Measurements of Top Quark Properties at the LHC

Efe Yazgan (Ghent University, Belgium)

on behalf of the ATLAS and CMS Collaborations

Rencontres de Moriond – QCD and High Energy Interactions
13 March 2013 La Thuile, Italy

The Top Quark

- The most massive particle known to date (m_t~173 GeV)
  - very short lifetime

$$\tau_t = \frac{1}{\Gamma_t} \sim 0.5\times10^{-24}s < \frac{1}{\Lambda_{QCD}} < \frac{m_t}{\Lambda_{QCD}^2} \sim 3\times10^{-21}s << \tau_b \sim 10^{-12}s$$

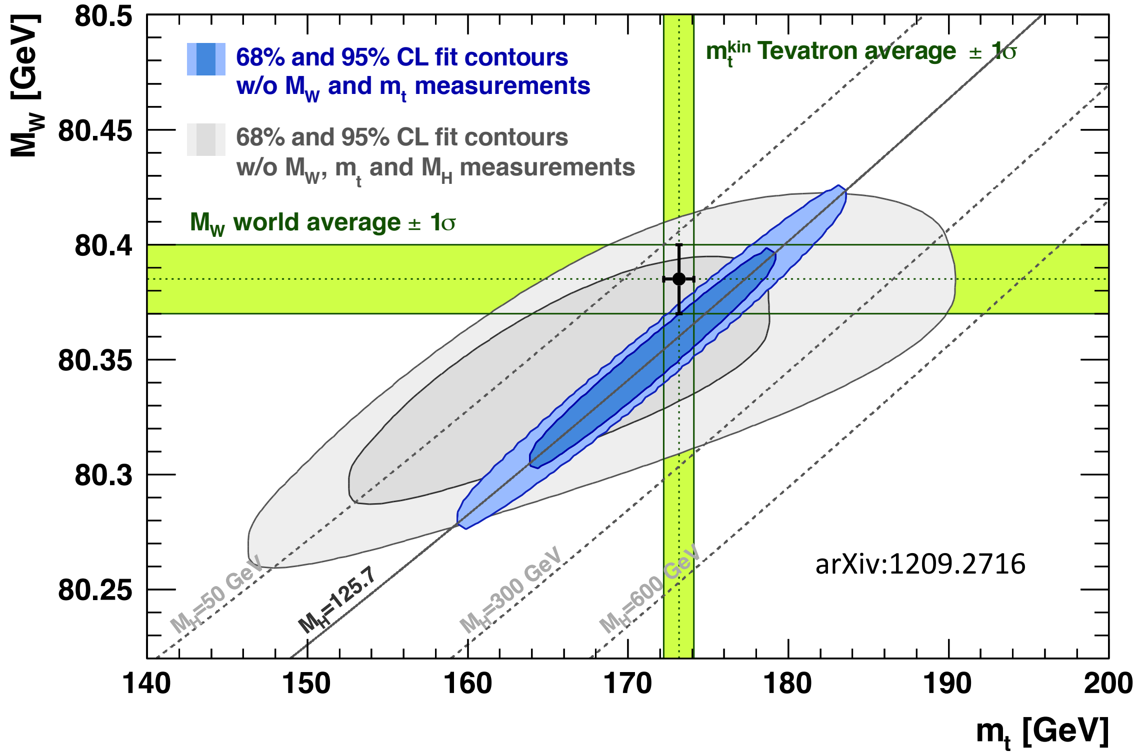
$$\tau_t < \tau(hadronization) < \tau(spin-decorrelation) << \tau_b$$

No hadronic bound states→ bare quark properties are accessible (mass, V_{tb}, spin, charge, …).

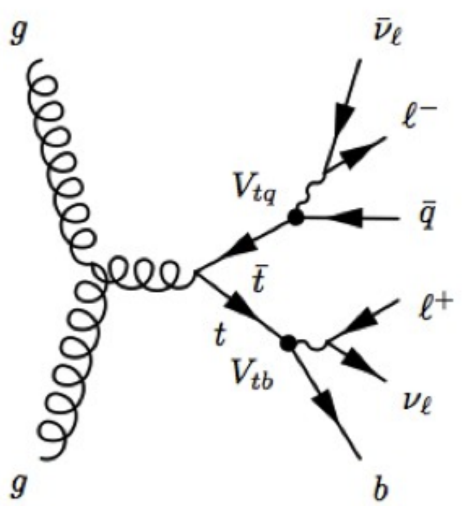
spin effects passed on to decay products.

The Top Quark

- Top decays practically always through t→bW
- Top quark has the largest coupling to the Higgs boson: y_t~1.
- Backgrounds or decay products of new physics processes.
- Loop corrections to many tree level SM processes (W, Z mass, BB mixing, ...)
- (Input to theoretical studies of electroweak vacuum stability).



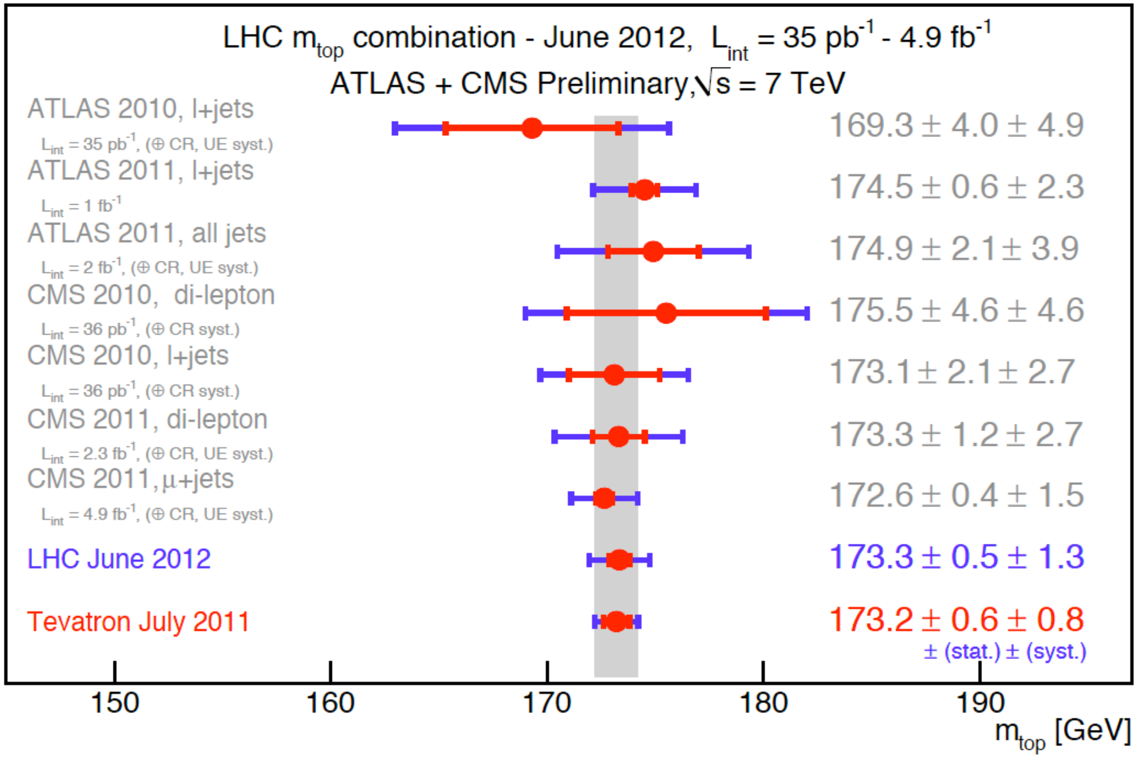
Top Quark Properties



- Top Quark Mass
  - LHC Combined results
  - Dependence of top mass measurement on event kinematics
  - m_t-$m_{t\sim}$ (CPT)
- Top Quark Couplings
  - Bottom quark content in top decay, $|V_{tb}|$
  - W boson polarization and anomalous couplings
  - Search for CP violation in single top events
  - ttZ, ttW
- Top Polarization

- Not covered
  - Charge asymmetry [ATLAS: EPJC (2012) 2039, ATLAS-CONF-2012-057; CMS: PLB717 (2012) 129, CMS-PAS-TOP-12-010]
  - tt~ spin correlation [ATLAS: PRL108 (2012) 212001; CMS-TOP-PAS-12-004]
  - Charge [ATLAS-CONF-2011-141; CMS-PAS-TOP-11-031]
  - ttγ [ATLAS-CONF-2011-153]
  - FCNC [ATLAS: PLB712 (2012) 351; CMS: CMS-PAS-TOP-11-028]
  - …

Top Quark Mass – LHC Combination



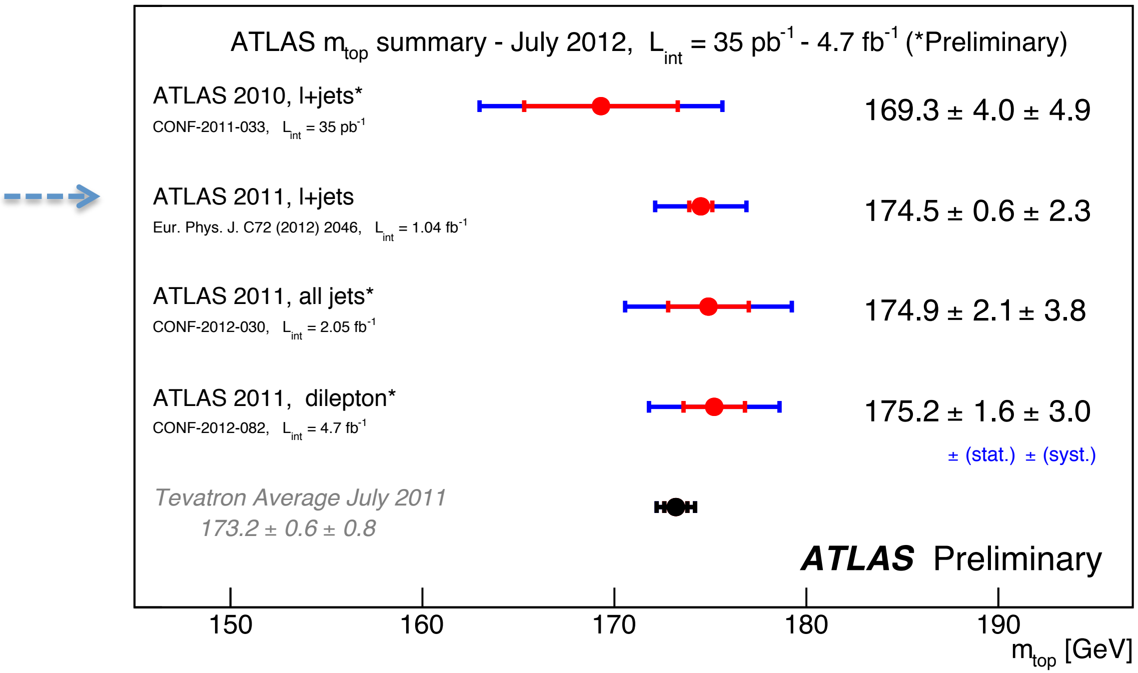
ATLAS-CONF-2012-095
CMS-PAS-TOP-12-001

- BLUE method (Best Linear Unbiased Estimator)
  - linear combination of each input measurement, categorize each source according to correlations
- most recent CMS/ATLAS measurements are not included yet.
- LHC combination precision: 0.8%
- Tevatron combination precision: 0.6%

Most precise individual measurements are from LHC and they are not included yet.

Top Quark Mass at the LHC

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults

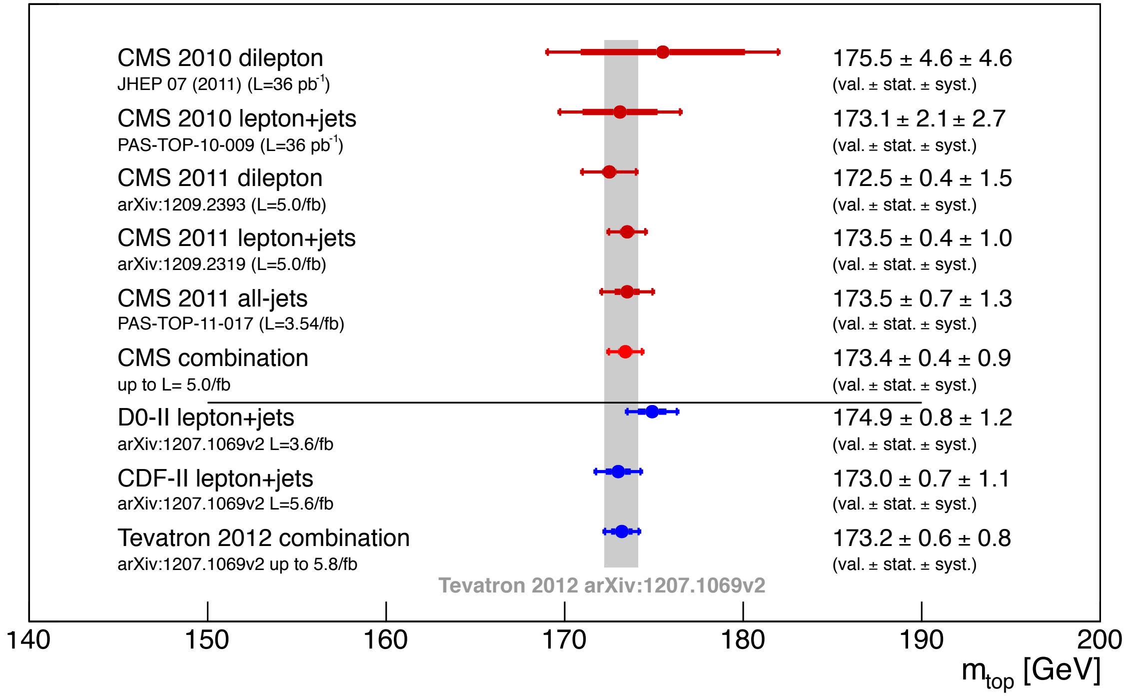


- l+jets, all-jets
  - Template
- dilepton
  - Kinematic endpoints

- General features of top mass measurements:
  - Assigning each jet to a top decay product (constrained kinematic fits)
  - Simultaneous determination of mass and JES
  - Calibration of the method

Top Quark Mass at the LHC

CMS-PAS-TOP-11-018

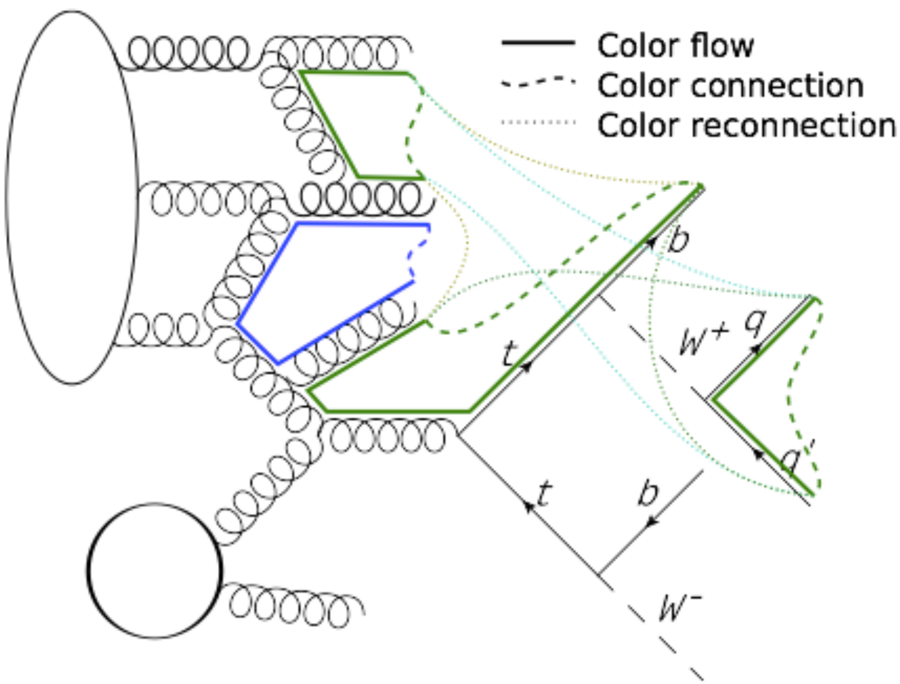


- l+jets
  - Ideogram
- all-jets
  - template
- dilepton
  - Analytical matrix weighting, KINb, Kinematic endpoints

- General features of top mass measurements:
  - Assigning each jet to a top decay product (constrained kinematic fits)
  - Simultaneous determination of mass and JES
  - Calibration of the method

Dependence of Top Mass on Event Kinematics

- Top mass measurements reached a remarkable precision.
- However, interpretation of the top mass measurements is not straightforward for δ ~< 1 GeV ~Γ_t.
  - Difficult to define a pole mass for an unstable and colored particle.



Since top decays before hadronizing to have a colorless final state, additional quarks are needed.

$$m_t^{\exp} \neq m_t^{pole}$$ and event dependent.

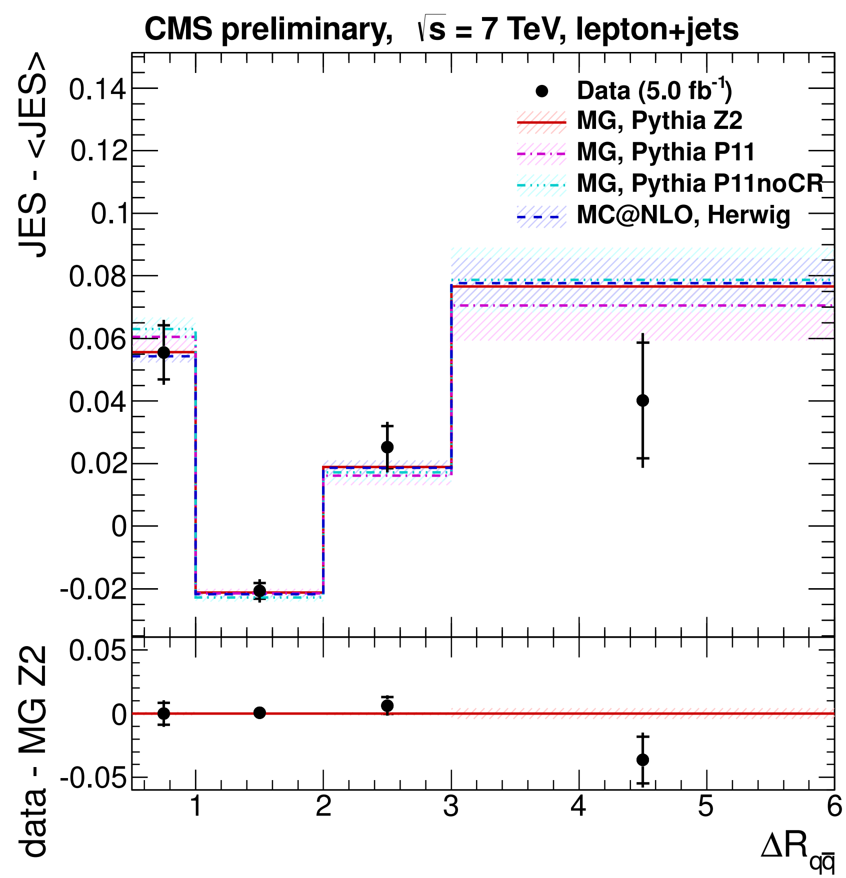
https://indico.cern.ch/getFile.py/access?contribId=3&resId=0&materialId=slides&confId=189617 (M. Mangano)

Dependence of Top Mass on Event Kinematics

- Based on CMS-PAS-TOP-11-015 in lepton+jets: the most precise single measurement.
- Mass reconstruction using kinematic fit to the decay products.
- Top mass determined simultaneously with the jet energy scale with the known W mass in W→qq.

NEW

CMS-PAS-TOP-12-029



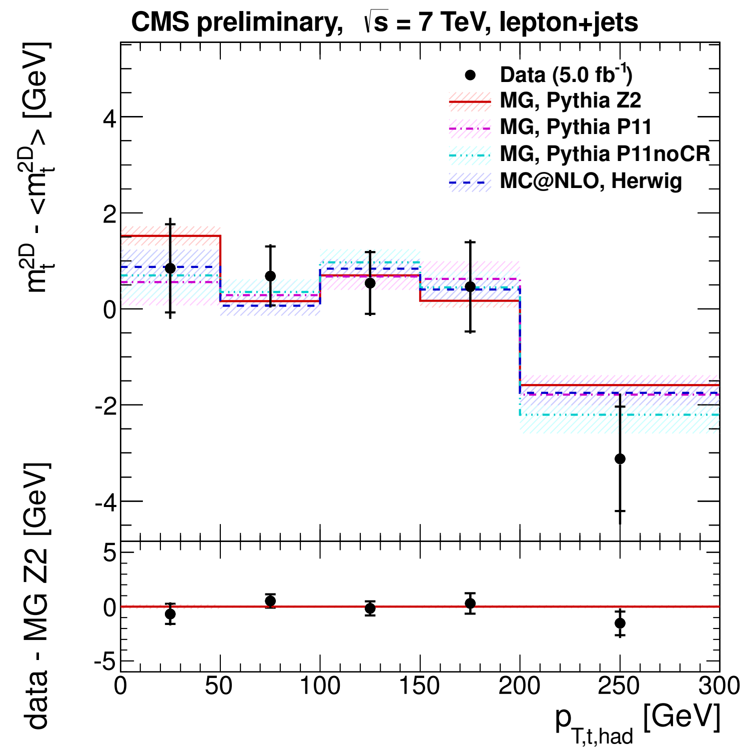
MadGraph + Pythia
MC@NLO + Herwig6
Color reconnection:
Pythia P11 and P11noCR

Dependence of Top Mass on Event Kinematics

CMS-PAS-TOP-12-029

NEW

	Fig.	Observable
color recon.	1	$\Delta R_{q\bar{q}}$
	2	$\Delta\phi_{q\bar{q}}$
	3	$p_{T,t,had}$
	4	$\lvert\eta_{t,had}\rvert$
ISR/FSR	5	H_T
	6	$m_{t\bar{t}}$
	7	$p_{T,t\bar{t}}$
	8	Jet multiplicity
b-quark kin.	9	$p_{T,b,had}$
	10	$\lvert\eta_{b,had}\rvert$
	11	$\Delta R_{b\bar{b}}$
	12	$\Delta\phi_{b\bar{b}}$



- *First top mass measurement binned in kinematic observables.*
- Additional validation for the top mass measurements.
- With the current precision, no mis-modelling effect due to
  - color reconnection, ISR/FSR, b-quark kinematics, difference between pole or MS~ masses.

tt~ Mass Difference

CMS-PAS-TOP-12-031

- CPT invariance → Mass of particle = Mass of antiparticle
- Top decays before hadronization → m_t-$m_{t\sim}$ can be measured directly.
- CMS measurement in l+jets channel using Ideogram method:
  - With kinematic fit only to the hadronic side of the event (t→bW→bqq')
  - divided into two samples with opposite lepton charge.

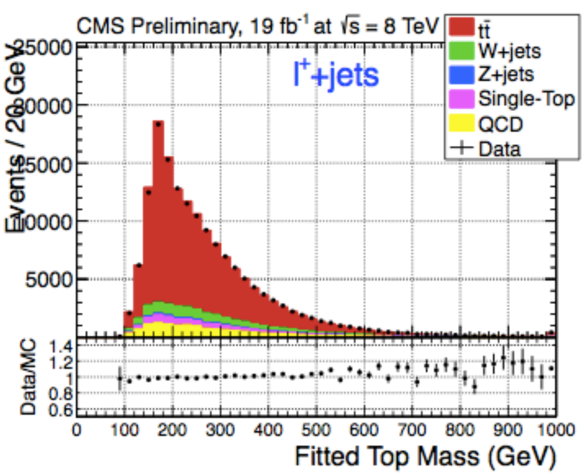
NEW

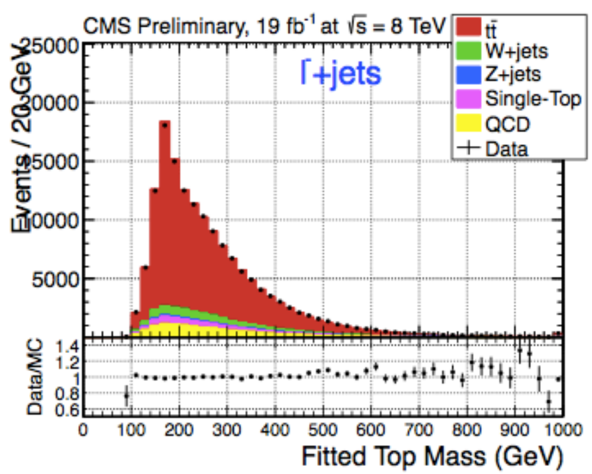
$$\Delta m_t = m_t^{had} - m_{\bar{t}}^{had} = -272 \pm 196\ (stat) \pm 122\ (syst.)\ MeV$$

$$CMS\ @7\ TeV:\ \Delta m_t = -0.44 \pm 0.46\ (stat) \pm 0.27\ (syst.)\ GeV$$

*JHEP*06 (2012) 109

The best measurement of Δm_t.
> 2x better than the previous most precise result.



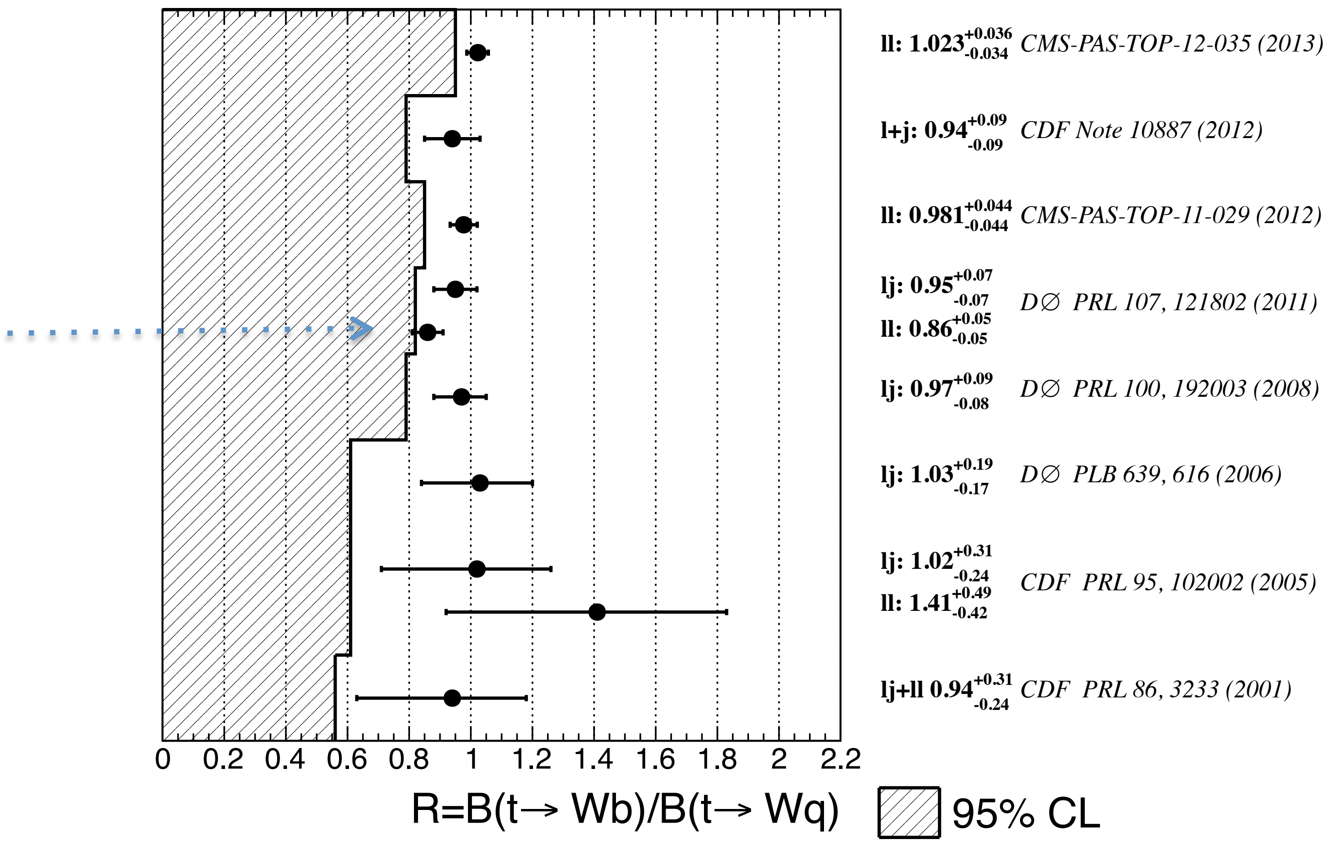


Dominant systematic uncertainties:
- b vs b~ jet response
- background composition
- signal fraction
- b vs b~ tagging efficiency

Bottom Quark Content in Top Decay

$$R = \frac{B(t \to Wb)}{\sum_{q=d,s,b} B(t \to Wq)} = |V_{tb}|^2$$

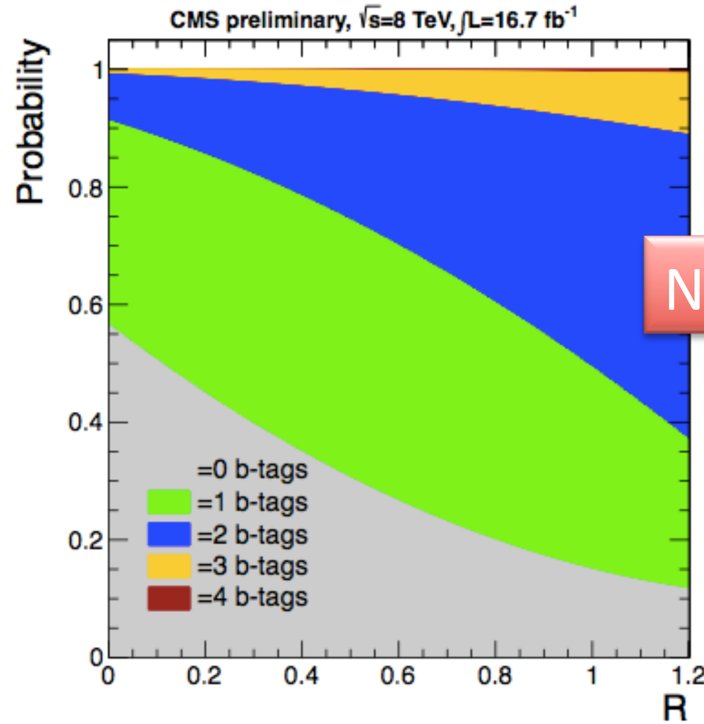
- A deviation from R=1 → a 4th generation quark or a charged Higgs boson, ...



Bottom Quark Content in Top Decay

- tt~ dilepton final state
- Count N(t→Wb) and compare to total N(t→Wq) taking into account
  - the signal purity
    - data-driven estimation of the main bkg (DY)
    - single top from simulation
  - number of reconstructed t→lνj in 0,1 and 2 jet categories.
    - Using M(lj)
  - number of b-tags
    - measure b-tag jet efficiency and mis-identification
    - determine number of b-tags
    - compare to data-driven probability functions vs R.

R is extracted from a profile likelihood fit to analytic data-driven analytic probability models for each 36 event category.

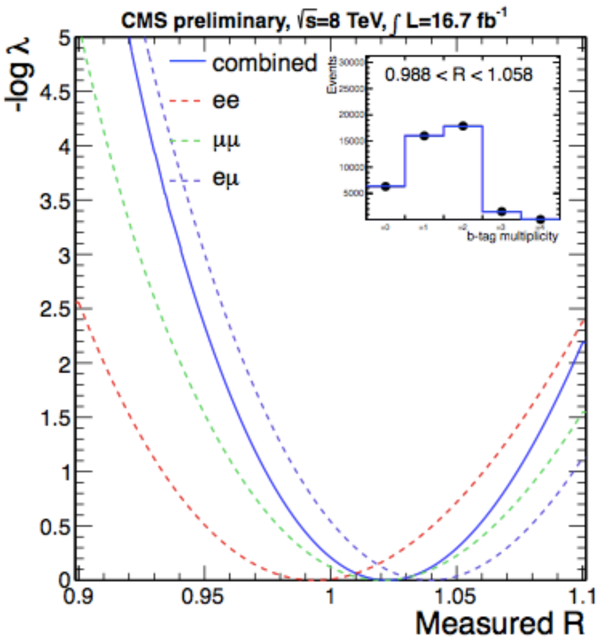


NEW

Probability model for different b-tag multiplicities

CMS-TOP-PAS-12-035

Bottom Quark Content in Top Decay



NEW

$$R = 1.023^{+0.036}_{-0.034}\,(stat + syst)$$

$$\text{If } R \leq 1 \rightarrow R > 0.945 \text{ @ } 95\% \text{ CL}$$

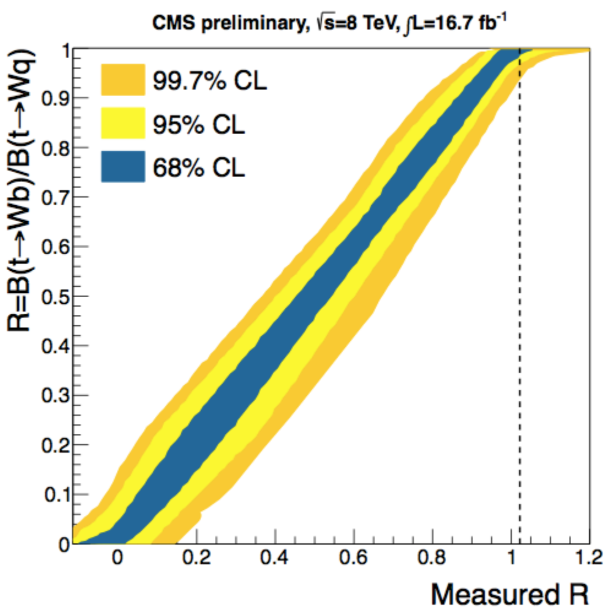
R → $|V_{tb}|$ with the assumption of CKM unitarity and 3 generations.

$$|V_{tb}| = 1.011^{+0.018}_{-0.017}\,(stat + syst)$$

$$if\ \ |V_{tb}| < 1 \rightarrow |V_{tb}| > 0.972\ \text{ @ }\ 95\%\ CL$$

Result systematic uncertainty dominated

- mainly b-tagging efficiency, purity, fraction of correct assignments from data.



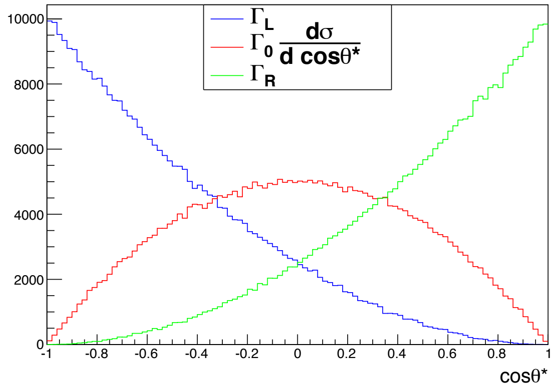
The most precise measurement of R and the most stringent direct lower bound on $|V_{tb}|$.

CMS-TOP-PAS-12-035

W Boson Polarization from tt~ Events

- Parametrization of top quark partial width in terms of W-helicity fractions

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



θ*: angle between the p(d-type fermion) in W rest-frame and p(W) in top rest-frame.

Wtb: magnitude determined by $|V_{tb}|$.

- BSM contributions to Wtb vertex modify helicity fractions.
- In the effective operative framework Wtb vertex can be parametrized as

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

EPJ-C 50 (2007) 519

$$SM:\ V_L = V_{tb} \approx 1$$
$$V_R = g_L = g_R = 0$$

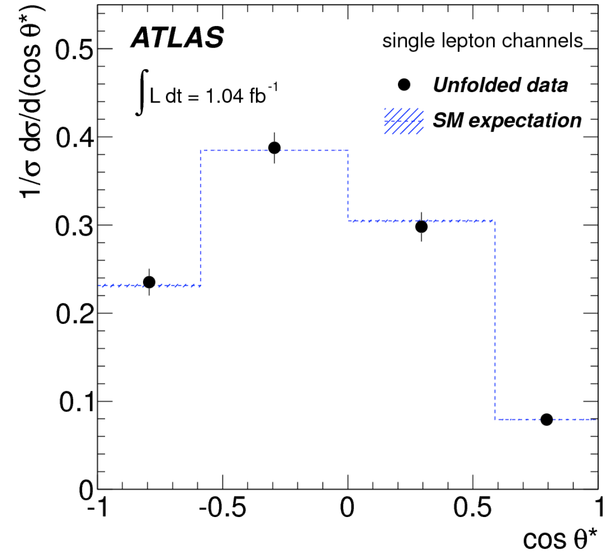
Non-zero anomalous couplings V_R, g_L, g_R can be probed with helicity fractions.

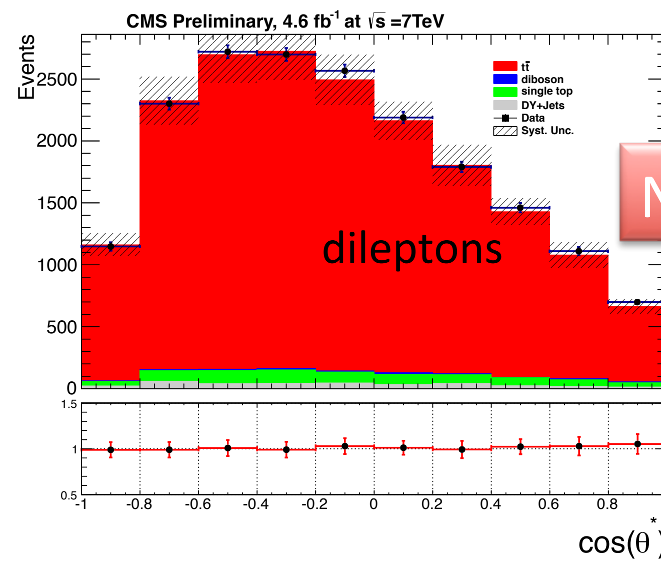
W Boson Polarization from tt~ Events

- Dilepton channel [CMS-PAS-TOP-12-015, ATLAS: JHEP1206 (2012) 088]
  - Analytical solution for the tt~ system.
- Lepton+jets [CMS-PAS-TOP-11-020, ATLAS: JHEP1206 (2012) 088]
  - Kinematic fit with m_t and m_W constraints.
- CMS:
  - Fit based on event-by-event reweighting for resolution and efficiencies.
- ATLAS:
  - Asymmetry and template methods
    - Protos for templates

$$A_{\pm} = \frac{N(\cos\theta^* > z) - N(\cos\theta^* < z)}{N(\cos\theta^* > z) + N(\cos\theta^* < z)}, \quad z = \pm\left(1 - 2^{2/3}\right)$$

PRD67(2003), EPJC50(2007)





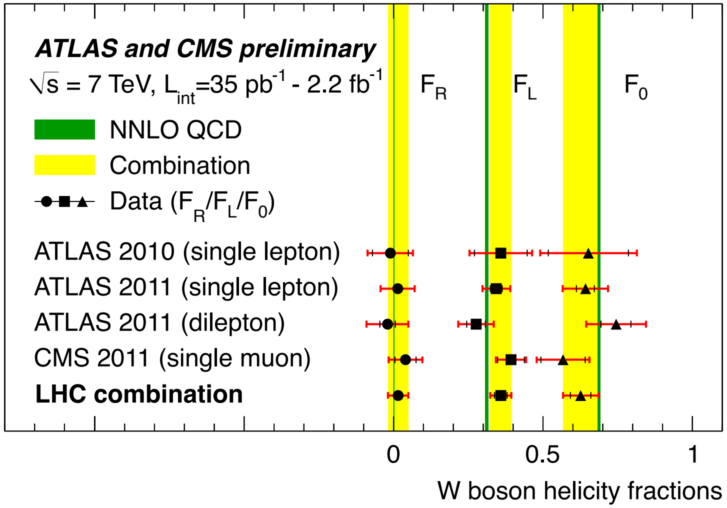
NEW

All results consistent with each other and SM predictions.

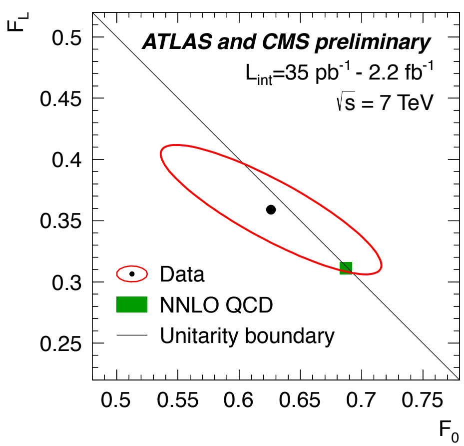
W Boson Polarization - LHC Combination

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

NEW



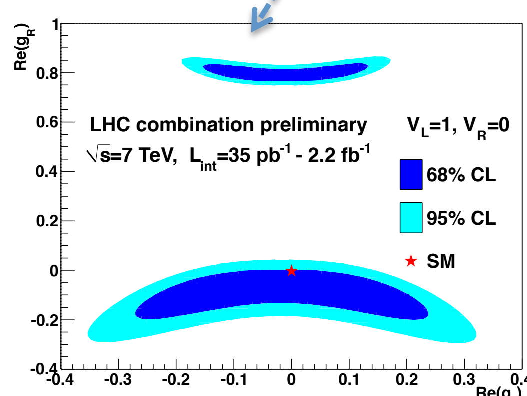
- All measurements utilize cos(θ*)
- Unitarity constraint: $F_L+F_R+F_0=1$ in each measurement and the combination



- BLUE method for the combination
  - Results stable against wrong correlation hypotheses.

$$F_0 = 0.626 \pm 0.034(stat) \pm 0.048(syst)$$
$$F_L = 0.359 \pm 0.021(stat) \pm 0.028(syst)$$
$$F_R = 0.015 \pm 0.034(stat + syst)$$

Strongly constrained by the single-top cross section measurements.



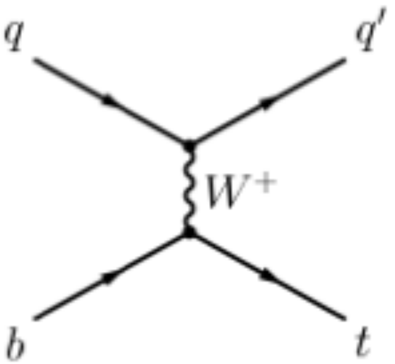
contours from profile likelihood method

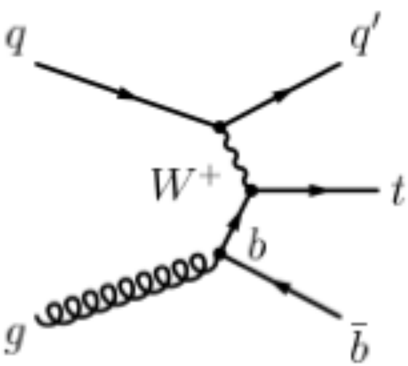
SM prediction: F_0 = 0.687(5), F_R = 0.0017(1), and F_L = 0.311(5) [assuming m_t: 172.8+/-1.3 GeV]

W Helicity in Single Top Topologies

NEW

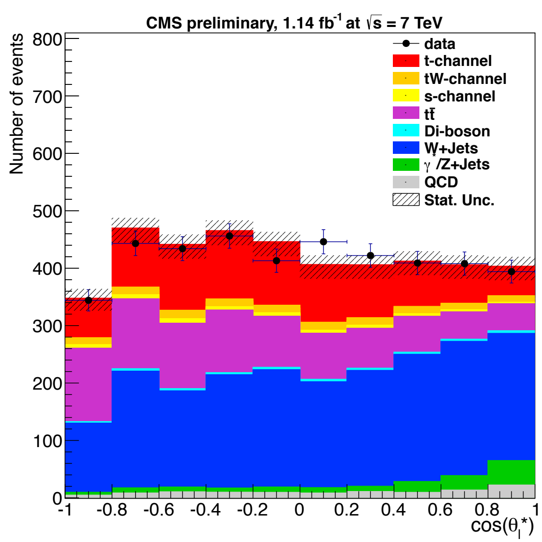
CMS-PAS-TOP-12-020

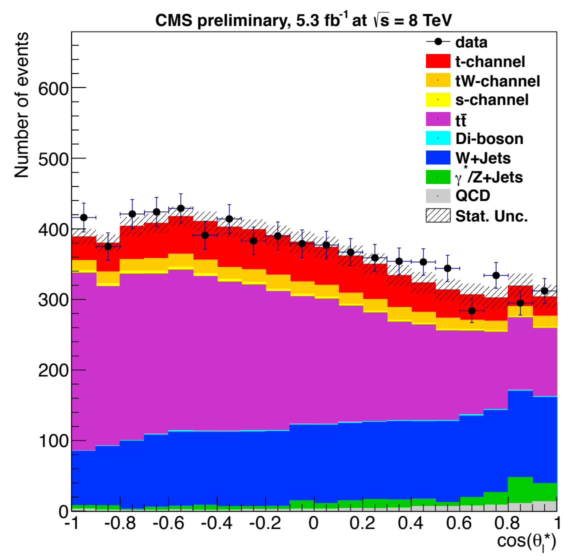




t-channel has
the highest cross-section

- First measurement of the W-helicity fractions in single-top events.
    - μ+jets final state
- Helicities obtained from likelihoods with reweighted signals.
    - including all processes involving the top quark (t-,s-,tW-channels, and tt~ semileptonic and dileptonic final states)
    - Helicity fractions and W+jets contribution simultaneously extracted.
- 7 and 8 TeV results combined by combining the two likelihoods.





→ p(z,ν) calculated using the W-mass constraint and energy conservation.

→ Real solutions: lower value is taken

→ Imaginary solutions: W-mass smeared within its width (2.1 GeV) → a real solution.

W Helicity in Single Top Topologies

NEW

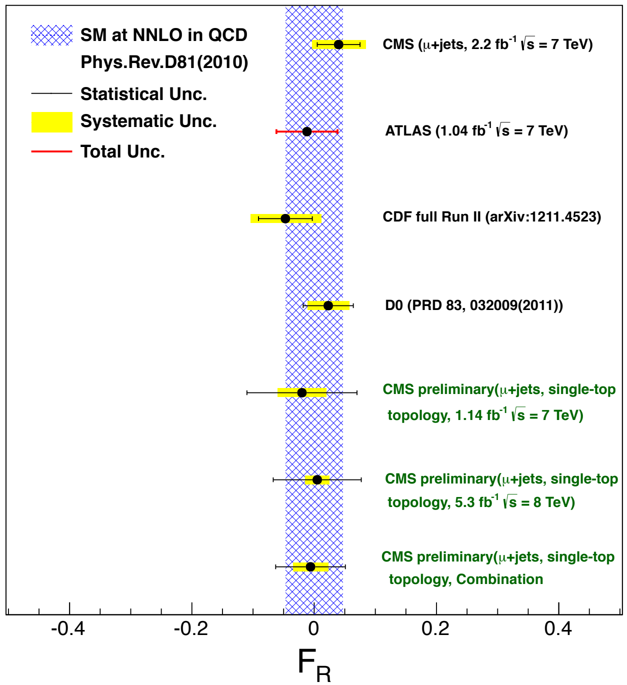
CMS-PAS-TOP-12-020

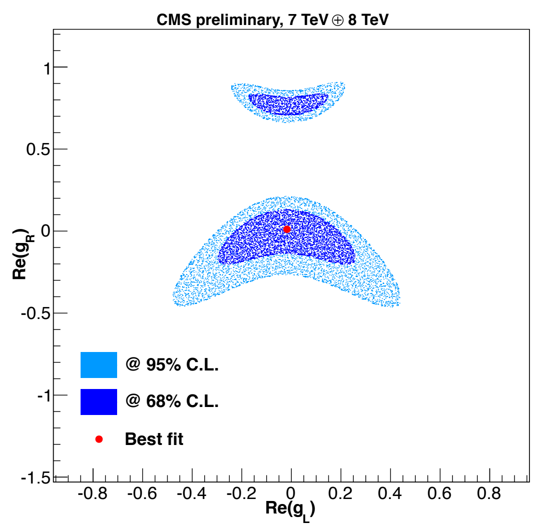
7+8 TeV combined results

$$F_L = 0.293 \pm 0.069(stat.) \pm 0.030(syst.)$$
$$F_0 = 0.713 \pm 0.114(stat.) \pm 0.023(syst.)$$
$$F_R = -0.006 \pm 0.057(stat.) \pm 0.027(syst.)$$

Results consistent with the SM and measurements in tt~ channels.

- Dominant systematic uncertainties
  - MET uncertainty from the fluctuations in un-clustered energy, JES/JER
  - Q2 and simulation
  - W+jet shape



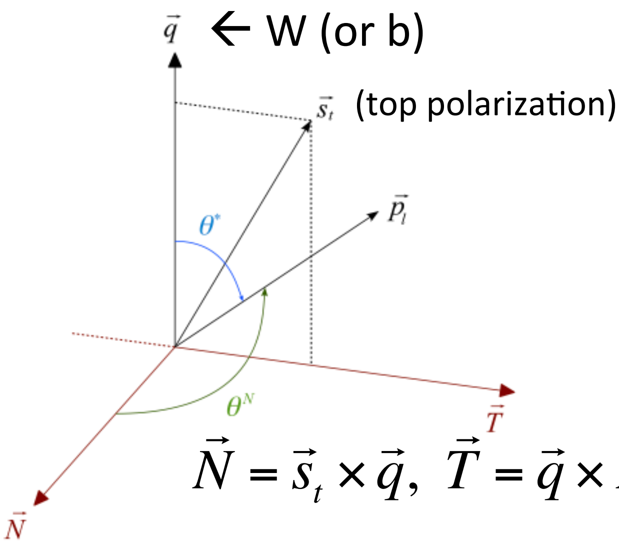


Search for CP Violation in Single Top Quark Events (t-channel)

NEW

ATLAS-CONF-2013-032

- The presence of non-zero, complex anomalous couplings V_R, $g_{L,R}$ may indicate new physics.
- θ^* not sensitive to the complex phases but A_{FB}^N α $Im(g_R)$.
- Two jets (1 b-tag), significant MET, and one lepton in the final state.



$$\vec{N} = \vec{s}_t \times \vec{q},\ \vec{T} = \vec{q} \times \vec{N}$$

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

$\theta^*, \theta^N, \theta^T$ defined as the angle between the lepton in W rest frame and W,N,T in the top rest frame.

$$A_{FB}^N = \frac{3}{4} P(F_R^N - F_L^N) \approx 0.64 P \mathrm{Im}(g_R)$$

becomes exact for g_R<<1, and V_L=1, V_R=g_R=0.

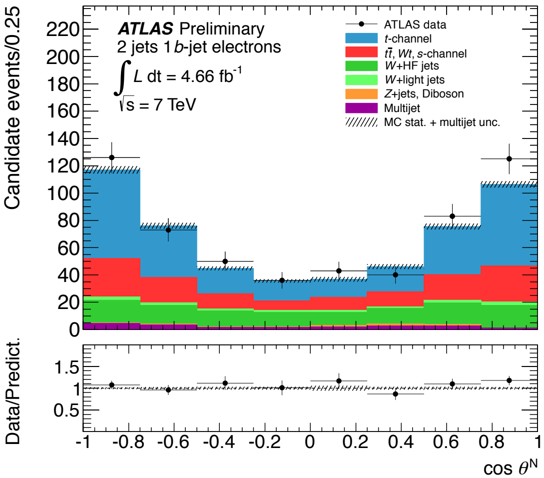
P=degree of polarization
(tops are highly polarized in the single top t-channel)

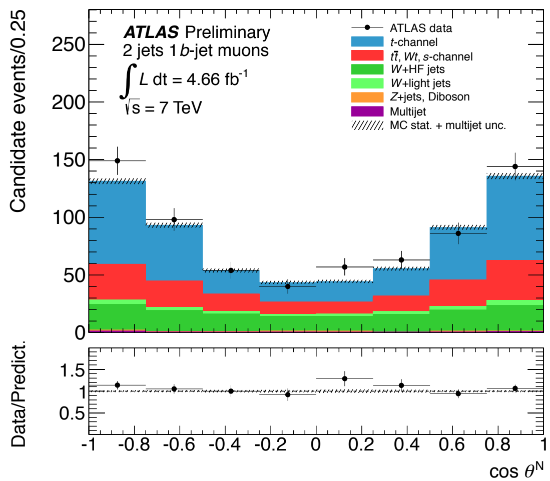
g_R=(-7.17-1.23i)x10^{-3} (including one loop electroweak corrections).
$Im(g_R)\neq0$ → CP-violating contribution to Wtb vertex not in SM

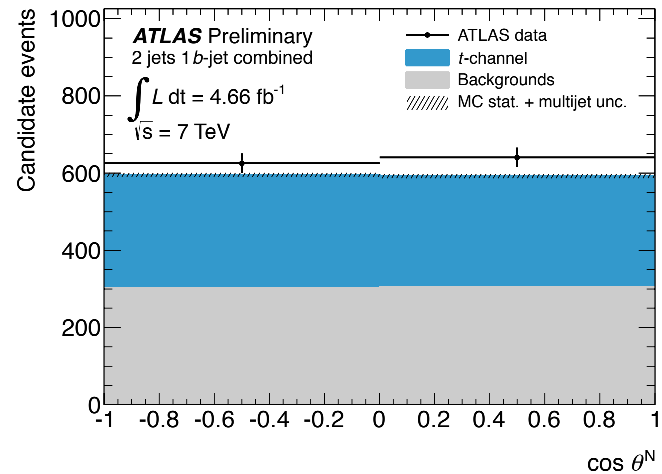
Search for CP Violation in Single Top Quark Events (t-channel)

NEW

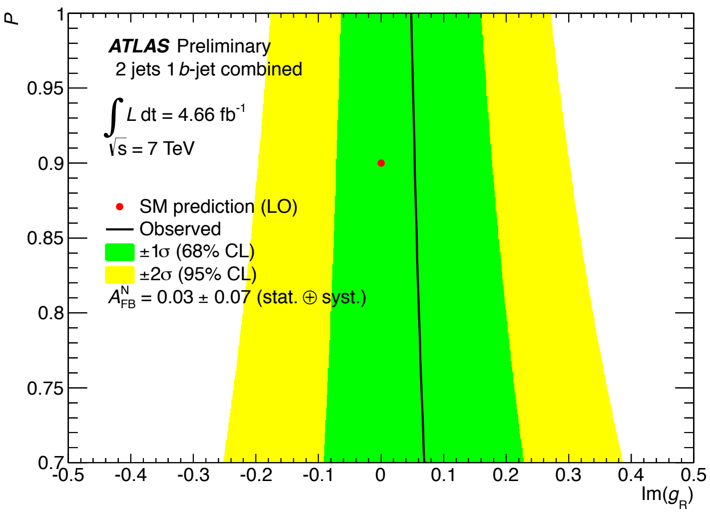
ATLAS-CONF-2013-032







unfolded to the parton level



$$A_{FB}^{N} = 0.031 \pm 0.065(stat.)^{+0.029}_{-0.031}(syst.)$$

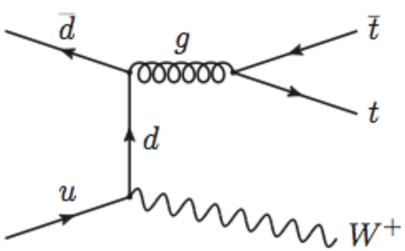
Major systematic uncertainties:
→ t-channel and tt~ generator, tt~ parton shower, background normalization.

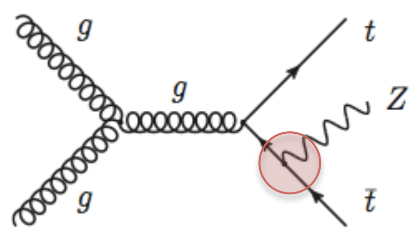
Assuming P=0.9 → Im(g_R)=[-0.20,0.30] @ 95% CL

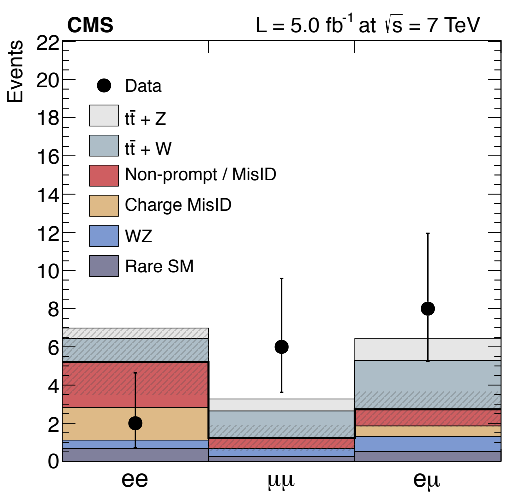
First limit on Im(g_R).
Results consistent with the SM predictions.

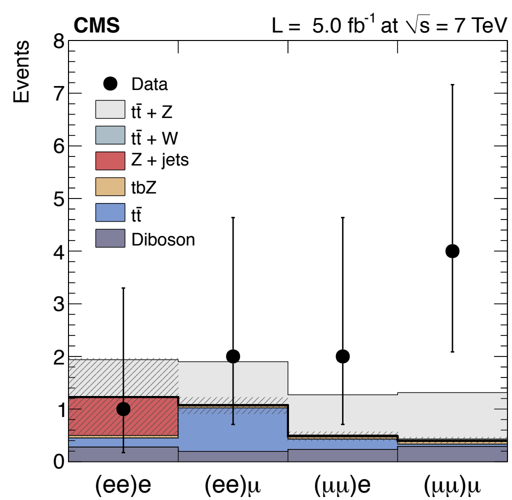
ttW and ttZ Production

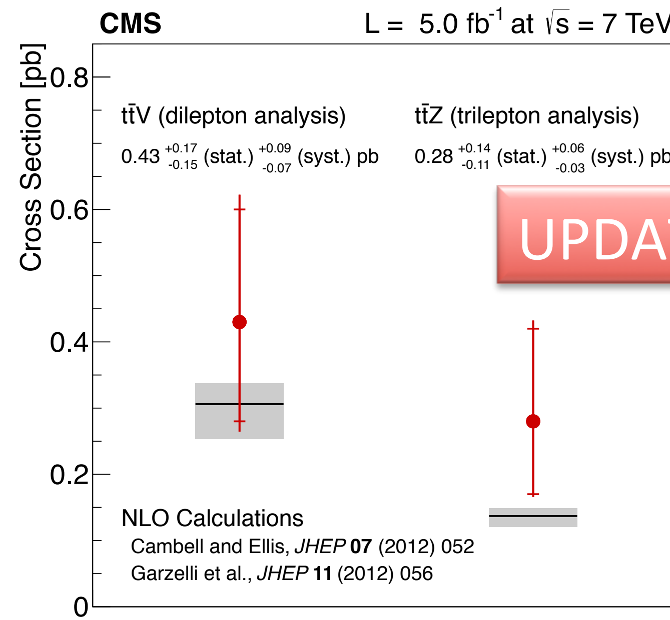
- ttV measurement → test SM top-vector boson coupling.
- Important background in new physics searches and ttH $\sigma(ttH) \approx \sigma(ttV)$
- The first cross section measurement of ttV.
  - Same-sign dilepton signature for ttV (V=W,Z) [CMS: PAPER-TOP-12-014]
  - Trilepton signature for ttZ [ATLAS: ATLAS-CONF-2012-126 , CMS: PAPER-TOP-12-014]











UPDATED

First direct measurements of top-Z coupling.

Both ATLAS and CMS measurements are compatible with the SM NLO predictions.

Top Polarization in tt~ Events

ATLAS-CONF-2012-133

- Parity conservation in QCD and the unpolarized initial state → Tops are produced unpolarized.
- BSMs can produce polarized tops.
- CMS (dilepton channel): CMS-PAS-TOP-12-016.
- ATLAS (l+jets):
  - Full reconstruction of tt~ system using a likelihood fit to determine neutrino momentum and correct jet assigment.
  - Template fit to data to the reconstructed $\cos\theta_l$ distribution.
  - Assume: $\cos\theta_l$ for + and – leptons are the same = CP conservation in production → $\alpha_l p(\text{top}) = \alpha_l p(\text{antitop})$

fraction of positively polarized top quarks: f

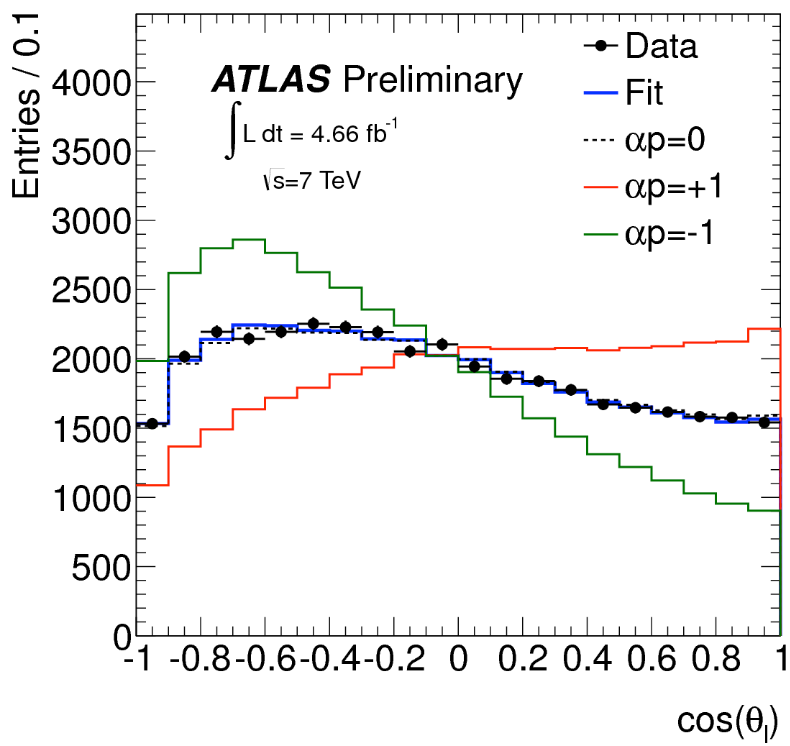
$$f = 0.470 \pm 0.009(stat)^{+0.023}_{-0.032}(syst),$$

$$f(SM) = 0.5$$

Distribution of polar angle

$$W(\cos\theta_i) \propto 1 + \alpha_i p \cos\theta_i$$

α=spin analyzing power
p=degree of polarization
θ=polar angle of charged lepton in parent top rest frame



Conclusions

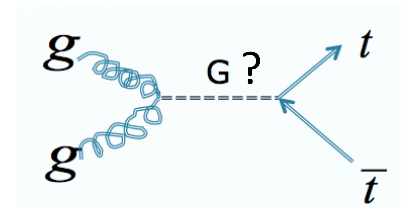
- Measurements of top quark properties at the LHC are providing thorough tests of the standard model.
- So far, all top quark properties measurements show good agreement with the standard model predictions (and no signs of new particles from direct searches).
- Many new and more precise top quark measurements to come from 8 TeV data
  - new experimental, theoretical and statistical challenges with increased precision.

All public results at:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP

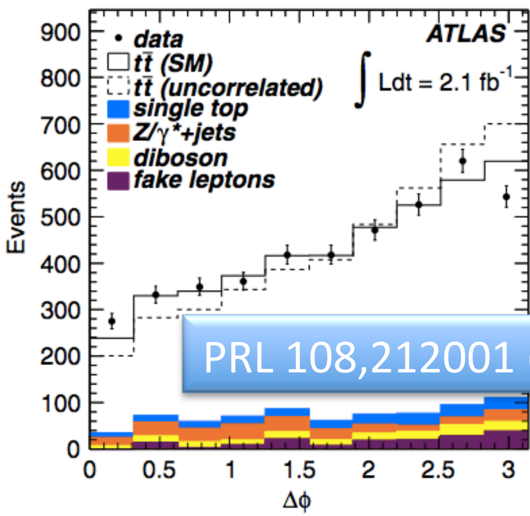
Backup

$t\bar{t}$ Spin Correlation at the LHC from Dileptons

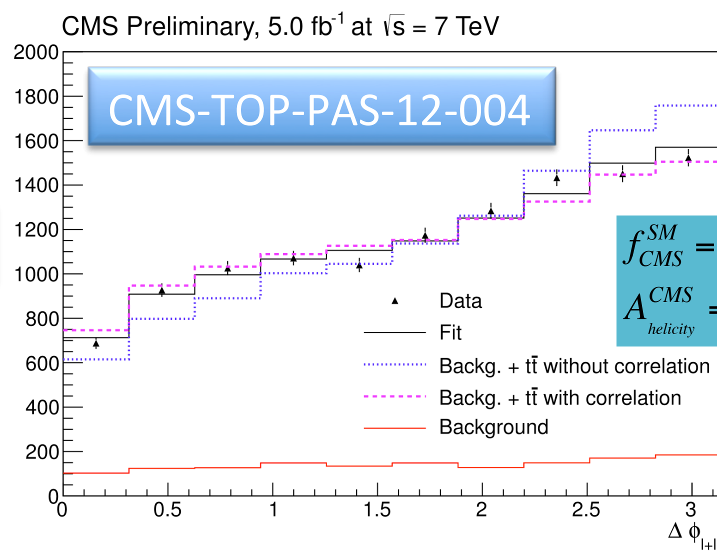
- Does the top quark have a new type of strong interaction that would cause a much faster decorrelation?
- Is the spin of the top (1/2) and top-anti-top spin correlation consistent with the SM?
- t→H⁺b, ... ?



template fits to 3 dilepton channels



PRL 108,212001 (2012)



CMS-TOP-PAS-12-004

$$f^{SM} = \frac{N_{SM}}{N_{SM} + N_{uncorr}} = 1.30 \pm 0.14(stat)^{+0.27}_{-0.22}(syst)$$

$$\rightarrow A^{measured}_{basis} = A^{SM}_{basis} f^{SM}$$

$$A_{helicity} = 0.40 \pm 0.04(stat)^{+0.08}_{-0.07}(syst)$$

$$A_{maximal} = 0.57 \pm 0.06(stat)^{+0.12}_{-0.10}(syst)$$

$$f^{SM}_{CMS} = 0.74 \pm 0.08(stat) \pm 0.24(syst)$$

$$A^{CMS}_{helicity} = 0.24 \pm 0.02(stat) \pm 0.08(syst)$$

$$f^{SM} = 1.0$$

$$A^{SM}_{helicity}(NLO) = 0.31$$

$$A^{SM}_{maximal}(NLO) = 0.44$$

All results consistent with the SM.

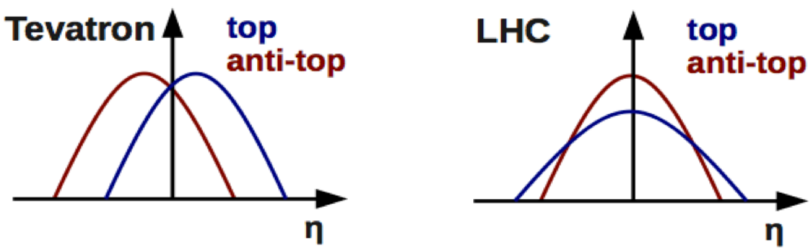
Charge Asymmetry at the LHC

- Interferences between the Born and the box diagram and between ISR & FSR causes the (anti)top direction to be correlated to the initial state (anti)quark
- Charge asymmetry occurs in quark anti-quark initial states.
- Possible deviation from SM observed at the Tevatron (A_{FB}).
  - $A_C \neq A_{FB}$ but are related in a model dependent way.

Tevatron: annihilation of two valence quarks
LHC: annihilation of one valence and a sea quark and gluon fusion dominated.
→ Much smaller asymmetry.

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

$$\Delta|y| = |y_t| - |y_{\bar{t}}|, \ \ or \ \ \Delta|y| = |y_{\ell^+}| - |y_{\ell^-}|$$



$$A_C^{NLO}\left(t\bar{t}, \sqrt{s} = 7 \ TeV\right) = 0.0115 \pm 0.0006$$

EPJ-C 72 (2012) 2039

ATLAS-CONF-2012-057

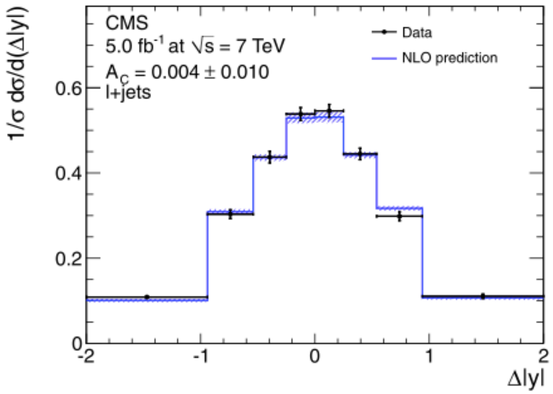
	lepton+jets	dileptons
ATLAS	−0.019 ± 0.028 (stat) ± 0.024 (syst) [1.04 /fb]	0.057 ± 0.024 (stat) ± 0.015 (syst) [4.7 /fb]
ATLAS (lepton rap.)		0.023 ± 0.012 (stat) ± 0.008 (syst) [4.7 /fb]
CMS	0.004 ± 0.010 (stat) ± 0.011 (syst) [5 /fb]	0.050 ± 0.043(stat) $^{+0.010}_{-0.039}$ (syst) [5 /fb]
CMS (lepton rap.)		0.010 ± 0.015(stat)±0.006 (syst) [5 /fb]

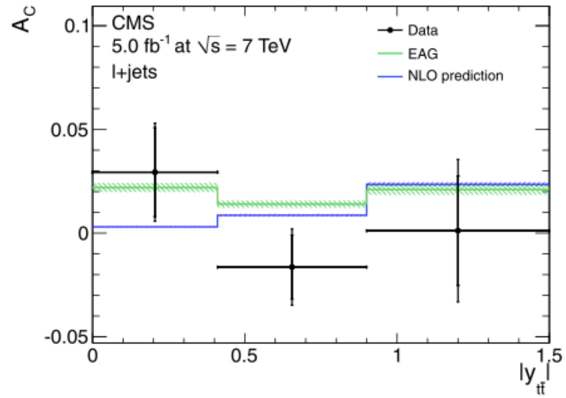
PLB 717 (2012) 129

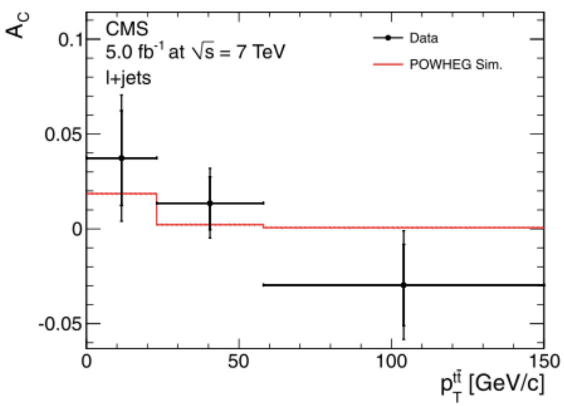
CMS-PAS-TOP-12-010

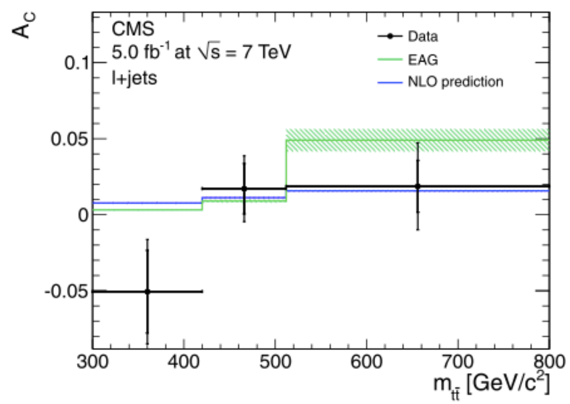
Charge Asymmetry at the LHC

PLB 717 (2012) 129

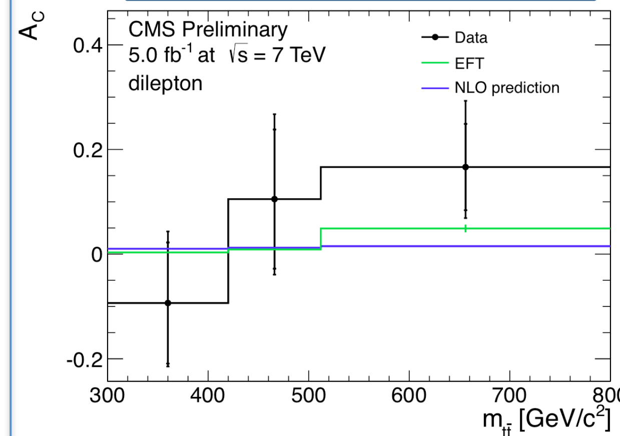




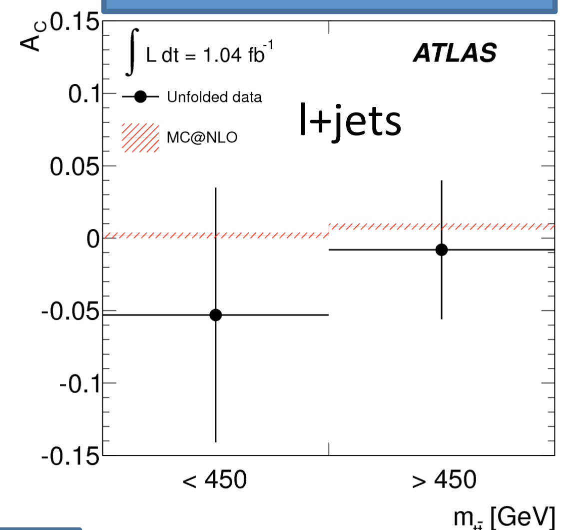




CMS-PAS-TOP-12-010



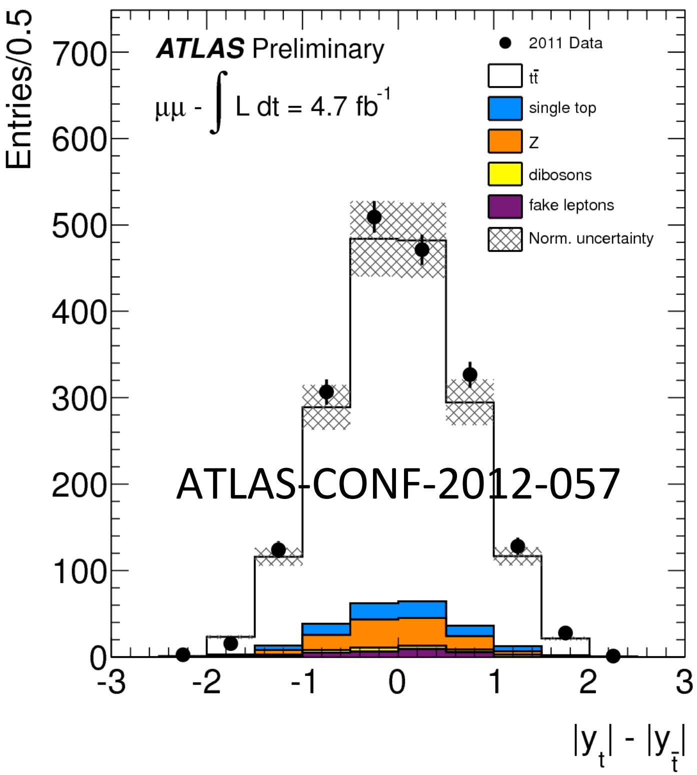
EPJ-C 72 (2012) 2039



EFT/EAG: A model featuring an effective axial-vector coupling of the gluon that could describe the A_{FB} vs m_{tt} dependence [PRD 8 (2011) 054017].

No deviations from the SM (still large uncertainties)

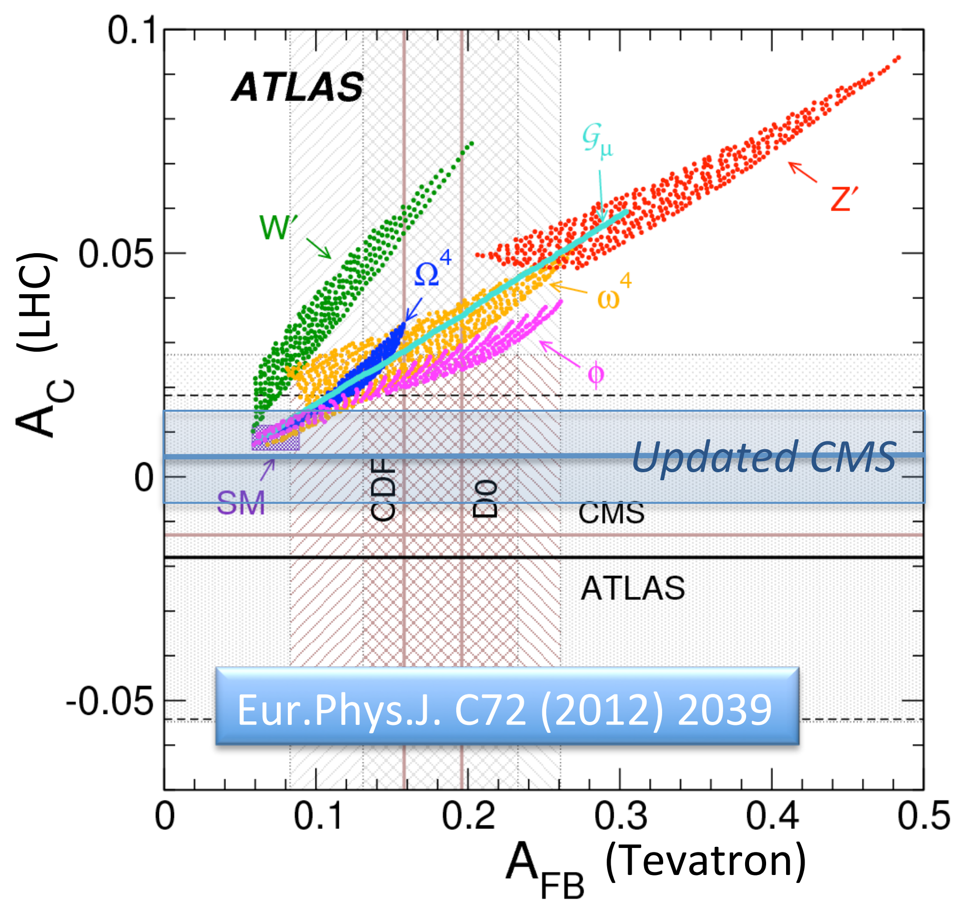
Charge Asymmetry at the LHC



Colored areas: ranges of predicted values for each model.

Horizontal lines: LHC measurements

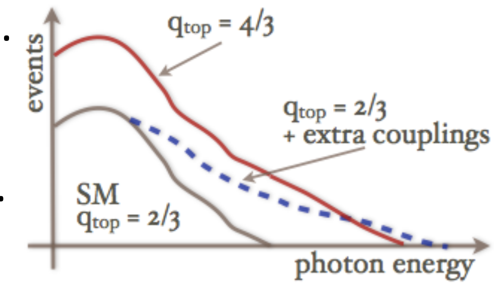
Vertical lines: Tevatron measurements

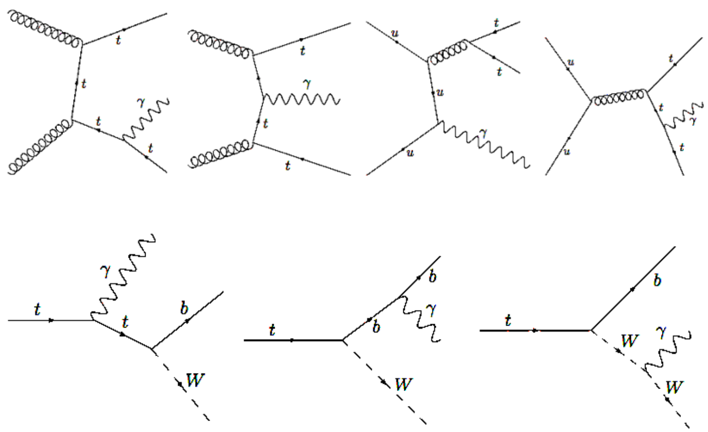


All results consistent with SM

$t\bar{t}\gamma$ Production

- Can probe electromagnetic couplings of the top quark directly.
- Test of vector and axial vector couplings in $t\bar{t}\gamma$ events will be possible with the already collected LHC data.
- First step with smaller dataset: measure pp→$t\bar{t}\gamma$ cross section.
- Understanding Higgs backgrounds from direct measurements





→ photons from off-shell top, ISR photons

→ photons from an on-shell top, its decay products, or W decay products

Analysis doesn't distinguish → interference between the two process taken into account.

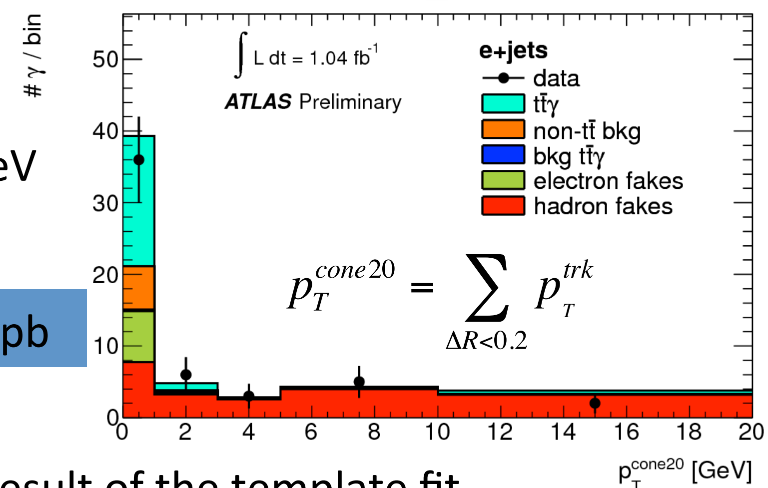
Event generation: WHIZARD
full calculation of 7-particle final states with all diagrams at LO. m(p1,p2) > 5 GeV, $p_T(\gamma)$>8 GeV

$\sigma_{t\bar{t}\gamma}(NLO) = 2.1 \pm 0.4\ pb$	*with large k-factor.*

$\sigma_{t\bar{t}\gamma}$ = 2.0 ± 0.5 (stat.) ± 0.7 (syst.) ± 0.08 (lumi.) pb

($p_T(\gamma)$>15 GeV → 58% w.r.t. 8 GeV used for generation)

mainly photon id eff. & ISR, JES, JES pileup



ATLAS-CONF-2011-153

Result of the template fit to the trk-iso distributions using both channels.

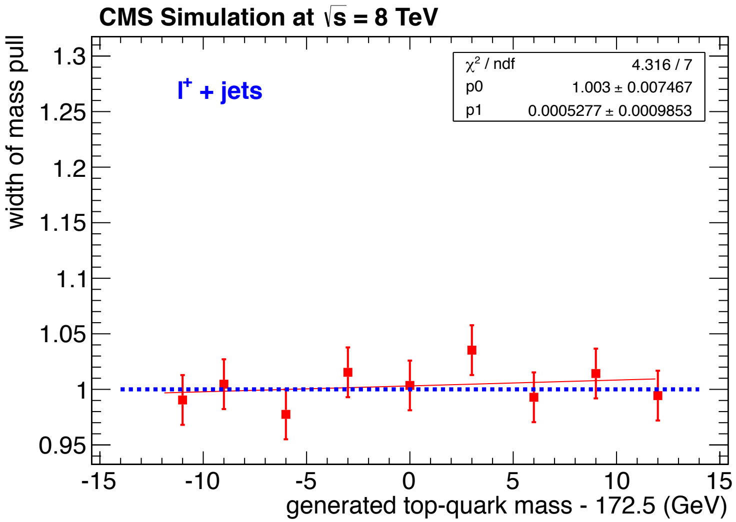
W Boson Polarization - LHC Combination

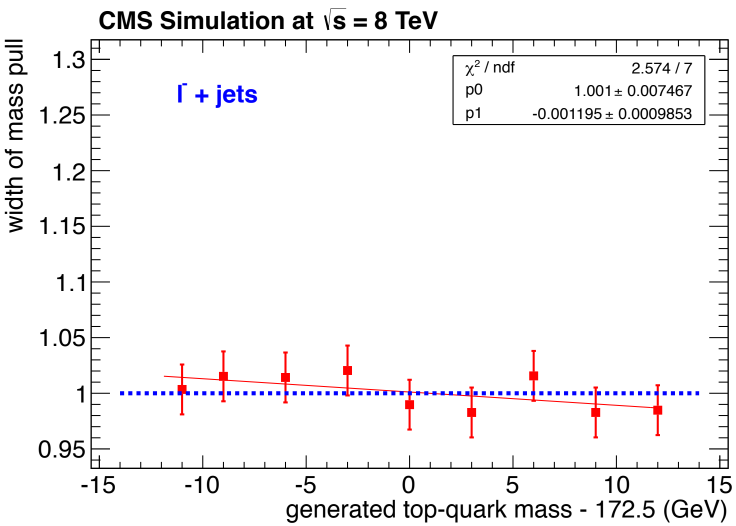
ATLAS-CONF-2013-033 & CMS-PAS-TOP-12-025

Measurement	Coefficient [%] w_{F_0}	w_{F_L}
F_0 ATLAS 2010 (single lepton)	12.4	7.2
F_L ATLAS 2010 (single lepton)	19.4	11.4
F_0 ATLAS 2011 (single lepton)	39.7	- 8.5
F_L ATLAS 2011 (single lepton)	-15.5	35.2
F_0 ATLAS 2011 (dilepton)	13.2	2.7
F_L ATLAS 2011 (dilepton)	5.2	15.0
F_0 CMS 2011 (single lepton)	34.7	- 1.4
F_L CMS 2011 (single lepton)	- 9.1	38.4
Total weight:	100.0	100.0

- The negative weights occur due to the large anti-correlations between *F0* and *FL* .

$t\tilde{t}$ Mass Difference



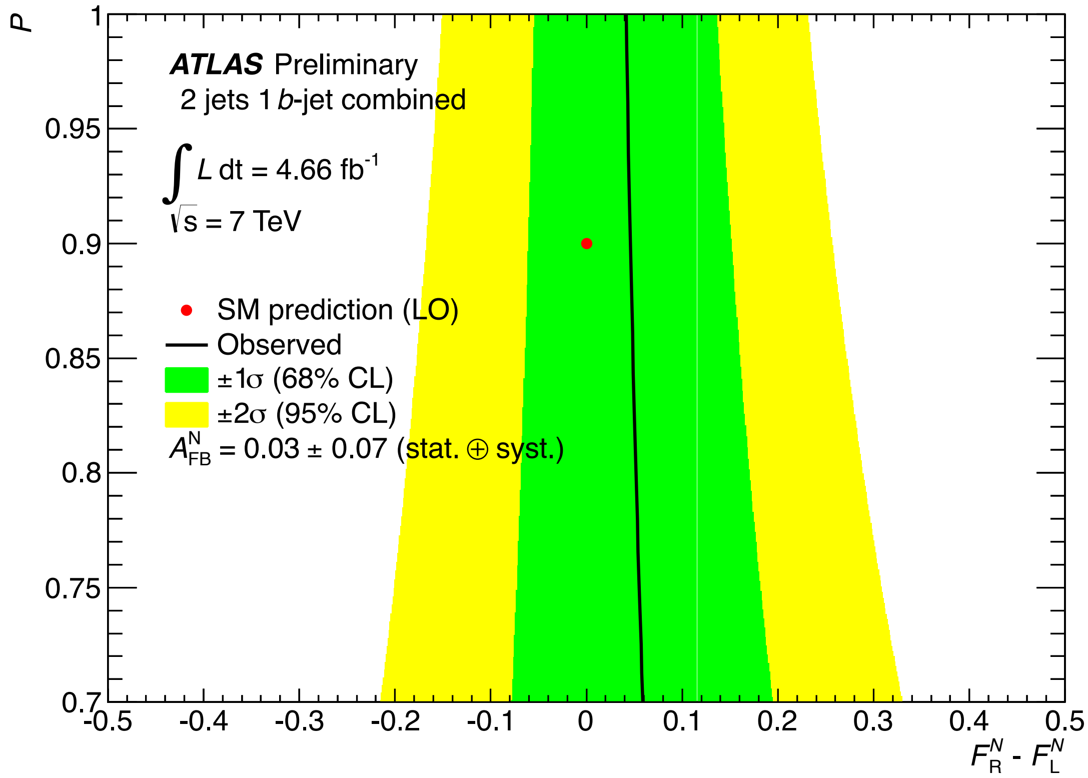


CMS-PAS-TOP-12-031

- Systematic Uncertainties

Source	Estimated effect (MeV)
Jet energy scale	**17** ± 15
Jet energy resolution	8 ± **11**
b vs. $\bar{b}$ jet response	**64** ± 7
Signal fraction	**45** ± 2
Background charge asymmetry	**12.43** ± 0.03
Background composition	**50** ± 1
Pileup	**17.4** ± 0.4
b-tagging efficiency	**20** ± 8
b vs. $\bar{b}$ tagging efficiency	**43** ± 6
Method calibration	15 ± **54**
Parton distribution functions	**12** ± 3
Total	122

Search for CP Violation in Single Top Quark Events (t-channel)



ATLAS-CONF-2013-032