

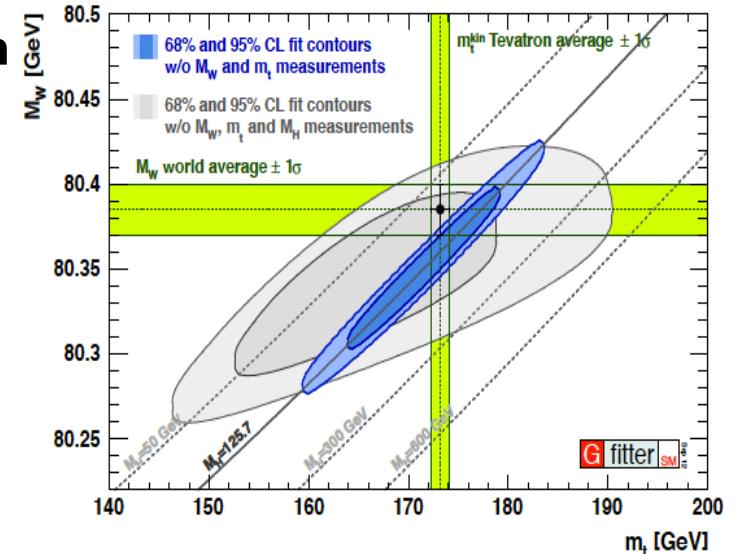
**LHC Seminar**  
**Tuesday, 25 February 2014**

## Recent top physics results from CMS

Rebeca Gonzalez Suarez

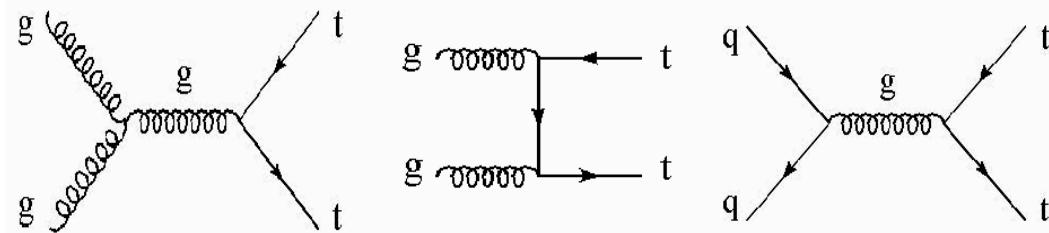
# The top quark

- ▶ It is the **heaviest elementary particle known**
  - ▶ large coupling to the Higgs boson
  - ▶ candidate to play a special role in the EW symmetry breaking and in many scenarios of physics beyond the SM (BSM)
  - ▶ decays before hadronizing
    - ▶ **direct access to properties** (spin, charge, polarization...)
- ▶ Discovered by the **Tevatron** experiments (1995)  
(first collisions on November 30, 1986)  
[PRL 74, 2626–2631](#), [PRL 74, 2632–2637](#)
  - ▶ **Tevatron legacy** still of main importance in top physics



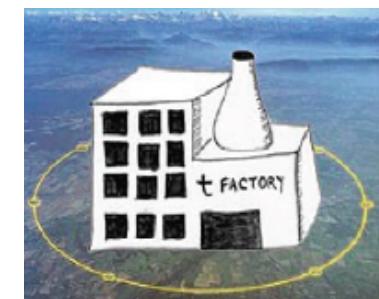
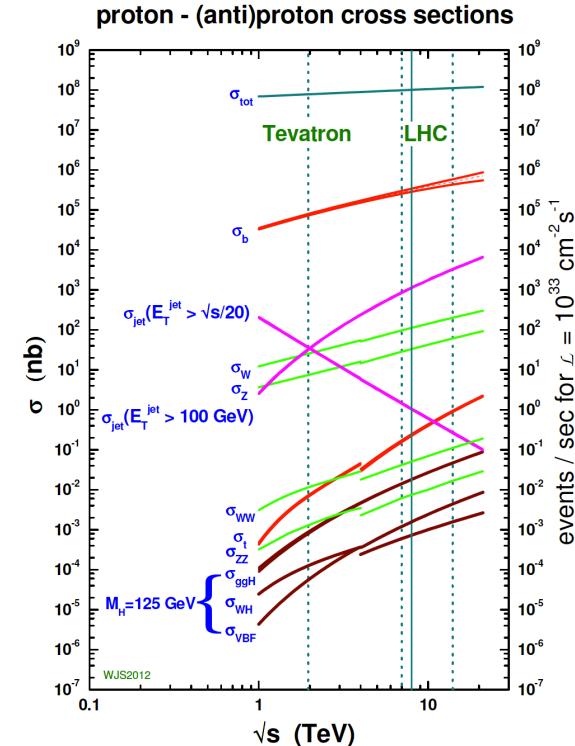
# Top quarks at the LHC

- ▶ At the **LHC**:
  - ▶ top quarks produced at a **much higher rate**



Main production:  $t\bar{t}$  pairs, via strong interaction

x-sec (pb)	ttbar
Tevatron	7.08 (+0.00-0.24) (+0.36-0.27) approx. NNLO
LHC @ 7TeV	163 (+7-5)(±9) approx. NNLO
LHC @ 8TeV	234 (+10-7)(±12) approx. NNLO

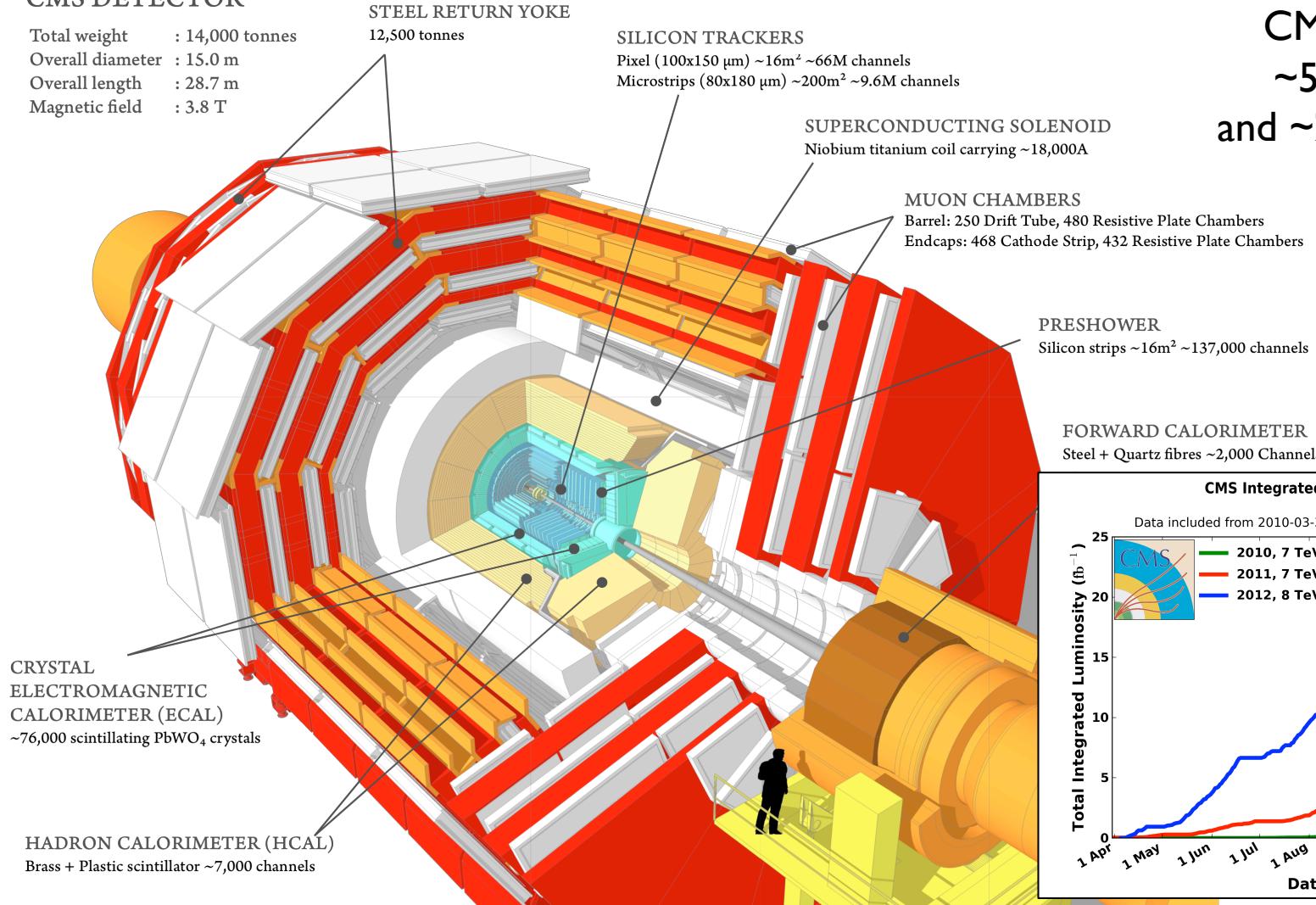


**"The LHC is a top quark factory!"**

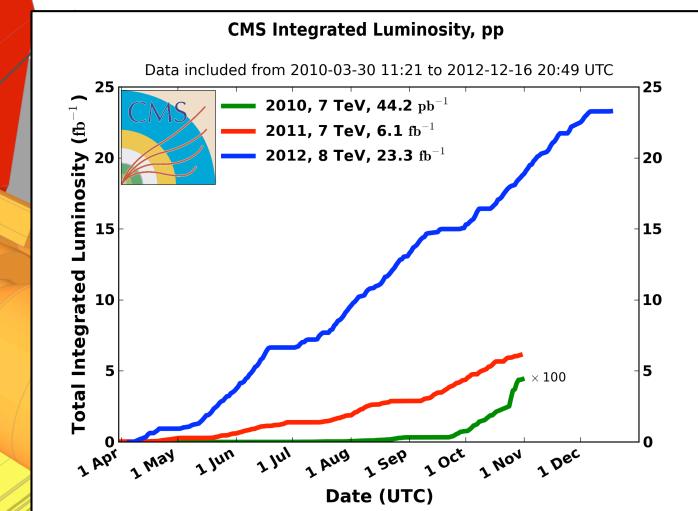
# Compact Muon Solenoid (CMS)

## CMS DETECTOR

Total weight : 14,000 tonnes  
Overall diameter : 15.0 m  
Overall length : 28.7 m  
Magnetic field : 3.8 T



CMS recorded  
 $\sim 5\text{fb}^{-1}$  at 7TeV  
and  $\sim 20 \text{ fb}^{-1}$  at 8TeV



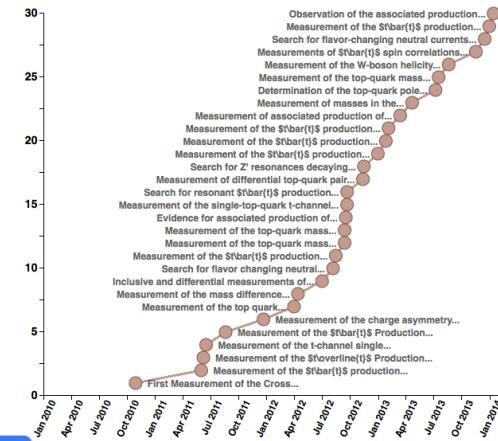
# Top Physics in CMS

- ▶ Since the start of the data-taking, CMS has measured and studied the **ttbar** and **single top production** modes in many final states, at 7 and 8TeV
  - ▶ A variety of top properties have been studied
  - ▶ 31 papers published in standard model top physics
    - ▶ + many preliminary results

This talk will cover recent results concerning:

- ▶ Single top production
  - ▶ A selection of top properties

- ▶ All the top results summarized in  
<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP>

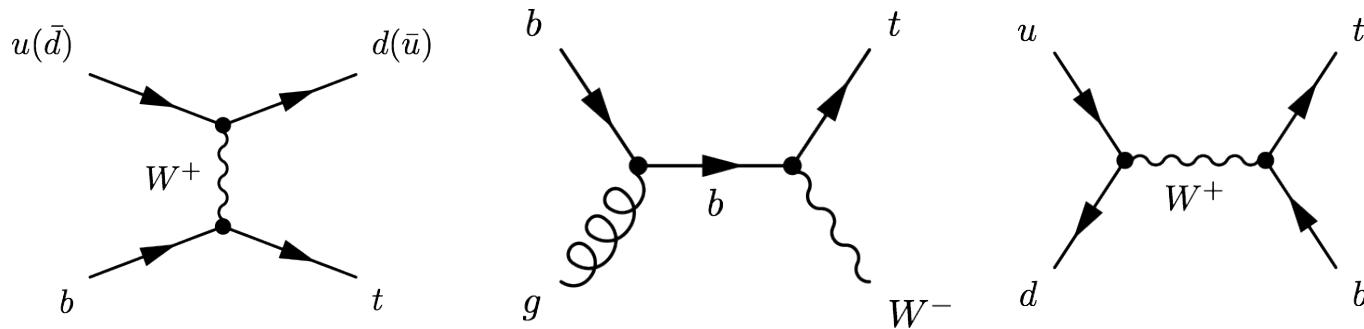


## Single top results

t-channel, tW associated production, s-channel

# Single top production

- ▶ Alternative top quark production via electroweak interaction, at a lower rate than pair production, involving a  $Wtb$  vertex
- ▶ Three main processes: **t-channel, tW associated production, s-channel**



- ▶ sensitive to many models of **new physics**
  - ▶ FCNC, Anomalous couplings
  - ▶ New particles ( $W'$ , charged Higgs)
- ▶ characteristic scenario in which to perform **SM measurements**:
  - ▶ Top polarization,  $W$  helicity, top mass,  $|V_{tb}|$
- ▶ **background** to searches (Higgs, SUSY)

# Single top world status

- ▶ First observed at the Tevatron (2009) [PRL103:092002](#), [PRL.103:092001](#)
- ▶ At the Tevatron:
  - ▶ t-channel and s-channel were observed (**s-channel fresh from last Friday!** [arXiv:1402.5126](#)), tW associated production was not accessible

$\sigma$ [pb]	t-channel	tW	s-channel
Tevatron (1.96 TeV)	2.08	0.22	1.046
LHC (7 TeV)	64.6	15.6	4.59
LHC (8 TeV)	87.1	22.2	5.55

The diagram illustrates the status of single top production cross sections across different experiments and energy levels. Red boxes indicate 'Not accessible' for tW at Tevatron and 'Evidence' for tW at LHC 7 TeV. Green boxes indicate 'Established' for all other channels and energy levels. ATLAS and CMS collaborations are mentioned for LHC 7 TeV and LHC 8 TeV respectively.

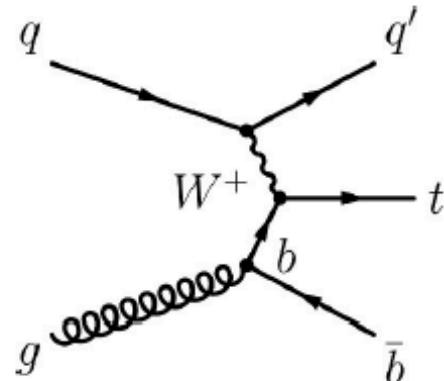
- ▶ CMS presented the first t-channel studies with 7TeV data **early 2011**
- ▶ Since then, all the main modes have been studied, the t-channel has been used to measure SM properties, the tW has been discovered, and single top related signatures have been explored on the search for new physics

*Established: observed with  $\geq 5 \sigma$  significance. Evidence :  $\geq 3 \sigma$*

**“The LHC is a SINGLE top quark factory!”**

# t-channel

- ▶ Dominant process with the highest cross section at the Tevatron and the LHC



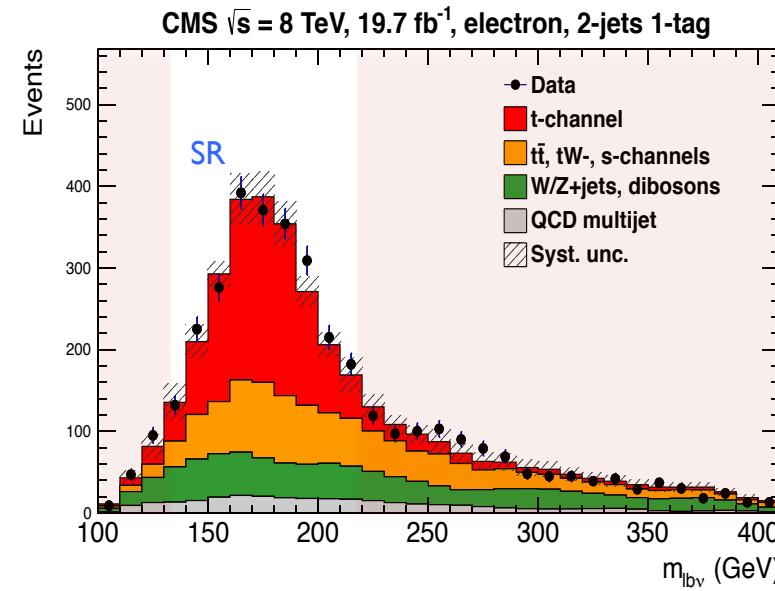
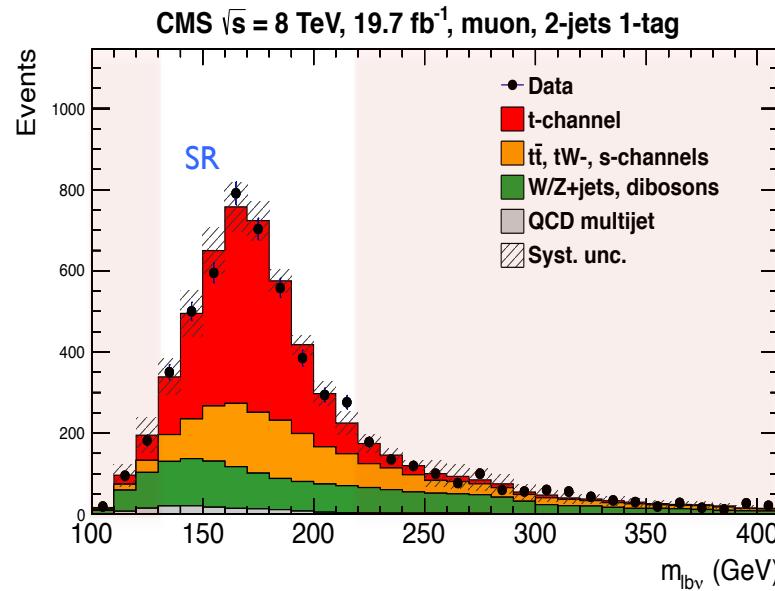
- ▶ The final state studied is a lepton + jets signature
- ▶ Signal events characterized by:
  - One isolated muon or electron
  - Missing transverse energy (MET)
  - A central b jet
- Leptonic top decay
- ▶ Main backgrounds: W+jets, ttbar, multijet

Measurement at 7TeV:  
[JHEP12\(2012\) 035](#)



# t-channel at $\sqrt{s} = 8$ TeV: Analysis

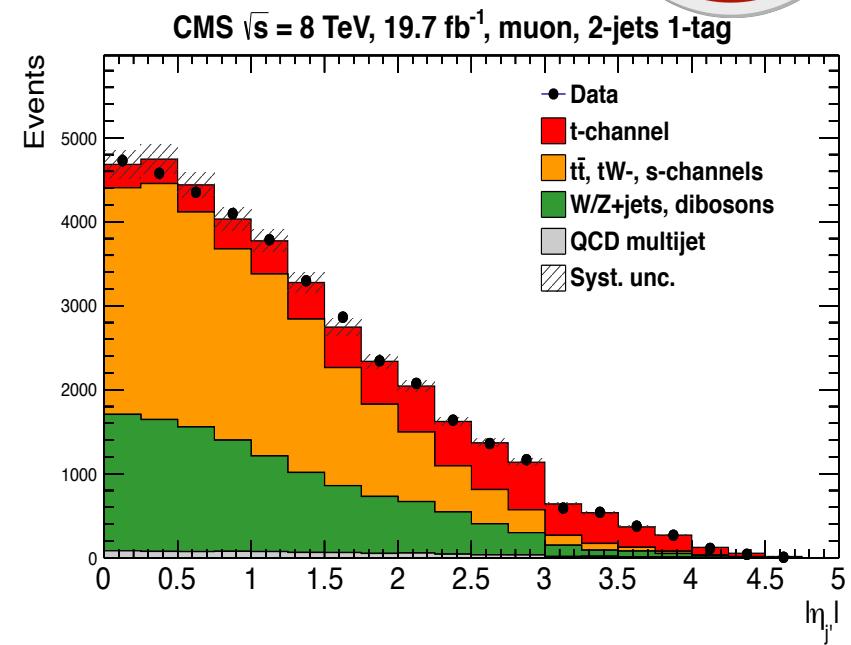
- ▶ Fit on  $|\eta_{j'}|$ , pseudorapidity of the recoiling light jet exploiting forward kinematics
- ▶ Event selection
  - ▶ 1 isolated lepton ( $\mu/e$ )
  - ▶ Kinematic cuts (anti QCD):  $m_T(W) (\mu) / \text{MET} (e)$
- ▶ Several exclusive regions using jet and b-tag multiplicity (Njets-Mtag):
  - ▶ Signal extraction 2jets-1 tag region, divided into “signal region” (SR) and “sideband” (SB) ( $130 < m_{lbv} < 220$  GeV)





# t-channel at $\sqrt{s} = 8$ TeV: Analysis

- ▶ Other regions used as **Control Regions**
  - ▶ ttbar: 3jets-1tag, 3jets-2tag
  - ▶ W/Z+jets: 2jets-0tag
- ▶ Background estimation:
  - ▶ QCD multijet: Maximum likelihood fit to MET (e) or  $m_T(W)(\mu)$  before cut. Template from data, inverting isolation.
  - ▶ W/Z+jets: From SB to SR
  - ▶ tt: normalization from simulation, template from 3jet-2tag region



$$\sigma_{\text{t-channel}} = 83.6 \pm 2.3(\text{stat.}) \pm 7.4(\text{syst.}) \text{ pb}$$

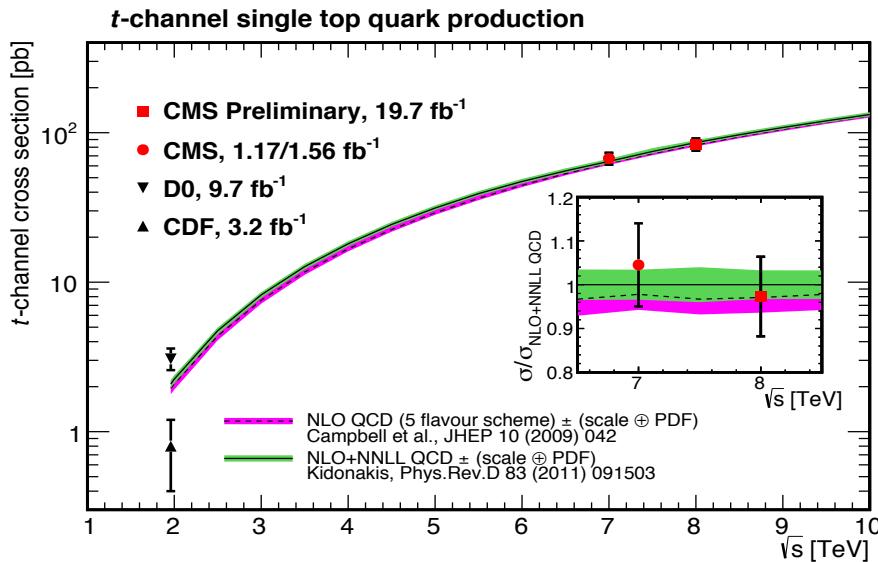
$$\sigma_{t\text{-channel}}^{th} = 87.2 + 2.8 - 1.0(\text{scale}) + 2.0 - 2.2(\text{PDF}) \text{ pb (app. NNLO)}^*$$

$$|V_{tb}| = \sqrt{\frac{\sigma}{\sigma^{th}}} = 0.979 \pm 0.045(\text{exp.}) \pm 0.016(\text{th.}) \rightarrow |V_{tb}| > 0.92$$

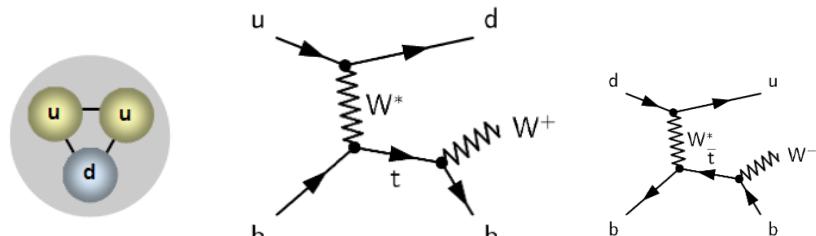
$$|V_{tb}|(7 + 8 \text{ TeV combination}) = 0.998 \pm 0.038(\text{exp.}) \pm 0.016(\text{th.})$$



# t-channel at $\sqrt{s} = 8$ TeV: Results



$$\frac{\sigma_{t-ch}(8\text{TeV})}{\sigma_{t-ch}(7\text{TeV})} = 1.24 \pm 0.08(\text{stat.}) \pm 0.12(\text{syst.})$$



CMS Preliminary,  $19.7 \text{ fb}^{-1}$ ,  $\sqrt{s} = 8 \text{ TeV}$

Due to the relative proportion of u and d quarks in the proton, more tops than anti-tops are expected to be produced

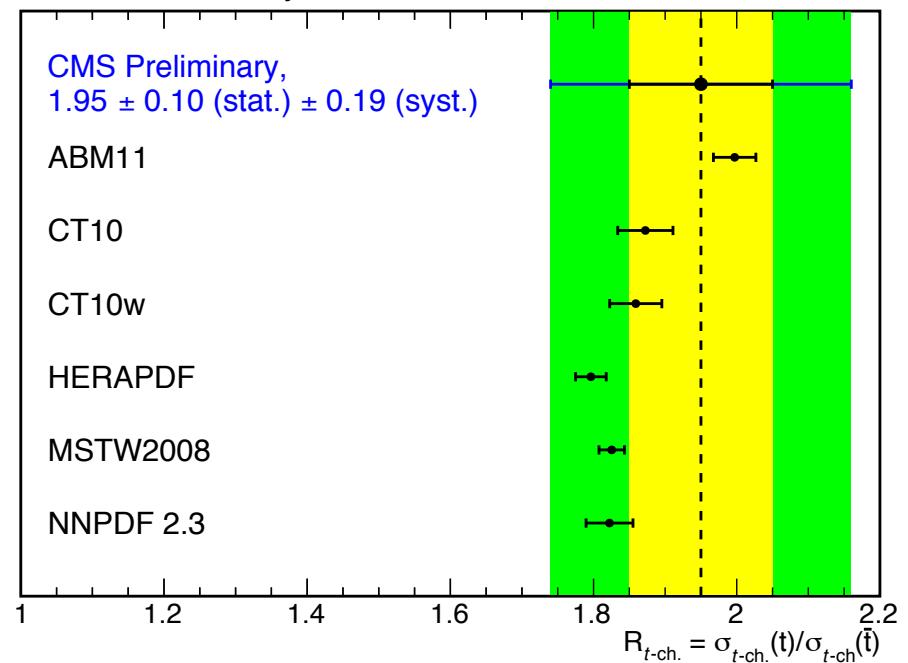
$$\sigma_{top} = 53.8 \pm 1.5(\text{stat.}) \pm 4.4(\text{syst.}) \text{ pb}$$

$$\sigma_{top}^{th} = 56.4 + 2.1 - 0.3(\text{scale}) \pm 1.1(\text{PDF}) \text{ pb}$$

$$\sigma_{anti-top} = 27.6 \pm 1.3(\text{stat.}) \pm 4.4(\text{syst.}) \text{ pb}$$

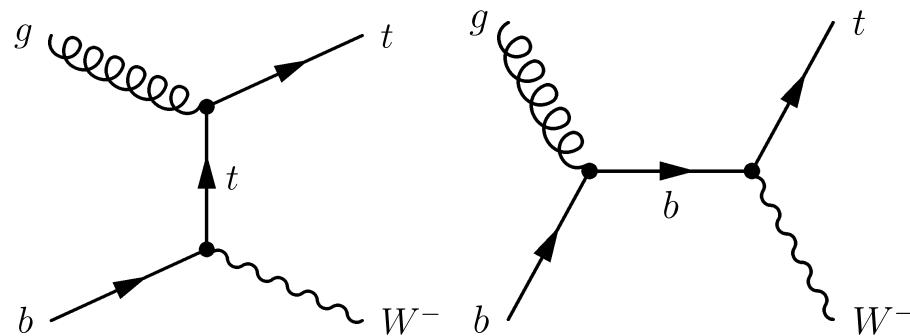
$$\sigma_{anti-top}^{th} = 30.7 \pm 0.7(\text{scale}) + 0.9 - 1.1(\text{PDF}) \text{ pb}$$

$$R_{t-channel} = 1.95 \pm 0.10(\text{stat.}) \pm 0.19(\text{syst.})$$



# tW associated production

- ▶ Single top process with the second largest cross-section at the LHC, inaccessible small at the Tevatron
- ▶ **ATLAS** showed evidence at 7 TeV quickly followed by **CMS** (first experiments study this process)



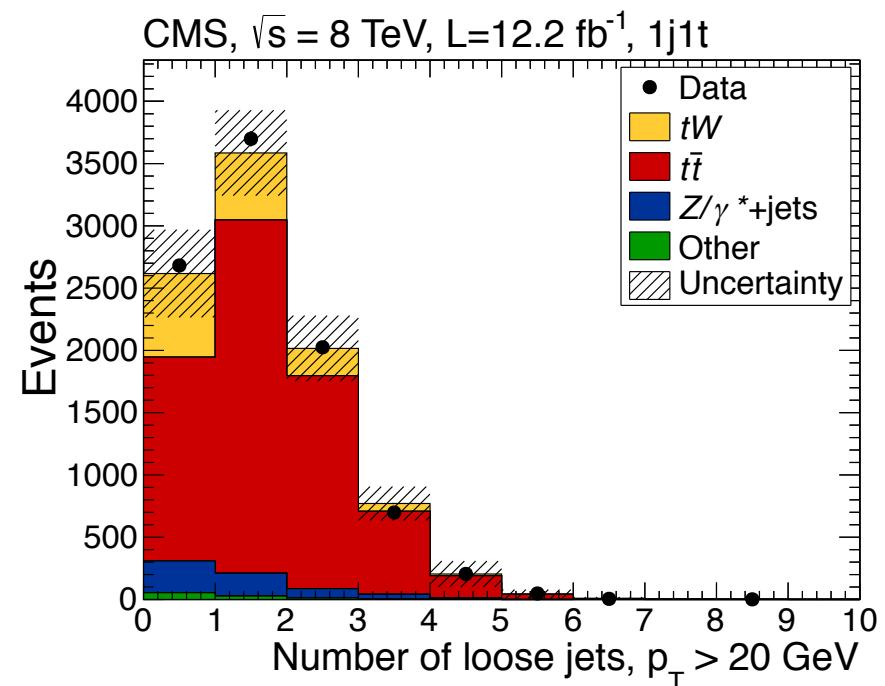
- ▶ The final state studied is a **dilepton signature**
- ▶ Signal events are characterized by:
  - **Two opposite-sign, isolated leptons**
  - Missing transverse energy (2 neutrinos in the final state)
  - A jet coming from a **b decay**
- ▶ **Backgrounds: ttbar (main challenge), DY**

Evidence at 7TeV:  
[Phys.Rev.Lett 110, 022003 \(2013\)](#)

# tW at $\sqrt{s} = 8$ TeV: Analysis

- ▶  $12.2\text{fb}^{-1}$
- ▶ Event selection:
  - ▶ 2 isolated leptons, opposite charge ( $e, \mu$ )
  - ▶ Vetoing  $Z$  mass window ( $m_{||}$ ), MET cut
- ▶ Regions:
  - ▶ Signal: Exactly 1 jet, b-tagged (**1j1t**)
  - ▶ Control Regions: Exactly 2 jets either one or both of them b-tagged (**2j1t** and **2j2t**) (ttbar)
- ▶ Background estimation:
  - ▶ ttbar: 2 control regions included in the fit.
  - ▶ Z+jets: MET-dependent data-driven scale factors. Inverting  $Z$  mass cut

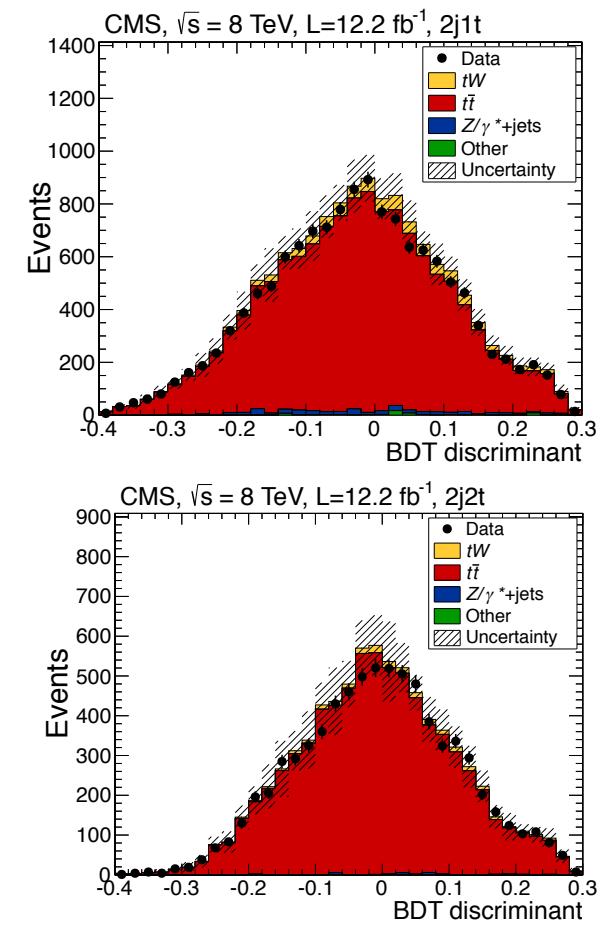
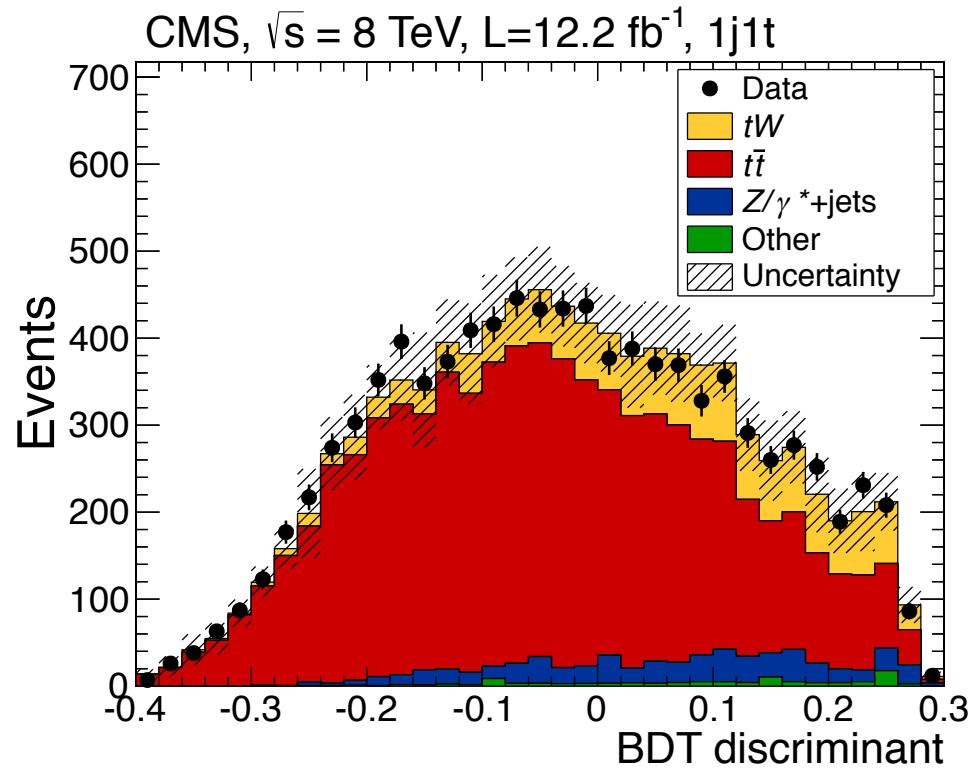
ttbar with 1 jet outside acceptance or miss-reconstructed  $\rightarrow$  main background



Handle to discriminate tW and ttbar: jets that have not been selected by the main quality criteria (looser pt cut, more open  $\eta$  angle, b-tagging information)

# tW at $\sqrt{s} = 8$ TeV: Analysis

- ▶ **BDT build with 13 variables** (variables related to loose jets most powerful to discriminate)
- ▶ 2 control regions of ttbar included in the fit



# tW at $\sqrt{s} = 8$ TeV: Results

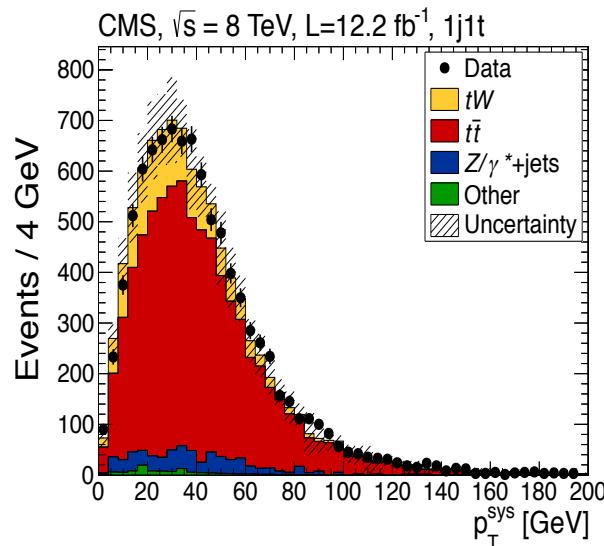
**tW signal observed with a significance of  $6.1\sigma$**   
 (expected significance  $5.4 \pm 1.4\sigma$ )

$$\sigma_{tW} = 23.4 \pm 5.4 \text{ pb}$$

$$\sigma^{th}_{tW} = 22.2 \pm 0.6(\text{scale}) \pm 1.4(\text{PDF}) \text{ pb (app. NNLO)}^*$$

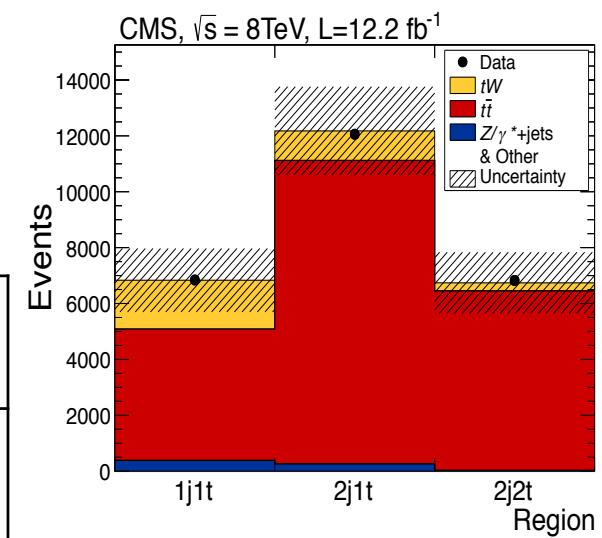
$$|V_{tb}| = 1.03 \pm 0.12(\text{exp.}) \pm 0.04(\text{th.}) \rightarrow |V_{tb}| > 0.78 \text{ (95% CL)}$$

First observation of the process!



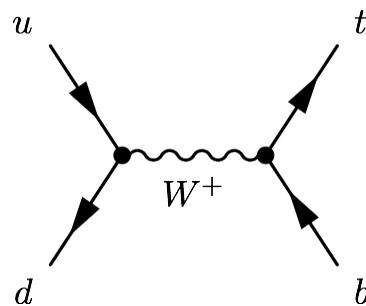
**Two cross-check analyses**  
 Same selection + additional cut in  $e\mu$   
 Fit on shape of  $p_T$  of the system  
 (leptons, jet, MET), and event counting

Fit to the $p_T$ of the system	<b><math>4.0\sigma</math> (<math>3.2+0.4-0.9</math>)</b> $\sigma_{tW} = 24.3+8.6-8.8 \text{ pb}$
Cut-based analysis	<b><math>3.6\sigma</math> (<math>2.8+0.9-0.8\sigma</math>)</b> $\sigma_{tW} = 33.9+8.6-8.6 \text{ pb}$



# s-channel

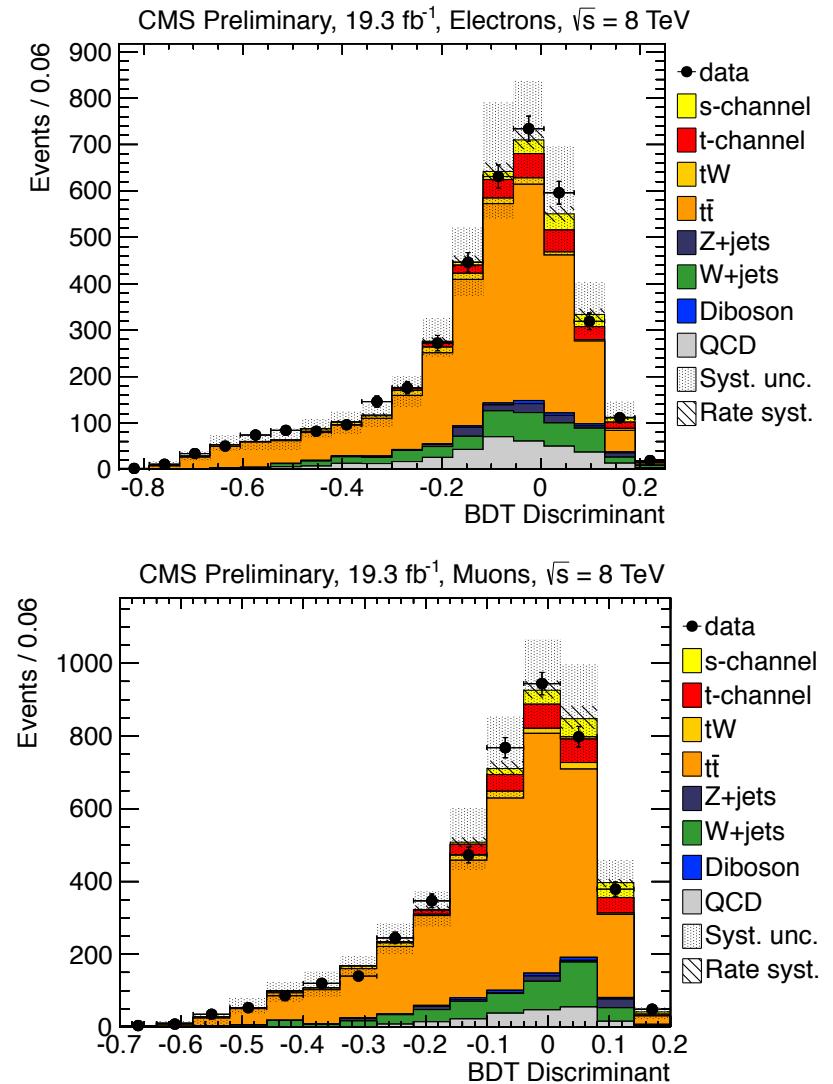
- ▶ Lowest cross-section at the LHC, more important at the **Tevatron** (where the study of data after the shutdown allowed for the **observation of the process**)
- ▶ Production mode sensitive to new physics: **W'** bosons, charged Higgs bosons
- ▶ **Very challenging final state:** low cross-section, difficult to separate from backgrounds



- ▶ Signal signature: **lepton + jets**
  - ▶ **A lepton ( $e, \mu$ ) and MET** from the decay of a  $W$  boson
  - ▶ **Two jets with high transverse momentum originating from b-quarks**
- ▶ **Main backgrounds:**  $W+jets$  and  $tt\bar{b}$ , multijet

# s-channel at $\sqrt{s} = 8$ TeV: Analysis

- ▶ **First CMS result on this channel**
- ▶ Event Selection
  - ▶ 1 isolated lepton ( $\mu/e$ )
  - ▶ 2 b-tagged jets
- ▶ Background estimation:
  - ▶ QCD : data-driven. Maximum likelihood fit to MET (e) or  $m_T(W)(\mu)$ . Template from data inverting isolation.
  - ▶ ttbar: control region included in the fit (3jet-2tag)
- ▶ **Multivariate analysis based on a BDT**
- ▶ 11 variables (e), 10 ( $\mu$ ); no single “golden” discriminant variable



# s-channel at $\sqrt{s} = 8$ TeV: Results

$\sigma_{s\text{-channel}} = 6.2 \pm 5.4(\text{exp.}) \pm 5.9(\text{th}) \text{ pb} = 6.2 + 8.0 - 5.1 \text{ pb (FC*)}$

$\sigma_{s\text{-channel}}^{th} = 5.55 \pm 0.08 (\text{scale}) \pm 0.21 (\text{PDF}) \text{ pb (NNLL)**}$

Observed significance of the s-channel signal  $0.7\sigma$

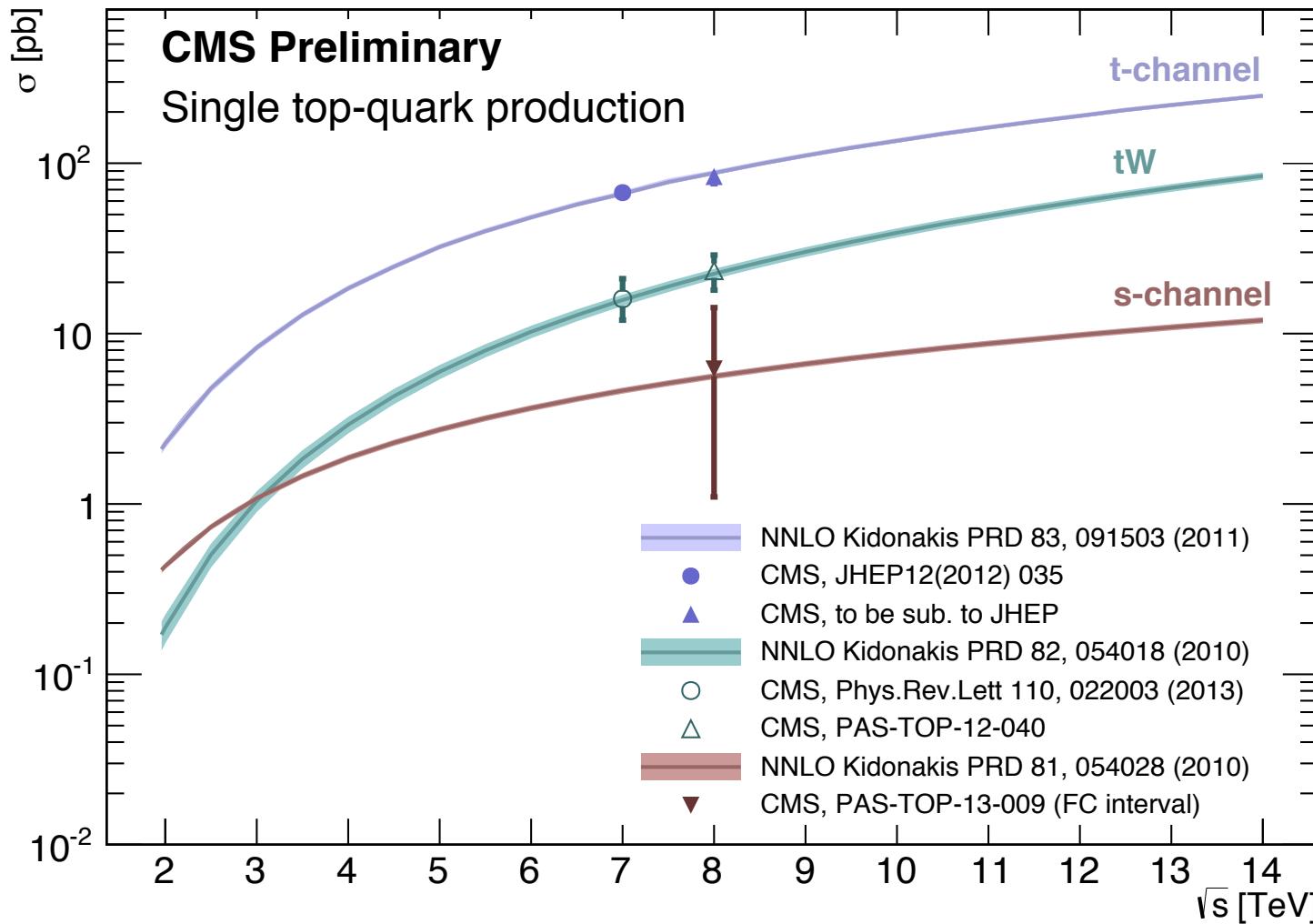
Expected significance  $0.9\sigma$

Upper limit of 2.1 (3.1,1.6) times the SM  $\rightarrow 11.5$  (17.0,9.0) pb

\* 68%CL interval using the Feldman-Cousins unified approach which does not reach negative x-sec values

\*\*arXiv:1205.3453

# Single top in CMS





## Top properties



# Top properties

- ▶ To fully characterize the top quark, its mass, couplings, and other properties need to be measured and established
  - ▶ **Test consistency of SM predictions**
  - ▶ Search for hints of new physics in **deviations from SM**
- ▶ In CMS many top measurements have been performed
  - ▶ The high rate of top production at the LHC allowed competitive measurements since early data taking
- ▶ ttbar events have been classically used to study top properties
  - ▶ **The single top production at the LHC is large enough to measure top properties**
    - ▶ Complementary approach
    - ▶ Valuable to get the **full picture**



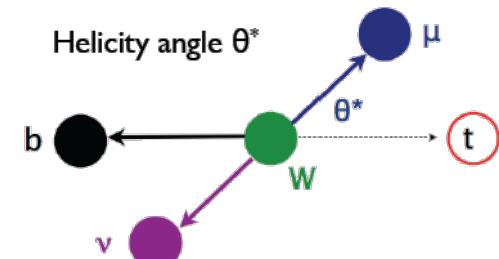
# W-helicity fractions

- ▶ In the SM,  $t \rightarrow Wb$  (most of the time)
- ▶ W (massive, spin 1 boson) can have longitudinal, left- or right-handed helicity states
- ▶ Assuming SM couplings:
  - ▶ helicity fractions:  $\sim 70\%$  longitudinal ( $F_0$ ),  $\sim 30\%$  left-handed ( $F_L$ ),  $0\%$  right-handed ( $F_R$ ) -due to helicity suppression at LO (unitarity condition:  $F_0 + F_L + F_R = 1$ )
  - ▶ Helicity fractions can be extracted from the angular distributions of the top decay products:

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

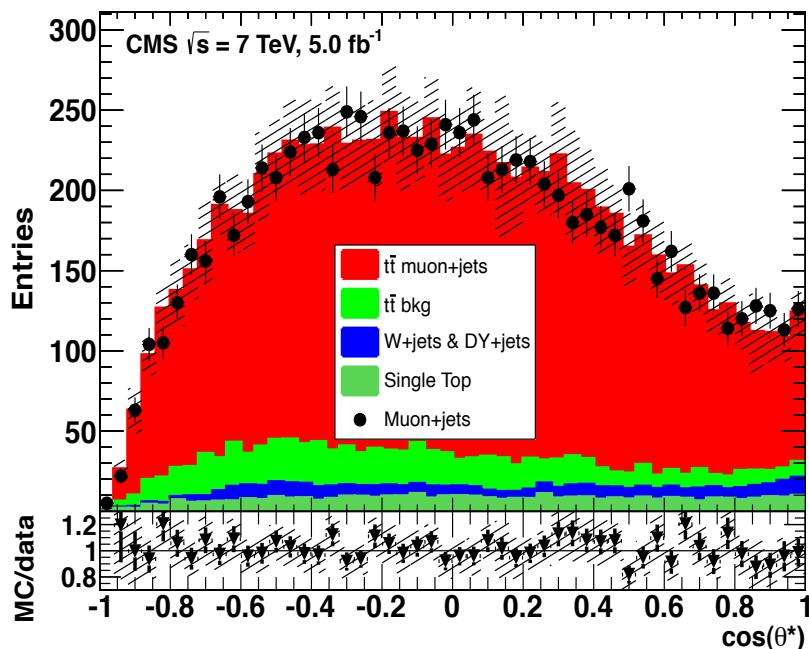
- ▶ Helicity angle,  $\theta^*$  : Angle between the momentum of the d-type fermion (lepton in leptonic decays) in the W boson rest frame, and the momentum of the W boson in the top quark rest frame

Direct probe of the  $Wtb$  vertex, sensitive to BSM effects



# W-helicity in lepton+jets tt events (7TeV)

- ▶ Event selection
  - ▶ 1 isolated lepton ( $\mu/e$ );  $\geq 4$  Jets, at least 2 b-tagged
  - ▶  $m_T(W)$  cut against QCD
- ▶ ttbar reconstructed using a kinematic fit using W and top mass constraints
- ▶ W+jets and Z/ $\gamma$ +jets partially data-driven (normalization by exploiting charge asymmetry and from control region with 1 additional lepton)



Simulation reweighted using generator level  $\cos\theta^*$  distribution to obtain any helicity scenario

2D ( $F_0$  free parameter,  $F_R=0$ ,  $F_L = 1-F_0$ ) and 3D ( $F_0$ ,  $F_L$  free,  $F_R$  constrained as  $1-F_0-F_L$ ) fits

$\cos\theta^*_{\text{lep}}$  and  $\cos\theta^*_{\text{had}}$  considered

Most precise 3D: combined e/ $\mu$  results, leptonic

$$\begin{aligned} F_L &= 0.310 \pm 0.022 \text{ (stat.)} \pm 0.022 \text{ (syst.)} \\ F_R &= 0.008 \pm 0.012 \text{ (stat.)} \pm 0.014 \text{ (syst.)} \\ F_0 &= 0.682 \pm 0.030 \text{ (stat.)} \pm 0.033 \text{ (syst.)} \end{aligned}$$

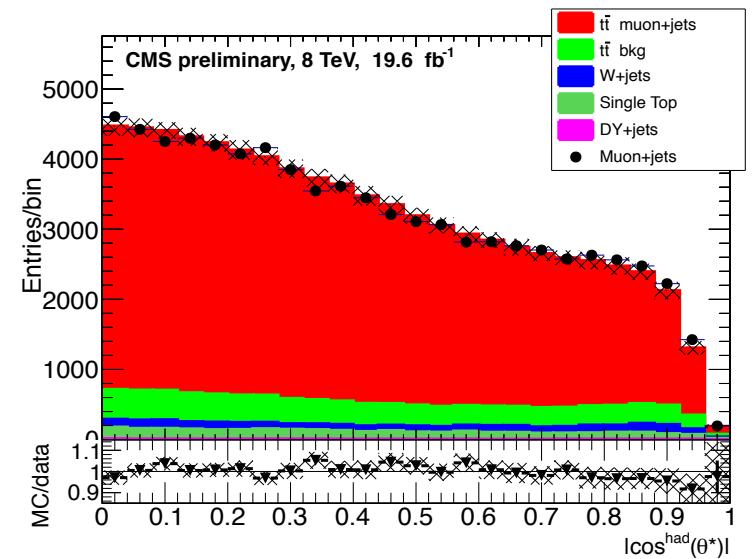
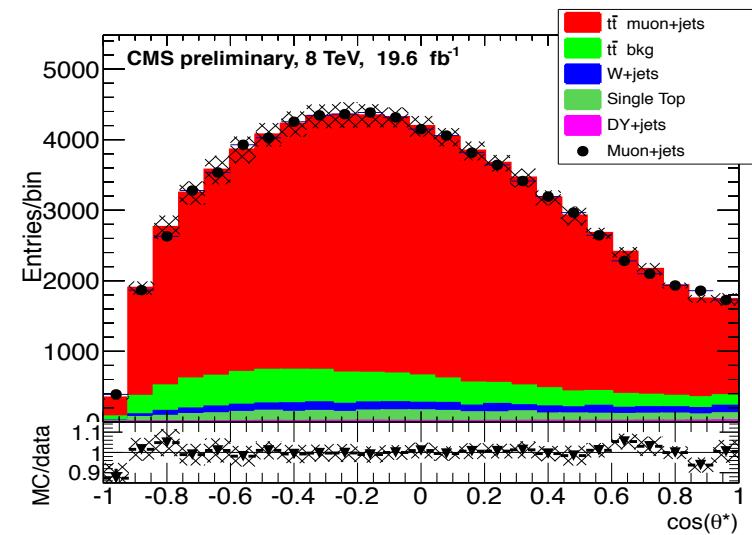
# W-helicity in lepton+jets tt events (8TeV)

- ▶ Update of the analysis at 8TeV
  - $\sigma_{tt}(8\text{ TeV}) \sim 1.6 \sigma_{tt}(7\text{ TeV})$
  - $\sigma_{W\text{jets}}(8\text{ TeV}) \sim 1.2 \sigma_{W\text{jets}}(7\text{ TeV})$   
→ W-helicity measurement in a purer sample
- ▶ Muon channel
- ▶ 3D fit

Results:

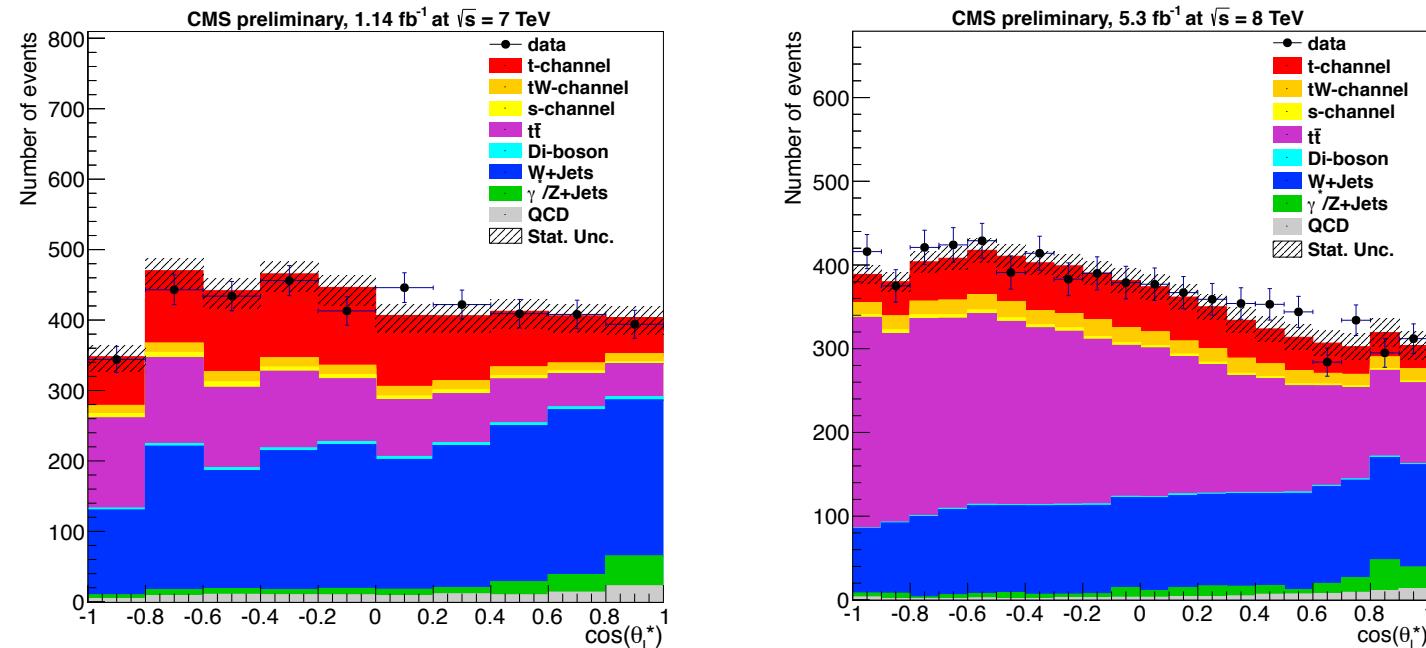
$$\begin{aligned} F_L &= 0.350 \pm 0.010 \text{ (stat.)} \pm 0.024 \text{ (syst.)} \\ F_R &= -0.009 \pm 0.006 \text{ (stat.)} \pm 0.020 \text{ (syst.)} \\ F_0 &= 0.659 \pm 0.015 \text{ (stat.)} \pm 0.023 \text{ (syst.)} \end{aligned}$$

Leptonic branch



# W-helicity in Single top signatures

- ▶ First measurement using **single top**
- ▶ **t-channel** standard (cross-section measurement) **event selection**
- ▶ Preliminary result with only muons,  $1.14\text{fb}^{-1}(7\text{TeV})$  and  $5.3\text{fb}^{-1}(8\text{TeV})$



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

# CMS measurements of $F_0$ , $F_L$ , $F_R$

	7 TeV	8 TeV
Theory prediction (NNLO)	$F_L = 0.311 \pm 0.005$ $F_R = 0.0017 \pm 0.0001$ $F_0 = 0.687 \pm 0.005$ <a href="#">PRD 81, 111503(R) (2010)</a>	
tt l+jets	$F_L = 0.310 \pm 0.022 \text{ (stat.)} \pm 0.022 \text{ (syst.)}$ $F_R = 0.008 \pm 0.012 \text{ (stat.)} \pm 0.014 \text{ (syst.)}$ $F_0 = 0.682 \pm 0.030 \text{ (stat.)} \pm 0.033 \text{ (syst.)}$ <a href="#">JHEP 10 (2013) 167</a>	$F_L = 0.350 \pm 0.010 \text{ (stat.)} \pm 0.024 \text{ (syst.)}$ $F_R = -0.009 \pm 0.006 \text{ (stat.)} \pm 0.020 \text{ (syst.)}$ $F_0 = 0.659 \pm 0.015 \text{ (stat.)} \pm 0.023 \text{ (syst.)}$ <a href="#">CMS-PAS-TOP-13-008</a>
tt dilepton	$F_L = 0.288 \pm 0.035 \text{ (stat)} \pm 0.040 \text{ (sys)}$ $F_R = 0.014 \pm 0.027 \text{ (stat)} \pm 0.042 \text{ (sys)}$ $F_0 = 0.698 \pm 0.057 \text{ (stat)} \pm 0.063 \text{ (sys)}$ <a href="#">CMS-PAS-TOP-12-015</a>	
Single top t-channel	$F_L = 0.293 \pm 0.069 \text{ (stat.)} \pm 0.030 \text{ (syst.)}$ $F_R = -0.006 \pm 0.057 \text{ (stat.)} \pm 0.027 \text{ (syst.)}$ $F_0 = 0.713 \pm 0.114 \text{ (stat.)} \pm 0.023 \text{ (syst.)}$ <a href="#">CMS-PAS-TOP-12-020</a>	
LHC combination (l+jet and dilep)	$F_L = 0.359 \pm 0.021 \text{ (stat.)} \pm 0.028 \text{ (syst.)}$ $F_R = 0.015 \pm 0.034$ $F_0 = 0.626 \pm 0.034 \text{ (stat.)} \pm 0.048 \text{ (syst.)}$ <a href="#">CMS-PAS-TOP-12-025</a>	

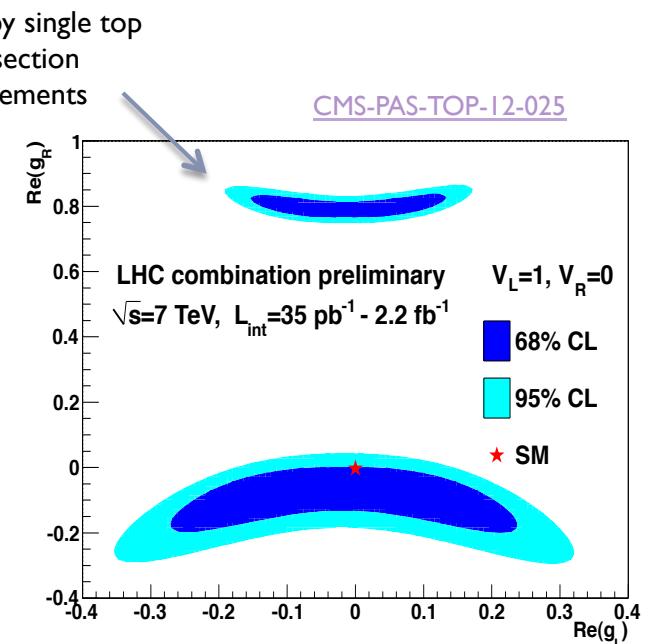
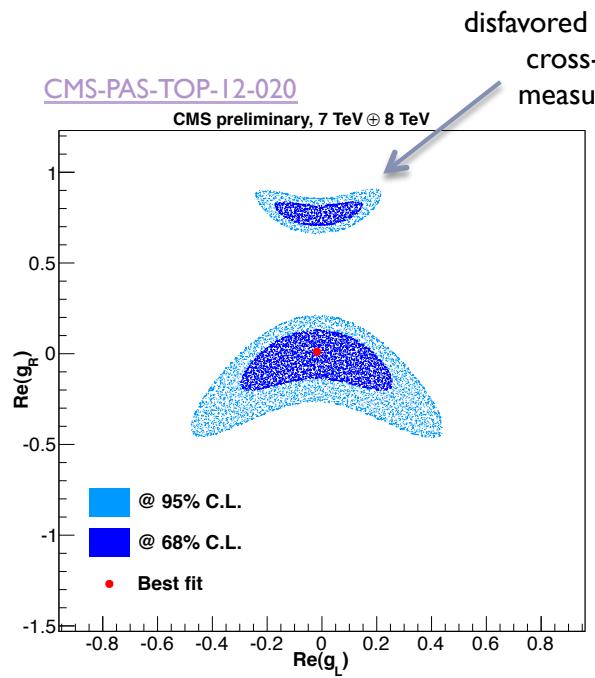
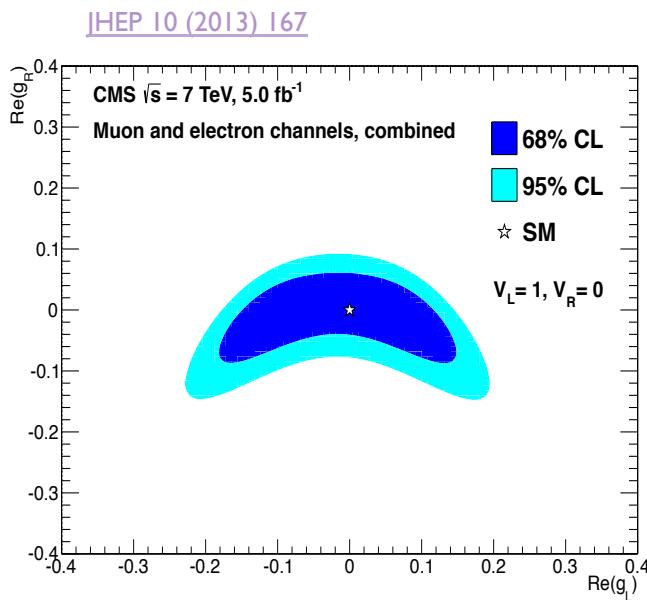
# Limits on anomalous couplings

- ▶ Deviations on the measured helicity fractions from the SM can be interpreted in terms of anomalous  $Wtb$  couplings
- ▶ General  $Wtb$  vertex lagrangian:

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

left and right handed vector couplings  
SM part,  $V_L = V_{tb}$ 
left and right handed tensor couplings  
anomalous couplings (zero in SM)

limits set on real components of  $g_L$  and  $g_R$



# Top polarization and spin correlations

- ▶ spin of the top in generation → decay products
  - ▶ **Information retrieved from angular distributions**
  - ▶ Measurements using angular asymmetry variables (unfolded to parton level)
- ▶ Top spin studied in ttbar using  $\theta_l$  (angle of lepton in parent top's rest frame, relative to the direction of the top in the ttbar center of mass frame)
- ▶ ttbar → tops unpolarized: polarization  $\mathbf{P}$  given by  $\mathbf{P} = 2\mathbf{A}_P$ , where  $\mathbf{A}_P$  is

$$A_P = \frac{N(\cos(\theta_\ell) > 0) - N(\cos(\theta_\ell) < 0)}{N(\cos(\theta_\ell) > 0) + N(\cos(\theta_\ell) < 0)}$$

- ▶  $A_{c_1 c_2}$

$$A_{c_1 c_2} = \frac{N(c_1 \cdot c_2 > 0) - N(c_1 \cdot c_2 < 0)}{N(c_1 \cdot c_2 > 0) + N(c_1 \cdot c_2 < 0)}$$

Direct measure of spin correlation coefficient  $C_{\text{hel}}$  using helicity angles of the two leptons in each event:  $C_{\text{hel}} = -4A_{c_1 c_2}$

$$c_1 = \cos(\theta_{l+}), c_2 = \cos(\theta_{l-})$$

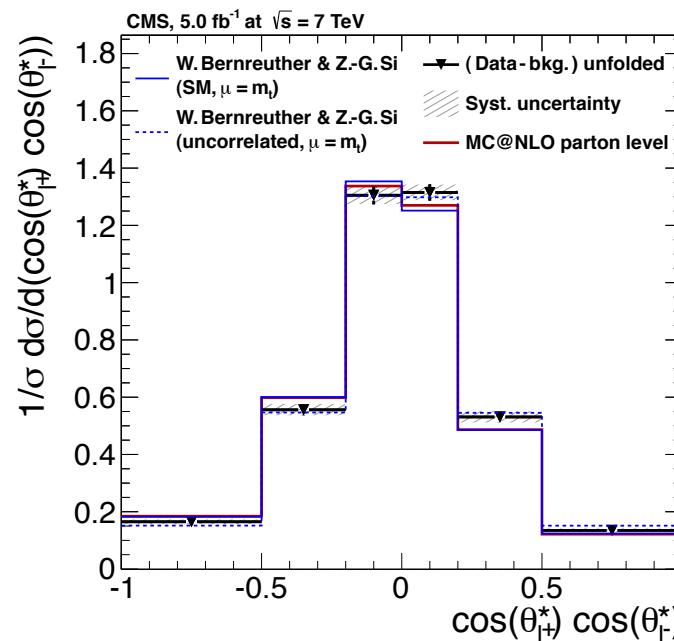
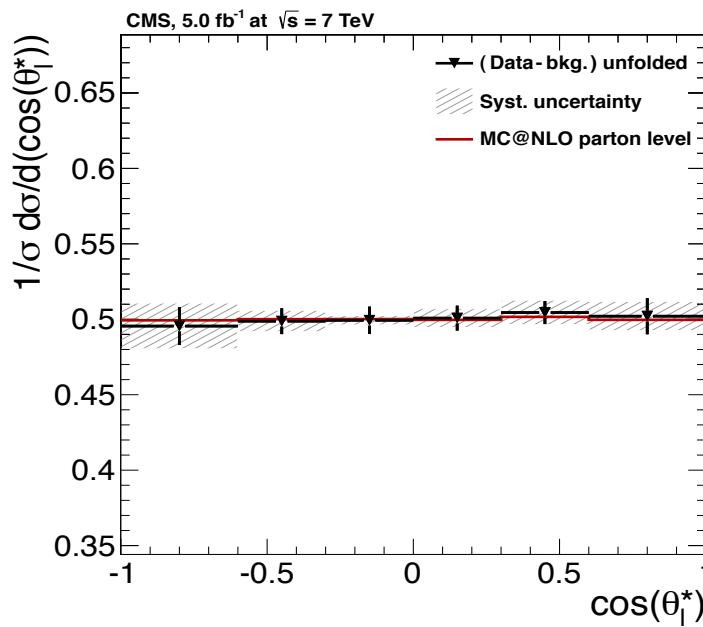
- ▶ And finally  $A_{\Delta\phi}$ , sensitive to ttbar spin correlations

$$A_{\Delta\phi} = \frac{N(\Delta\phi_{\ell^+\ell^-} > \pi/2) - N(\Delta\phi_{\ell^+\ell^-} < \pi/2)}{N(\Delta\phi_{\ell^+\ell^-} > \pi/2) + N(\Delta\phi_{\ell^+\ell^-} < \pi/2)}$$

discrimination between correlated and uncorrelated top and anti-top spins

# Polarization and spin in $t\bar{t}$ dilepton

- ▶ 7TeV
- ▶ Event selection
  - ▶ 2 isolated leptons ( $e, \mu$ );  $\geq 2$  jets,  $\geq 1$  b-tagged
  - ▶  $ee/\mu\mu$ : vetoing  $Z$  mass window ( $m_{||}$ ), MET cut
- ▶ **Analytical matrix weighting technique (AMWT) to reconstruct ttbar system**

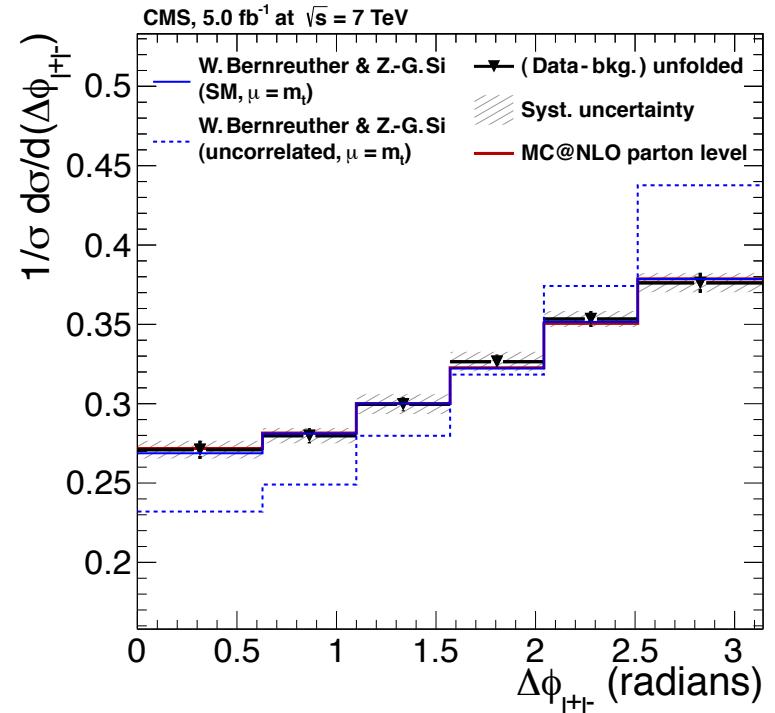


## Regularized unfolding algorithm

distributions corrected  
for detector effects  
allowing for direct  
comparison with  
theoretical predictions

# Polarization and spin in $t\bar{t}$ dilepton

- ▶ The **Asymmetries** determined from the unfolded distributions are also at **parton level**
- ▶ Uncertainties are statistical, systematic, and from the modeling of the top  $p_T$  distribution
- ▶  $A_{\Delta\phi}$  result indicates **tt spin correlations**, disfavoring the uncorrelated case



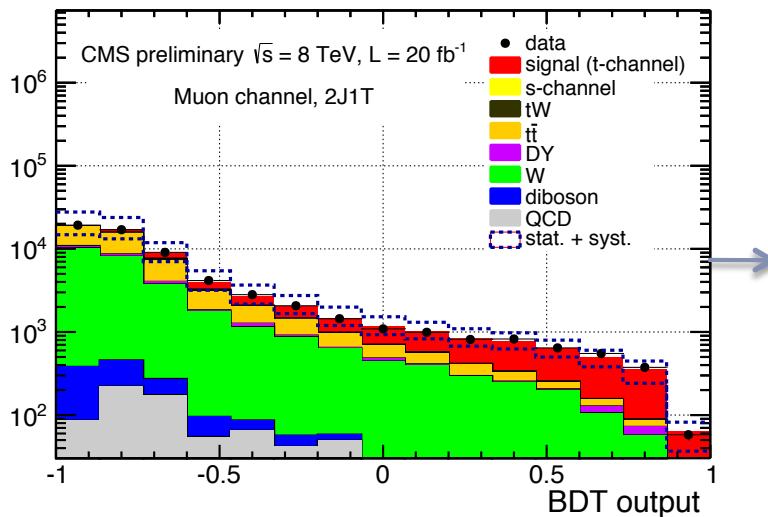
Asymmetry	Data (unfolded)	MC@NLO	NLO (SM, correlated)	NLO (uncorrelated)
$A_{\Delta\phi}$	$0.113 \pm 0.010 \pm 0.007 \pm 0.012$	$0.110 \pm 0.001$	$0.115^{+0.014}_{-0.016}$	$0.210^{+0.013}_{-0.008}$
$A_{c_1 c_2}$	$-0.021 \pm 0.023 \pm 0.027 \pm 0.010$	$-0.078 \pm 0.001$	$-0.078 \pm 0.006$	0
$A_p$	$0.005 \pm 0.013 \pm 0.020 \pm 0.008$	$0.000 \pm 0.001$	N/A	N/A

# Top polarization in single top

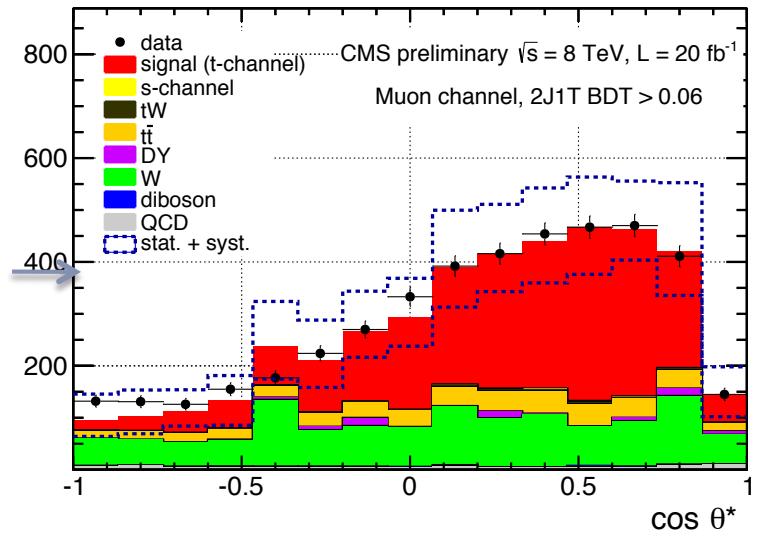
- ▶ **Single top quarks → highly polarized**, spin aligned with the recoiling light jet
- ▶ Polarization (related to the spin asymmetry) measured from unfolded  **$\cos\theta^*$** , **distribution** (angle between the charged lepton and the untagged jet in the top quark rest frame) using the **spin asymmetry**

$$A_l \equiv \frac{1}{2} \cdot P_t \cdot \alpha_l \quad A_l = \frac{N(\cos\theta_{unfolded}^* > 0) - N(\cos\theta_{unfolded}^* < 0)}{N(\cos\theta_{unfolded}^* > 0) + N(\cos\theta_{unfolded}^* < 0)}$$

- ▶ Analysis performed at 8TeV (e/ $\mu$ )
- ▶ t-channel event selection, BDT discriminant built to obtain a signal enriched sample

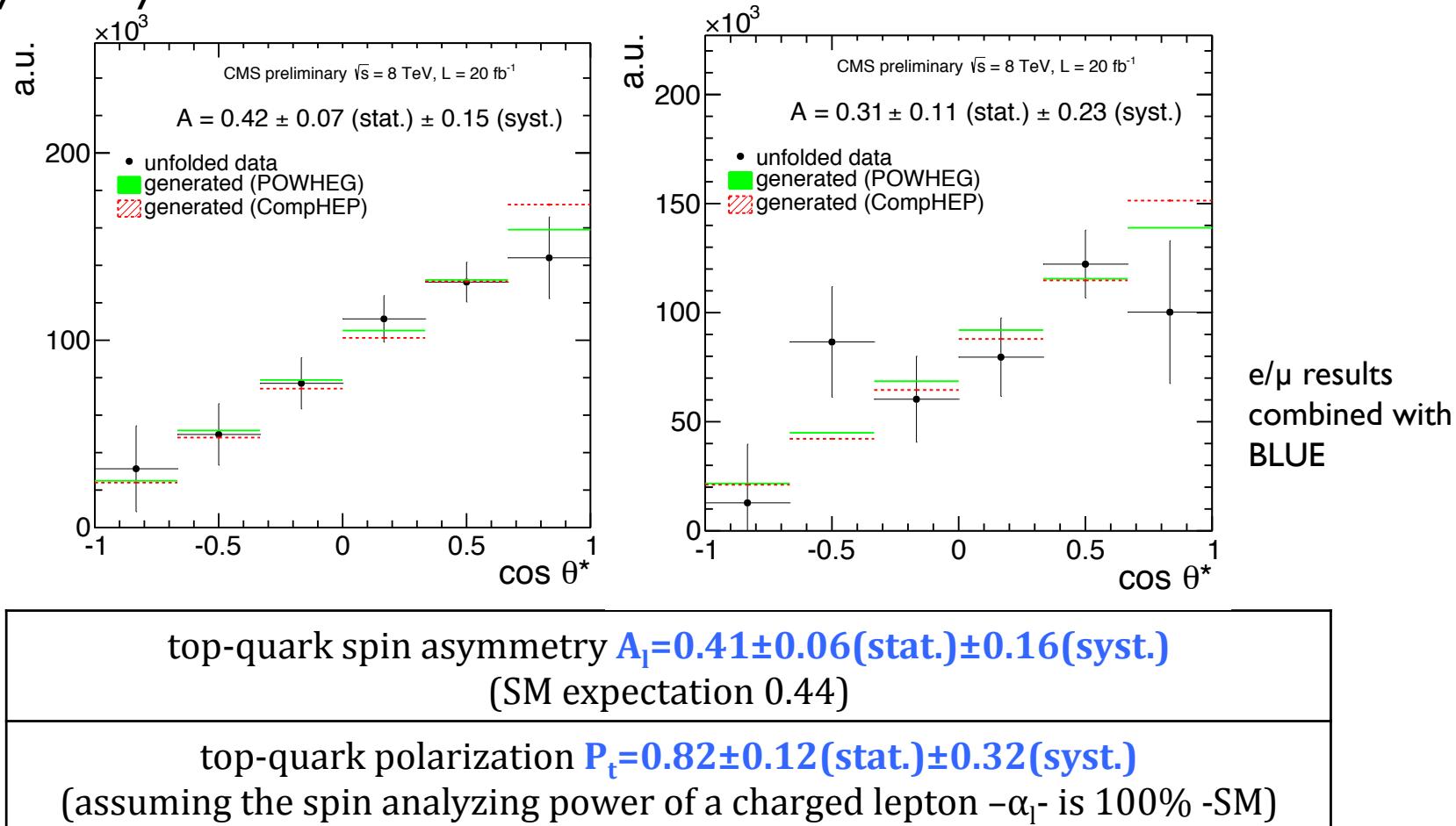


Cut on optimal  
S/B point



# Top polarization in single top: Results

- ▶  $\cos\theta_1$  distributions unfolded to parton level, used to extract the top-quark spin asymmetry

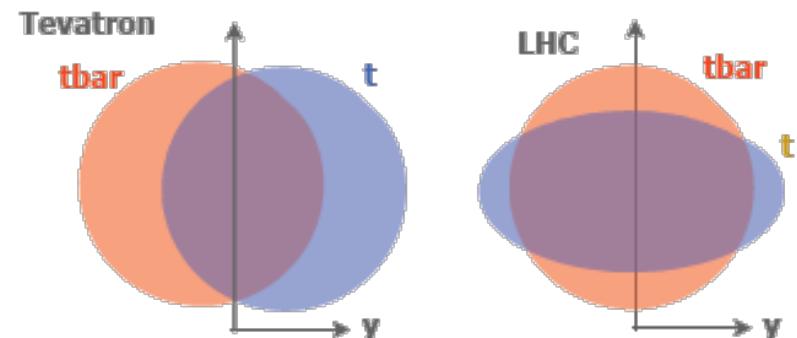


# Charge asymmetry

- ▶ Tevatron found a potential **hint for new physics** in the top quark sector → discrepancy of measured ttbar forward–backward asymmetry with SM expectations ( $>2\sigma$  effect)
- ▶ Correlation between the direction of the momentum of the top (anti-top) quark and incoming quark (anti-quark)
  - ▶ Forward–backward asymmetry ( $A_{FB}$ ) at the Tevatron (**proton-antiproton** collider)
  - ▶ **Not the case at the LHC (proton-proton)**
- ▶ At the LHC, larger average momentum fraction of valence quarks → excess of top quarks in the forward and backward directions, anti-top quarks produced more centrally.

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

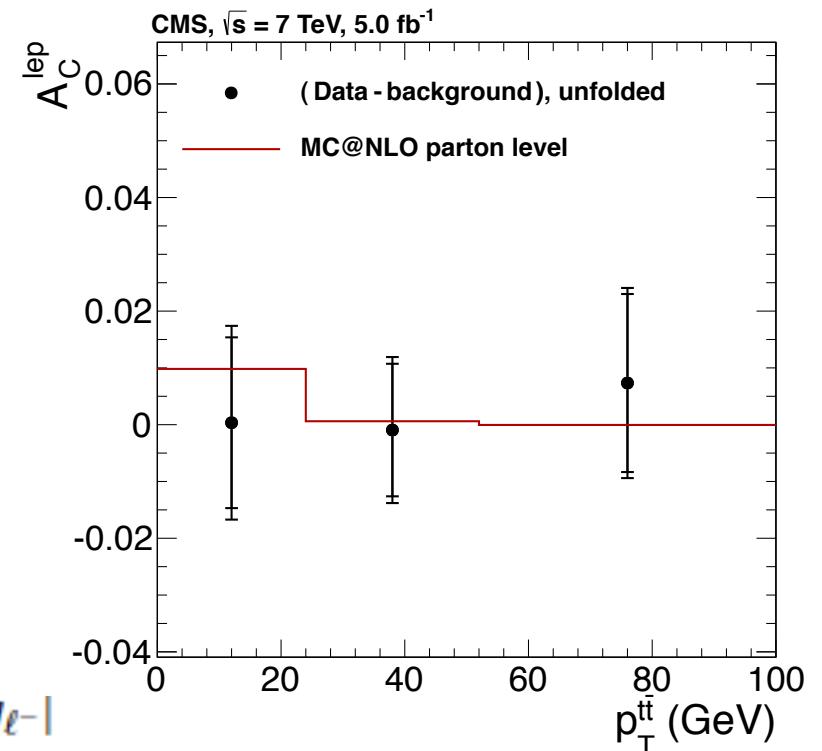
Variable used ( $y$  = rapidity)



# Charge asymmetry: dilepton tt events

- ▶ 7TeV
- ▶ Event selection
  - ▶ 2 isolated leptons, removing Z mass window (ee/ $\mu\mu$ )
  - ▶  $\geq 2$  jets;  $\geq 1$  btag
  - ▶ MET cut
- ▶ Fake lepton background from data, Z+jets from in/out Z mass window
- ▶ ttbar system reconstructed (AMWT)
- ▶ **Charge asymmetry and lepton charge asymmetry**

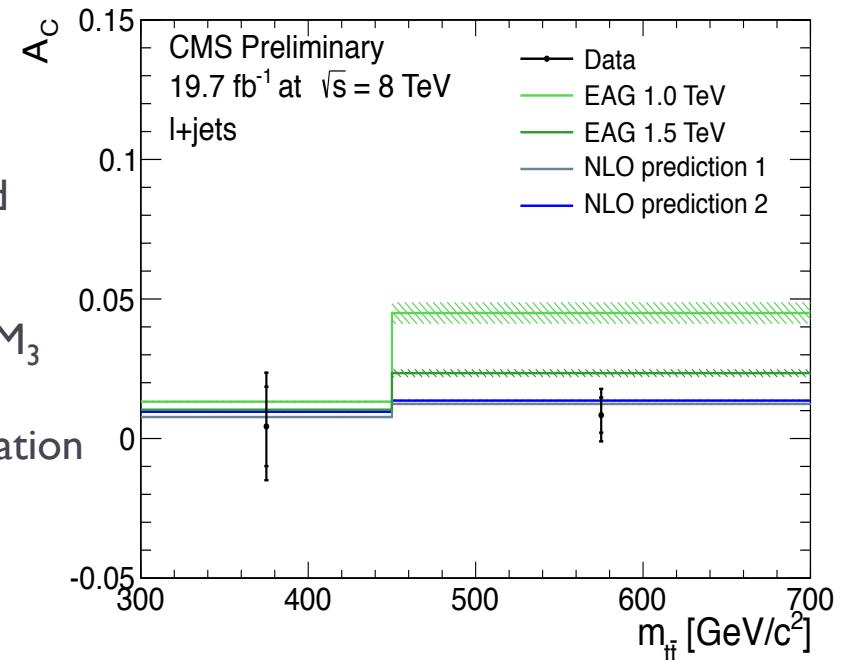
$$A_C^{\text{lep}} = \frac{N(\Delta|\eta_\ell| > 0) - N(\Delta|\eta_\ell| < 0)}{N(\Delta|\eta_\ell| > 0) + N(\Delta|\eta_\ell| < 0)} \quad \Delta|\eta_\ell| = |\eta_{\ell^+}| - |\eta_{\ell^-}|$$



Variable	Data (unfolded)	MC@NLO prediction	NLO theory
$A_C$	$-0.010 \pm 0.017 \pm 0.008$	$0.004 \pm 0.001$	$0.0123 \pm 0.0005$
$A_C^{\text{lep}}$	$0.009 \pm 0.010 \pm 0.006$	$0.004 \pm 0.001$	$0.0070 \pm 0.0003$

# Charge asymmetry: lepton+jets tt events

- ▶ 8 TeV
- ▶ Event selection
  - ▶ 1 isolated lepton ( $\mu/e \geq 4$ ) Jets, at least 1 b-tagged
- ▶ Background estimation
  - ▶ Fit on regions of  $m_T(W)$  (leptonic decay), fitting  $M_3$  (mass of the 3 jets on the hadronic side) simultaneously; QCD from data inverting the isolation
- ▶ Reconstructed tt system
- ▶ inclusive and differential distributions of  $\Delta |y|$



Asymmetry	$A_C$
Reconstructed	$0.003 \pm 0.002$ (stat.)
BG-subtracted	$0.002 \pm 0.002$ (stat.)
Unfolded	$0.005 \pm 0.007$ (stat.) $\pm 0.006$ (syst.)
Theory prediction [Kühn, Rodrigo] [9, 33]	$0.0102 \pm 0.0005$
Theory prediction [Bernreuther, Si] [34, 35]	$0.0111 \pm 0.0004$

EAG: model featuring an effective axial-vector coupling of the gluon PRD 8 (2011) 054017

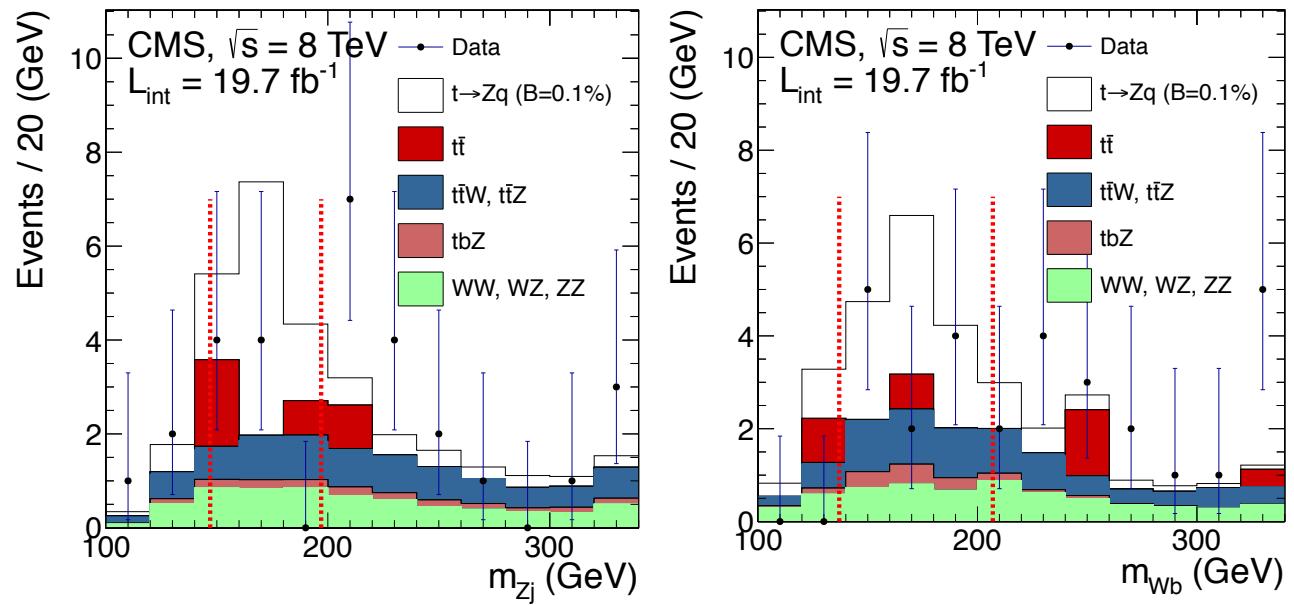
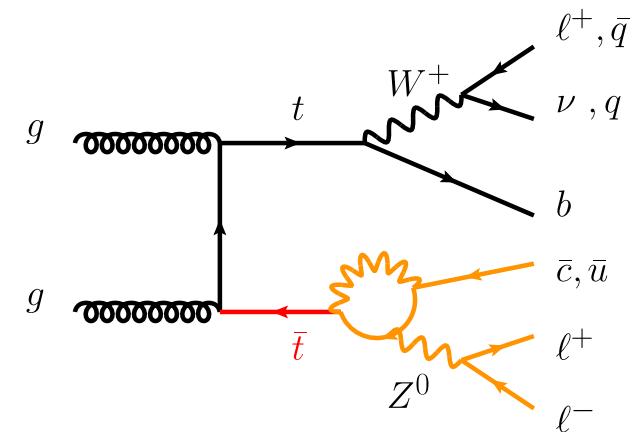
# CMS measurements of charge asymmetry

	7 TeV	8 TeV
Theory prediction (NLO)	$0.0123 \pm 0.0005$ <a href="#">PRD 86, 034026 (2012)</a>	$0.0111 \pm 0.0004$ <a href="#">PRD 86, 034026 (2012)</a>
tt l+jets	$0.004 \pm 0.010$ (stat.) $\pm 0.011$ (syst.) <a href="#">PLB 717 (2012) 129</a>	$0.005 \pm 0.007$ (stat.) $\pm 0.006$ (syst.) <a href="#">CMS-PAS-TOP-12-033</a>
tt dilepton	$-0.010 \pm 0.017$ (stat.) $\pm 0.008$ (syst.) <a href="#">arXiv:1402.3803</a>	

Everything in agreement with SM predictions

# FCNC in ttbar events, $t \rightarrow Zq$

- ▶ Flavor Changing Neutral Currents in top decays using ttbar events, 8TeV
- ▶  $t \rightarrow Wb \sim 100\%$  of the times,  $t \rightarrow Zq$  highly suppressed by the GIM mechanism, predicted  $B(t \rightarrow Zq) O(10^{-14})$
- ▶ Event selection:
  - ▶ 3 leptons, ( $\mu, e$ ) (pair compatible with  $Z$  decay)
  - ▶  $\geq 2$  jets; 1 jet b-tagged
  - ▶ MET cut
- ▶ Background estimation
  - ▶ using b-tag information
  - ▶  $0 > 1$  tag samples
- ▶ Cuts on  $m_{Wb}$  and  $m_{Zq}$



# FCNC in ttbar events, t $\rightarrow$ Zq

- ▶ **Upper 95% CL limits for  $B(t \rightarrow Zq)$**
- ▶ ~ four times lower than the previous  
in this channel

$B(t \rightarrow Zq)$	8 TeV	7 TeV + 8 TeV
Expected upper limit	<0.10%	<0.09%
Observed upper limit	<0.06%	<0.05%
1 $\sigma$ boundary	0.06–0.13%	0.06–0.13%
2 $\sigma$ boundary	0.05–0.20%	0.05–0.18%

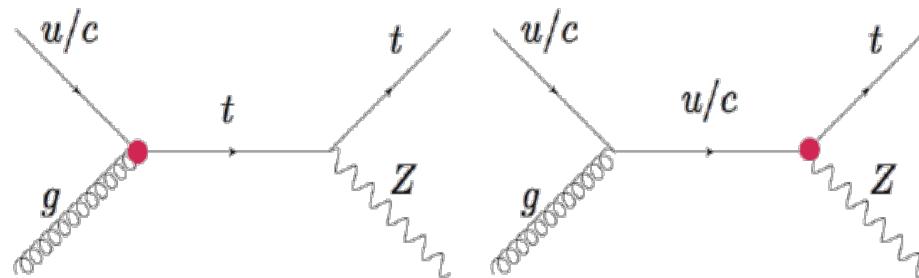
t  $\rightarrow$ Zq decays at a high rate would indicate BSM physics  
Extensions of SM predict enhancement of  $B(t \rightarrow Zq)$  as large as  $O(10^{-4})$

- ▶ Projections of the sensitivity of the analysis at high energy and luminosity

$B(t \rightarrow Zq)$	19.5 fb $^{-1}$ @ 8 TeV	300 fb $^{-1}$ @ 14 TeV	3000 fb $^{-1}$ @ 14 TeV
Exp. bkg. yield	3.2	26.8	268
Expected limit	< 0.10%	< 0.027%	< 0.010%
1 $\sigma$ range	0.06 – 0.13%	0.018 – 0.038%	0.007 – 0.014%
2 $\sigma$ range	0.05 – 0.20%	0.013 – 0.051%	0.005 – 0.020%

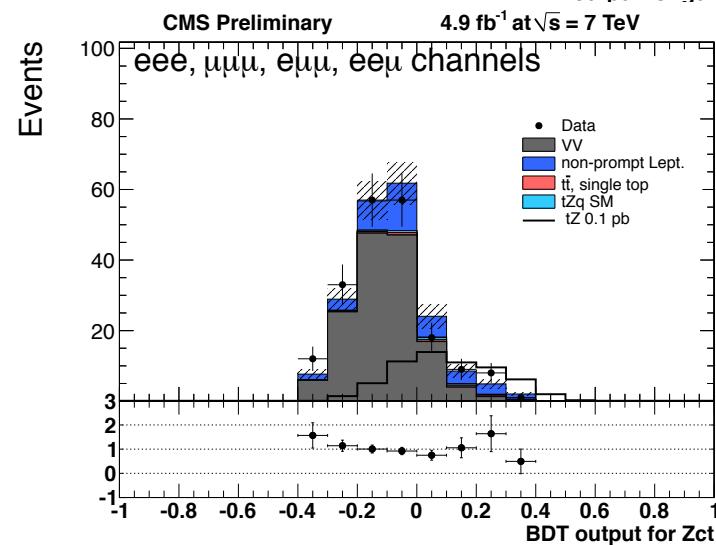
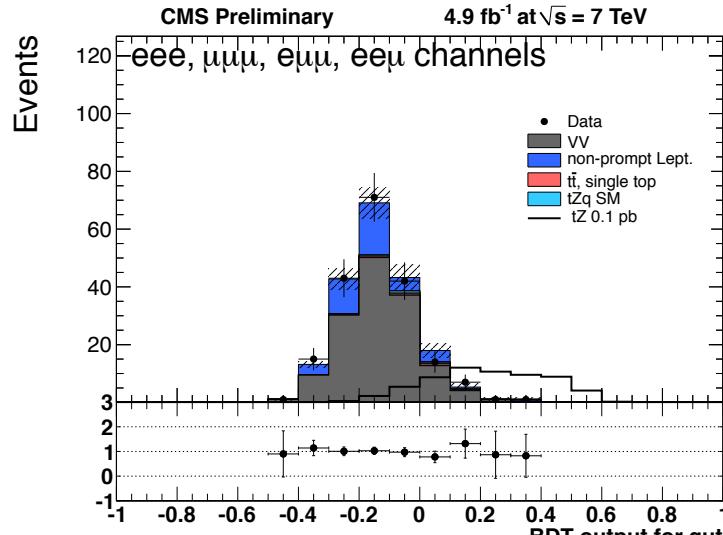
# FCNC in single top events, tZ

- ▶ 7 TeV
- ▶ Single top quark produced in association with a Z (tZ),
- ▶ Signature sensitive to both **Zqt** and **gqt** anomalous vertices



- ▶ Event selection:
  - ▶ 3 leptons, ( $e, \mu$ ) (one pair compatible with a  $Z$  decay), exactly 1 b-jet
  - ▶ Cut on  $m_T(W)$
- ▶ Main background from fake leptons ( $Z+jets$ ):
  - ▶ shapes from data, inverting third lepton isolation + low MET
- ▶ Analysis based on a BDT discriminant
  - ▶ 11 variables, all the leptonic final states together

# FCNC in single top events, tZ



Limits on couplings and branching fractions:

couplings	Expected	Observed	$\mathcal{B}(t \rightarrow gq/Zq)$
$\kappa_{gut}/\Lambda$	0.096	0.096	0.56 %
$\kappa_{gct}/\Lambda$	0.427	0.354	7.12 %
$\kappa_{Zut}/\Lambda$	0.492	0.451	0.51 %
$\kappa_{Zct}/\Lambda$	2.701	2.267	11.40 %

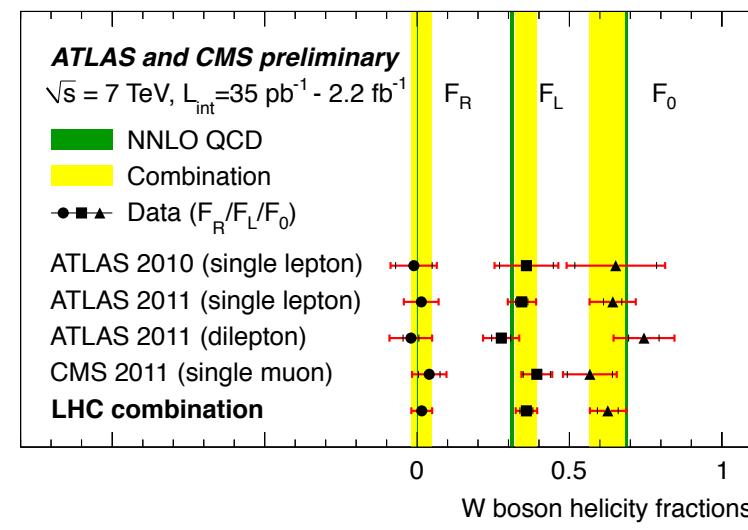
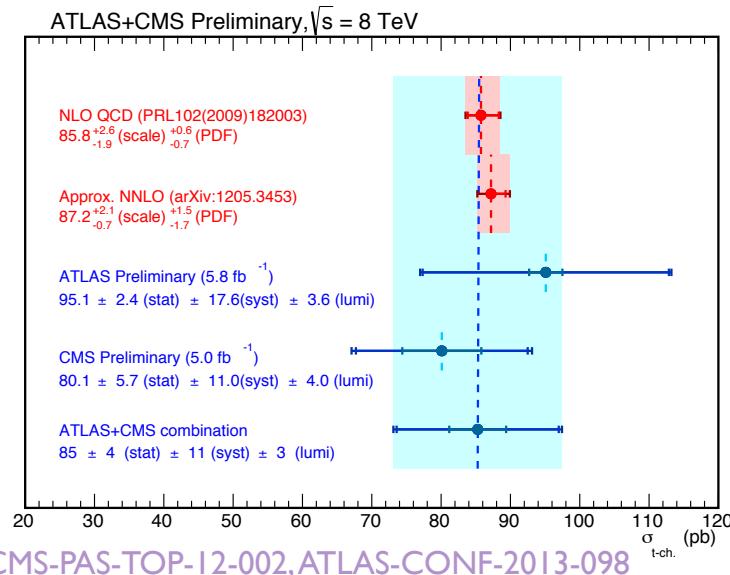
Ztq promising

# TOP LHC Working Group

- ▶ There's an open dialogue between the LHC experiments and the theory group in the context of the TOP LHC working group



- ▶ ATLAS and CMS coordinate efforts in top physics to provide combination of experimental results
- ▶ 5 preliminary results (top cross-section, mass, single top, W-helicity)



# Summary I

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- ▶ Single top quark production was observed for the first time in 2009 by the Tevatron
- ▶ It has been studied in CMS in the three main production modes
  - ▶ **t-channel:** observed in early data, **well established at 7 and 8TeV**
  - ▶ **tW associated production:** never accessible before, CMS has the **first observation of the process** at 8TeV, evidence was found at 7TeV
  - ▶ **s-channel:** extremely challenging signature, **work is in progress**, with a first result in this channel at 8TeV
- ▶ Search for new physics (Anomalous couplings, FCNC) also performed in single top events
- ▶ The t-channel sample is so large that it can already be exploited to perform **measurements of top properties**
  - ▶  $|V_{tb}|$ , W-helicity fractions, top polarization (more to come)
  - ▶ Moving towards a full characterization of the top quark using all its production modes

# Summary II

- ▶ For the full characterization of the top quark, the measurement of top properties is necessary
  - ▶ Is the top a SM one?
  - ▶ Will we find surprises?
- ▶ Wide catalog of top properties measured in CMS
- ▶ Reported today:
  - ▶ **W-helicity fractions**
    - ▶ Related to the angular distribution of the top decays, used to set limits on Anomalous Couplings
  - ▶ **Top polarization and spin correlations**
    - ▶ From the angular correlations of the decay products in  $t\bar{t}$  events
  - ▶ **Charge asymmetry**
    - ▶ Using the kinematics of the top and anti-top quarks (Tevatron has a  $2\sigma$  effect with respect to the SM)
  - ▶ **Flavor Changing Neutral Currents** in top decays and production





## Backup slides



# t-channel at $\sqrt{s} = 8$ TeV: Systematics

Uncertainty source	$\sigma_{t\text{-ch.}} (\%)$	Uncertainty source	$\sigma_{t\text{-ch.}(t)} (\%)$	$\sigma_{t\text{-ch.}(\bar{t})} (\%)$	$R_{t\text{-ch.}} (\%)$
Stat. uncertainty	$\pm 2.7$	Stat. uncertainty	$\pm 2.7$	$\pm 4.9$	$\pm 5.1$
JES, JER, MET, and pileup	$\pm 4.3$	JES, JER, MET, and pileup	$\pm 4.2$	$\pm 5.2$	$\pm 1.1$
b-tagging and mis-tag	$\pm 2.5$	b-tagging and mis-tag	$\pm 2.6$	$\pm 2.6$	$\pm 0.2$
Lepton reconstruction/trig.	$\pm 0.6$	Lepton reconstruction/trig.	$\pm 0.5$	$\pm 0.5$	$\pm 0.3$
QCD multijet extraction	$\pm 2.3$	QCD multijet extraction	$\pm 1.6$	$\pm 3.5$	$\pm 1.9$
W+jets, $t\bar{t}$ extraction	$\pm 2.2$	W+jets, $t\bar{t}$ extraction	$\pm 1.7$	$\pm 3.6$	$\pm 3.0$
Other backgrounds ratio	$\pm 0.3$	Other backgrounds ratio	$\pm 0.1$	$\pm 0.2$	$\pm 0.6$
Signal modeling	$\pm 5.7$	Signal modeling	$\pm 4.9$	$\pm 9.4$	$\pm 6.1$
PDF uncertainty	$\pm 1.9$	PDF uncertainty	$\pm 2.5$	$\pm 4.8$	$\pm 6.2$
Simulation statistics	$\pm 0.7$	Simulation statistics	$\pm 0.6$	$\pm 1.1$	$\pm 1.2$
Luminosity	$\pm 2.6$	Luminosity	$\pm 2.6$	$\pm 2.6$	-
Total systematic	$\pm 8.9$	Total systematic	$\pm 8.2$	$\pm 13.4$	$\pm 9.6$
Total uncertainty	$\pm 9.3$	Total uncertainty	$\pm 8.7$	$\pm 14.2$	$\pm 10.9$
Measured cross section	$83.6 \pm 7.8$ pb	Measured cross section or ratio	$53.8 \pm 4.7$ pb	$27.6 \pm 3.9$ pb	$1.95 \pm 0.21$

# tW at $\sqrt{s} = 8$ TeV: BDT Variables

---

Table 2: Variables used for BDT training

Variable Name	Description
# of loose jets	Number of loose jets, $p_T > 20$ GeV, $ \eta  < 4.9$
# of central loose jets	Number of loose jets, $p_T > 20$ GeV, $ \eta  < 2.4$
# of b-tagged loose jets	Number of loose jets, $p_T > 20$ GeV, q <sub>b</sub> -tagged, $ \eta  < 2.4$
$p_T^{\text{sys}}$	Vector sum of $p_T$ of leptons, jet, and $E_T^{\text{miss}}$
$H_T$	Scalar sum of $p_T$ of leptons, jet, and $E_T^{\text{miss}}$
$p_T(\text{jet})$	$p_T$ of the leading, tight, b-tagged jet
$p_T(\text{loose jet})$	$p_T$ of leading loose jet, defined as 0 for events with no loose jet present
$p_T^{\text{sys}}/H_T$	Ratio of $p_T^{\text{sys}}$ to $H_T$ for the event
$m_{\text{sys}}$	Invariant mass of the combination of the leptons, jet, and $E_T^{\text{miss}}$
Centrality( $j\ell\ell$ )	Centrality of jet and leptons, defined as ratio of transverse to total energy
$p_T(\text{leptons})/H_T$	Ratio of scalar sum of $p_T$ of the leptons to the $H_T$ of full system
$p_T(j\ell\ell)$	Vector sum of $p_T$ of jet and leptons
$E_T^{\text{miss}}$	Missing transverse energy in the event

# tW at $\sqrt{s} = 8$ TeV: Systematics

Table 3: Contributions to the systematic uncertainty in the measured cross section. The values are estimated by fixing each source one at a time and evaluating the change in the measured cross section uncertainty. Systematic uncertainties apply to all processes unless specifically noted.

Systematic uncertainty	$\Delta\sigma$ (pb)	$\Delta\sigma/\sigma$	Notes
ME/PS matching thresholds	3.3	14%	Matching threshold 2× and 1/2× nominal 20 GeV value in $t\bar{t}$ simulation
Renormalization/factorization scale	2.9	12%	Scale value 2× and 1/2× nominal value of $m_t^2 + \sum p_T^2$ in $t\bar{t}$ and tW simulation
Top-quark mass	2.2	9%	$m_t$ varied in tW and $t\bar{t}$ simulation by $\pm 2$ GeV
Fit statistical	1.9	8%	Remaining uncertainty in fit when all other systematic uncertainties are removed
Jet energy scale	0.9	4%	Jet energy scale varied up/down
Luminosity	0.7	3%	2.6% uncertainty in the measured luminosity
Z+jets data/simulation scale factor	0.6	3%	Varying scale factors used for correcting Z+jets $E_T^{\text{miss}}$ simulation
tW DR/DS scheme	0.5	2%	Difference between DR and DS scheme used for defining tW signal
$t\bar{t}$ cross section	0.4	2%	Uncertainty in the cross section of $t\bar{t}$ production
Lepton identification	0.4	2%	Uncertainty in scale factors for lepton efficiencies between data/simulation
PDF	0.4	2%	From choice of PDF
Jet energy resolution	0.2	1%	Energy resolution for jets varied up/down
b-tagging data/simulation scale factor	0.2	<1%	Variations in scale factors
$t\bar{t}$ spin correlations	0.1	<1%	Difference between $t\bar{t}$ simulation with/without spin correlations
Pileup	0.1	<1%	Varying effect of pileup
Top-quark $p_T$ reweighting	0.1	<1%	Uncertainty due to differences in top quark $p_T$ between data and $t\bar{t}$ simulation
$E_T^{\text{miss}}$ modeling	0.1	<1%	Uncertainty in amount of unclustered $E_T^{\text{miss}}$
Lepton energy scale	0.1	<1%	Uncertainty in energy of leptons
Total	5.5	24%	

# s-channel at $\sqrt{s} = 8$ TeV: Variables

Variable	Description
$m_T$	tranverse W boson mass
$\Delta\Phi_{top,b'}$	difference in azimuthal angle between top quark and recoiled b-tagged jet
$\cancel{E}_T$	missing transverse energy
$M_{\ell b2}$	invariant mass of the lepton and the second-to-leading b-tagged jet
$\cos\theta^*$	cosine of the angle between the lepton and the b-tagged jet recoiling against the top quark, in the top-quark rest frame
$p_T^{bb}$	vector sum of $p_T$ of the two b-tagged jets
$\Delta R_{bb} (*)$	angular separation between the two b-tagged jets
$p_T^\ell$	transverse momentum of the lepton
$m_{\ell vb\text{-best}}$	invariant mass of lepton, neutrino and one of the b-tagged jets reconstructed with the best-mass top method, as described in Sec.2
$\Delta R_{b'\ell}$	angular separation between the b-tagged jet recoiling against the top quark and the lepton
$H_T$	scalar sum of $p_T$ of all jets

$$(*) \quad \Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

Variable	Description
$p_T^{bb}$	vector sum of $p_T$ of the two b-tagged jets
$m_{\ell vb\text{-best}}$	invariant mass of lepton, neutrino and one of the b-tagged jets reconstructed with the best-mass top method, as described in Sec.2
$m_T$	tranverse W boson mass
$M_{\ell b2}$	invariant mass of the lepton and the second-to-leading b-tagged jet
$\cancel{E}_T$	missing transverse energy
$\Delta\Phi_{top,b'}$	difference in azimuthal angle between top quark and the recoiled b-tagged jet
$\cos\theta_l$	cosine of the angle between the lepton and the beam axis in top-quark rest frame
$\Delta R_{bb}$	angular separation between the two b-tagged jets
$H_T$	scalar sum of $p_T$ of all jets
$p_T^\ell$	transverse momentum of the lepton

2jet-2tag electron channel

2jet-2tag muon channel

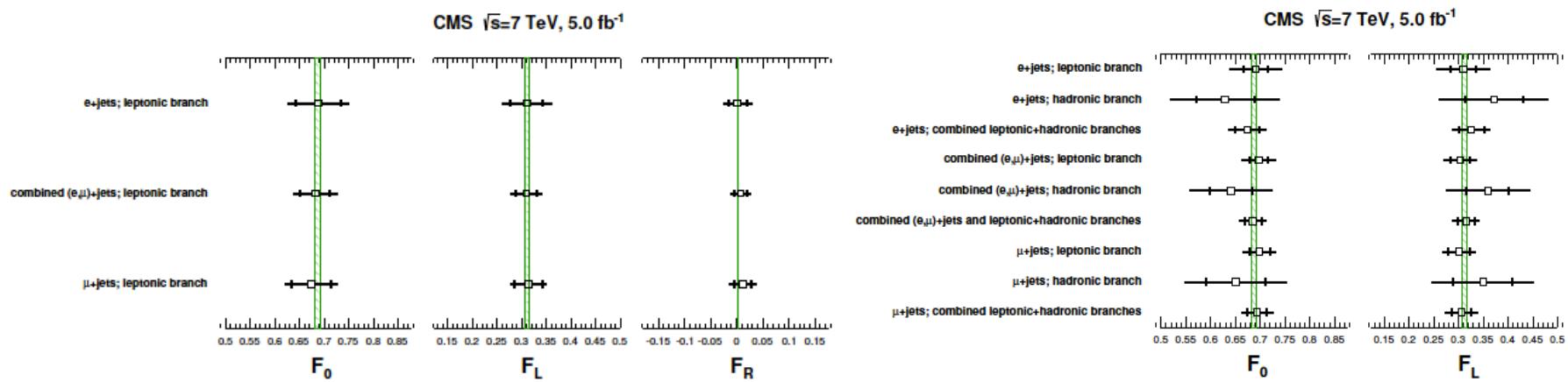
# W-helicity in lepton+jets tt events (7TeV)

Systematic Uncertainties	$\mu+\text{jets} (\cos \theta^*)$			$e+\text{jets} (\cos \theta^*)$			$\ell+\text{jets} (\cos \theta^*)$		
	3D fit		2D fit	3D fit		2D fit	3D fit		2D fit
	$\pm \Delta F_0$	$\pm \Delta F_L$	$\pm \Delta F_0$	$\pm \Delta F_0$	$\pm \Delta F_L$	$\pm \Delta F_0$	$\pm \Delta F_0$	$\pm \Delta F_L$	$\pm \Delta F_0$
JES	0.005	0.003	0.001	0.006	0.002	0.003	0.006	0.003	0.001
JER	0.009	0.005	0.001	0.014	0.009	0.003	0.011	0.007	0.001
Lepton eff.	0.001	0.001	0.001	0.009	0.012	0.015	0.001	0.002	0.002
b-tag eff.	0.001	0.001	$< 10^{-3}$	$< 10^{-3}$	$< 10^{-3}$	0.001	0.001	$< 10^{-3}$	$< 10^{-3}$
Pileup	0.013	0.011	0.008	0.008	0.007	0.005	0.002	$< 10^{-3}$	0.008
Single-t bkg.	0.004	$< 10^{-3}$	0.003	0.004	$< 10^{-3}$	0.004	0.004	0.001	0.003
W+jets bkg.	0.019	0.007	0.006	0.009	0.006	0.022	0.013	0.004	0.006
DY+jets bkg.	0.002	0.001	0.001	0.001	$< 10^{-3}$	0.001	0.001	$< 10^{-3}$	0.001
MC statistics	0.016	0.012	0.009	0.019	0.015	0.012	0.016	0.012	0.010
Top-quark mass	0.011	0.008	0.007	0.025	0.018	0.014	0.016	0.011	0.019
t̄t scales	0.013	0.009	0.007	0.015	0.018	0.030	0.009	0.009	0.011
t̄t match. scale	0.004	0.001	0.006	0.010	0.013	0.016	0.011	0.010	0.008
PDF	0.002	0.001	0.003	0.004	0.002	0.002	0.002	$< 10^{-3}$	0.003

**Table 2.** Summary of the systematic uncertainties for the analysis using only the leptonic branch of the event, for the 3D fit, fitting  $F_0, F_L$ , and  $\mathcal{F}_{t\bar{t}}$  (columns 2–3 for muon+jets analysis, 5–6 for electron+jets analysis, and 8–9 for the combination of both decay modes); and the 2D fit, fitting  $F_0$  and  $\mathcal{F}_{t\bar{t}}$  only (column 4 for muon+jets analysis, 7 for electron+jets analysis, and 10 for the combination of both decay modes). The numbers given correspond to the absolute uncertainty with respect to the central analysis:  $\Delta F = (F^{\text{central}} - F^{\text{check}})$ .

# W-helicity in lepton+jets tt events (7TeV)

Leptonic branch: $\cos \theta^*$					
Fit	Channel	$F_0 \pm (\text{stat.}) \pm (\text{syst.})$	$F_L \pm (\text{stat.}) \pm (\text{syst.})$	$F_R \pm (\text{stat.}) \pm (\text{syst.})$	$\rho_{0L}^{\text{stat}}$
3D	$\mu+\text{jets}$	$0.674 \pm 0.039 \pm 0.035$	$0.314 \pm 0.028 \pm 0.022$	$0.012 \pm 0.016 \pm 0.020$	-0.95
3D	$e+\text{jets}$	$0.688 \pm 0.045 \pm 0.042$	$0.310 \pm 0.033 \pm 0.037$	$0.002 \pm 0.017 \pm 0.023$	-0.95
2D	$\mu+\text{jets}$	$0.698 \pm 0.021 \pm 0.019$	$0.302 \pm 0.021 \pm 0.019$	fixed at 0	-1
2D	$e+\text{jets}$	$0.691 \pm 0.025 \pm 0.047$	$0.309 \pm 0.025 \pm 0.047$	fixed at 0	-1
Hadronic branch: $ \cos^{\text{had}} \theta^* $					
Fit	Channel	$F_0 \pm (\text{stat.}) \pm (\text{syst.})$	$F_L \pm (\text{stat.}) \pm (\text{syst.})$	$F_R \pm (\text{stat.}) \pm (\text{syst.})$	$\rho_{0L}$
2D	$\mu+\text{jets}$	$0.651 \pm 0.060 \pm 0.084$	$0.349 \pm 0.060 \pm 0.084$	fixed at 0	-1
2D	$e+\text{jets}$	$0.629 \pm 0.060 \pm 0.093$	$0.371 \pm 0.060 \pm 0.093$	fixed at 0	-1



# W-helicity in lepton+jets tt events (8TeV)

Systematics	$\pm \Delta F_0$	$\pm \Delta F_L$
JES	0.002	<0.001
JER	0.004	0.003
Lepton eff.	0.001	<0.001
b-tag eff.	0.001	<0.001
Pileup	<0.001	0.001
Single-t bkg.	0.002	<0.001
DY+jets bkg.	0.001	<0.001
W+jets bkg.	0.009	<0.001
MC statistics	0.003	0.002
Top-quark mass	0.012	0.008
t̄t scales	0.012	0.012
t̄t match. scale	0.012	0.008
t̄t $p_T$ reweig.	0.001	<0.001
$E_T^{\text{miss}}$ shape	0.004	0.018
Total syst.	0.023	0.024

# W-helicity in Single top signatures

Systematic source	$\sqrt{s} = 8 \text{ TeV}$		$\sqrt{s} = 7 \text{ TeV}$	
	$\Delta F_L$	$\Delta F_0$	$\Delta F_L$	$\Delta F_0$
JES	0.006	0.006	0.020	0.020
JER	0.008	0.003	0.015	0.010
unclustered energy	0.013	0.003	0.015	0.015
pileup	0.002	0.003	0.004	0.000
b-flavored scale factor	0.004	0.006	0.009	0.009
non-b-flavored scale factor	0.004	0.007	0.002	0.001
single-top generator	0.008	0.014	0.004	0.004
$Q^2$ scale	0.009	0.012	0.040	0.007
$m_{\text{top}}$	0.005	0.006	0.010	0.010
PDF	0.005	0.005	0.000	0.000
$t\bar{t}$ normalization	0.002	0.003	0.008	0.008
QCD shape	0.002	0.002	0.004	0.004
W+jets shape	0.008	0.010	0.010	0.010
integrated luminosity	0.003	0.003	0.007	0.007
SM W-helicity reference	0.004	0.003	0.001	0.002
total systematic uncertainty (w/o generator)	0.022	0.021	0.054	0.035
total systematic uncertainty	0.024	0.026	0.054	0.035

Table 2: Summary of systematics.

$$\begin{aligned} F_L &= 0.24 \pm 0.11(\text{stat.}) \pm 0.05(\text{syst.}), \\ F_0 &= 0.78 \pm 0.17(\text{stat.}) \pm 0.03(\text{syst.}), \\ F_R &= -0.02 \pm 0.09(\text{stat.}) \pm 0.04(\text{syst.}). \end{aligned}$$

7TeV

$$\begin{aligned} F_L &= 0.327 \pm 0.089(\text{stat.}) \pm 0.024(\text{syst.}), \\ F_0 &= 0.668 \pm 0.149(\text{stat.}) \pm 0.026(\text{syst.}), \\ F_R &= 0.005 \pm 0.072(\text{stat.}) \pm 0.020(\text{syst.}). \end{aligned}$$

8TeV

Systematic source	$\Delta F_L$	$\Delta F_0$
JES	0.007	0.007
JER	0.011	0.003
unclustered energy	0.018	0.010
pileup	0.002	0.002
b-flavored scale factor	0.003	0.001
non-b-flavored scale factor	0.001	0.002
single-top generator	0.005	0.009
$Q^2$ scale	0.006	0.008
$m_{\text{top}}$	0.001	0.001
PDF	0.003	0.003
$t\bar{t}$ normalization	0.003	0.002
QCD shape	0.003	0.003
W+jets shape	0.012	0.011
integrated luminosity	0.010	0.010
SM W-helicity reference	0.002	0.001
total systematic uncertainty	0.030	0.023

Table 3: Summary of systematics in combined likelihood.

# Polarization and spin in $t\bar{t}$ dilepton

Table 1: Systematic uncertainties in the background-subtracted and unfolded values of  $A_{\Delta\phi}$ ,  $A_{c_1c_2}$ , and  $A_p$ .

Asymmetry variable	$A_{\Delta\phi}$	$A_{c_1c_2}$	$A_p$
Jet energy scale	0.002	0.012	0.009
Lepton energy scale	0.001	0.001	0.001
Background	0.003	0.001	0.006
Fact. and renorm. scales	0.001	0.010	0.004
Top-quark mass	0.002	0.009	0.016
Parton distribution functions	0.002	0.002	0.001
Jet energy resolution	< 0.001	< 0.001	< 0.001
Pileup	0.002	0.002	0.004
b-tagging scale factor	< 0.001	< 0.001	0.001
Lepton selection	< 0.001	< 0.001	< 0.001
$\tau$ decay polarization	0.001	0.002	0.001
Unfolding	0.004	0.020	0.002
Total systematic uncertainty	0.007	0.027	0.020
Top $p_T$ reweighting uncertainty	0.012	0.010	0.008

# Top polarization in single top

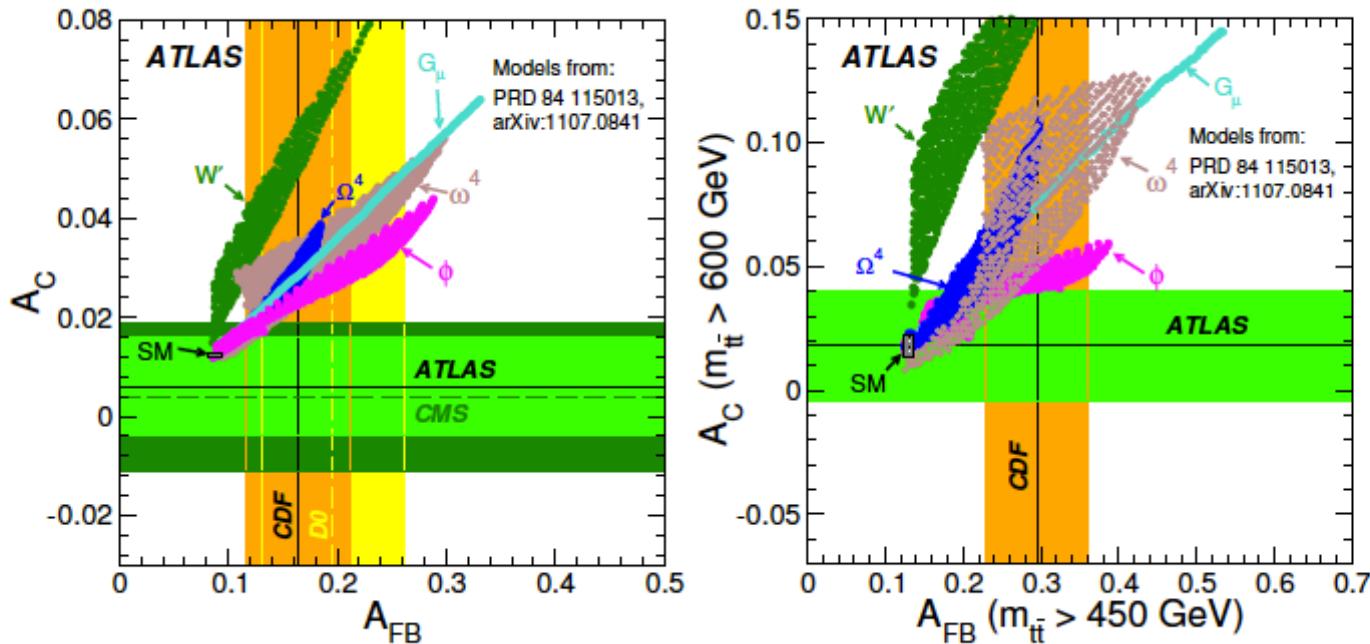
Uncertainty source	$\delta A_l^\mu$	$\delta A_l^e$
generator	0.025	0.009
$Q^2$ scale $t$ -channel	0.024	0.055
$Q^2$ scale, $t\bar{t}$	0.015	0.005
$Q^2$ scale, $W+jets$	0.036	0.038
top quark mass	0.058	0.042
$W+jets$ shape	0.016	0.007
$W+jets$ flavour	0.005	0.008
top $p_T$ , $t\bar{t}$	0.010	0.025
matching, $t\bar{t}$	0.028	0.052
matching, $W+jets$	0.025	0.038
PDF	0.013	0.014
JES	0.074	0.074
JER	0.016	0.179
unclustered $E_T$	0.013	0.006
lepton ID and isolation	0.001	0.002
lepton trigger	0.001	0.002
pileup	0.015	0.002
b tagging	0.007	0.009
mistagging	0.001	0.003
lepton weight	0.001	0.009
anti-isolation range of QCD	0.010	0.053
QCD fraction	0.092	0.028
background fractions	0.007	0.018
unfolding bias	0.002	0.003
total systematics	0.15	0.23
statistical	0.07	0.11
total	0.17	0.26

$$A_l^\mu = 0.42 \pm 0.07(stat.) \pm 0.15(syst.),$$

$$A_l^e = 0.31 \pm 0.11(stat.) \pm 0.23(syst.).$$

Table 3: List of systematic uncertainties and their impact to the measurement of  $A_l$  for the muon ( $\delta A_l^\mu$ ) and electron channel ( $\delta A_l^e$ ).

# Charge asymmetry



**Figure 3.** Measured forward–backward asymmetries  $A_{FB}$  at Tevatron and charge asymmetries  $A_C$  at LHC, compared with the SM predictions (black box) as well as predictions incorporating various potential new physics contributions (as described in the figure) [8, 60]. In both plots, where present, the horizontal bands and lines correspond to the ATLAS (light green) and CMS (dark green) measurements, while the vertical ones correspond to the CDF (orange) and D0 (yellow) measurements. The inclusive  $A_C$  measurements are reported in the left plot. In the right plot a comparison is reported between the  $A_{FB}$  measurement by CDF for  $m_{t\bar{t}} > 450$  GeV and the  $A_C$  measurement for  $m_{t\bar{t}} > 600$  GeV.

# Charge asymmetry: dilepton tt events

Table 3: Systematic uncertainties in the unfolded values of  $A_C$  and  $A_C^{\text{lep}}$  from the sources listed.

Variable	$A_C$	$A_C^{\text{lep}}$
<b>Experimental uncertainties</b>		
Jet energy scale	0.003	0.001
Lepton energy scale	<0.001	<0.001
Background	0.001	0.001
Jet energy resolution	<0.001	<0.001
Pileup	<0.001	0.001
Scale factor for b tagging	<0.001	<0.001
Lepton selection	<0.001	<0.001
<b>tt modelling uncertainties</b>		
Fact. and renorm. scales	0.004	0.005
Top-quark mass	0.001	0.001
Parton distribution functions	<0.001	<0.001
$\tau$ -lepton decay	<0.001	<0.001
Top-quark $p_T$ reweighting	0.001	<0.001
Unfolding	0.006	0.001
Total systematic uncertainty	0.008	0.006

# Charge asymmetry: lepton+jets tt events

Table 2: Systematic uncertainties for the inclusive measurement of  $A_C$  and ranges of systematic uncertainties for the differential measurements.

Systematic uncertainty	shift in inclusive $A_C$	range of shifts in differential $A_C$
Lepton ID/sel. efficiency	JES	0.001
	JER	0.001
	Pileup	0.001
	b tagging	0.000
	Generator	0.002
	Hadronization	0.003
	$p_T$ weighting	0.000
	$Q^2$ scale	0.001
	W+jets	0.002
	Multijet	0.001
Unfolding	PDF	0.001
	Total	0.001
		0.002
		0.004
	Total	0.006
		0.007 – 0.022

# FCNC in ttbar events, $t \rightarrow Zq$

Table 3: Summary of the systematic uncertainties for the signal selection acceptance. An additional 2.6% uncertainty is due to the luminosity measurement.

Source	Uncertainty %
Renormalization/factorization scales	12
Parton distribution functions	7
$t\bar{t}$ cross section	7
Parton matching threshold	6
Lepton selection	6
Trigger efficiency	5
b-tagging	5
Top-quark mass	4
Jet energy scale	4
Missing transverse energy resolution	3
Pileup modeling	3
Total	20

# Event selections

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- ▶ t-channel 8TeV (paper TOP-12-038)
  - ▶ 1 isolated lepton,  $\mu(e)$   $p_T > 26$  ( $30$ ) GeV;  $|\eta| < 2.1$  ( $2.4$ )
  - ▶ Jets: Anti-kt (0.5)  $p_T > 40$  GeV,  $|\eta| < 4.5$ ; b-tagging
  - ▶  $m_T(W) > 50$  GeV ( $\mu$ ) / MET  $> 45$  (e)
- ▶ tW observation ([arXiv:1401.2942](#))
  - ▶ 2 leptons, opposite charge  $\mu(e)$   $p_T > 20$  GeV,  $|\eta| < 2.4$ ( $2.5$ ), isolated
  - ▶ 1 or 2 jets:  $p_T > 30$  GeV,  $|\eta| < 2.4$  corrected  
(+ loose jets: failing  $p_T/|\eta|$  ;  $p_T > 20$  GeV,  $|\eta| < 4.9$ ), b-tag
  - ▶  $m_{ll} > 20$  GeV
  - ▶ ee/ $\mu\mu$ : veto events with  $81 < m_{ll} < 101$  GeV  
MET  $> 50$  GeV
- ▶ s-channel ([CMS-PAS-TOP-13-009](#))
  - ▶ 1 isolated  $\mu(e)$   $p_T (E_T) > 26$  ( $30$ ) GeV,  $|\eta| < 2.1$  ( $2.4$ )
  - ▶ 2 b-tagged jets  $p_T > 40$  GeV,  $|\eta| < 4.5$

# Event selections (II)

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- ▶ W-helicity (7TeV) [JHEP 10 \(2013\) 167](#)
  - ▶ 1 isolated lepton  $\mu$  ( $e$ ) with  $p_T > 25$  (30) GeV;  $|\eta| < 2.1$  (2.5)
  - ▶  $\geq 4$  Jets  $p_T > 30$  GeV,  $|\eta| < 2.5$ ; at least 2 b-tagged
  - ▶  $m_T(W) > 30$
- ▶ Spin asymmetries ( $t\bar{t}$  dilep) [arxiv:1311.3924](#)
  - ▶ 2 leptons,  $e$  ( $\mu$ ) with  $p_T > 20$  GeV  $|\eta| < 2.5$  (2.4), isolated (vetoing  $Z$  mass window for  $ee/\mu\mu$ )
  - ▶  $\geq 2$  jets  $p_T > 30$  GeV  $|\eta| < 2.5$ ;  $\geq 1$  b-tagged
  - ▶ MET  $> 40$ GeV  $ee/\mu\mu$
- ▶ Charge asymmetry [arXiv:1402.3803](#)
  - ▶ 2 isolated leptons  $p_T > 20$ ,  $|\eta| < 2.4$ , removing  $Z$  mass window ( $ee/\mu\mu$ )
  - ▶  $\geq 2$  Jets  $p_T > 30$ ,  $|\eta| < 2.4$ ;  $\geq 1$  btag
  - ▶ MET  $> 40$

# Event selections (III)

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- ▶ Charge Asymetry [CMS-PAS-TOP-12-033](#)
  - ▶ 1 isolated lepton:  $\mu$  ( $e$ )  $p_T > 26$  ( $30$ ) GeV;  $|\eta| < 2.1$  ( $2.5$ )
  - ▶  $\geq 4$  Jets  $p_T > 30$  GeV,  $|\eta| < 2.5$ ; at least 1 b-tagged
- ▶ FCNC  $t\bar{t}$ 
  - ▶ 3 leptons,  $e$  ( $\mu$ )  $p_T > 20$  GeV,  $|\eta| < 2.5$  ( $2.4$ ) (pair compatible with  $Z$  decay)
  - ▶  $\geq 2$  jets  $p_T > 30$  GeV,  $|\eta| < 2.4$ ; 1 b-tagged
  - ▶ MET  $> 30$ GeV
- ▶ FCNC  $tZ$ 
  - ▶ 3 leptons,  $e$  ( $\mu$ )  $p_T > 20$  GeV  $|\eta| < 2.5$  ( $2.4$ ) (one pair compatible with a  $Z$  decay)
  - ▶ Jets  $p_T > 30$  GeV and  $|\eta| < 2.4$ ; exactly 1 b-jet
  - ▶  $m_T(W) > 20$ GeV