Top Quark Physics at LHC. Results on CP violation and FCNC in top quark decays.

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Outline

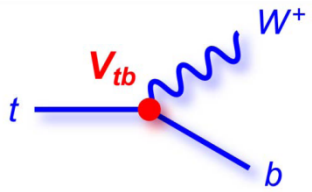
- Introduction
- Search for FCNC in top quark events in *pp* collisions.
  - Results from ATLAS and CMS both for tt and single top decays.
- Search for CP violation in single top quark events in *pp* collisions. (ATLAS)
- Measurements of the top-antitop mass difference in *pp* collision. Test of CPT conservation. (CMS)
- Combination of the ATLAS and CMS measurements on the W polarization.

Introduction

- The **top quark is the heaviest particle** of the SM (173.3±0.5 (stat) ±1.3 (syst) GeV) → Yukawa coupling to the Higgs field close to 1→ **Most interesting object to test the SM**.

- **decay time of O(10^{-24} s)** shorter than the hadronisation time scale → a unique possibility to study a "bare" quark.

- The SM predicts BR (t→Wb)~100%.



- **Extensions of the SM predict t→Zq (q=c,u)**. This decay is **suppressed** in the SM **by the GIM mechanism**. The BR(t->Zq) should be O(10^{-14}), far below the experimental reach of the LHC.

- Previous results: BR(t->Zq) <3.7%(3.2%) for CDF(D0) @ 95 CL.

FCNC in tt events using data at 7 TeV collected by CMS (5.0 fb^{-1}) (I)

Physics Letter B 718 (2013) 1252-1272

- **The signature we are looking for is: tt→Zq+Wb→llq+l υ b**
- **Trigger**: double electron or double muon trigger.
- **Offline selection**:
- At least one good PV (due to the high pileup conditions).

- 2 Opposite Sign (OS) and isolated leptons. 60<m(e^+e^-), m($\mu^+\mu^-$)<120 GeV compatible with the Z mass. Compatible with the same good PV.

- 2 jets with p_T >30 GeV, $|\eta|$ <2.4, ΔR(jet,lepton)>0.4, $E_T^{Miss.}$>30 GeV.

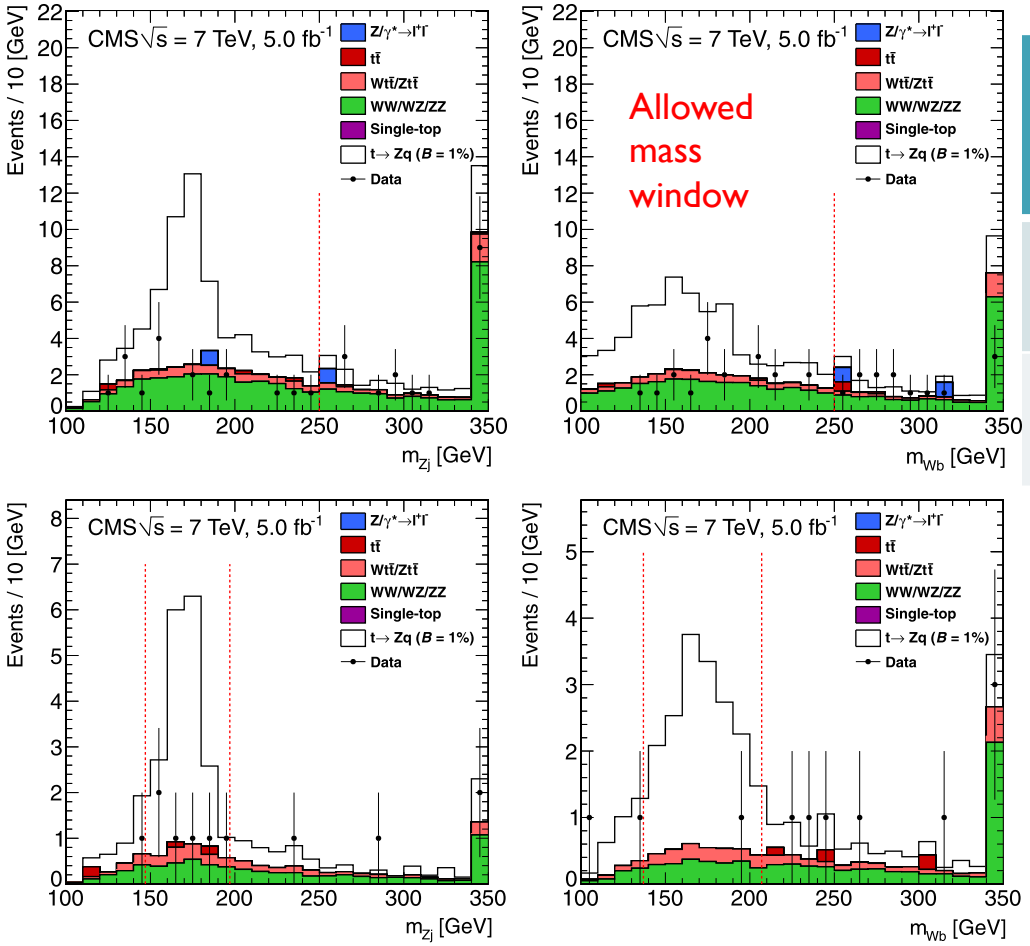
FCNC in tt events using data at 7 TeV collected by CMS (5.0 fb^{-1}) (II)

- **Signal Reconstruction**:
  - For the t→Zq signal a full reconstruction of the m_{zj} is possible.
  - For the m_{Wb} the reconstruction is possible by assuming $p_T^{\upsilon} = E_T^{Miss}$
  - **Two possible methods are exploited**:
    1. **$S_T^{(1)}$ method**: 2 jets p_T>30GeV, S_T>250GeV, m_{zj} and m_{wb} within [100, 250] GeV
    2. **B-tagging method**: 2 jets p_T>30GeV, one of them b-tagged. The jet with the m_{zj} closest to the top mass is selected. m_{zj} within 25 GeV of the top mass. m_{Wb} within 35GeV of the top mass.

    (1) S_T= scalar sum of the transverse energy of the three leptons, two jets and E_T^{Miss}

Background estimation: WW, WZ, ZZ, Wtt, Ztt and single top production are evaluated using MC. tt and Z+jets estimated from data.

FCNC in tt events using data at 7 TeV collected by CMS (5.0 fb^{-1}) (III)



method	Observed [%]	Expected [%]	+/- 1sigma
S_T	0.21	0.40	0.30-0.59
B-tagging	0.30	0.41	0.30-0.53

Upper limit computed from the **observed number of events, the background prediction, and the fraction of all tt→Zq + Wb→llq + lb expected to be selected**.

Comparison of data and MC of m_{zj} and m_{wb}, after the basic selection + the S_T requirement (top), and + the b-tagging request (bottom)

FCNC in tt events using data at 7 TeV collected by ATLAS (2.1 fb^{-1}) (I)

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- **The leptonic channel is used: tt→zq+Wb→llq+l υ b**
- **Trigger:** SingleMuon or SingleElectron.

- Two kinds of reconstruction for the lepton in ATLAS:
  - 1) using information coming from all subdetectors (ID lepton)
  - 2) using the inner tracker detector (TL lepton). Only one TL lepton is allows for each events.

- **Signal candidates** are divided in two categories:
  - **1) 3 ID**: 1 lepton with p_T> 25 GeV, the other two p_T>20 GeV. They have to be isolated. ID e^- in $|\eta_{cl}|$<2.47
  - **2) 2 ID + TL**: TL lepton p_T> 25 GeV, the other two p_T>20 GeV

- **At least two jets** isolated from the selected leptons are required. **In the 2ID +TL category one of them has to be b-tagged**. E_T^{Miss} > 20GeV.

FCNC in tt events using data at 7 TeV collected by ATLAS (2.1 fb^{-1}) (II)

- **Background estimation:**
  - **two categories:**

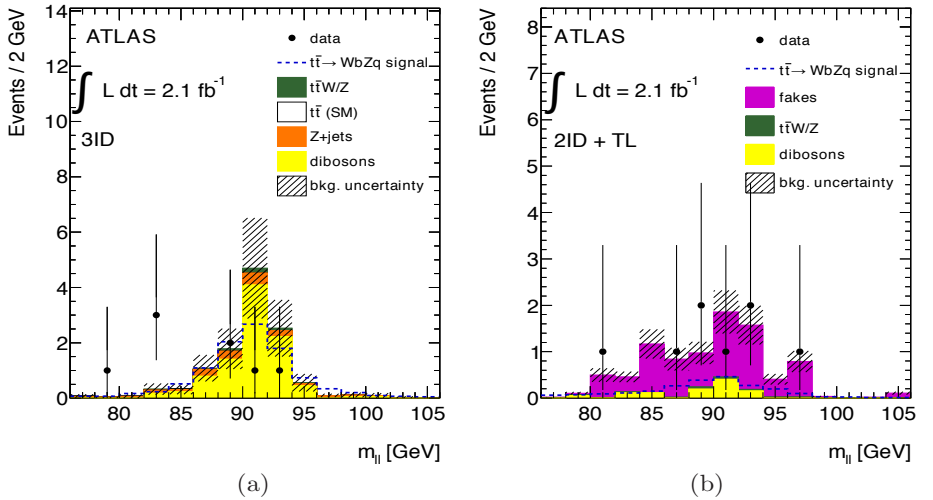
1. **3 real leptons in the final state** (WZ,ZZ production) are evaluated using MC.

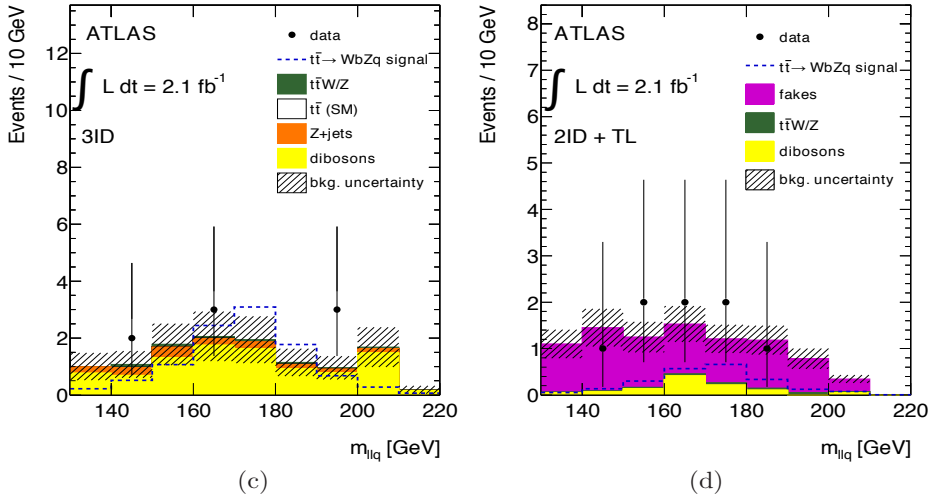
2. **at least one fake lepton**:

   - 3ID: main contribution Z+jets → Data Driven method. A DD method is implemented also for W+jets and single top bkg.

   - 2ID+TL: main contribution from events in which the TL is a fake lepton. A DD method is implemented using γ +jets events to evaluate the probability that a jet is misidentified as lepton.

FCNC in tt events using data at 7 TeV collected by ATLAS (2.1 fb^{-1}) (III)





channel	observed	(-1σ)	expected	$(+1\sigma)$
3ID	0.81%	0.63%	0.95%	1.4%
2ID+TL	3.2%	2.15%	3.31%	4.9%
Combination	0.73%	0.61%	0.93%	1.4%

Top quark mass (left top) and Z boson mass (left bottom).
In 3ID and 2ID+TL categories.
tt→WbZq normalized to observed limit in each channel.

No evidence of t→Zq decay mode is found. 95% C.L. Upper limit on the BR(t→Zq) using the NNLO cross section calculation and constraining BR(t→Wb)=1-BR(t→Zq).

FCNC in single top events using data at 7 TeV collected by ATLAS (2.05 fb^{-1}) (I)

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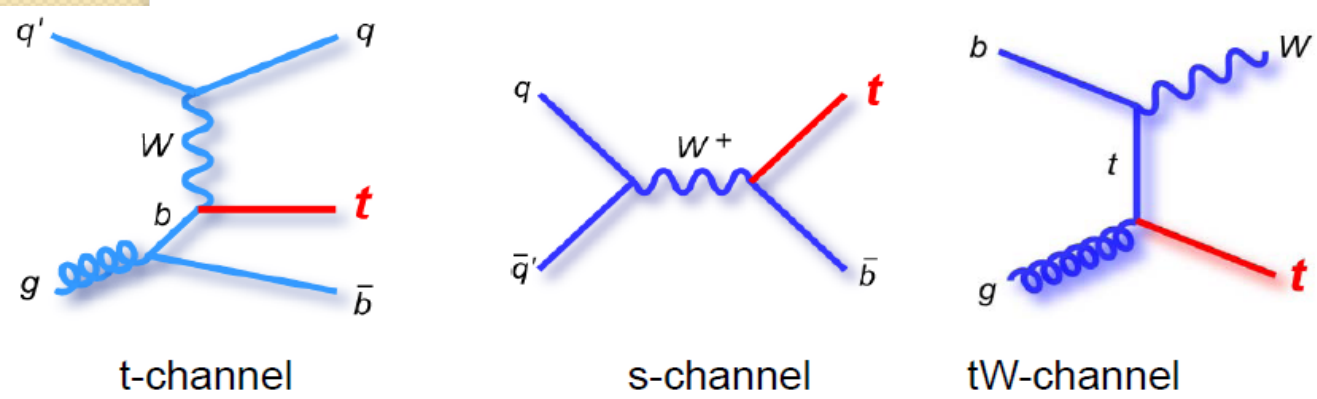
- **Three main single top process** are expected: t-channel, Wt associated production and s-channel.



Kidonakis, NLO+NNLL
t-channel: PRD 83 (2011) 091503
s-channel: PRD 81 (2010) 054028
tW-channel: PRD 82 (2010) 054018

- The goal is to observe a t→qg decay (forbidden by the GIM mechanism) but it is easier to study **qg→t**.
- **The SM production is usually accompanied by additional jets**.

FCNC in single top events using data at 7 TeV collected by ATLAS (2.05 fb^{-1}) (II)

- **Leptonic decay of the top quark are used for this measuremenets.**
- **Trigger:** Single Lepton triggers for both channels.

- **Offline selection**
- electron p_T>25 GeV, | η |<2.47 and fully reconstructed muon, p_T>25 GeV, | η |<2.5 . Isolation cuts applied.

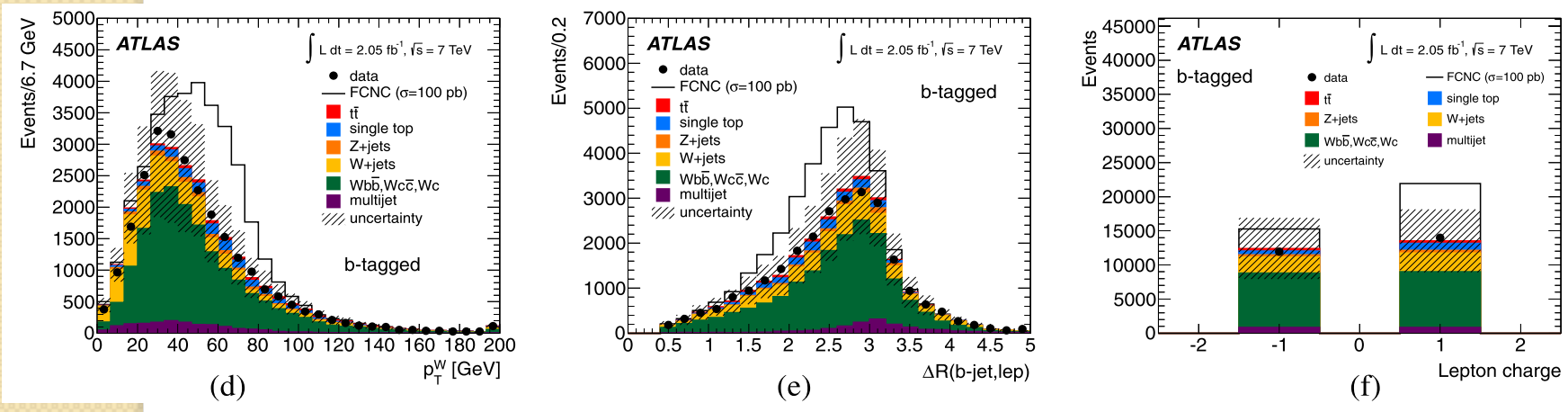
- 1 jet p_T>25 GeV b-tagged, MET>25GeV.

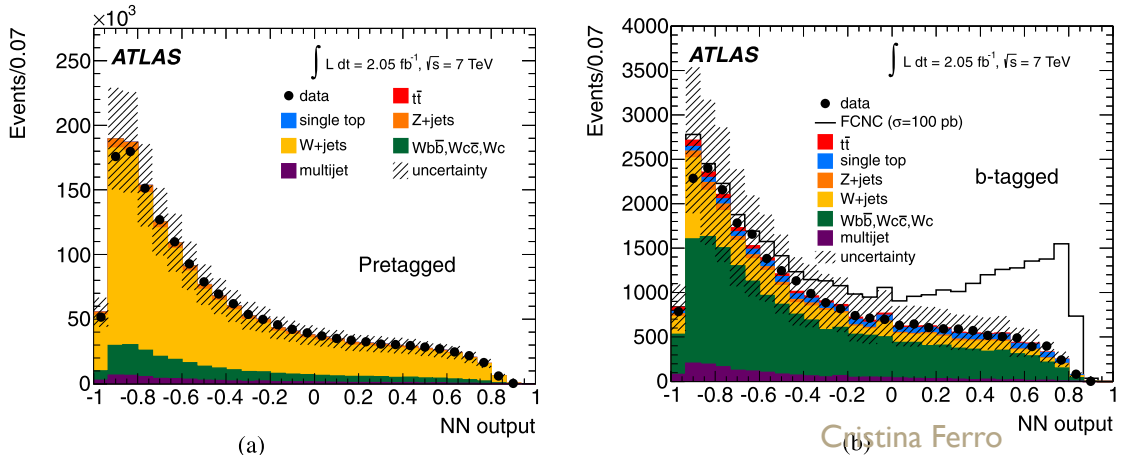
- $m_{T(W)}$+MET>60GeV (to reject multijet production)

- **Background estimation**: W+jets and Z+jets events taken from MC. Multijet background modeled using electron-like jets, normalisation from fit to MET distribution.

FCNC in single top events using data at 7 TeV collected by the ATLAS (2.05 fb^{-1}) (III)

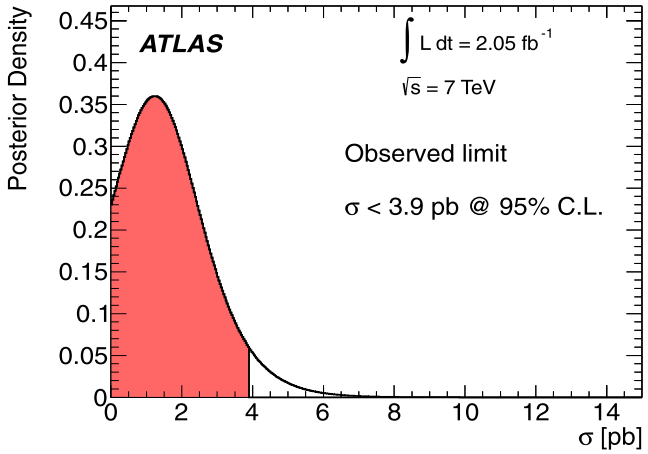
- A multivariate technique is used to separate signal from BKG.
- 11 variables are used for the training phase.
- Main three: p_T of the W boson, ΔR(jet,lepton), charge of the lepton.

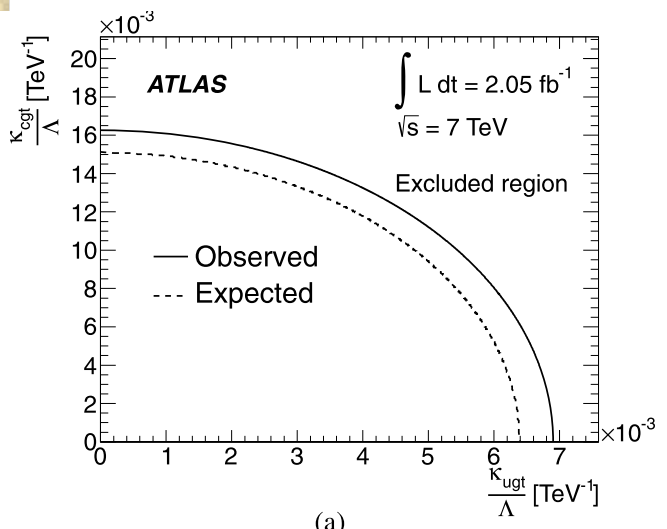




FCNC in single top events using data at 7 TeV collected by ATLAS (2.05 fb^{-1}) (IV)

- A Bayesian statistical analysis using a binned likelihood method is applied to the NNoutput distribution to retrieve an upper limit on the FCNC single top production cross section.





- The PDF gives the probability of the signal hypotesis as function of the signal cross section.
- No rate of FCNC single top production is observed→an upper limit is set by integrating the PDF.

- **The measured upper limit is converted in an upper limit on the coupling costant k_{ugt}/λ , k_{cgt}/λ .**
- **For $k_{ugt}/\lambda = 0 \rightarrow k_{cgt}/\lambda < 1.6*10^{-2} TeV^{-1}$**
- **For $k_{cgt}/\lambda = 0$, $k_{ugt}/\lambda < 6.9*10^{-3} TeV^{-1}$**

- *Λ is the new physics scale.*
- *K_{ugt}, k_{cgt} are the dimensionless parameter that relate the strength of the new coupling to the strong coupling costant g_R*

Search for CP violation in the single top events in *pp* collision at 7 TeV with ATLAS (4.66 fb^{-1}) (I)

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}\left(V_{\mathrm{L}}P_{\mathrm{L}} + V_{\mathrm{R}}P_{\mathrm{R}}\right)tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{m_{W}}\left(g_{\mathrm{L}}P_{\mathrm{L}} + g_{\mathrm{R}}P_{\mathrm{R}}\right)tW_{\mu}^{-} + \mathrm{h.c.}$$

- SM predicts: Wtb ~V_L~1 and (at LO) anomalous couplings V_R=$g_{R,L}$=0

- We want to **probe the coupling of the top quark in the W_{tb}** vertex by measuring the **asymmetry in the angular distribution of the charged lepton** from the W decay in the single top quark t-channel.

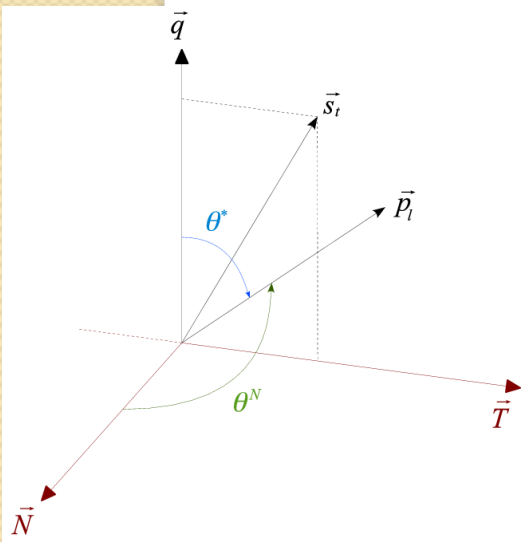
- *(Nucl.Phys. B840 (2010) 349-378)*
- **Angular asymmetry definition**: $$A_z \equiv \frac{N_{\mathrm{evt}}(\cos\theta > z) - N_{\mathrm{evt}}(\cos\theta < z)}{N_{\mathrm{evt}}(\cos\theta > z) + N_{\mathrm{evt}}(\cos\theta < z)},$$

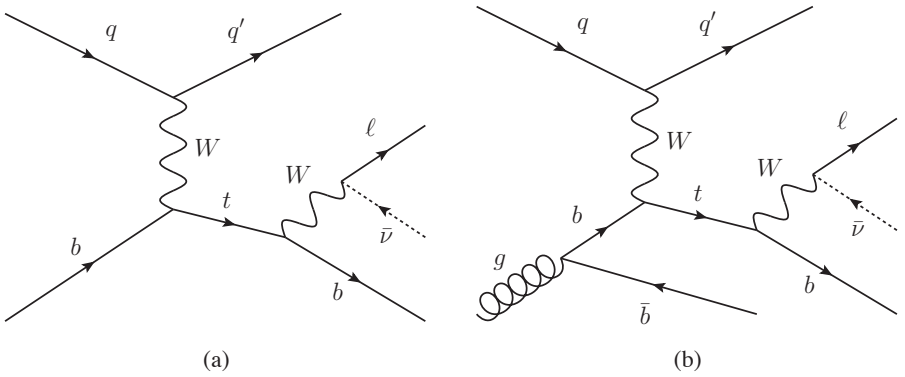
- Z is a given point in the angular distribution.
- For z=0 the asymmetry is called forward-backward (A_{FB}).

ATLAS-CONF-2013-032

Search For CP violation in the single top events in *pp* collision at 7 TeV with ATLAS (4.66 fb^{-1}) (II)

- ϑ = angle between lepton (in the W boson rest frame) end the momentum *q* of the W boson (in the top quark rest frame). This angle (ϑ^*) it is not sensitive to the complex phase of the g_R.





Feynman diagrams for t-channel single top quark production. The initial-state b-quark stems from a b sea quark (a) or from a gluon splitting into a bb pair (b).

- Top quark expected to be produced highly polarized along the direction of the spectator quark (s_t) → two new reference directions:

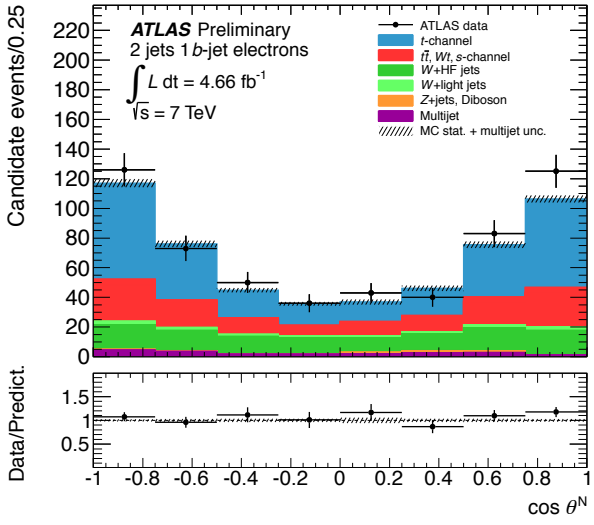
$$\vec{N} = \vec{s}_t \times \vec{q}\,,$$
$$\vec{T} = \vec{q} \times \vec{N}\,,$$

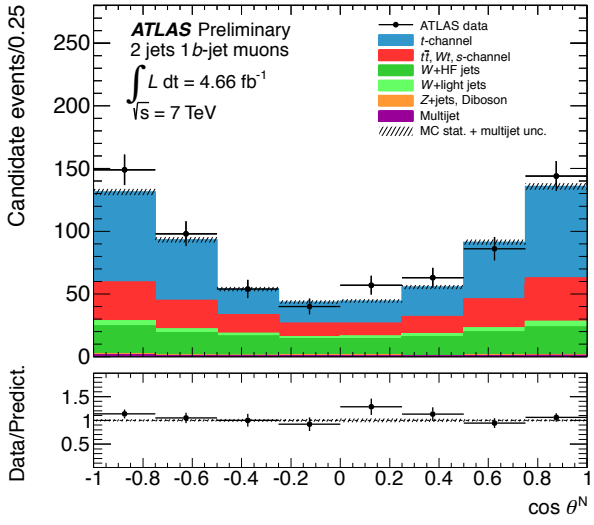
- A forward-background asymmetry w.r.t N , A_{FB}^{N}, is used to probe the complex phase of g_R.

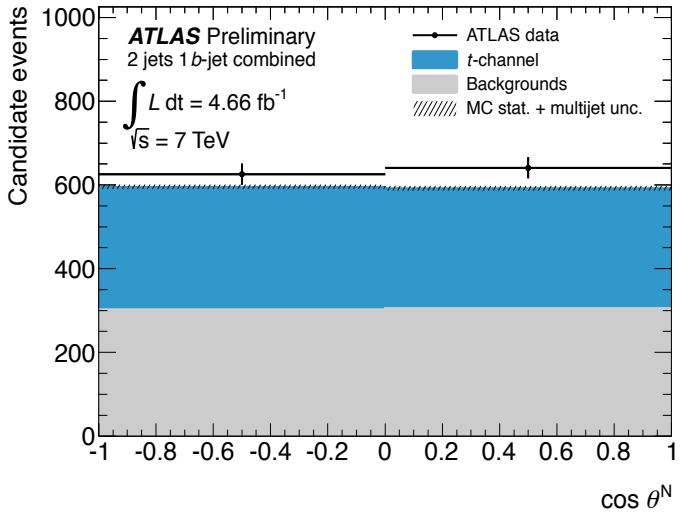
Search For CP violation in the single top events in pp collision at 7 TeV with the ATLAS detector (4.66 fb^{-1}) (III)

- **Trigger**: Single lepton is required.
- **Event preselection**: 1 lepton p_T>25GeV, $|\eta|$<2.5. Exactly 2 jets p_T>30GeV, $|\eta|$<4.5 (p_T > 35GeV if 2.75 < $|\eta|$ < 3.5). One of them b-tagged. MET and m_W >30GeV (to reduce the multijet background).
- **Reconstruction of the top quark:** reconstructed from the b-jet and W boson to reconstruct the $\cos\vartheta^N$.
- **The longitudinal component of neutrino is computed from the four-vector of the lepton and the E_T^{Miss} using the W mass as constraint.**
- **Event Selection**: The $|\eta|$<2.0 is used for the preselected jets. H_T > 210 GeV. 50< m_{top} < 190 GeV, $\Delta\eta$ (light jet, b-jet) > 1
- **Background estimation**: multijet and W+jets modeled on data using control region, other bkg taken from MC.

Search For CP violation in the single top events in *pp* collision at 7 TeV with ATLAS r (4.66 fb^{-1}) (IV)







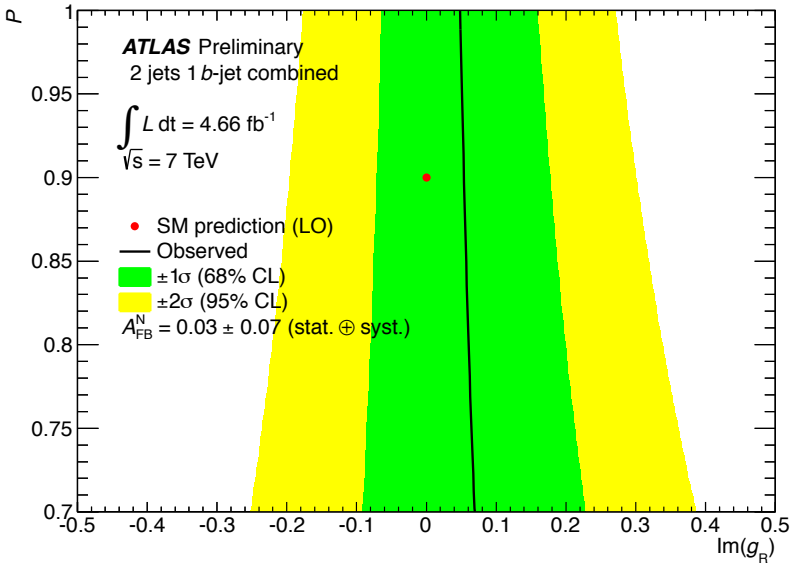
Reconstructed cos θ^N angular distribution obtained at selection level for electron (left) and muon (Center) channels. The combined results is shown on the left.

- The measured A_{FB}^N has to be unfolded for the comparison with the theoretical prediction. The efficiency of the signal selection is not flat in the bin of the angular distribution→this leads to migration of events between bins→migration matrix computed on MC to unfold the final distribution.

Search For CP violation in the single top events in *pp* collision at 7 TeV with the ATLAS detector (4.66 fb^{-1}) (V)

	A_{FB}^{N}
Data, before background subtraction	0.012 ± 0.028 (stat.)
Data, after background subtraction	0.018 ± 0.055 (stat.)
Data unfolded	0.031 ± 0.065 (stat.) $^{+0.029}_{-0.031}$ (syst.)

- Using the unfolded value of the A_{FB}^{N} and the relation $A_{FB}^{N} \sim 0.64\ I(g_R)$ it is possible to constrain the immaginary part of the g_R coupling.



The first experimental limits on I(gR):

- with **P*=0.9, I(gR) is determined to be [−0.20, 0.30] at 95% confidence level.**

(*) polarization of the top quark.

Measurement of the top anti-top mass difference in *pp* collision at 8 TeV with CMS (18.92 fb^{-1}) (I)

CMS-PAS-TOP-12-031

- **CPT invariance implies equality of particle and anti-particle masses.**
- Several extensions of the SM include CPT violation effects.
- The top quark is unique for this kind of CPT test in the quark sector for two main reasons:
  1. because it decays before hadronization.
  2. large dataset due to the large top quark cross section production at LHC

Measurement of the top anti-top mass difference in *pp* collision at 8 TeV with CMS (18.92 fb^{-1}) (II)

CMS-PAS-TOP-12-031

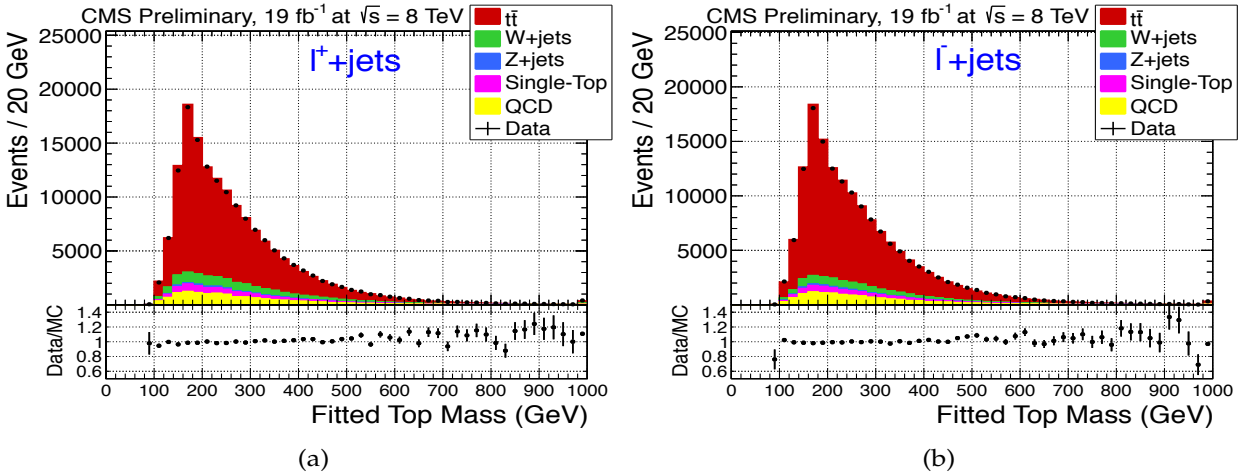
- The **tt semileptonic channel has been used**.
- **Trigger:** Single Lepton triggers
- The charge of the hadronically decaying top is computed from the charge of the leptonically decaying top.
- **Offline selection:**

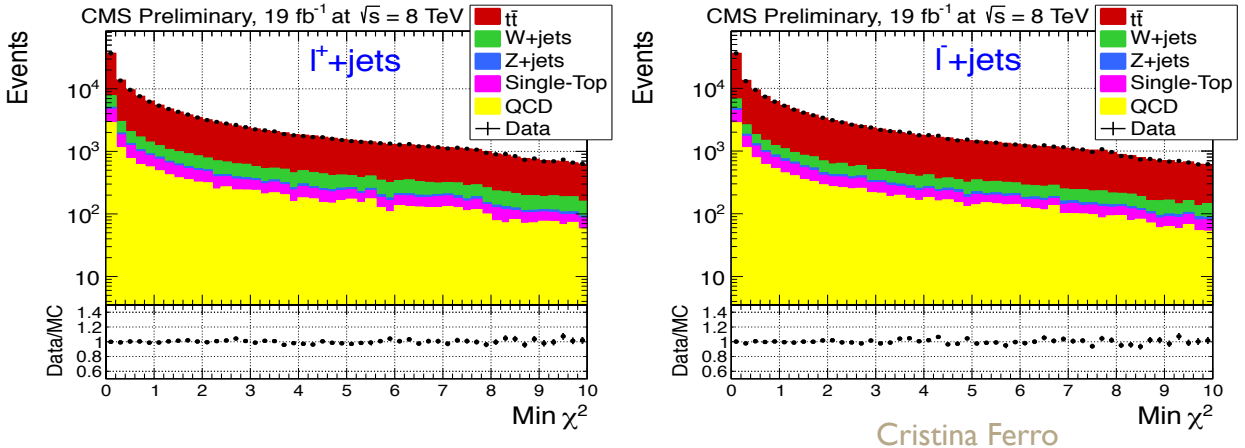
Offline selection	Muons	electrons	jets
	At least 1	At least 1	At least 4
isolation	✓	✓	Separated from leptons
pT	25 GeV	32 GeV	30 GeV
$\lvert\eta\rvert$	< 2.1	< 2.5	< 2.5
B-tagging			1 jet b-tagged

- kinematic fit is used to reconstruct the mass of the hadronically decaying top quark

Measurement of the top anti-top mass difference in pp collision at 8 TeV with CMS (18.92 fb^{-1}) (III)

- For each event, the four leading jets are considered. They can be associated to the four quarks for the tt-decay hypotesis $tt \rightarrow bbW^+W^- \rightarrow bbqq'l\upsilon_l$ in 12 possible ways. The kinematic fit is performed for each combination.





Measurement of the top anti-top mass difference in $p\bar{p}$ collision at 8 TeV with CMS (18.92 fb^{-1}) (IV)

- The fitted value of the top-quark mass m_i is used as input of the Ideogram method.
- In the Ideogram method an event-by-event likelihood is constructed as function of m_t .
- A combined likelihood for the full event sample is computed as the product of the individual event likelihoods for all selected events.
- The results are:

μ + jets $m_t = -230 \pm 264 \text{ (stat.) MeV},$

e^- + jets $m_t = -325 \pm 294 \text{ (stat.) MeV},$

The results for Δm_t are compatible with the expectation from the hypothesis of CPT symmetry.

combined $m_t = -272 \pm 196 \text{ (stat.)} \pm 122 \text{ (syst.) MeV}.$

This is more precise by at least a factor two than any of the previous public results.

Combination of ATLAS and CMS measurements of the W-boson polarization in top-quark decays

- **The V-A structure of the Wtb vertex can be tested** by measuring the polarization of W bosons produced in top-quark decays.
- The fractions of events containing W bosons with longitudinal, left-handed and right-handed polarization, are predicted by the pQCD at NNLO.
- helicity fractions can be measured using events where a top-quark pair is produced.

The distribution of $\cos\vartheta^*$ is sensitive to the helicity fractions.

($\cos\vartheta^*$ is defined as the angle between the direction of the charged lepton and the reversed direction of the top quark, both in the rest frame of the W boson)

- ATLAS and CMS measurements are done using data collected in 2010 and 2011 pp collision at 7 TeV with a dataset of 35 pb^{-1} and 2.2 fb^{-1} respectively.
- The semileptonic and dileptonic channels have been investigated.

Combination of ATLAS and CMS measurements of the W-boson polarization in top-quark decays

- The measurement are combined using the BLUE method. All measurements are weighted linearly in the combination under the constraints that the total uncertainty is minimal and that the estimator is unbiased.
- By construction, the sum of the three observables, F_0, F_L, F_R is constrained to 1. In the current analysis, measurements of , F_0, F_L are combined while the F_R is obtained as: $F_R = 1-F_0-F_L$.

Measurement	F_0	F_L	F_R
ATLAS 2010 (single lepton) [Alj2010]	$0.652 \pm 0.134 \pm 0.092$	$0.359 \pm 0.088 \pm 0.056$	$-0.011 \pm 0.060 \pm 0.046$
ATLAS 2011 (single lepton) [Alj2011]	$0.642 \pm 0.030 \pm 0.071$	$0.344 \pm 0.020 \pm 0.042$	$0.014 \pm 0.014 \pm 0.055$
ATLAS 2011 (dilepton) [Adil2011]	$0.744 \pm 0.050 \pm 0.087$	$0.276 \pm 0.031 \pm 0.051$	$-0.020 \pm 0.026 \pm 0.065$
CMS 2011 (single lepton) [Clj2011]	$0.567 \pm 0.074 \pm 0.048$	$0.393 \pm 0.045 \pm 0.024$	$0.040 \pm 0.035 \pm 0.043$

$$F_0 = 0.626 \pm 0.034\,(\text{stat.}) \pm 0.048\,(\text{syst.}),$$
$$F_L = 0.359 \pm 0.021\,(\text{stat.}) \pm 0.028\,(\text{syst.})$$
$$F_R = 0.015 \pm 0.034,$$

CONCLUSIONS

- Many different measurements searching for FCNC as well as CP and CPT violation, using top quark pair and single top events.
- No evidence of physics beyond the Standard Model for the moment.
- Many other measurements are underway, using the full statistics recorded by the ATLAS and CMS experiments.