

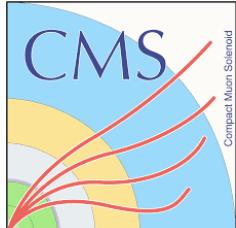


# TOP-QUARK PROPERTY MEASUREMENTS IN SINGLE TOP

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TOP2016

20<sup>TH</sup> September



EXCELENCIA  
SEVERO  
OCHOA



CONSEJO SUPERIOR  
DE INVESTIGACIONES  
CIENTÍFICAS

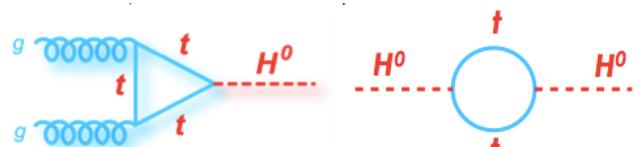


# WHAT MAKES TOP QUARK INTERESTING?

1

## Heaviest fundamental particle in the Standard Model

Larger mass → Larger coupling to SM Higgs +  $m_{top}$  is a fundamental parameter in SM

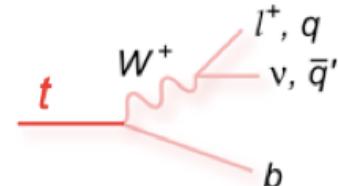


Allows for Self-Consistency Checks of SM Post Higgs Discovery

2

## Short Lifetime( $\sim 10^{-25}$ s)

Decays before hadronization – Unique among the quarks!



Access to Polarization and Spin Correlations

3

## Processes including top are backgrounds for new physics

e.g.  $H \rightarrow b\bar{b}$

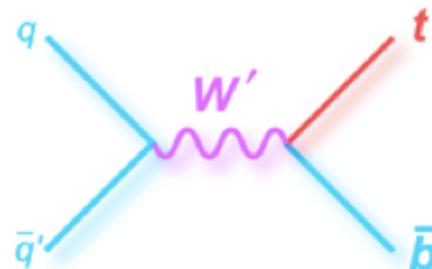
$H \rightarrow WW$

+ Exotics and SUSY

Good Understanding → Improvements in Searches

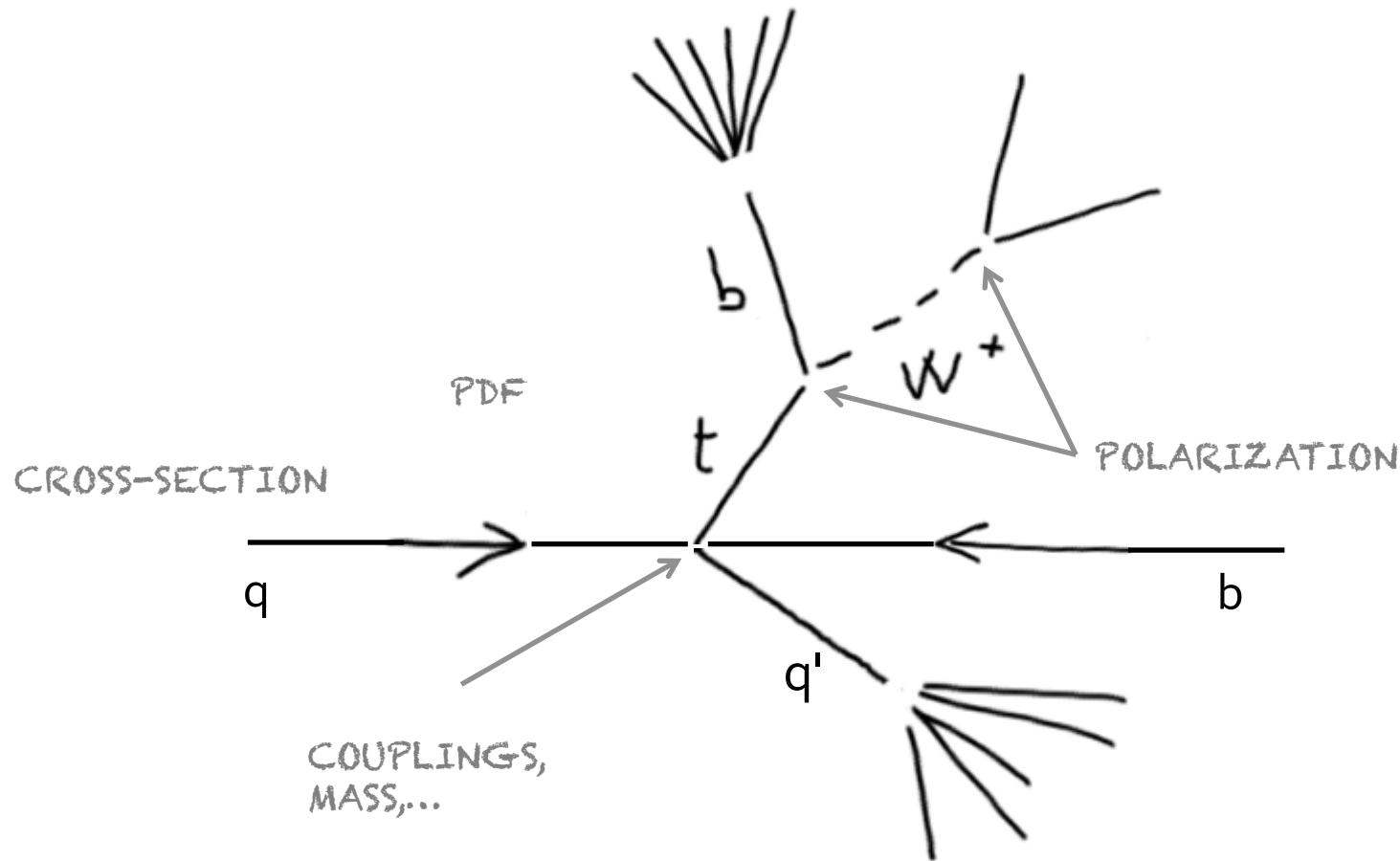
4

## Hints of new BSM/physics?



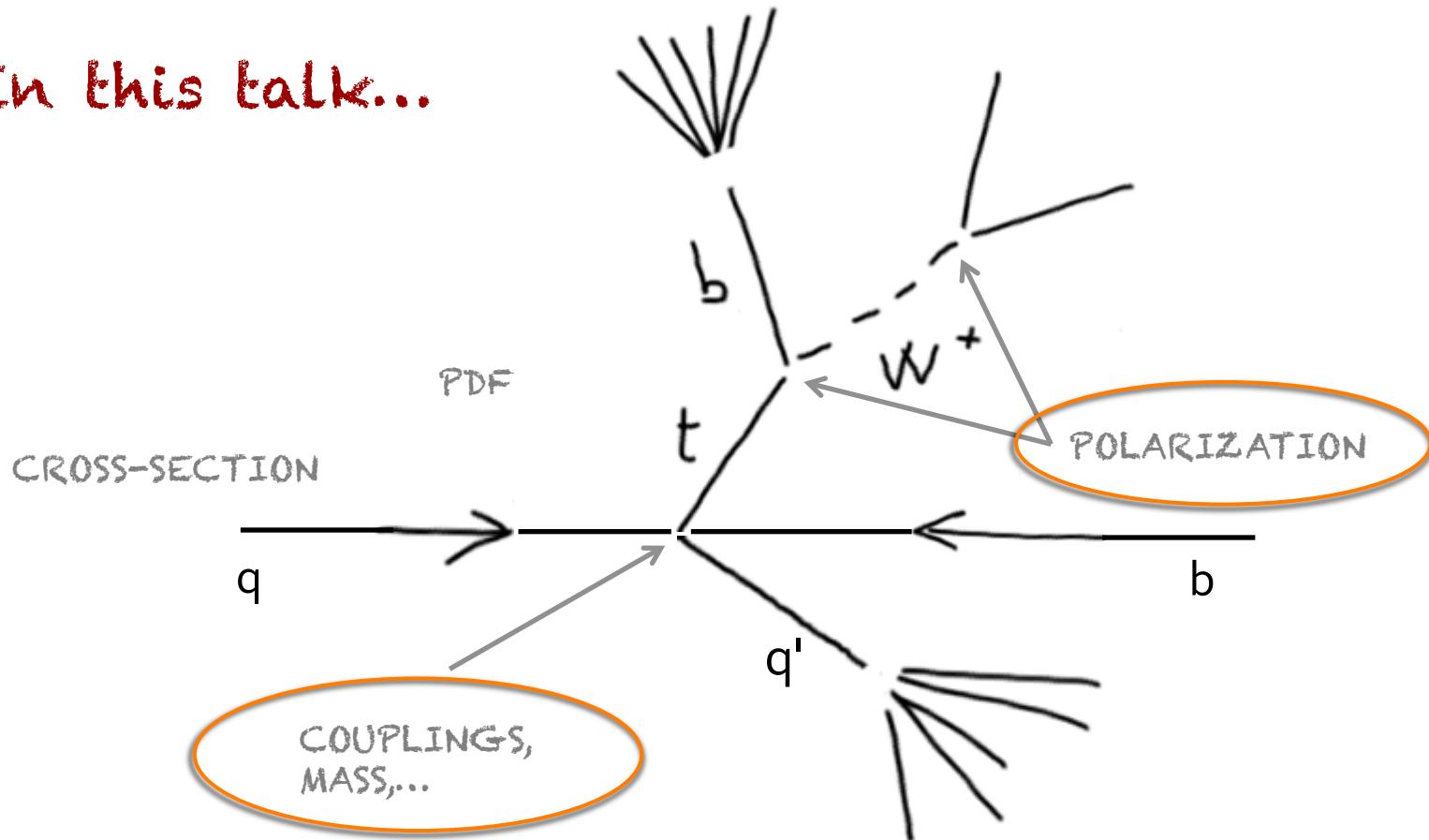
Exotic Particles Could Decay Preferentially to Top Quarks

# WHAT CAN WE MEASURE?



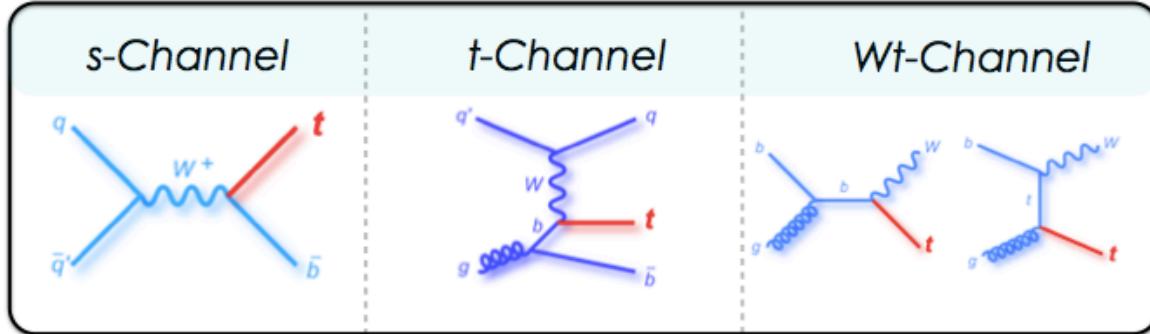
# WHAT CAN WE MEASURE?

In this talk...

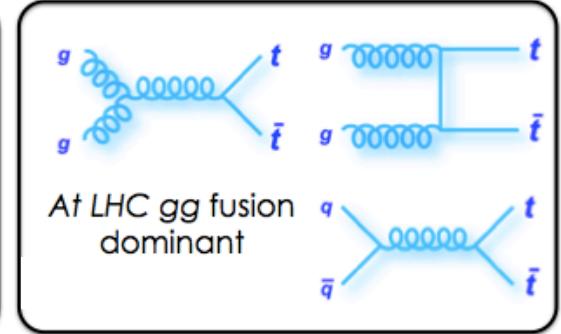


# TOP QUARK PRODUCTION

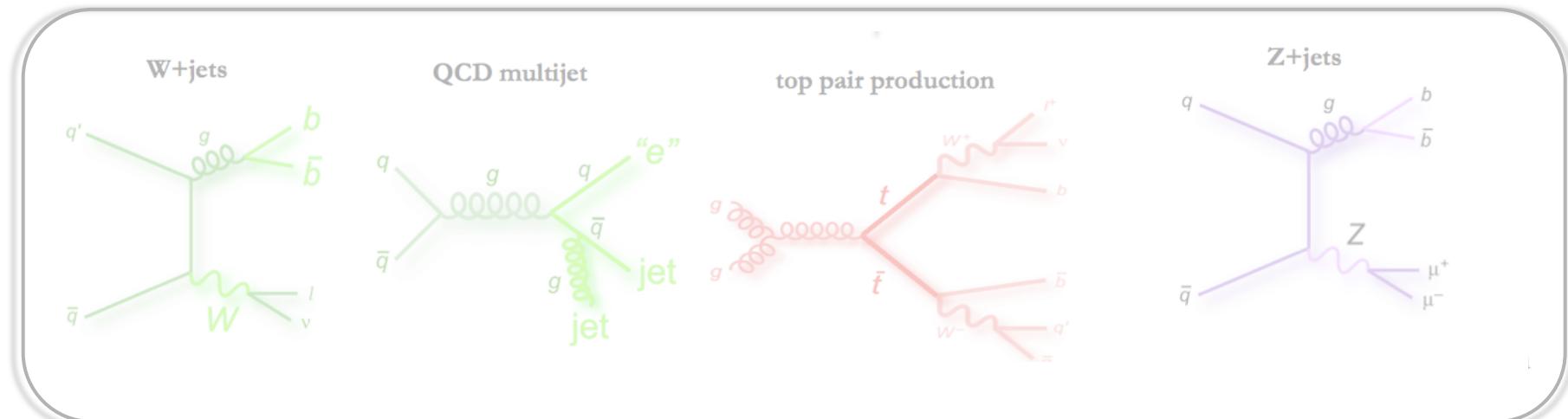
single top\* : production via EW interaction



top pair production

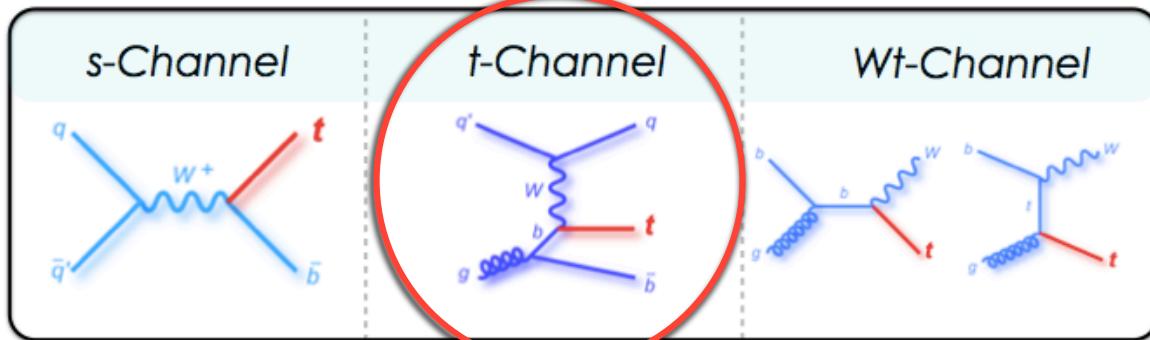


Backgrounds

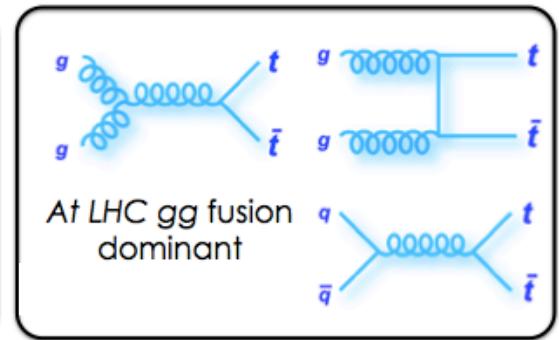


# TOP QUARK PRODUCTION

single top\* : production via EW interaction



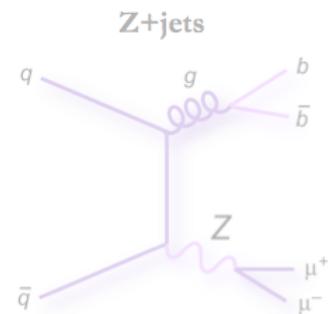
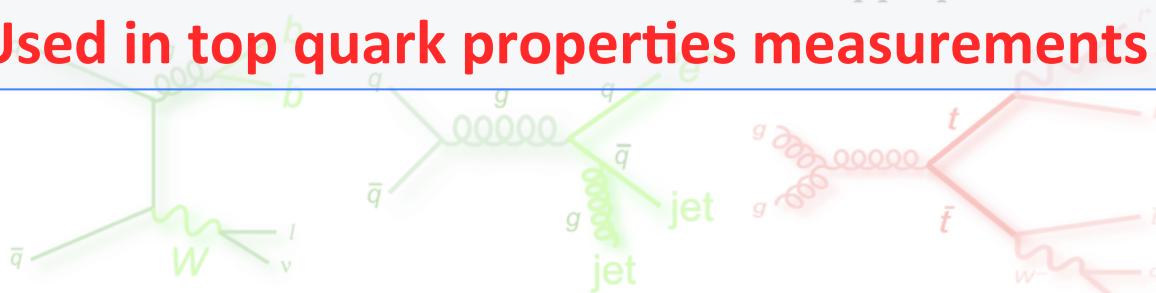
top pair production



Backgrounds

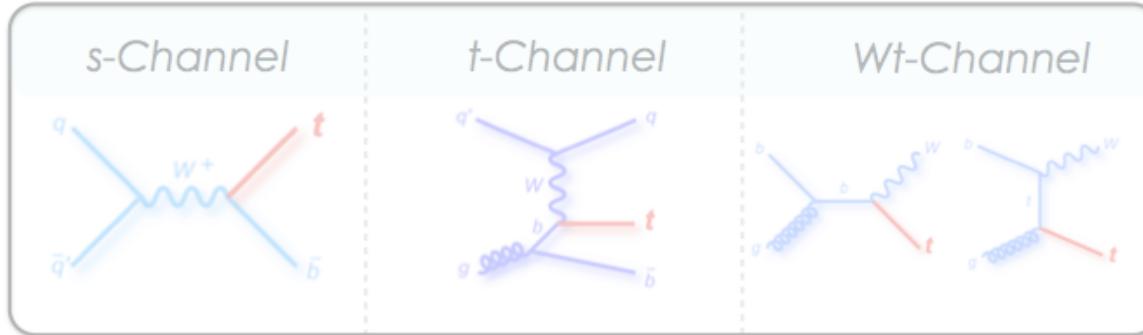


**Single top channel with highest statistics:  
Used in top quark properties measurements**



# TOP QUARK BACKGROUNDS

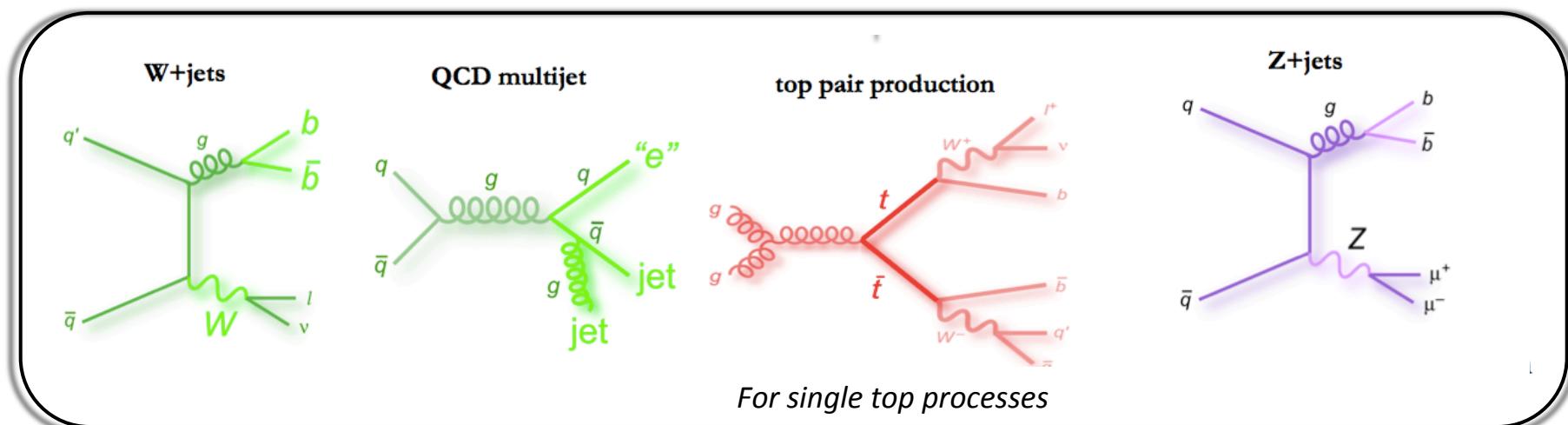
single top : production via EW interaction



top pair production



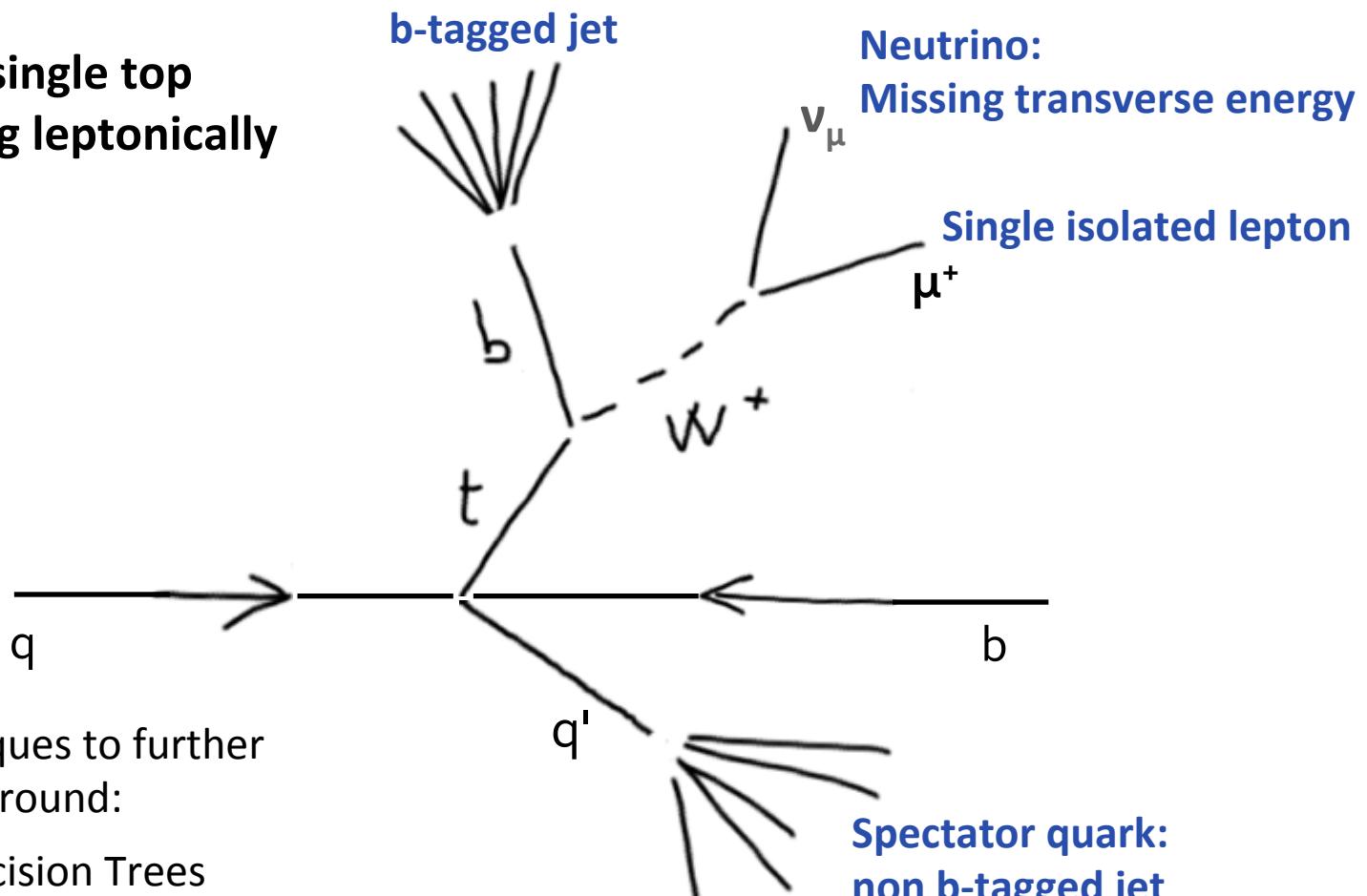
## Backgrounds



# BASIC SELECTION (LEPTONIC DECAY)

Example:

- t-channel single top
- W decaying leptonically



Specific techniques to further suppress background:

- Boosted Decision Trees
- Neuronal Networks
- Cut based techniques



# TOP QUARK

*POLARIZATION  
&  
ANOMALOUS COUPLINGS*

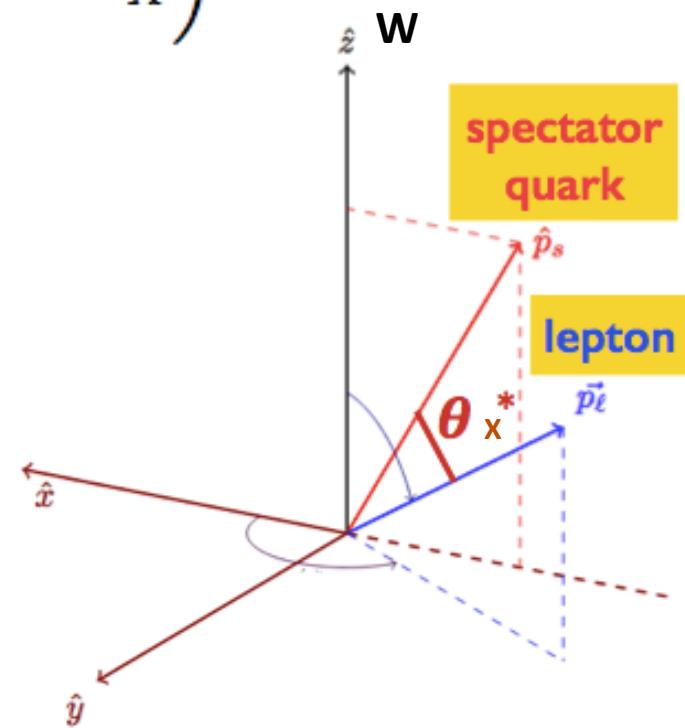
# TOP QUARK POLARIZATION

- V-A nature of the SM predicts large top polarization,  $P$ , along the direction of momentum of the spectator quark in the top rest-frame.
- Direction of a top decay product with respect to this direction follows

$$\frac{1}{\sigma} \frac{d\sigma}{d \cos \theta_X^*} = \left( \frac{1}{2} + A_X \cos \theta_X^* \right)$$

- Where  $A_X \equiv \frac{1}{2} P_t \alpha_X$
- For  $t \rightarrow W b$ ,  $W \rightarrow l \nu$ ,  $\alpha_1=1$
- Top quark spin tends to be aligned with the direction of the spectator quark momentum
- By measuring the  $\cos \theta_X^*$  distribution, one can potentially determine the top polarization.
- It can be extracted through fits to the distributions or through asymmetries.

$$A_X \equiv \frac{1}{2} P_t \alpha_X = \frac{N(\uparrow) - N(\downarrow)}{N(\uparrow) + N(\downarrow)}$$



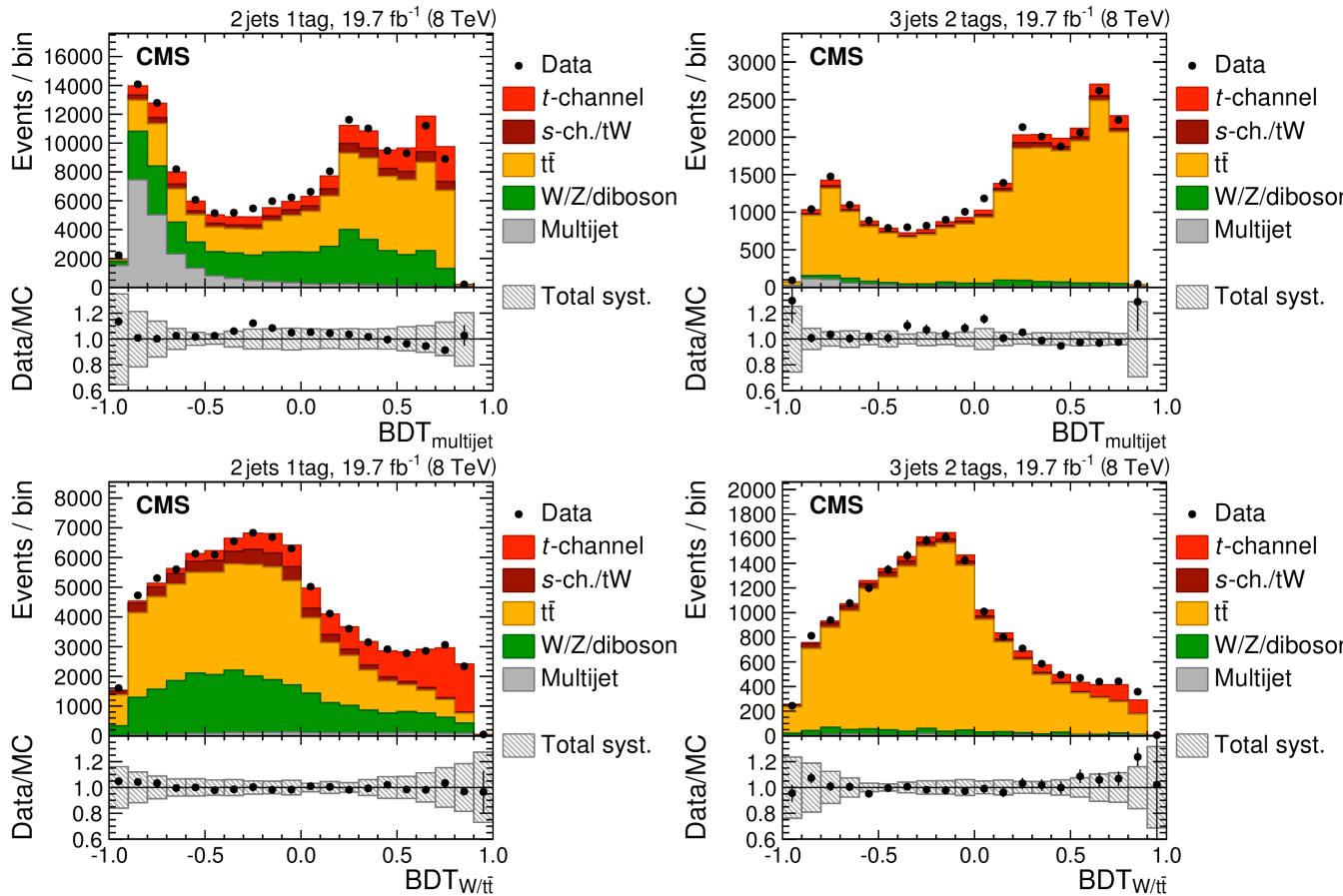


# TOP QUARK POLARIZATION

2012 data:  $\sqrt{s} = 8 \text{ TeV}$ ,  $L = 19.7 \text{ fb}^{-1}$

Check poster by Andres Tiko

- The top quark spin asymmetry is measured in t-channel single top production.
- Two consecutive BDT are used to reject background events and to enrich the sample.



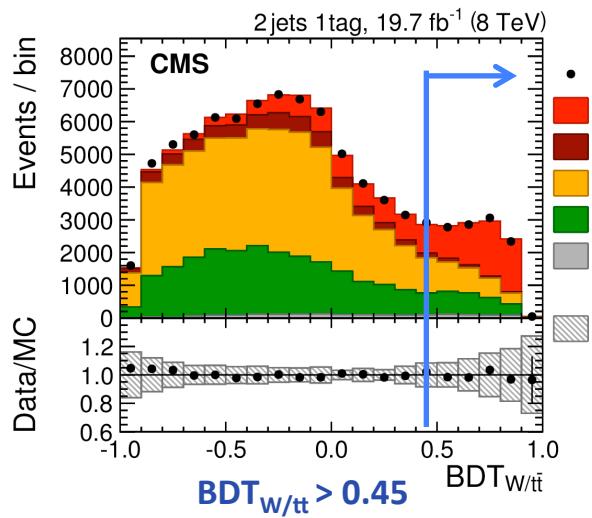
- Only muon decay**
- Multijet events are suppressed with the first BDT.
- Second BDT further suppress W+jets and ttbar events.
- None of the BDT uses the  $\cos \theta^*_\mu$
- A 3 jet 2btags region is included to constrain the ttbar contribution.

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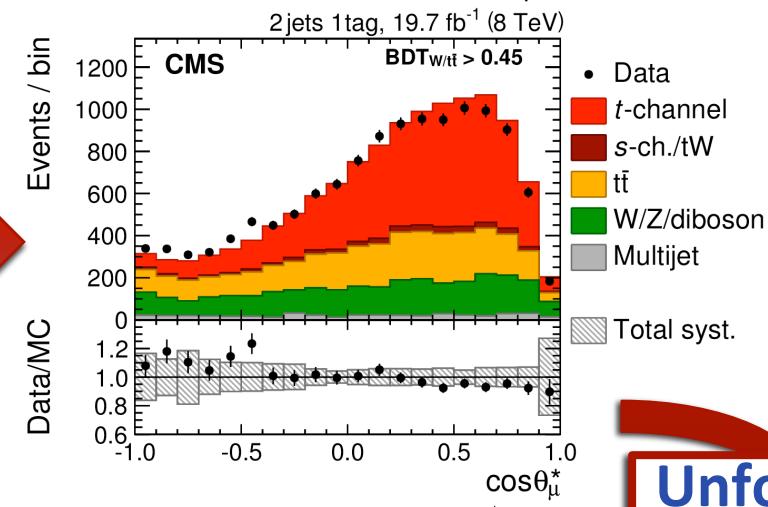


# TOP QUARK POLARIZATION

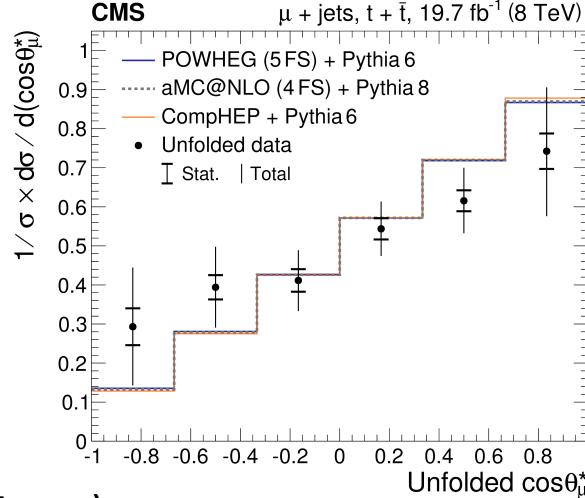
2012 data:  $\sqrt{s} = 8 \text{ TeV}$ ,  $L = 19.7 \text{ fb}^{-1}$



The BDT is not biasing the  $\cos \theta_\mu^*$  distribution



Unfolding



Data is unfolded at parton level to correct for efficiency and resolution.

Largest systematics associated with  $W+\text{jets}$ .

A **smaller slope than expected** is observed  
(SM predicts  $A_\mu = 0.44$ )

$$A_\mu = 0.26 \pm 0.03 \text{ (stat)} \pm 0.10 \text{ (syst)}$$

Compatible with a p-value of 4.6% (equiv. to 2 sigma)

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# ANOMALOUS COUPLINGS

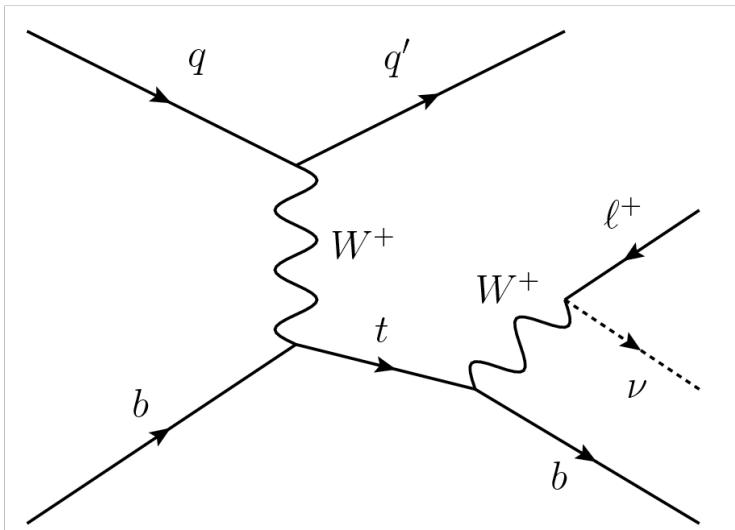
The most general form of the  $Wtb$  vertex is

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

Anomalous couplings in the SM:  $V_L = V_{tb}$  ;  $V_R = g_L = g_R = 0$

Deviations would provide hints of BSM physics.

Complex values could imply top quark decay has a CP-violating component.



By utilizing the polarization of the top in  $t$ -channel production and measuring multi-differential decay rates, complex couplings can be searched.

The increased statistics for single-top at LHC allows measurement of double differential decay rates of the top quark.



# W BOSON HELICITY

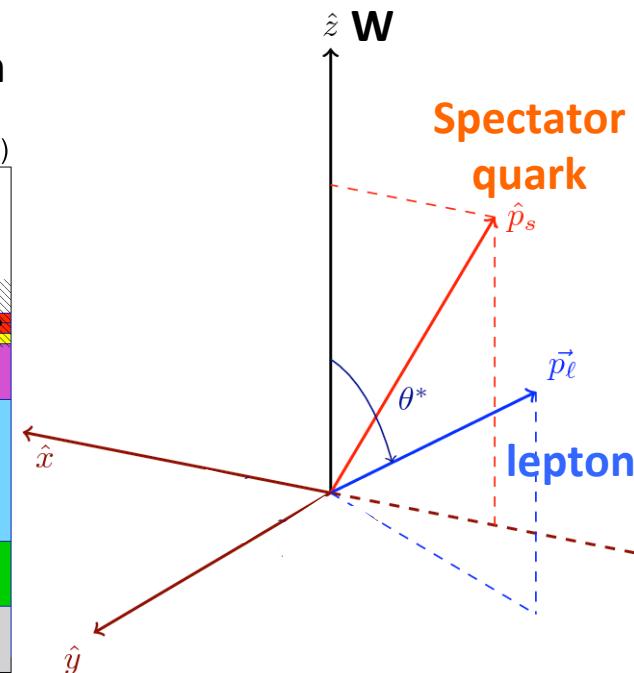
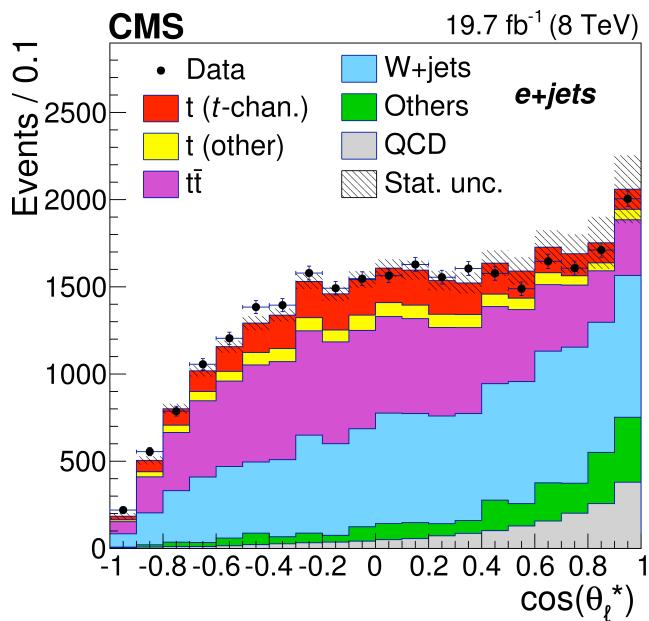
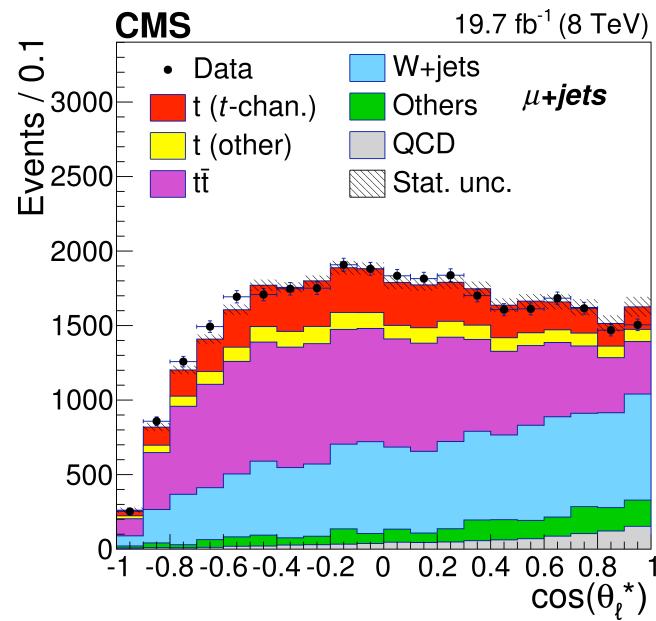
2012 data:  $\sqrt{s} = 8 \text{ TeV}$ ,  $L = 19.7 \text{ fb}^{-1}$

The probability distribution function of  $\cos \theta_L^*$  can be expressed as:

$$\rho(\cos \theta_\ell^*) \equiv \frac{1}{\Gamma} \frac{d\Gamma}{d \cos \theta_\ell^*} = \frac{3}{8} (1 - \cos \theta_\ell^*)^2 F_L + \frac{3}{4} \sin^2 \theta_\ell^* F_0 + \frac{3}{8} (1 + \cos \theta_\ell^*)^2 F_R$$

Where  $F_{R,L}$  denote the W boson right- and left-handed helicity fractions, and  $F_0$  the longitudinal one.

$F_0$ ,  $F_R$  and  $F_L$  can be extracted through a fit to this distribution



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# W BOSON HELICITY

2012 data:  $\sqrt{s} = 8 \text{ TeV}$ ,  $L = 19.7 \text{ fb}^{-1}$

- A fit is performed to **signal plus background** with MC-reweighted samples.
- $F_L$  and  $F_0$  are used as **free parameters**, together with the **W+jets normalization**.
- $F_R$  is extracted from the condition  $F_R + F_L + F_0 = 1$
- Limits in  $\text{Re}(g_R)$  and  $\text{Re}(g_L)$  from the helicity fraction values.
- Dominant sources of uncertainty: data statistics and MC modeling.

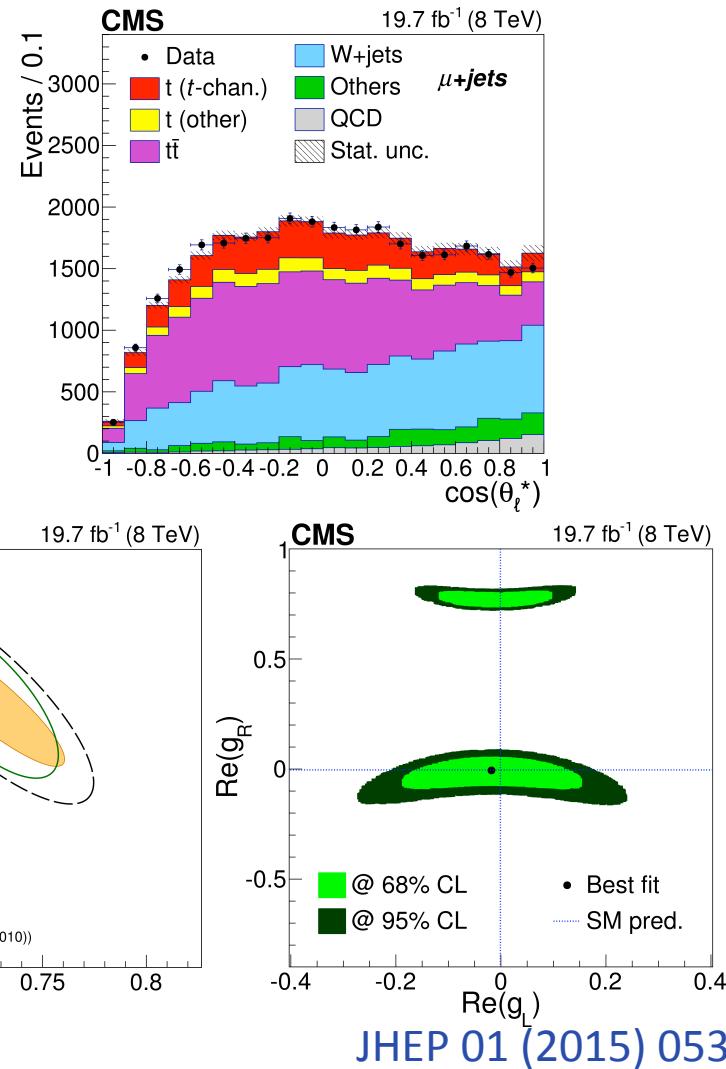
$$F_L = 0.298 \pm 0.028 \text{ (stat)} \pm 0.032 \text{ (syst)}$$

$$F_0 = 0.720 \pm 0.039 \text{ (stat)} \pm 0.037 \text{ (syst)}$$

$$F_R = -0.018 \pm 0.019 \text{ (stat)} \pm 0.011 \text{ (syst)}$$

$$\rho(F_L, F_0) = -0.80$$

Assumptions:  $V_R = 0$ ,  $V_L = 1$



2011 data:  $\sqrt{s} = 7 \text{ TeV}$ ,  $L = 4.59 \text{ fb}^{-1}$

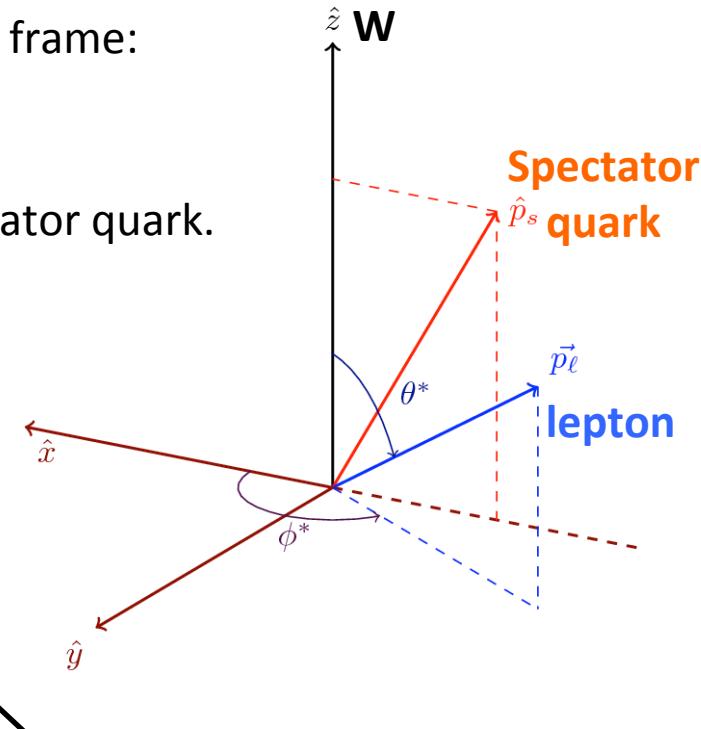
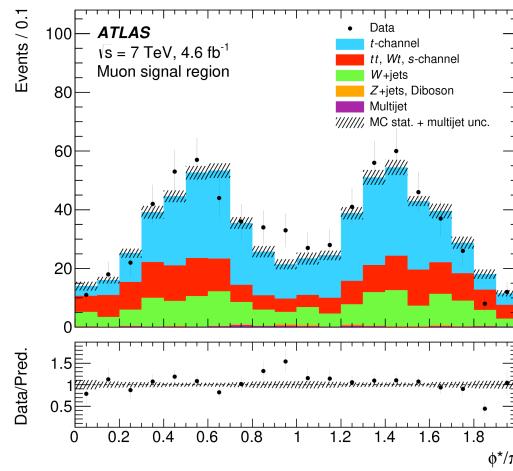
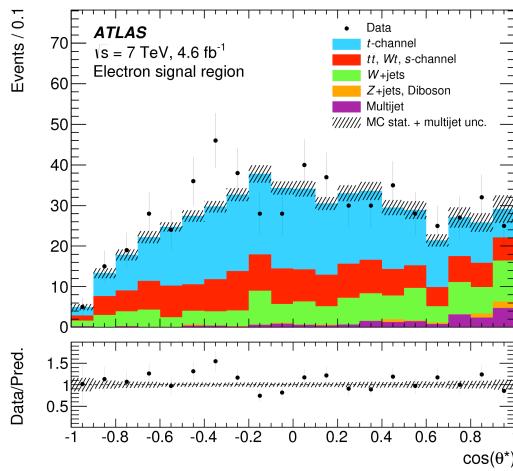
t-channel cross section can be written as a finite series of Spherical Harmonics:

$$\rho(\theta^*, \phi^*; \vec{\alpha}, P) \equiv \frac{1}{N} \frac{dN}{d\Omega^*} = \sum_{l=0}^2 \sum_{m=-l}^l a_{l,m}(\vec{\alpha}, P) Y_l^m(\theta^*, \phi^*).$$

Angles are defined by lepton direction in the W helicity frame:

- $\theta^*$  defined relative to W direction in top rest frame
- Same as used to measure W helicity fractions
- $\phi^*$  defined relative to plane containing W and spectator quark.

Perform a normalized **double differential** angular measurement in  $\theta^*$  and  $\phi^*$  in single top events



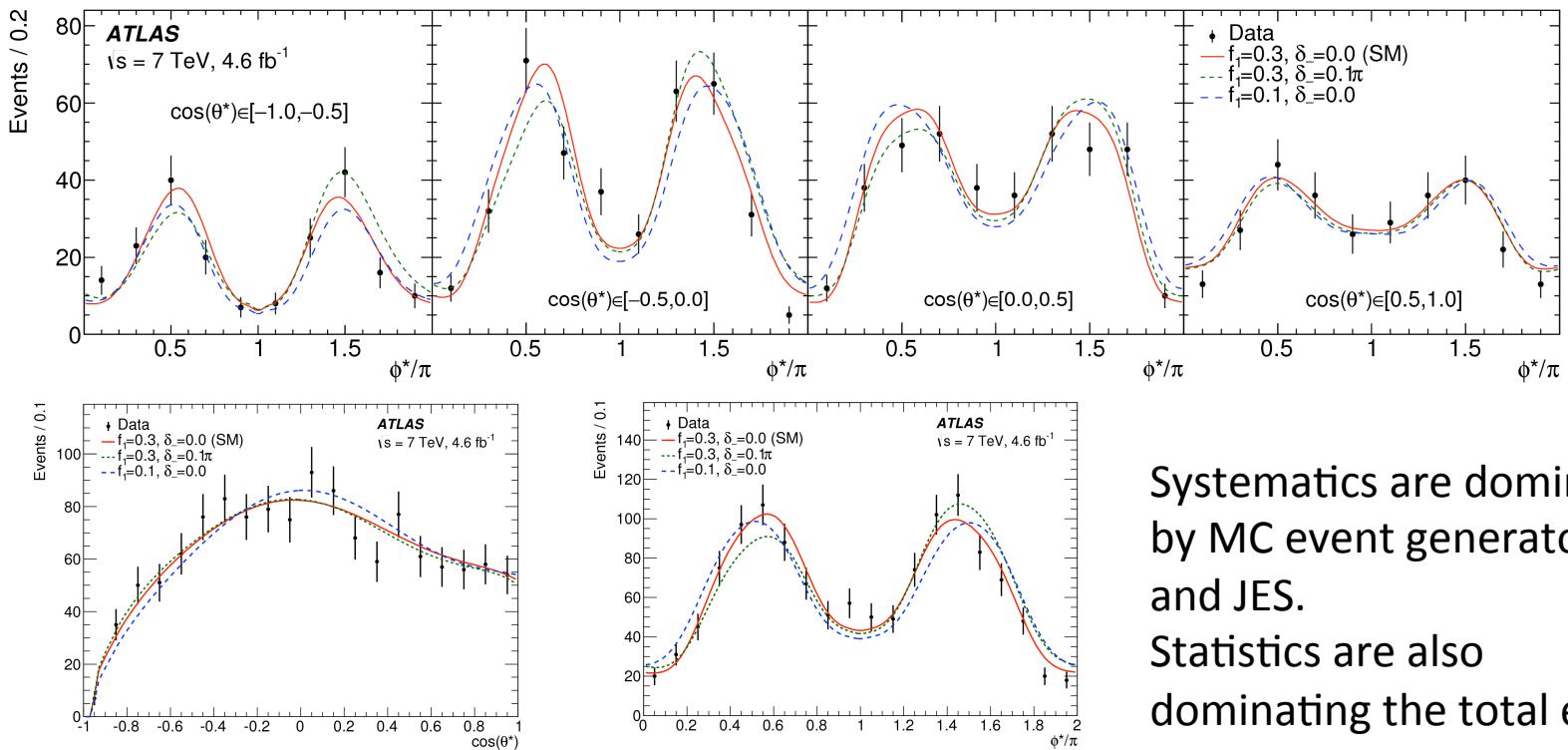
Signal region enriched through cuts.

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2011 data:  $\sqrt{s} = 7 \text{ TeV}$ ,  $L = 4.59 \text{ fb}^{-1}$

Assumptions:  $V_R = g_L = 0$

- $f_1$  = fraction of W's with transverse polarization. ( $f_1 = F_R + F_L$ )
- $\delta_-$  = phase between amplitudes for long. and trans. W, produced with left-handed b's



Systematics are dominated by MC event generators and JES.  
Statistics are also dominating the total error.

$$f_1 = 0.37 \pm 0.05 \text{ (stat)} \pm 0.05 \text{ (syst)}$$

$$\delta_- = -0.014\pi \pm 0.023\pi \text{ (stat)} \pm 0.028\pi \text{ (syst)}$$

# ANOMALOUS Wtb COUPLINGS

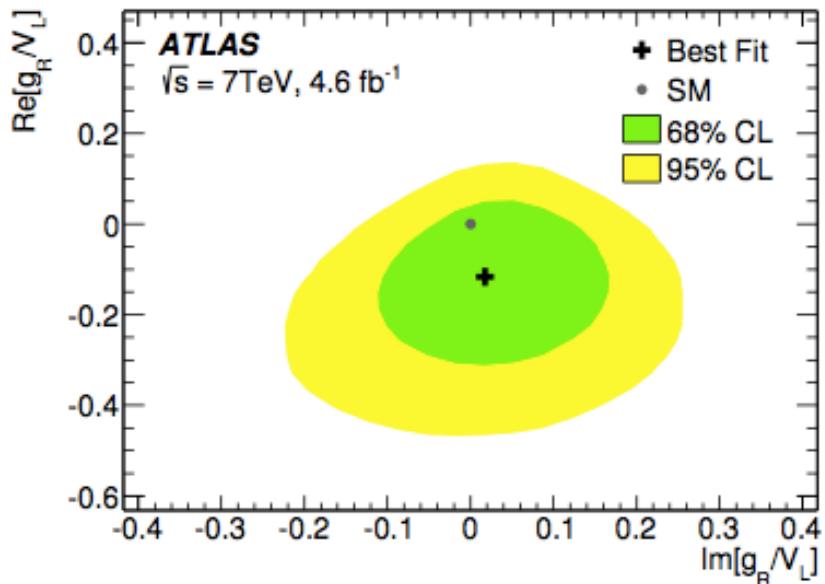
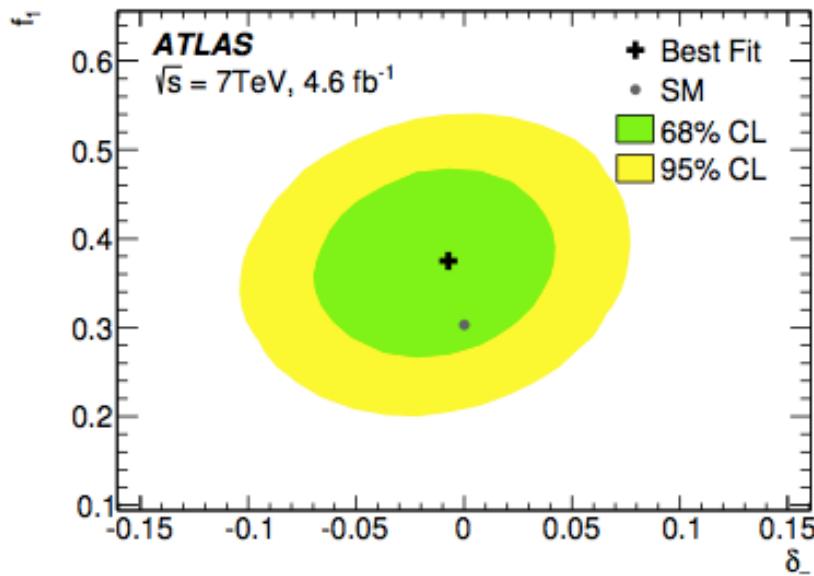
2011 data:  $\sqrt{s} = 7 \text{ TeV}$ ,  $L = 4.59 \text{ fb}^{-1}$

Assumptions:  $V_R = g_L = 0$

Since only shapes are measured, it is **only sensitive to coupling ratios**.

$$\text{Re}\left[\frac{g_R}{V_L}\right] = -0.13 \pm 0.07 \text{ (stat.)} \pm 0.10 \text{ (syst.)}$$

$$\text{Im}\left[\frac{g_R}{V_L}\right] = 0.03 \pm 0.06 \text{ (stat.)} \pm 0.07 \text{ (syst.)}$$



$$\text{Re}[g_R/V_L] \in [0.36, 0.12]$$

$$\text{Im}[g_R/V_L] \in [-0.17, 0.23]$$

$$\rho(\text{Re}[g_R/V_L], \text{Im}[g_R/V_L]) = 0.11$$

A three angle analysis is needed to fully describe the top production (polarization) and decay. This analysis is close to be published. Stay tuned!

[JHEP 04 \(2016\) 023](#)

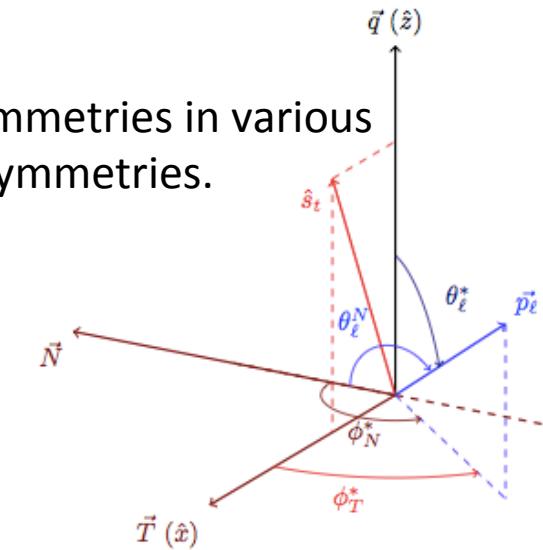
2012 data:  $\sqrt{s} = 8 \text{ TeV}$ ,  $L = 20.2 \text{ fb}^{-1}$

- Top and W polarization observables can be extracted from asymmetries in various angular distributions of the decay products. New angles and asymmetries.

Asymmetry	Angular observable	Polarisation observable	SM prediction
$A_{\text{FB}}^{\ell}$	$\cos \theta_\ell$	$\frac{1}{2} \alpha_\ell P$	0.45
$A_{\text{FB}}^{tW}$	$\cos \theta_W \cos \theta_\ell^*$	$\frac{3}{8} P (F_R + F_L)$	0.10
$A_{\text{FB}}$	$\cos \theta_\ell^*$	$\frac{3}{4} \langle S_3 \rangle = \frac{3}{4} (F_R - F_L)$	-0.23
$A_{\text{EC}}$	$\cos \theta_\ell^*$	$\frac{3}{8} \sqrt{\frac{3}{2}} \langle T_0 \rangle = \frac{3}{16} (1 - 3F_0)$	-0.20
$A_{\text{FB}}^T$	$\cos \theta_\ell^T$	$\frac{3}{4} \langle S_1 \rangle$	0.34
$A_{\text{FB}}^N$	$\cos \theta_\ell^N$	$-\frac{3}{4} \langle S_2 \rangle$	0
$A_{\text{FB}}^{T,\phi}$	$\cos \theta_\ell^* \cos \phi_T^*$	$-\frac{2}{\pi} \langle A_1 \rangle$	-0.14
$A_{\text{FB}}^{N,\phi}$	$\cos \theta_\ell^* \cos \phi_N^*$	$\frac{2}{\pi} \langle A_2 \rangle$	0

### W boson rest frame:

$$\begin{aligned} \frac{1}{\Gamma} \frac{d\Gamma}{d(\cos \theta_\ell^*) d\phi_\ell^*} &= \frac{3}{8\pi} \left\{ \frac{2}{3} - \frac{1}{\sqrt{6}} \langle T_0 \rangle (1 - 3 \cos^2 \theta_\ell^*) + \langle S_3 \rangle \cos \theta_\ell^* \right. \\ &+ \langle S_1 \rangle \cos \phi_\ell^* \sin \theta_\ell^* + \langle S_2 \rangle \sin \phi_\ell^* \sin \theta_\ell^* \\ &\left. - \langle A_1 \rangle \cos \phi_\ell^* \sin 2\theta_\ell^* - \langle A_2 \rangle \sin \phi_\ell^* \sin 2\theta_\ell^* \right\}. \end{aligned}$$



### Asymmetries:

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

$$A_{\text{EC}} = \frac{N(|\cos \theta| > \frac{1}{2}) - N(|\cos \theta| < \frac{1}{2})}{N(|\cos \theta| > \frac{1}{2}) + N(|\cos \theta| < \frac{1}{2})}.$$

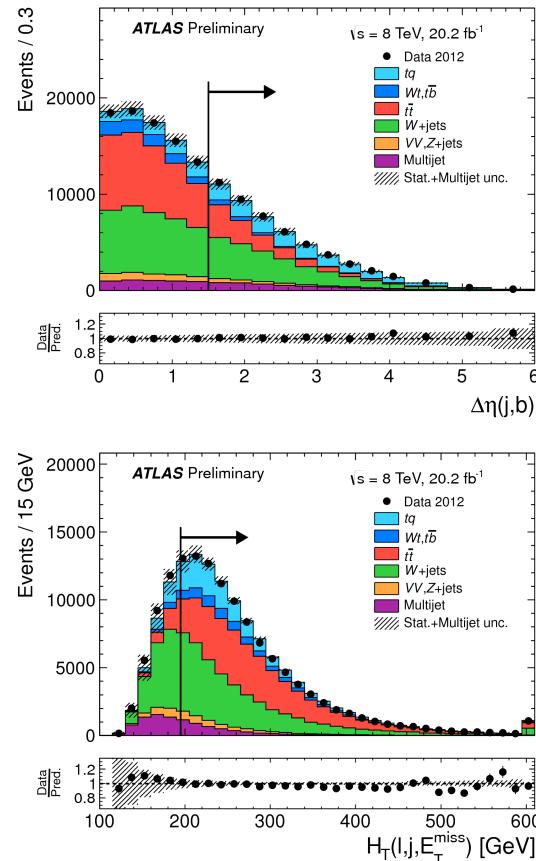
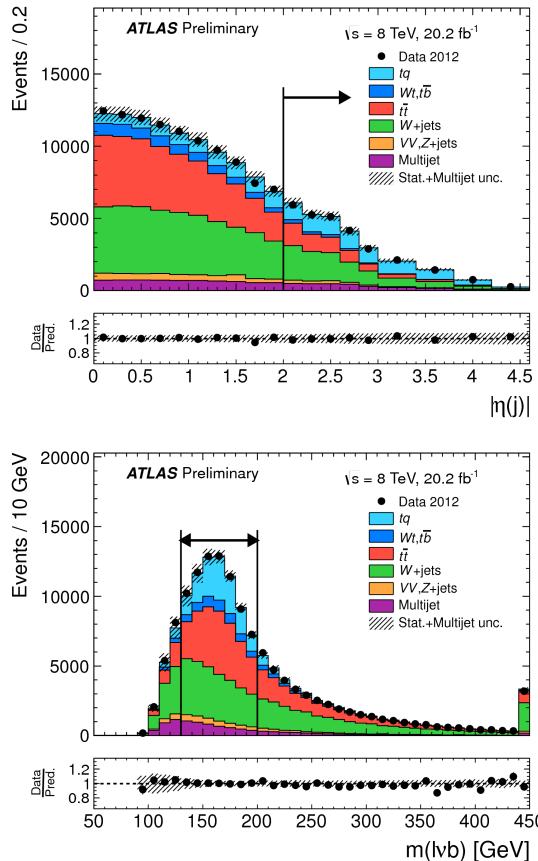
### Top quark rest frame:

$$\frac{1}{\Gamma} \frac{d\Gamma}{d(\cos \theta_X)} = \frac{1}{2} (1 + \alpha_X P \cos \theta_X)$$

ATLAS-CONF-2016-097

2012 data:  $\sqrt{s} = 8 \text{ TeV}$ ,  $L = 20.2 \text{ fb}^{-1}$

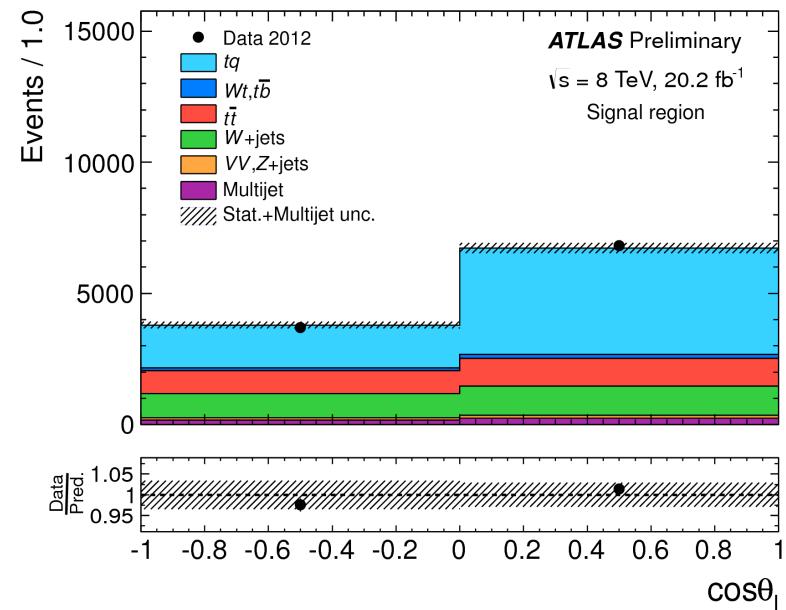
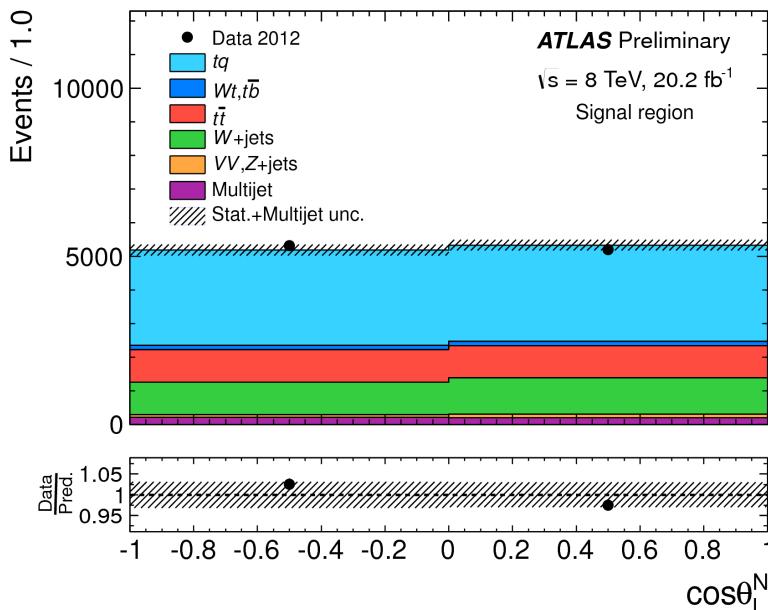
- In order to enrich the signal region, **four selection cuts** are used to discriminate signal from backgrounds ( $S/B=1.2$ ): Same cuts than in previous analysis.



ATLAS-CONF-2016-097

2012 data:  $\sqrt{s} = 8 \text{ TeV}$ ,  $L = 20.2 \text{ fb}^{-1}$

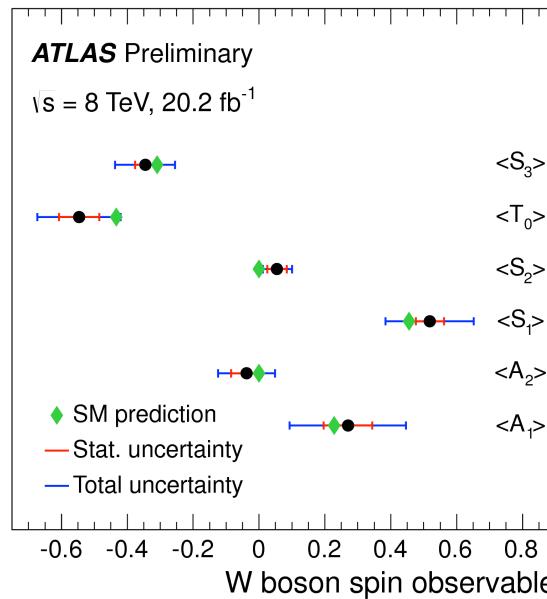
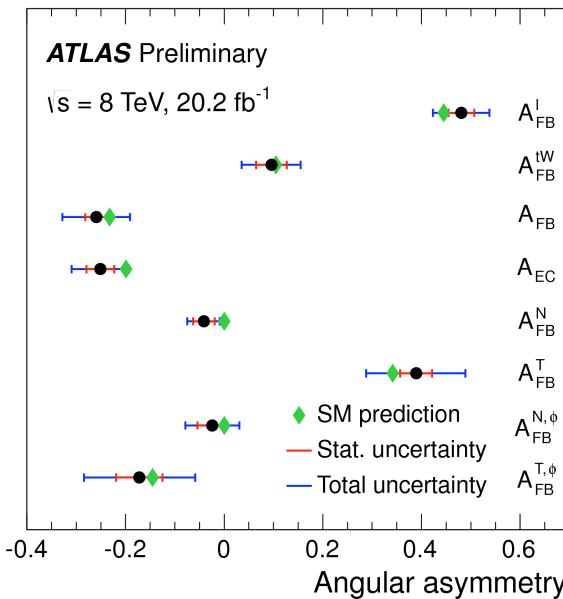
- Measured angular distributions are **unfolded** at parton level after subtracting the background contributions (iterative Bayesian unfolding for  $A_{FB}^N$  and SM bayesian unfolding for the other observables).
- Angular asymmetries extracted from the unfolded distributions.



- Dominant sources of uncertainty: data statistics, t-channel and ttbar modeling and jet energy scale.

2012 data:  $\sqrt{s} = 8 \text{ TeV}$ ,  $L = 20.2 \text{ fb}^{-1}$

- Results in **agreement with the Standard Model** predictions. No tension seen in  $A_{FB}^I$
- **Limits on  $\text{Im } g_R$**  extracted by combining two particular asymmetries:  $A_{FB}^N$  is only sensitive to  $\text{Im } g_R$  and  $A_{FB}^I$  to constrain the top polarization entering in the measurement of  $A_{FB}^N$ .



$$\text{Im } g_R \in [-0.17, 0.06]$$

$\alpha_l P = 0.96 \pm 0.05 \text{ (stat)} \pm 0.10 \text{ (syst)}$   
 $P(F_R + F_L) = 0.26 \pm 0.08 \text{ (stat)} \pm 0.14 \text{ (syst)}$

Assumptions:  
 $V_L = 1$  ;  $V_R = g_L = 0$  ;  $\text{Re}[g_R] = 0$

ATLAS-CONF-2016-097



# ANOMALOUS Wtb COUPLINGS

New!

2011 data:  $\sqrt{s} = 7 \text{ TeV}$ ,  $L = 5.0 \text{ fb}^{-1}$ ; 2012 data:  $\sqrt{s} = 8 \text{ TeV}$ ,  $L = 19.7 \text{ fb}^{-1}$

- Focused on a singly produced top quark with leptonic decay of the W boson:
  - Request exactly one isolated muon (rejection is applied on extra leptons passing quality criteria).
  - Either 2 or 3 jets with at least one tagged as b-jet.
- A neural network is also used to diminish QCD background contamination.
- After preselection, 3 neural networks are defined for anomalous Wtb couplings.
- Also sets stringent limits on anomalous tug and tcg couplings. (see J.P. Araque Espinosa talk)

$$\mathcal{L} = \frac{g}{\sqrt{2}} \bar{b} \gamma^\mu \left( f_V^L P_L + f_V^R P_R \right) t W_\mu^- - \frac{g}{\sqrt{2}} \bar{b} \frac{\sigma^{\mu\nu} \partial_\nu W_\mu^-}{M_W} \left( f_T^L P_L + f_T^R P_R \right) t + \text{h.c.}$$

TOP-14-007

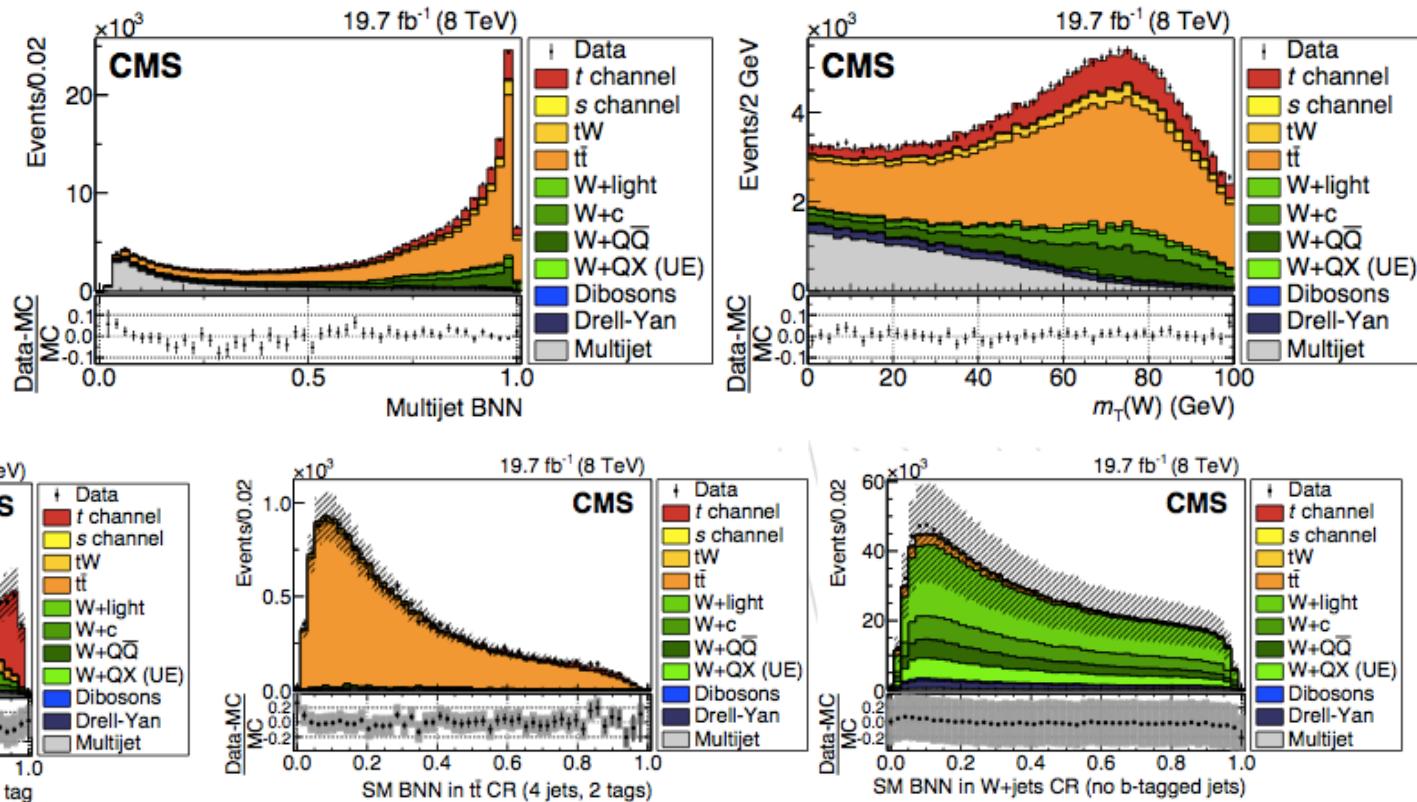


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New!

2011 data:  $\sqrt{s} = 7 \text{ TeV}$ ,  $L = 5.0 \text{ fb}^{-1}$ ; 2012 data:  $\sqrt{s} = 8 \text{ TeV}$ ,  $L = 19.7 \text{ fb}^{-1}$

- Multijet events are rejected with a dedicated Bayesian Neural Network (BNN).
- Other backgrounds are normalized to their theoretical predictions.
- Only muons used



TOP-14-007

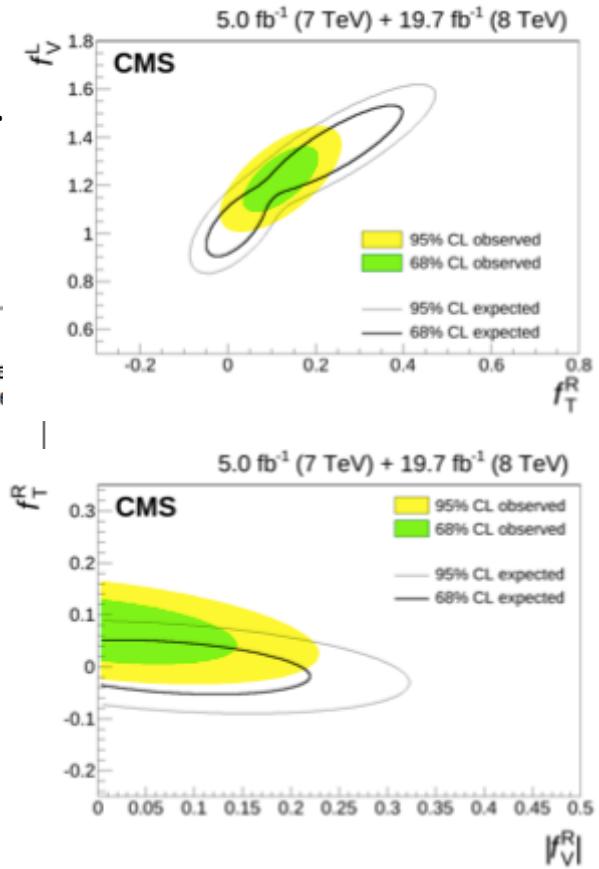
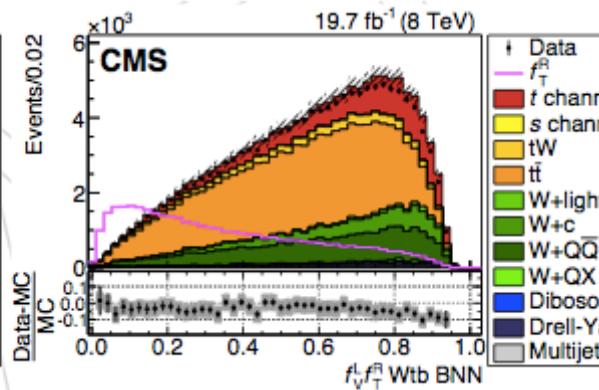
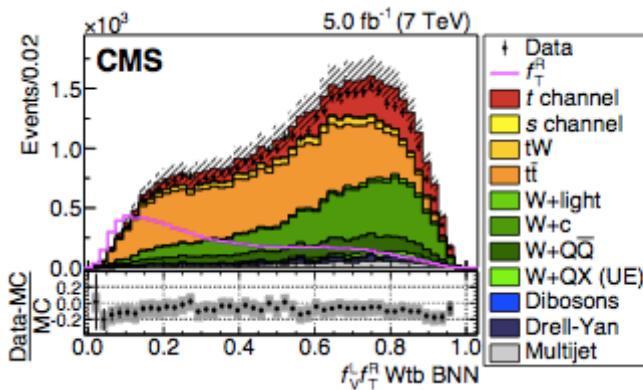


# ANOMALOUS Wtb COUPLINGS

New!

2011 data:  $\sqrt{s} = 7 \text{ TeV}$ ,  $L = 5.0 \text{ fb}^{-1}$ ; 2012 data:  $\sqrt{s} = 8 \text{ TeV}$ ,  $L = 19.7 \text{ fb}^{-1}$

- Two and three of four anomalous couplings are considered simultaneously in two- and three- dimensional scenarios.
- Dedicated anomalous Wtb BNNs are used in each scenario.
- Limits are extracted from a simultaneous fit to the SM BNN and anomalous Wtb BNNs outputs. Only real part.



$$f_V^L > 0.98, |f_V^R| < 0.16, |f_T^L| < 0.57 \\ -0.049 < |f_T^R| < 0.048$$

TOP-14-007



# TOP QUARK



*MASS*

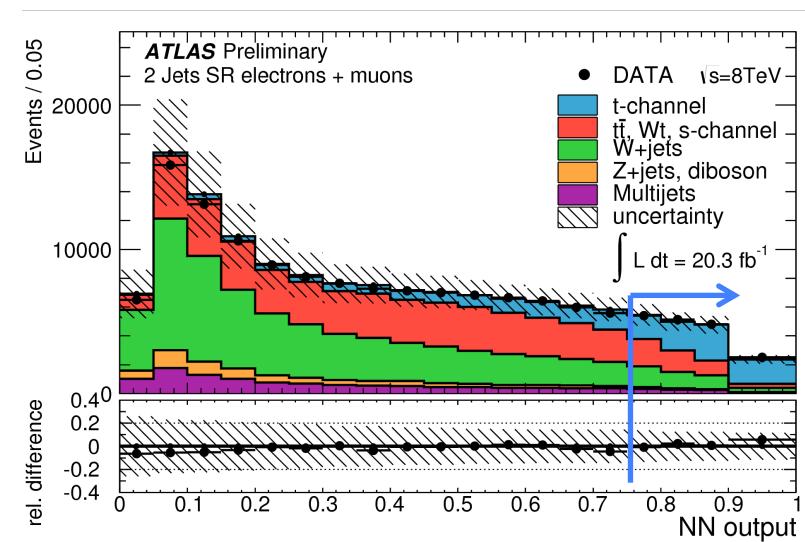
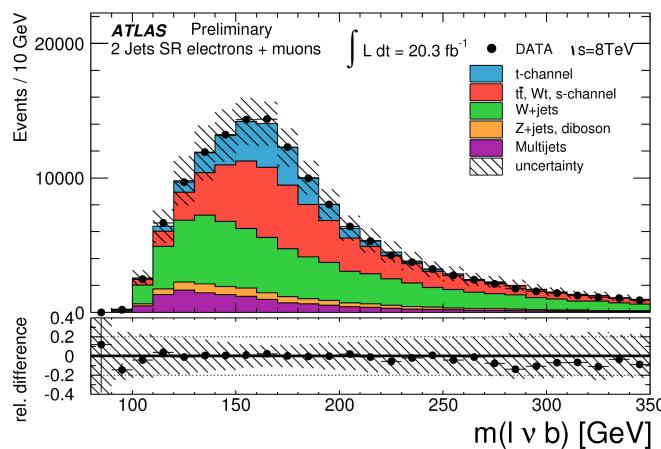
Most measurements of the top quark mass are obtained from samples of ttbar events. However, measuring the top-quark mass in single top quark events implies:

- An **enrichment** of the available measurements.
- **Less ambiguities** in the jet-parton assignment, as there is only one b-jet in the final state, and thereby, **less combinatorial background**.
- **Different production mechanism**, featuring a very **different color flow**. Useful to check that there are no large systematic biases in ttbar measurements due to the modelling of **non-perturbative QCD effects**.
- The typical **energy scale**  $Q^2$  of single-top production is much **smaller** than the ttbar one.
- Mass is obtained from an **statistically independent sample**.

2012 data:  $\sqrt{s} = 8 \text{ TeV}$ ,  $L = 20.3 \text{ fb}^{-1}$

- Top quark mass is measured in **topologies enhanced with single-top quarks** produced in the t-channel.
- The top quark processes are further enhanced using a **neural network-based discriminant**.

Variable	loss of total correlation (%)	Variable	loss of total correlation (%)
$m(\ell vb)$	38	$E_T^{\text{miss}}$	7
$m(jb)$	31	$m_T(W)$	7
$m(\ell b)$	18	$\cos \theta(\ell, j)$ in the top quark rest frame	6
$ \eta(j) $	14	$p_T(W)$	3
$\eta(\ell v)$	13	$\eta(lvb)$	2
$H_T(\ell, \text{jets}, E_T^{\text{miss}})$	10	$\Delta R(\ell, \ell vb)$	1



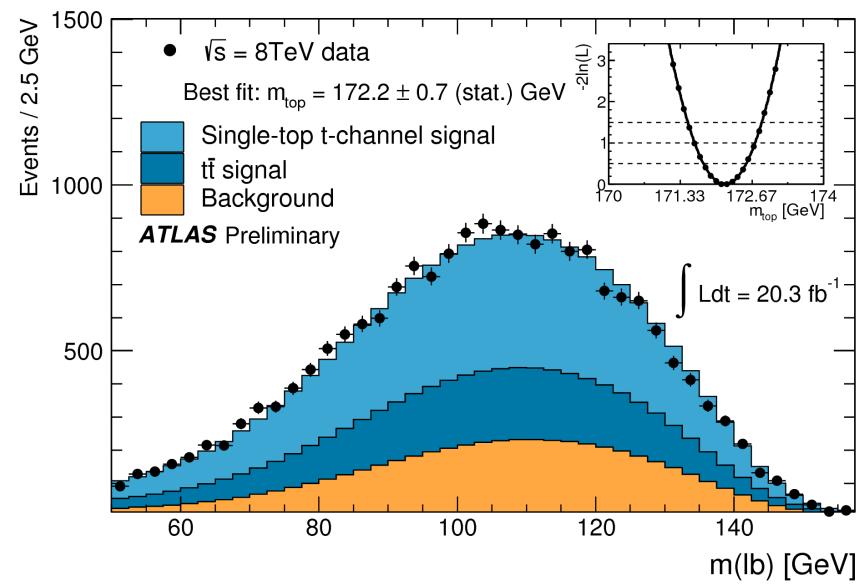
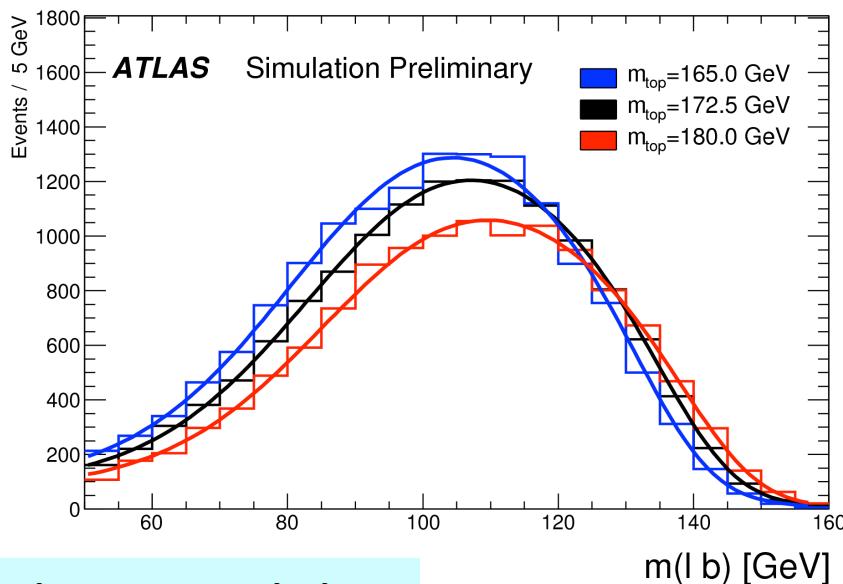
After the full event selection:

- Non-top quark background fraction is about 28%
- ttbar events fraction is about 26%

ATLAS-CONF-2014-055

2012 data:  $\sqrt{s} = 8 \text{ TeV}$ ,  $L = 20.3 \text{ fb}^{-1}$

- **Template method** used for mass extraction: Based on the distribution of the **invariant mass of the lepton and the b-tagged jet** as estimator.
- Using pseudo-experiments, a **good linearity** is found between the input top quark mass and the mean value derived from the distributions of the reconstructed top quark masses.



## Dominant uncertainties:

- JES
- t-channel modelling

$$m_{\text{top}} = 172.2 \pm 0.7(\text{stat.}) \pm 2.0(\text{syst.}) \text{ GeV}$$

ATLAS-CONF-2014-055

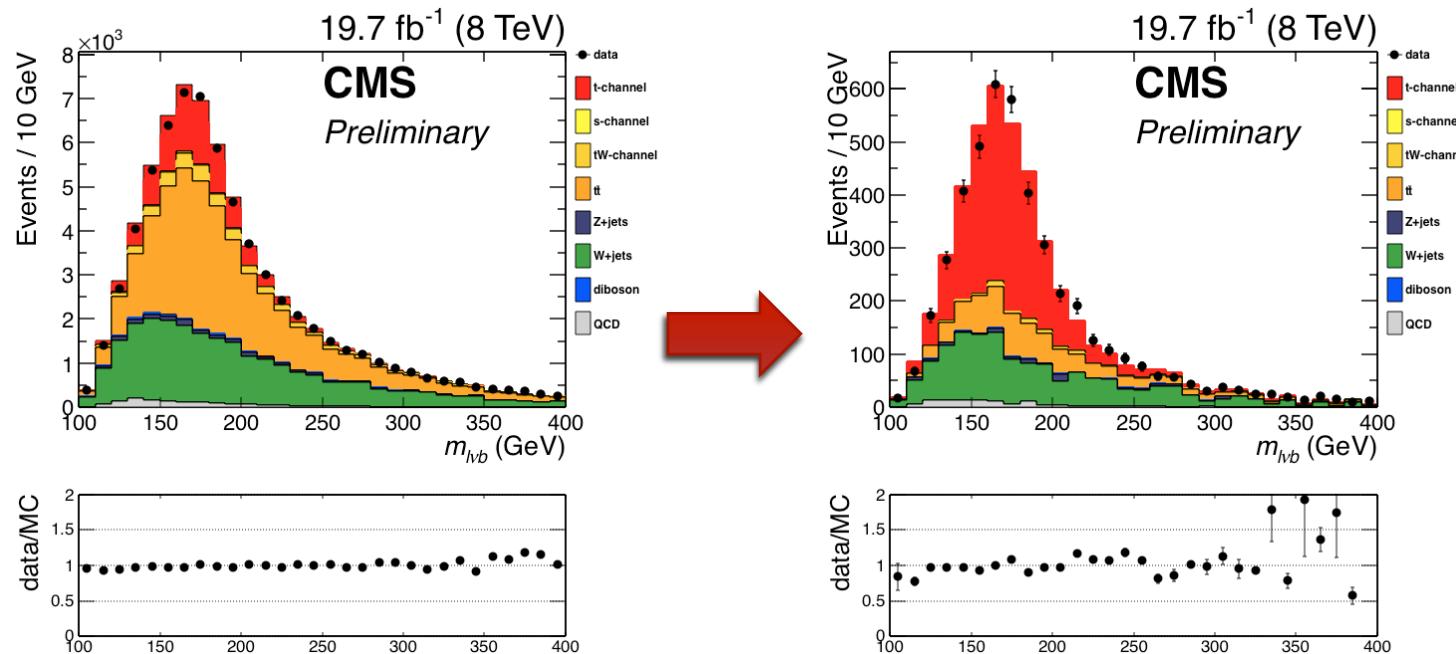


# TOP QUARK MASS

2012 data:  $\sqrt{s} = 8 \text{ TeV}$ ,  $L = 19.7 \text{ fb}^{-1}$

Cut-based analysis to enrich the signal region:

- The accompanied light jet appears in forward region: **cut at  $|\eta_{lj}| > 2.5$ .**
- In single-top production more tops than anti-top are created. **Only retain positively charged muons** for the mass measurement.



After the cuts, about 75% of the top quark sample are from single-top quark events.

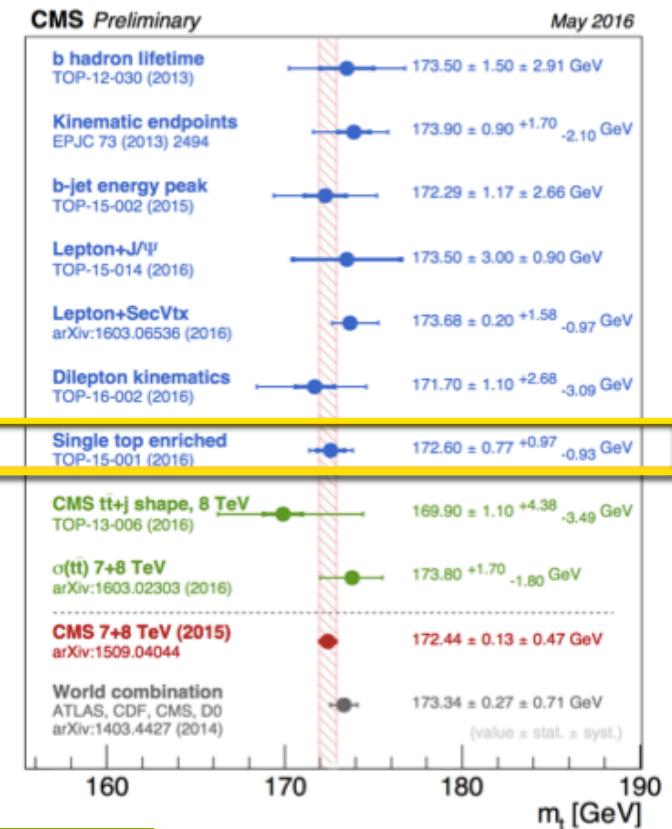
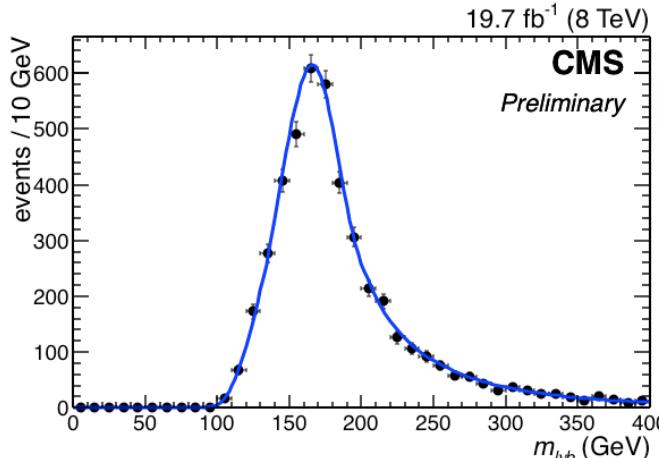
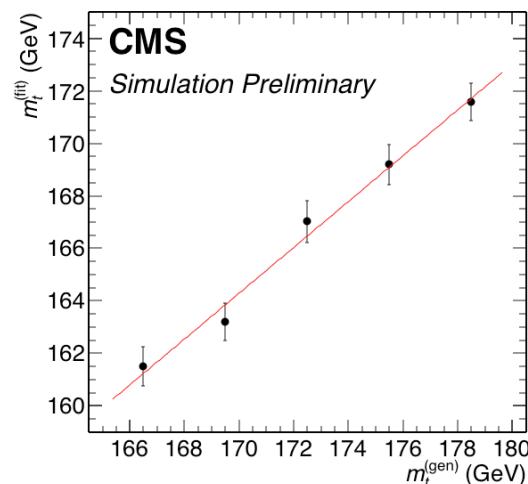
CMS-PAS-TOP-15-001



# TOP QUARK MASS

2012 data:  $\sqrt{s} = 8 \text{ TeV}$ ,  $L = 19.7 \text{ fb}^{-1}$

- The reconstructed top invariant mass distribution is fitted to extract the top mass.
- Fitting function: composed of **multiple fitting functions** for single-top, ttbar and background processes.
- Calibration curve** obtained from a set of simulated samples with different top masses .
- The correction to be applied to the fitted value is extracted, resulting in a **linear function**.



$$m_t = 172.60 \pm 0.77 \text{ (stat)} \quad {}^{+0.97}_{-0.93} \text{ (syst)}$$

Dominant uncertainties: JES

CMS-PAS-TOP-15-001

The ATLAS and CMS experiments have deeply studied the top quark properties in single-top production:

- Unique features of the electroweak top quark production are exploited in order to set limits to the  $Wtb$  anomalous couplings
- The Top-quark polarization has been measured by both experiments. CMS measurement of  $A_\mu$  shows a slight tension with SM prediction. ATLAS measurement is compatible with the SM value.
- Tighter limits has been set to the imaginary part of  $g_R$
- The mass of the top-quark has been measured both in ATLAS and CMS using single-top events, achieving a comparable precision with measurements obtained in  $t\bar{t}$
- There are still some analysis at 8 TeV to be published.
- The large data sample at 13 TeV may reveal something new!



# BACKUP

	$\delta A_\mu(t)/10^{-2}$	$\delta A_\mu(\bar{t})/10^{-2}$	$\delta A_\mu(t + \bar{t})/10^{-2}$
Statistical	3.2	4.6	2.6
ML fit uncertainty	0.7	1.2	0.6
Diboson bkg. fraction	<0.1	<0.1	<0.1
Z/ $\gamma^*$ +jets bkg. fraction	<0.1	<0.1	<0.1
s-channel bkg. fraction	0.3	0.2	0.2
tW bkg. fraction	0.1	0.7	0.2
Multijet events shape	0.5	0.7	0.5
Multijet events yield	1.9	1.2	1.7
b tagging	0.7	1.2	0.9
Mistagging	<0.1	0.1	<0.1
Jet energy resolution	2.7	1.8	2.0
Jet energy scale	1.3	2.6	1.1
Unclustered $E_T$	1.1	3.3	1.3
Pileup	0.3	0.2	0.2
Lepton identification	<0.1	<0.1	<0.1
Lepton isolation	<0.1	<0.1	<0.1
Muon trigger efficiency	<0.1	<0.1	<0.1
Top quark $p_T$ reweighting	0.3	0.3	0.3
W+jets W boson $p_T$ reweighting	0.1	0.1	0.1
W+jets heavy-flavour fraction	4.7	6.2	5.3
W+jets light-flavour fraction	<0.1	<0.1	0.1
W+jets $\cos\theta_\mu^*$ reweighting	2.9	3.4	3.1
Unfolding bias	2.5	4.2	3.1
Generator model	1.6	3.5	0.3
Top quark mass	1.9	2.9	1.8
PDF	0.9	1.6	1.2
$t$ -channel renorm./fact. scales	0.2	0.2	0.2
$t\bar{t}$ renorm./fact. scales	2.2	3.4	2.7
$t\bar{t}$ ME/PS matching	2.2	0.5	1.6
W+jets renorm./fact. scales	3.7	4.6	4.0
W+jets ME/PS matching	3.8	3.0	3.4
Limited MC events	2.1	3.2	1.8
Total uncertainty	10.5	13.8	10.5

## SYSTEMATICS BREAKDOWN

## CMS TOP POLARIZATION

# SYSTEMATICS BREAKDOWN

## CMS W BOSON HELICITY

	Muon channel		Electron channel		Combination	
	$\Delta F_0$	$\Delta F_L$	$\Delta F_0$	$\Delta F_L$	$\Delta F_0$	$\Delta F_L$
Experimental	0.010	0.009	0.008	0.005	0.010	0.010
Modeling	0.025	0.017	0.025	0.022	0.025	0.020
Normalization	0.002	0.008	0.012	0.014	0.011	0.012
SM W helicities	0.007	0.004	0.005	0.003	0.007	0.004
MC sample size	0.026	0.012	0.025	0.015	0.020	0.012
tWb in prod.	0.014	0.016	0.010	0.018	0.011	0.014
Total	0.041	0.030	0.040	0.036	0.037	0.032

## SYSTEMATICS BREAKDOWN

Source	$\sigma(f_1)$	$\sigma(\delta_-)/\pi$	$\rho(f_1, \delta_-)$
Data statistics	0.05	0.023	0.01
Jets	0.03	0.015	0.39
$b$ -tagging	< 0.01	< 0.001	-0.70
Leptons	0.02	0.007	0.39
$E_T^{\text{miss}}$	0.01	0.004	-0.27
Generator	0.02	0.017	0.40
Parton shower	0.02	0.001	0.98
PDF variations	0.01	0.009	0.23
Cross-sections	< 0.01	< 0.001	1.00
$W$ +jets shape	< 0.01	0.001	-0.59
Multijet normalisation	< 0.01	0.002	-1.00
Luminosity	< 0.01	< 0.001	-1.00
Model $l_{\max}$ variation	0.01	0.001	-0.70
MC statistics	0.02	0.011	0.14
Combined systematic	0.05	0.028	0.27
Total	0.07	0.036	0.15

ATLAS Wtb ANOMALOUS  
COUPLINGS AT 7TeV

## SYSTEMATICS BREAKDOWN

Uncertainty source	$\Delta A_{\text{FB}}^N * 10^2$	$\Delta A_{\text{FB}}^T * 10^2$	$\Delta A_{\text{FB}}^{N,\phi} * 10^2$	$\Delta A_{\text{FB}}^{T,\phi} * 10^2$	ATLAS PROBING THE Wtb VERTEX STRUCTURE AT 8TEV
Statistical uncertainty	$\pm 2.2$	$\pm 3.2$	$\pm 3.0$	$\pm 4.7$	
Simulation statistics	$\pm 1.3$	$\pm 2.0$	$\pm 1.8$	$\pm 2.9$	
Luminosity	$<0.1$	$<0.1$	$<0.1$	$<0.1$	
Background normalisation	$\pm 0.4$	$\pm 1.1$	$\pm 0.6$	$\pm 0.9$	
$E_T^{\text{miss}}$ reconstruction	$+0.1$ $-1.0$	$\pm 0.9$	$+0.5$ $-0.7$	$+0.1$ $-1.3$	
Lepton reconstruction	$+0.1$ $-0.3$	$+1.4$ $-1.6$	$+0.8$ $-0.4$	$+1.2$ $-1.0$	
Jet reconstruction	$\pm 0.3$	$+3.1$ $-3.2$	$\pm 1.3$	$\pm 1.8$	
Jet energy scale	$\pm 0.5$	$\pm 5.1$	$\pm 0.8$	$\pm 5.5$	
Jet flavour tagging	$\pm 0.2$	$\pm 0.6$	$\pm 0.2$	$\pm 0.7$	
PDF	$\pm 0.1$	$<0.1$	$\pm 0.1$	$\pm 0.4$	
$t\bar{t}$ generator	$\pm 0.6$	$\pm 4.1$	$\pm 0.1$	$\pm 1.2$	
$t\bar{t}$ parton shower	$\pm 0.9$	$\pm 1.7$	$\pm 0.4$	$\pm 1.5$	
$t\bar{t}$ scales	$\pm 0.3$	$\pm 0.7$	$\pm 0.3$	$\pm 1.2$	
$Wt,s$ -channel generator	$\pm 0.3$	$\pm 0.6$	$\pm 0.4$	$\pm 1.3$	
$Wt,s$ -channel scales	$\pm 0.6$	$\pm 0.5$	$\pm 0.4$	$\pm 0.9$	
$t$ -channel NLO generator	$\pm 0.4$	$\pm 3.8$	$\pm 2.6$	$\pm 5.4$	
$t$ -channel LO-NLO generator	$\pm 0.4$	$\pm 2.0$	$\pm 1.6$	$\pm 3.2$	
$t$ -channel parton shower	$\pm 0.2$	$\pm 0.9$	$\pm 1.4$	$\pm 1.2$	
$t$ -channel scales	$\pm 0.9$	$\pm 1.9$	$\pm 1.4$	$\pm 2.3$	
$W$ +jets, multijet modelling	$\pm 0.7$	$\pm 1.3$	$\pm 0.6$	$\pm 2.6$	
Systematic uncertainty	$+2.4$ $-2.6$	$+9.5$ $-9.6$	$\pm 4.6$	$+10.3$ $-10.2$	

## SYSTEMATICS BREAKDOWN

Uncertainty source	$\Delta A_{FB}^{\ell} * 10^2$	$\Delta A_{FB}^{tW} * 10^2$	$\Delta A_{FB} * 10^2$	$\Delta A_{EC} * 10^2$	
Statistical uncertainty	$\pm 2.6$	$\pm 3.1$	$\pm 2.3$	$\pm 2.8$	ATLAS PROBING
Simulation statistics	$\pm 1.8$	$\pm 1.9$	$\pm 1.4$	$\pm 1.7$	THE Wtb VERTEX
Luminosity	$<0.1$	$<0.1$	$<0.1$	$<0.1$	STRUCTURE AT
Background normalisation	$\pm 0.5$	$\pm 0.5$	$\pm 0.9$	$\pm 0.6$	8TEV
$E_T^{\text{miss}}$ reconstruction	$^{+0.9}_{-0.1}$	$\pm 0.8$	$\pm 0.9$	$\pm 0.6$	
Lepton reconstruction	$^{+0.7}_{-0.5}$	$^{+0.5}_{-1.3}$	$^{+1.2}_{-1.5}$	$^{+0.2}_{-0.4}$	
Jet reconstruction	$\pm 0.9$	$\pm 1.6$	$\pm 1.2$	$\pm 1.9$	
Jet energy scale	$\pm 1.8$	$\pm 2.1$	$\pm 3.4$	$\pm 1.4$	
Jet flavour tagging	$\pm 0.9$	$\pm 0.4$	$\pm 0.6$	$\pm 0.4$	
PDF	$\pm 0.1$	$<0.1$	$<0.1$	$\pm 0.1$	
$t\bar{t}$ generator	$\pm 2.5$	$\pm 1.4$	$\pm 0.3$	$\pm 1.1$	
$t\bar{t}$ parton shower	$\pm 0.1$	$\pm 1.0$	$\pm 2.5$	$\pm 0.3$	
$t\bar{t}$ scales	$\pm 0.4$	$\pm 0.3$	$\pm 1.2$	$\pm 0.2$	
$Wt,s$ -channel generator	$\pm 0.8$	$\pm 0.9$	$\pm 0.4$	$\pm 0.3$	
$Wt,s$ -channel scales	$\pm 0.9$	$\pm 0.3$	$\pm 0.3$	$\pm 0.3$	
$t$ -channel NLO generator	$\pm 1.5$	$\pm 1.1$	$\pm 0.7$	$\pm 2.7$	
$t$ -channel LO-NLO generator	$\pm 1.3$	$\pm 2.0$	$\pm 2.8$	$\pm 1.8$	
$t$ -channel parton shower	$\pm 0.4$	$\pm 0.5$	$\pm 1.2$	$\pm 0.4$	
$t$ -channel scales	$\pm 1.0$	$\pm 2.1$	$\pm 0.5$	$\pm 1.7$	
$W$ +jets, multijet modelling	$\pm 1.9$	$\pm 0.9$	$\pm 2.2$	$\pm 1.4$	
Systematic uncertainty	$^{+5.1}_{-5.2}$	$^{+5.1}_{-5.3}$	$^{+6.4}_{-6.5}$	$\pm 5.1$	

# SYSTEMATICS BREAKDOWN

	Value [GeV]
Measured value	172.2
Statistical uncertainty	0.7
Jet energy scale	1.5
Jet energy resolution	< 0.1
Jet vertex fraction	< 0.1
Flavour tagging efficiency	0.3
Electron uncertainties	0.3
Muon uncertainties	0.1
Missing transverse momentum	0.2
W+jets normalisation	0.4
W+jets shape	0.3
Z+jets/diboson normalisation	0.2
Multijet normalisation	0.2
Multijet shape	0.3
Top normalisation	0.2
<i>t</i> -channel generator	< 0.1
<i>t</i> -channel hadronisation	0.7
<i>t</i> -channel colour reconnection	0.3
<i>t</i> -channel underlying event	< 0.1
<i>t</i> <i>t</i> , <i>Wt</i> , and <i>s</i> -channel generator	0.2
<i>t</i> <i>t</i> hadronisation	< 0.1
<i>t</i> <i>t</i> colour reconnection	0.2
<i>t</i> <i>t</i> underlying event	0.1
<i>t</i> <i>t</i> ISR/FSR	0.2
Proton PDF	< 0.1
Simulation sample statistics	0.3
Total systematic uncertainty	2.0
Total uncertainty	2.1

ATLAS TOP MASS

# SYSTEMATICS BREAKDOWN

Source	Subcategory	Uncertainty
	In-situ correlation group	+0.20 -0.21
	Flavour correlation group	+0.40 -0.40
	Inter-calibration group	+0.00 -0.03
	Uncorrelated group	+0.48 -0.40
	Pile-up $p_T$ uncertainty	+0.18 -0.10
Total JES		+0.68 -0.61
b-quark JES and Hadronization Modeling		$\pm 0.15$
JER		< 0.05
Lepton energy scale		< 0.05
$E_T^{\text{miss}}$		$\pm 0.15$
Pile-up		$\pm 0.10$
b-tagging efficiency		$\pm 0.10$
Fit Calibration		$\pm 0.38$
	Background PDFs	$\pm 0.10$
	Background normalization	$\pm 0.14$
	Background $Q^2$ scale	$\pm 0.18$
	Background matching scale	$\pm 0.30$
Total Background Calculations		$\pm 0.39$
Generator modeling		$\pm 0.10$
Signal $Q^2$ scale		$\pm 0.23$
Underlying Event		$\pm 0.20$
Color Reconnection		< 0.05
PDF		< 0.05
Total		+0.97 -0.93

CMS TOP MASS