
  - Extract f: fraction of positive polarization
  - Simultaneous extraction of $t\bar{t}$ cross section
    → reduce uncertainties from normalization



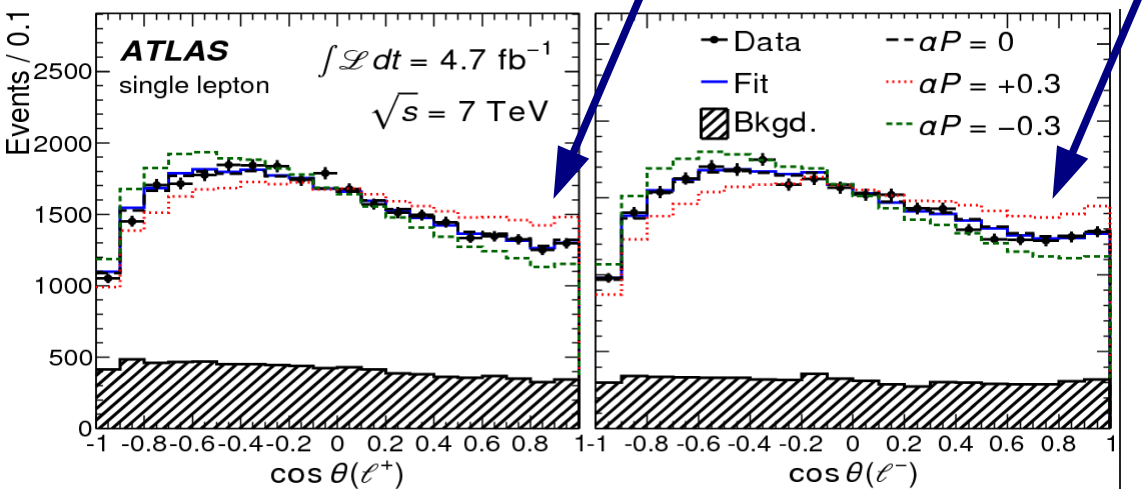
CP conserving

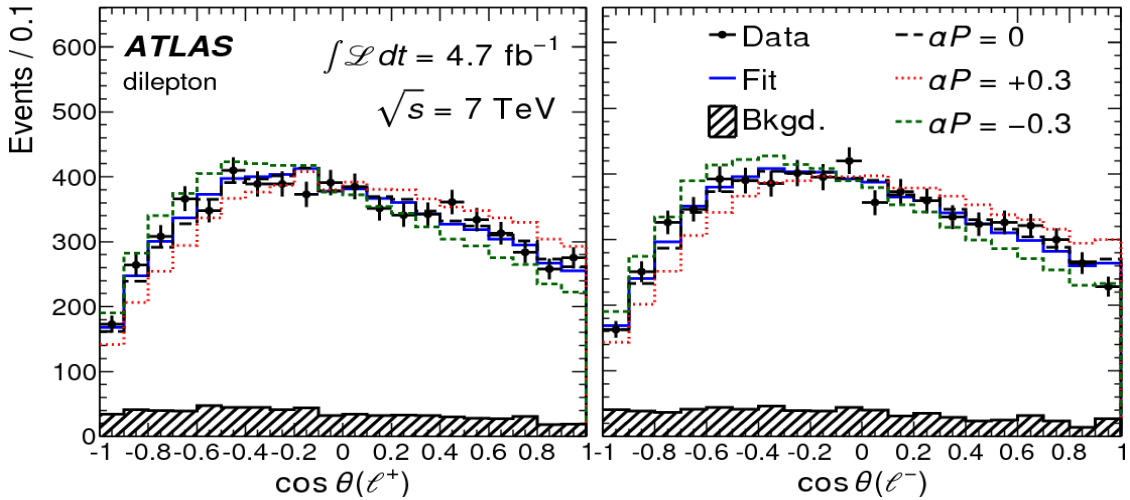


CP violating

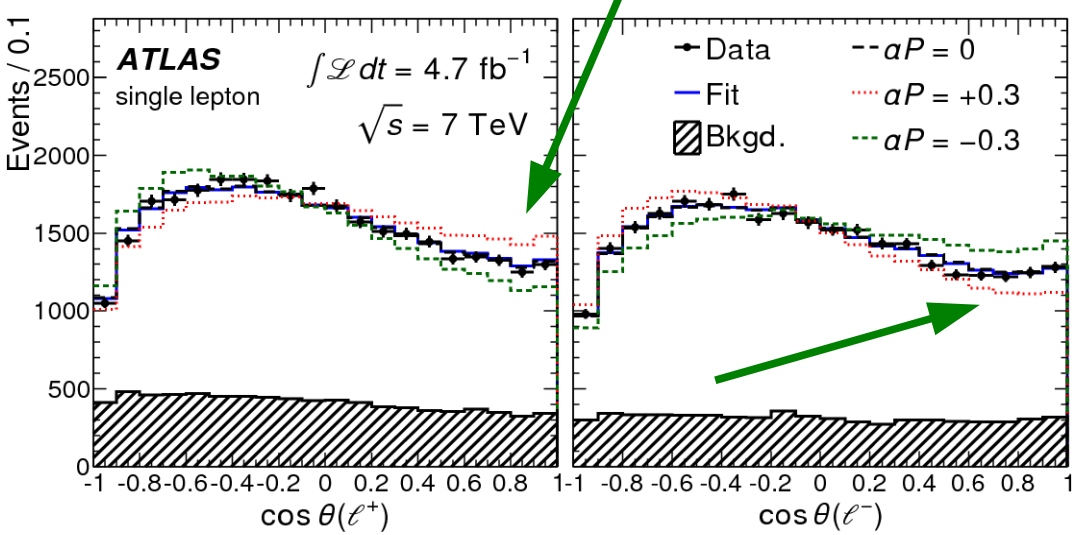
ATLAS Measurement: Results

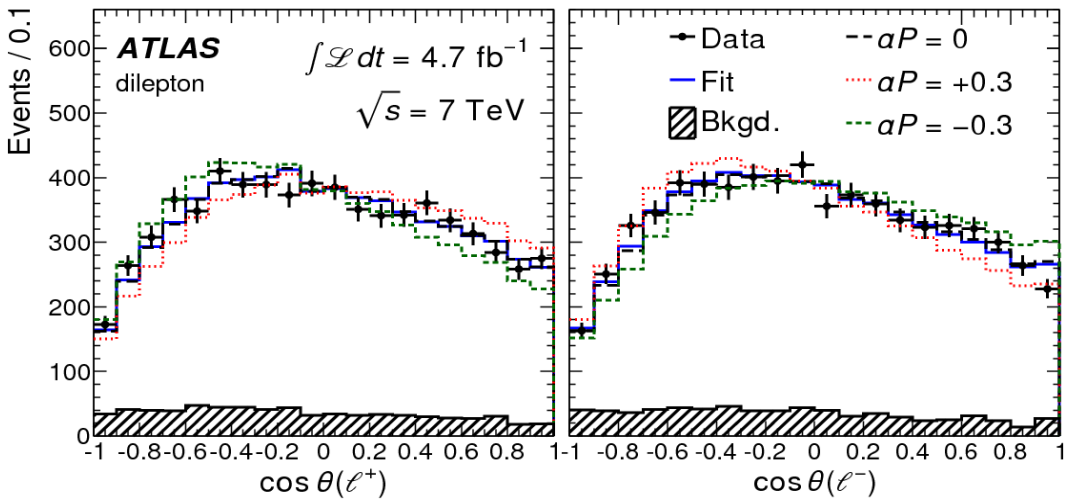
- CP conserving:





CP violating:





ATLAS Measurements: Results

- Final combined results:

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

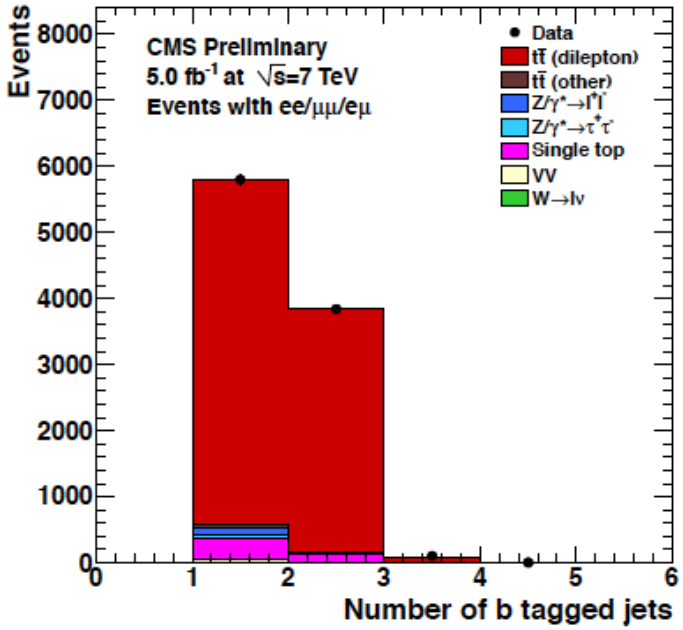
- Consistent with SM prediction
  - SM: negligible polarization (P=0.003 from weak contributions)
- Uncertainties for CP violating smaller
  → due to reverse behavior for top and antitops

CMS Measurement: Basics

- Calculate cos θ distribution using leptons
- Select dilepton events
  - At least 2 jets, of which at least 1 is b-tagged
  - Two isolated, opposite-sign high p_T leptons (e or μ)
  - No cut on $\not{E}_T$
- Signal and background estimation:
  - Signal generated with Powheg+Pythia (ATLAS: MC@NLO+Herwig)
  - Diboson and single top from MC
  - Fakes estimated from "loosened" selection criteria on lepton
    - Data-driven; like matrix-method
  - Z+jets in ee and $\mu\mu$: based on counting events in Z veto region (i.e. close to Z mass peak)

CMS Measurement: Basics

- CMS:



Sample	ee	$\mu\mu$	eμ	all
$t\bar{t} \to \ell^+\ell^-$	1791.7 ± 4.4	2127.3 ± 4.7	5069.4 ± 7.3	8988.5 ± 9.7
$t\bar{t} \to$ other	32.5 ± 2.9	4.8 ± 1.1	53.3 ± 3.6	90.7 ± 4.8
W + jets	< 1.9	4.7 ± 3.3	4.7 ± 3.4	9.4 ± 4.7
DY$\to$ ee	52.3 ± 5.8	< 0.6	< 0.6	52.3 ± 5.8
DY$\to \mu\mu$	< 0.6	72.8 ± 6.5	1.6 ± 0.9	74.4 ± 6.5
DY$\to \tau\tau$	17.6 ± 3.3	8.7 ± 2.2	18.7 ± 3.2	45.0 ± 5.1
Di-boson	10.6 ± 0.5	13.0 ± 0.5	24.0 ± 0.7	47.6 ± 1.0
Single top	84.9 ± 2.3	101.2 ± 2.4	252.1 ± 3.9	438.2 ± 5.1
Total (simulation)	1989.6 ± 8.8	2332.6 ± 9.3	5423.8 ± 10.3	9746.0 ± 16.4
Data	1961	2373	5412	9746

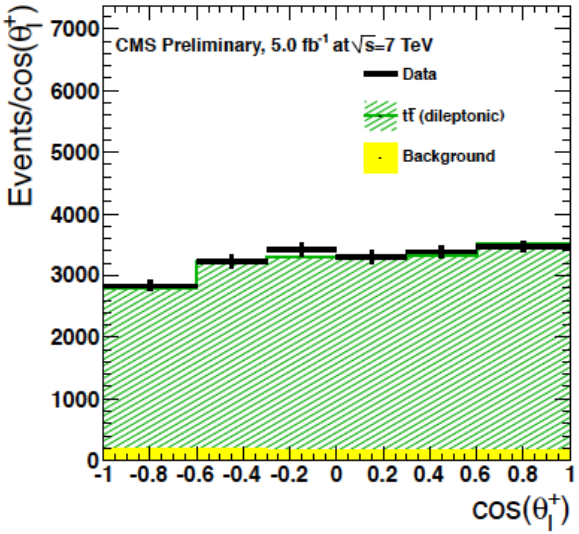
- For comparison: yields in ATLAS (before reconstruction)

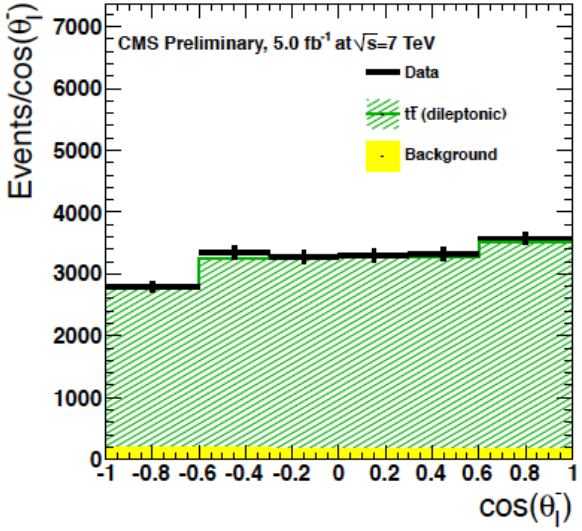
Source	e+jets	μ+jets	ee	$e\mu$	$\mu\mu$
$t\bar{t}$	16200	26500	570	4400	1660
Bkgd.	5100	9400	110	700	320
Total	21300	35900	690	5000	1980
Uncertainty	$\pm$1300	$\pm$1700	$\pm$80	$\pm$500	$\pm$180
Data	21956	37919	740	5328	2057

CMS Measurement: Procedure

- Extract cos θ distribution
  - Reconstruction of events: analytical matrix weighting technique
    - Do many hypotheses of top mass
    - For given top mass, constraints and measured observables restrict transverse momenta of neutrinos to lie on ellipse in px-py plane

      → intersection of ellipses from both neutrinos: solutions fulfilling the constraints
    - Calculate weight for each solution (based on probabilities to observe leptons of certain energy for assumed top mass)
  - Event with largest weight is used ($t\bar{t}$ kinematics and top mass)
- 33% of events with no solution





CMS PAS Top-12-016

CMS Measurement: Procedure

- Use only positively charged leptons
  - My guess: To avoid CP conserving/violating modeling?
- Extract polarization as:

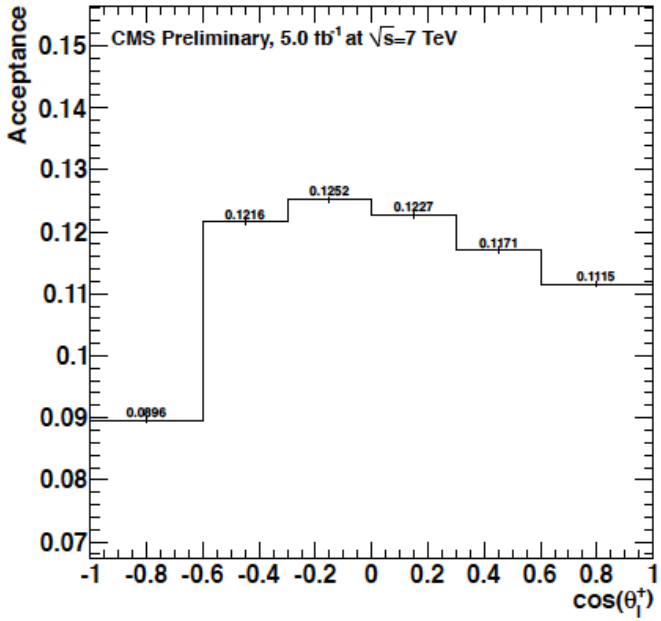
Note factor 2 wrt ATLAS definition!

$$P_n = \frac{N(\cos(\theta_l^+) > 0) - N(\cos(\theta_l^+) < 0)}{N(\cos(\theta_l^+) > 0) + N(\cos(\theta_l^+) < 0)}, \quad \text{with} \quad \frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{l,n}} = \frac{1}{2}(1 + 2\kappa_l P_n \cos\theta_{l,n})$$

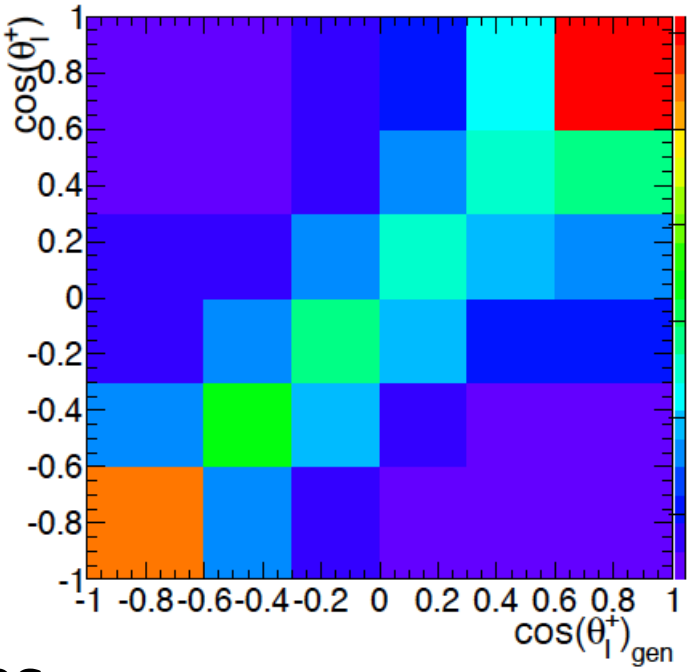
- $t\bar{t}$ yield normalized to data
- Reco level:
  - P_n=0.04±0.012 in data; P_n=0.049±0.002 in simulation
    - Negative leptons: only used as cross-check
  - Correction for background, resolution and acceptance effects still required

CMS Measurement: Procedure

- For resolution/acceptance correction: unfolding
- Binning chosen to optimize bin-to-bin oszillations
- Acceptance matrix bins:



- Smearing matrix:



  - Taken from Powheg+Pythia $t\bar{t}$ samples
- Regularized unfolding used (SVD)

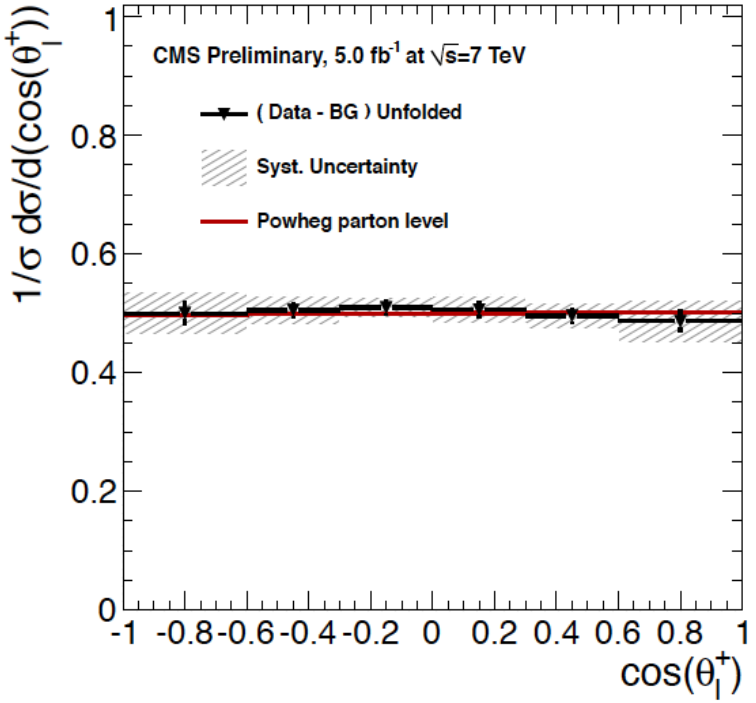
CMS Measurement: Result

- Result CMS:

  P_n=-0.009±0.029 (stat)±0.041(syst)

- Reminder ATLAS:

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



- Remember factor 2:
  - 2xCMS = what to compare to ATLAS!

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{i,n}} = \frac{1}{2}(1 + \mathcal{P}_n \kappa_i \cos\theta_{i,n})$$
ATLAS definition

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{l,n}} = \frac{1}{2}(1 + 2\kappa_l P_n \cos\theta_{l,n})$$
CMS definition

Systematics

- Systematics: ATLAS

Source	$\Delta\alpha_\ell P_{\mathrm{CPC}}$	$\Delta\alpha_\ell P_{\mathrm{CPV}}$
Jet reconstruction	+0.031 -0.031	+0.009 -0.005
Lepton reconstruction	+0.006 -0.007	+0.002 -0.001
$E_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction	+0.008 -0.007	+0.004 -0.001
$t\bar{t}$ Modeling	+0.015 -0.016	+0.005 -0.013
Background Modeling	+0.011 -0.010	+0.005 -0.007
Template Statistical Uncertainty	+0.005 -0.005	+0.006 -0.006
Total Systematic Uncertainty	+0.037 -0.037	+0.013 -0.017

- CMS

Table 3: Systematic uncertainties.

JES	lepton energy scale	M_t scan range	background	$t\bar{t}$ modeling	matching
0.020	0.001	0.024	0.009	0.014	0.004
Q^2 scale	simulated M_t	$b-$tagging eff.	Trig eff. and lep ID	pile-up	Total
0.007	0.019	0.001	0.005	0.002	0.041

- Let's compare for CP conserving scenario (more compatible model between the two experiments)

Systematics

- Systematics: ATLAS

Source	$\Delta\alpha_\ell P_{CPC}$		$\Delta\alpha_\ell P_{CPV}$	
Jet reconstruction	+0.031	-0.031	+0.009	-0.005
Lepton reconstruction	+0.006	-0.007	+0.002	-0.001
E_T^{miss} reconstruction	+0.008	-0.007	+0.004	-0.001
$t\bar{t}$ Modeling	+0.015	-0.016	+0.005	-0.013
Background Modeling	+0.011	-0.010	+0.005	-0.007
Template Statistical Uncertainty	+0.005	-0.005	+0.006	-0.006
Total Systematic Uncertainty	+0.037	-0.037	+0.013	-0.017

- CMS

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0.007	0.019	0.001	0.005	0.002	0.041

- Let's compare for CP conserving scenario (more compatible model between the two experiments)

Systematics

- Dominant systematics at ATLAS: Jet reconstruction
  - Mainly JES
  - Second dominant systematics for CMS
  - JES directly affects shape of cos θ (reco methods)
  - Similar order of magnitude for CMS and ATLAS
- Smaller contributions from
  - Background modeling, lepton reco, pile-up, etc
    - Similar in size
- Some systematics done differently between experiments
  - Matching and scale: shower matching p_T threshold and factorization/renormalization scales: done in CMS
    - Not in ATLAS → but very small compared to other signal modeling

Systematics

- Signal modeling: compare different MC (MC generator, reconnection, etc.)
  - MC generator: MC@NLO versus Powheg
    - At CMS: unfolding derived from alternative MC
    - At ATLAS: derive templates from alternative MC
  - Done at ATLAS:
    - Color reconnection
    - Fragmentation and parton shower (should be ~ covered in CMS due to using Herwig for MC@NLO)
    - Underlying event
    - ISR/FSR (at CMS: scale variation instead)

	$\Delta\alpha_\ell P_{\mathrm{CPC}}$		$\Delta\alpha_\ell P_{\mathrm{CPV}}$	
Top mass	+0.012	−0.012	+0.000	−0.000
Signal MC generator	+0.005	−0.008	+0.004	−0.013
ISR and FSR	+0.005	−0.004	+0.001	−0.002
Color reconnection	+0.001	−0.004	+0.002	−0.002
Fragmentation/parton shower	+0.002	−0.002	+0.000	−0.001
Underlying event	+0.002	−0.004	+0.002	−0.002
Proton PDF	+0.003	−0.003	+0.000	−0.000

Systematics

- Top mass:
  - ATLAS: use different top mass assumptions in MC
    - Assign fitted polarization for mass values ±1.4GeV around default of 172.5GeV
    - "Large" effect from reconstruction
  - CMS: use different top mass assumptions in MC (down to 166.5GeV and up to 178GeV)
- Choice of M_t scan for reconstruction technique
  - Take largest difference when changing scan range from default 165-180GeV to 0-2500GeV, 100-300GeV or fixed 172.5GeV
    - Conservative
- MC statistics: template statistics error for ATLAS small
  - CMS: ?

Summary

- Two measurements of top polarization on the market
  - ATLAS: publication submitted to journal
  - CMS: preliminary result in dilepton
- Pretty different techniques
  - ATLAS: “simple” template fit
  - CMS: full corrected distribution of cos θ
- So far: polarization in agreement with SM value

BACKUP


DESY

Jet Energy Scale