

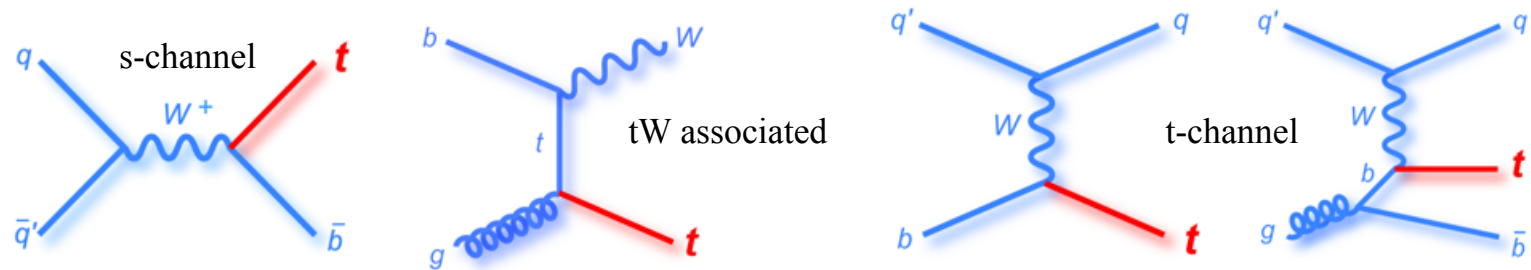


# Measurement of single top quark processes with CMS

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on behalf of the CMS Collaboration*



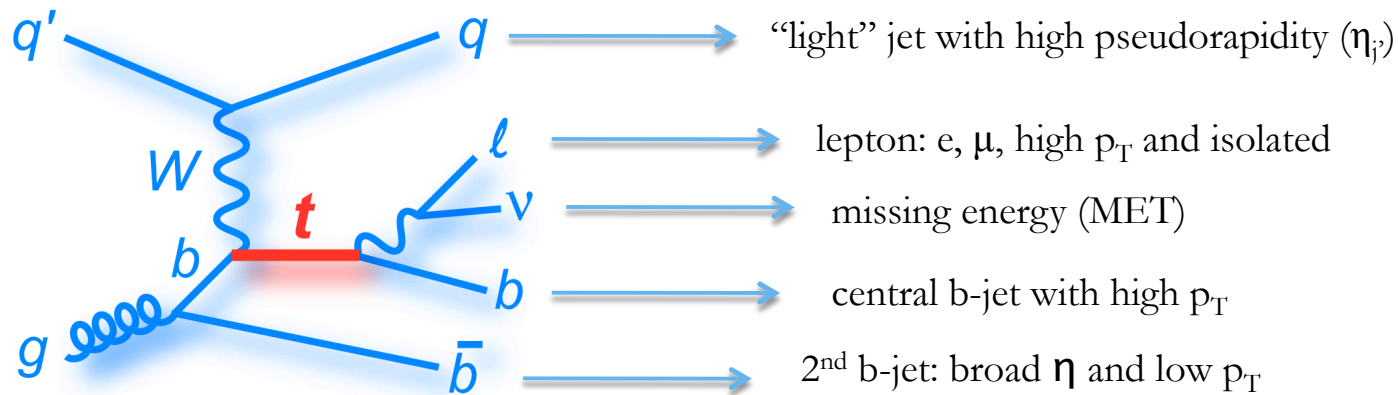
Top quarks produced singly via electroweak interaction:



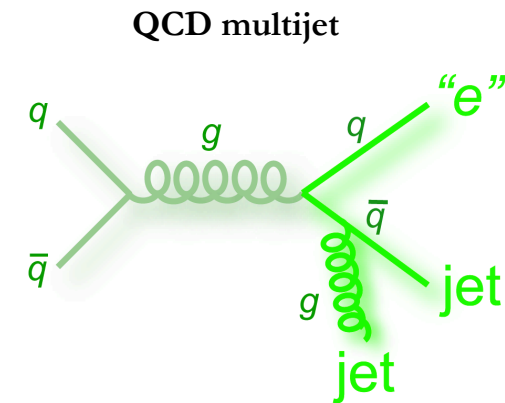
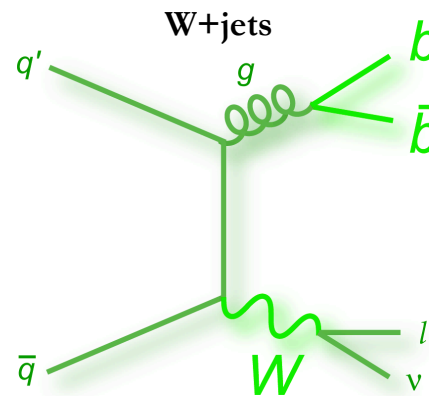
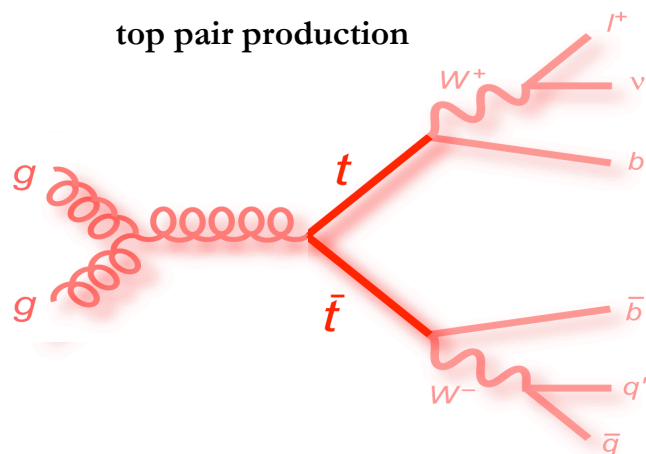
Cross sections (pb) (top mass = 173 GeV)	<b>s-channel</b> approx. NNLO, Phys. Rev. D 81, 054028 (2010), N. Kidonakis	<b>tW associated production</b> approx. NNLO, arXiv:1205.3453, N. Kidonakis	<b>t-channel</b> approx. NNLO, Phys. Rev. D 83, 091503 (2011), N. Kidonakis
LHC: pp @ 7 TeV	4.56	15.6	65.9
LHC: pp @ 8 TeV	5.55	22.2	87.2
Tevatron $p\bar{p}$ @ 1.96 TeV	1.04	0.22	2.08

- Standard model measurements: inclusive cross sections, top/anti-top charge ratio, top quark polarization, top mass, W-helicity,  $|V_{tb}|$ , PDFs
- Beyond standard model searches: FCNC, anomalous couplings, heavy bosons ( $W'$  and charged Higgs)

- t-channel
  - Inclusive cross section
  - Top charge asymmetry
  - Top polarization
- $tW$  associated production (cross section)
- s-channel production (upper limit)
- $W$  helicity
- Search for FCNC:  $tZ$  associated production



**Main backgrounds (examples):**



The phase space region with  $n$  jets,  $m$  of which are b-tagged is referred to as “ $njmt$ ”

- **Template analysis**  $|\eta_j|$

- fit to the pseudorapidity of the recoil jet in the signal region  $130 < m_{\text{top}} < 220$  GeV

- **Selection**

- exactly one muon with  $p_T > 26$  GeV
- two jets ( $\text{anti-}k_T$ ) with  $p_T > 60$  GeV, one b-tagged
- $m_T(W) > 50$  GeV

- Data-driven QCD, W+jets and  $t\bar{t}$

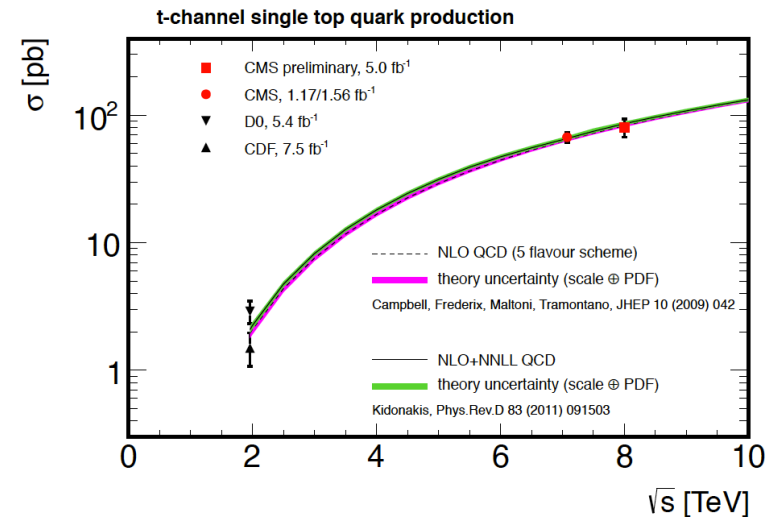
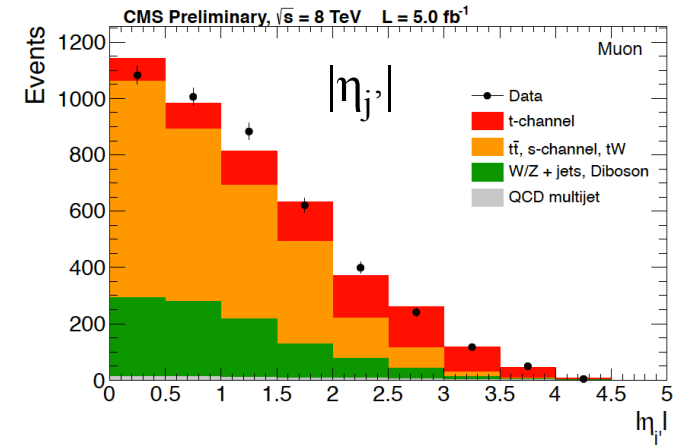
**Results:**

$$\sigma_{\text{t-channel}} = 80.1 \pm 5.7(\text{stat.}) \pm 9.0(\text{syst.}) \pm 6.3(\text{theor.}) \pm 4.0(\text{lumi.}) \text{ pb} = \mathbf{80.1 \pm 13.0 \text{ pb}}$$

$$|f_{L_V}^t \cdot V_{tb}| = \mathbf{0.96 \pm 0.08(\text{exp.}) \pm 0.02(\text{th.}),}$$

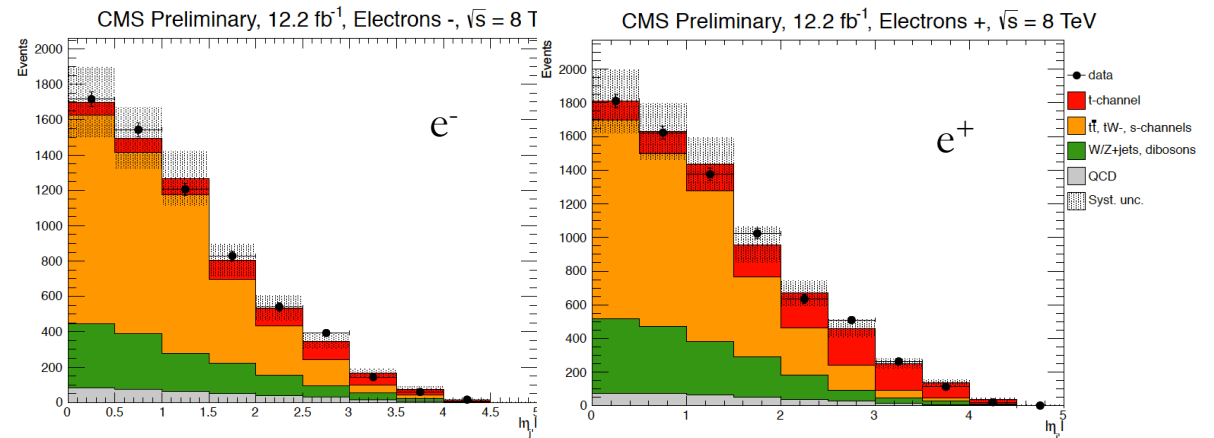
constrained  $|V_{tb}| > 0.81$  at 95%CL

Integrated luminosity = 5.0 fb<sup>-1</sup>



Integrated luminosity = 12.2 fb<sup>-1</sup>

- **Asymmetry in top-antitop production** related to u and d parton distribution functions (PDFs)
- Muon and electron channels considered
- Fit to  $|\eta_j|$  by lepton charge
- W+jets asymmetric,  $t\bar{t}$  symmetric
- Main systematic uncertainties: PDF, background estimation



## Results:

$$\sigma_{\text{top}} = 49.9 \pm 1.9(\text{stat}) \pm 8.9(\text{syst}) \text{ pb}$$

$$\sigma_{\text{anti-top}} = 28.3 \pm 2.4(\text{stat}) \pm 4.9(\text{syst}) \text{ pb}$$

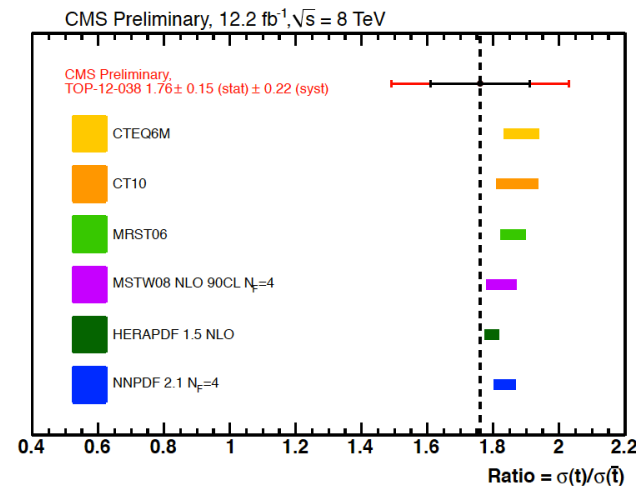
$$\mathbf{R = 1.76 \pm 0.15(\text{stat}) \pm 0.22(\text{syst})}$$

SM expectation (MSTW08 NNLO PDF set)

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

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

$$R \sim 1.84$$



- The Standard Model predicts top quarks to be highly polarised in t-channel production
- Measurement of top polarisation allows to **probe the V-A structure** of the electroweak interaction
- From the experimental point of view this translates into the **measurement of the spin asymmetry**

$$A_1 \equiv \frac{1}{2} \cdot P_t \cdot \alpha_1 = \frac{N(\uparrow) - N(\downarrow)}{N(\uparrow) + N(\downarrow)}$$

$P_t$  is the top polarisation,  $\alpha_1$  is the spin analyzing power, function of anomalous couplings, and  $N$  are the number of charged leptons aligned or counter-aligned with the top-quark spin axis

- This spin axis is well approximated by the direction of the jet recoiling against the top quark
- Asymmetry parameter  $A_1$  measured as slope of the  $\cos\theta^*$  distribution

$$\frac{d\Gamma}{d\cos\theta^*} = \Gamma \left( \frac{1}{2} + A_1 \cos\theta^* \right) \quad \theta^* = \angle(\vec{p}_1, \vec{p}_{\text{recoil-jet}})$$

- Standard t-channel selection: one lepton, two jets one of which is b-tagged
- Maximum likelihood fit to a multivariate discriminant (BDT) and cut to enhance the S/B ratio
- unfolding  $\cos\theta^*$  distribution by regularized matrix inversion method

$$A_1 = \frac{N(\cos\theta^* > 0) - N(\cos\theta^* < 0)}{N(\cos\theta^* > 0) + N(\cos\theta^* < 0)}$$

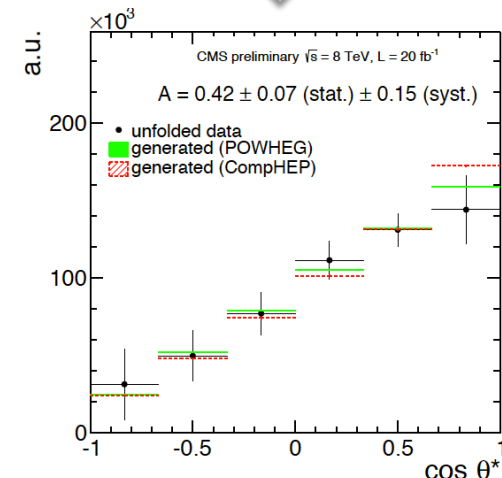
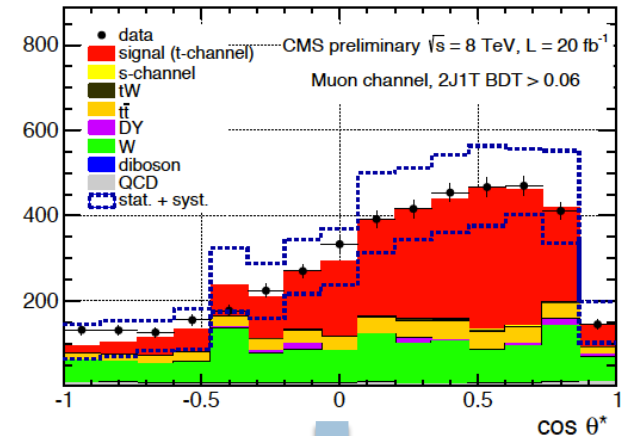
• **Results:**

$A_1 = 0.41 \pm 0.06(\text{stat}) \pm 0.16(\text{syst})$   
 $P_t = 0.82 \pm 0.12(\text{stat}) \pm 0.32(\text{syst})$   
 combined muon and electron channels

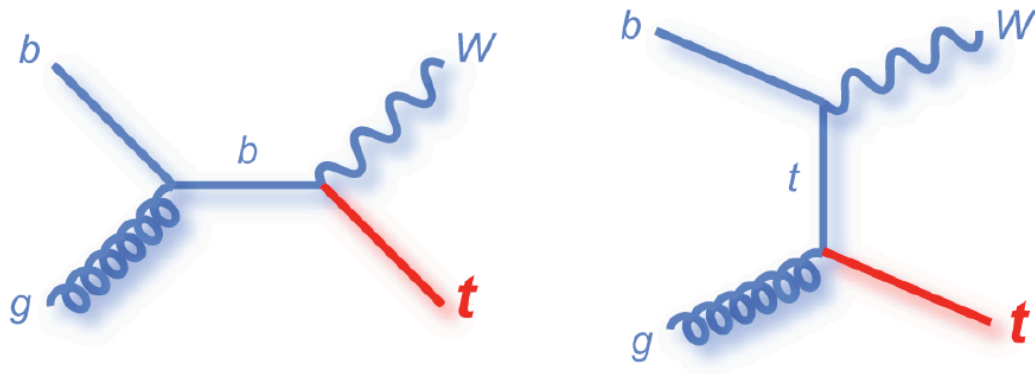
in agreement with SM expectations,  $A_1 \approx 0.5$ ,  $P_t \approx 1$

- First time **negative or null polarized single top quarks are excluded** (at  $2.4\sigma$ )

Integrated luminosity = 19.7 fb<sup>-1</sup>



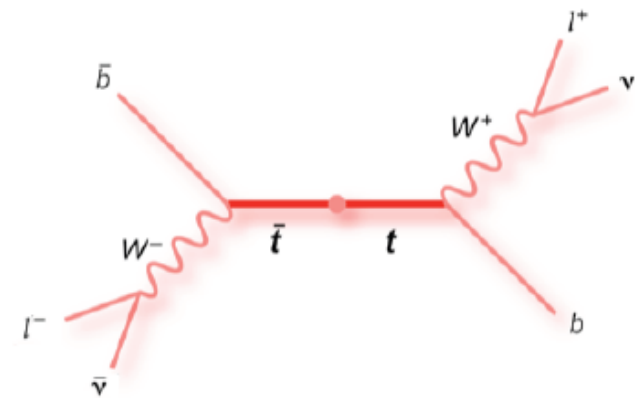




- 2 opposite sign isolated leptons
- Missing energy (2 neutrinos)
- 1 jet (coming from b quark)

• Process negligible at Tevatron, CMS and ATLAS presented evidence at 7 TeV and CMS first observation at 8 TeV

• Main backgrounds: **top pair production**, DY (Z+jets), W+jets, other single top processes



• **Selection**

- exactly two opposite-charge isolated leptons with  $p_T > 20$  GeV
- exactly one jet (anti- $k_T$ ) with  $p_T > 30$  GeV, b-tagged
- veto events with  $81 < m_{ll} < 101$  GeV
- MET > 50 GeV

• **Signal extraction procedure:** fit to BDT discriminant in the signal region (1j1t) and in control regions (2j1t, 2j2t), tt background dominated. The two control regions help to constrain the b-tagging uncertainty on the measurement.

• **Main systematic uncertainties:** matching thresholds, renormalization/factorization scales

• **Results**

$$\sigma_{tW} = 23.4^{+5.5}_{-5.4} \text{ pb}$$

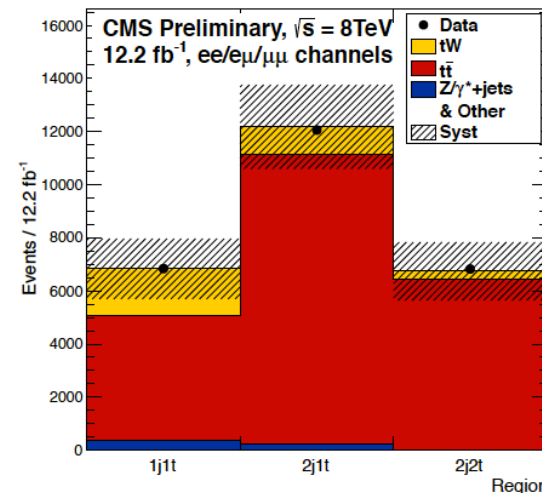
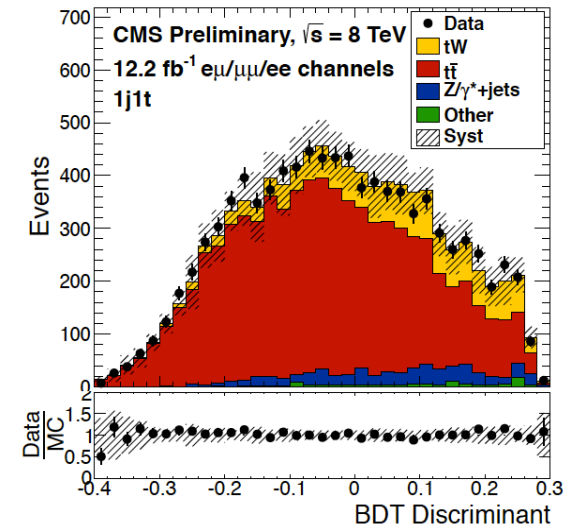
$$|V_{tb}| = 1.03 \pm 0.12(\text{exp.}) \pm 0.04(\text{th.}),$$

constrained  $|V_{tb}| > 0.78$  at 95% CL

$$\text{Significance} = 6.0\sigma \text{ (} 5.4^{+1.5}_{-1.4} \sigma \text{ expected)}$$

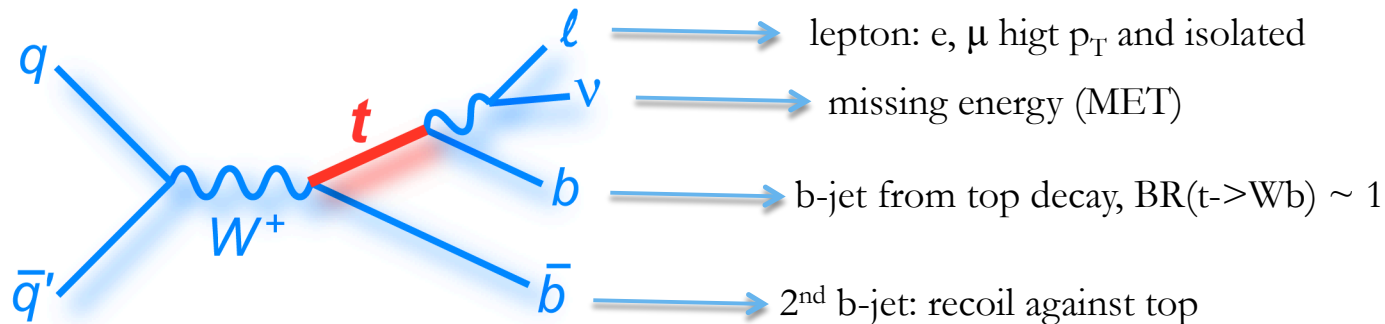
$$\sigma_{tW} = 22.2 \pm 0.6 \pm 1.4 \text{ pb, SM expectation}$$

Integrated luminosity = 12.2 fb<sup>-1</sup>



*new result*

- **Smallest cross section at the LHC** among the single top processes
- Process **observed at Tevatron** (2013), ATLAS set an upper limit at 7 TeV of  $\sigma_{s\text{-ch.}} < 26.5$  (20.5) pb (4.6 pb, SM expectation)



N.B. the jet coming from b-quark has broader  $\eta$  w.r.t. the jet stemming from anti-b-quark

- Main backgrounds: **top pair production**,  $W+b$  jets, single top t-channel
- Choice of b-jet for the top quark reconstruction: the one for which the  $M_{lb\nu}$  is the closest to 172.5 GeV (pdg mass)

Integrated luminosity = 19.3 fb<sup>-1</sup>

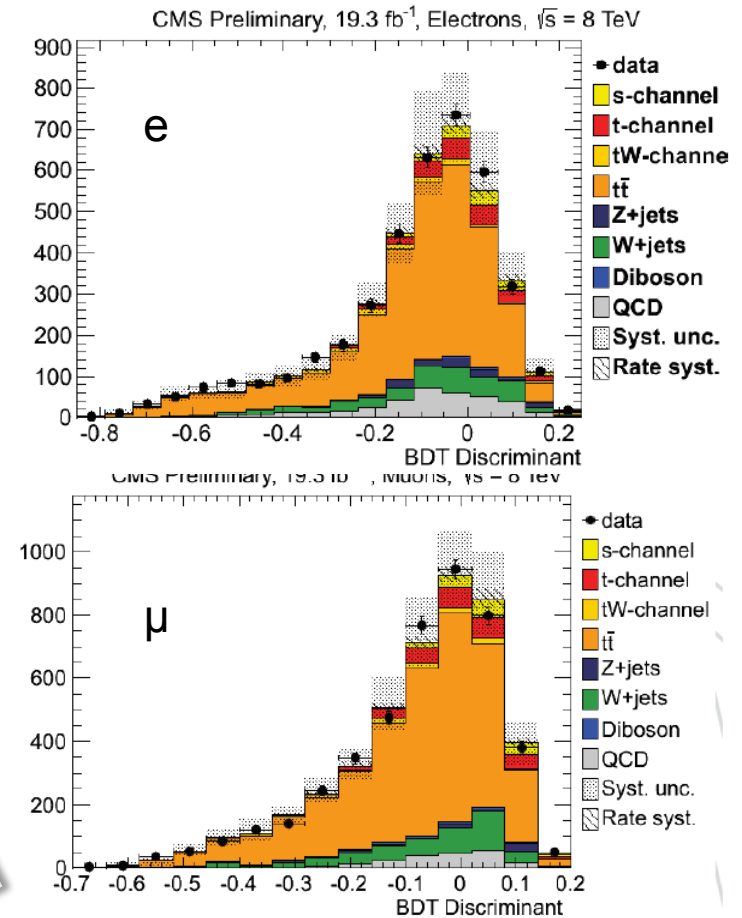
- **Selection**
  - exactly one muon/electron with  $p_T/E_T > 26/30$  GeV, isolated
  - exactly two b-tagged jets (anti- $k_T$ ) with  $p_T > 40$  GeV
  - veto other jets with  $p_T > 30$  GeV
- **Multivariate analysis** based on Boosted Decision Trees
- **Signal extraction:** binned maximum likelihood fit to the BDT discriminant distribution, simultaneously in the signal region (2j2t) and in the tt enriched control sample (3j2t). ttbar and W+jets backgrounds constrained in the fit as well.

• **Results:**

Upper limit:  $\sigma_{s\text{-channel}} < 11.5$  (17.0, 9.0) pb @ 95% CL, observed (expected with SM signal, expected with background only)

$\sigma_{s\text{-channel}} = 5.55 \pm 0.08 \pm 0.21$  pb, SM expectation

*new result*



- Motivation: study the **Wtb decay vertex** to spot eventual deviations from the pure left-handed SM interaction.

- **Decay**  $\Gamma(t \rightarrow Wb) = \Gamma_L + \Gamma_R + \Gamma_0$ ,  
**helicity fractions**  $F_{L,R,0} = \Gamma_{L,R,0} / \Gamma$

Less precise than measurement in ttbar final state, but non negligible contribution in future combinations (uncorrelated statistics and most of systematic uncertainties)

- **Unitarity**  $F_L + F_R + F_0 = 1$

- Look at the **partial width of top quark decay**

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

$\theta_l^*$  is defined in the top-quark rest frame as the angle between the lepton 3-momentum in the W-boson rest frame and the 3-momentum of the W boson

- Measure the helicity fraction parameters allows to set exclusion **limits on the anomalous couplings  $V_L, V_R, g_L, g_R$** .

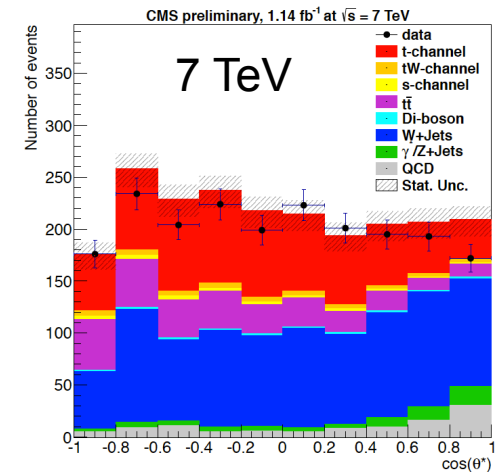
In the SM  $V_L = V_{tb} \sim 1, V_R = g_L = g_R = 0$

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

Integrated luminosity = 1.14/5.3 fb<sup>-1</sup> 7/8 TeV

- **Selection 7/8 TeV (single top enriched)**

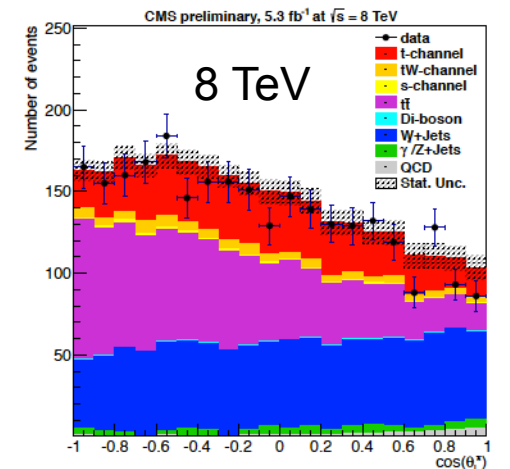
- exactly one muon with  $p_T > 20/26$  GeV
- exactly two jets (anti- $k_T$ ) with  $p_T > 30/60$  GeV, 1 b-tagged
- **Signal:** single top and top pair production (dominant)
- **Main background:** W+jets



- **Reweighting procedure**

- weight function  $W = \rho^{\text{non-SM}} / \rho^{\text{SM}}$
- probability of final state  $\cos\theta_{l,\text{reco}}^*$  =

$$= \rho(\cos\theta_{l,\text{reco}}^* | \vec{F}) \propto \int d\cos\theta_{l,\text{gen}}^* W_{\text{gen}} \cdot \rho(\cos\theta_{l,\text{gen}}^* | \vec{F}^{\text{SM}}) \cdot \mathfrak{R}(\cos\theta_{l,\text{gen}}^*, \cos\theta_{l,\text{reco}}^*)$$



- **Dominant systematic uncertainties:** MET, JES/JER, factorization/normalization scales, simulation and W+jets shape
- Integrated luminosity = 1.14/5.3 fb<sup>-1</sup> 7/8 TeV

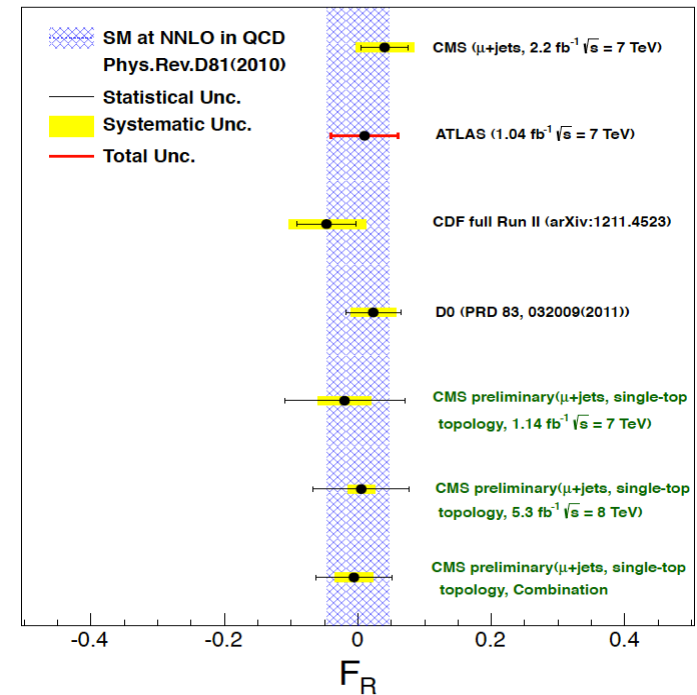
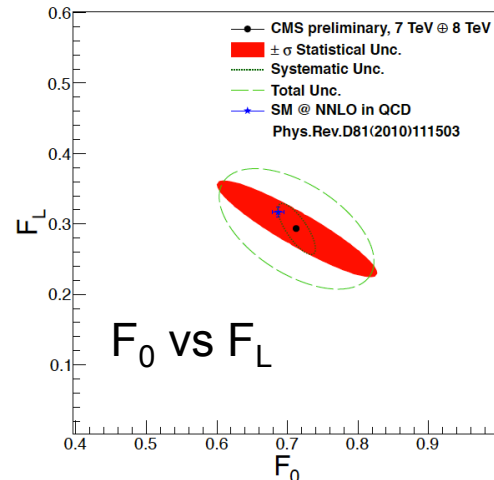
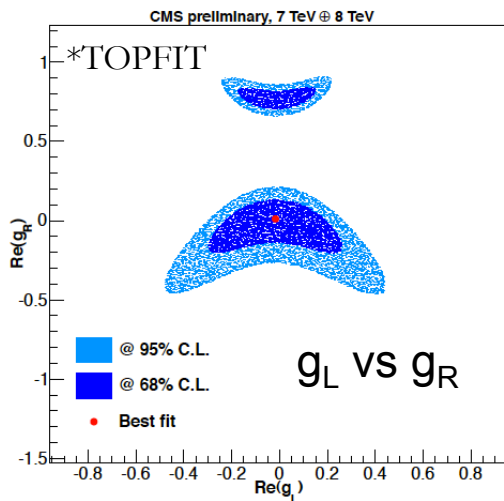
- **Binned maximum likelihood fit results**

$$F_L = 0.293 \pm 0.069(\text{stat.}) \pm 0.030(\text{syst.}),$$

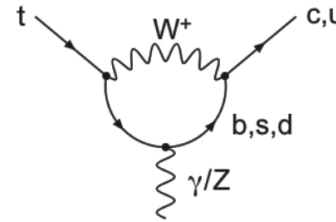
$$F_0 = 0.713 \pm 0.114(\text{stat.}) \pm 0.023(\text{syst.}),$$

$$F_R = -0.006 \pm 0.057(\text{stat.}) \pm 0.027(\text{syst.}).$$

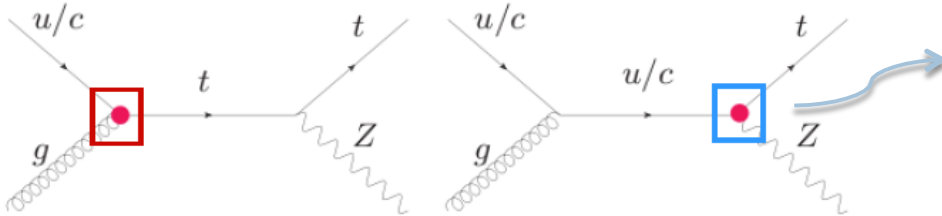
$F_L = 0.311(5), F_0 = 0.687(5), F_R = 0.0017(1)$   
 SM expectations with  $m_{\text{top}} = 172.8 \text{ GeV}, m_b = 4.8 \text{ GeV}$



- FCNCs are highly suppressed in the SM since they can occur only via penguin diagrams:

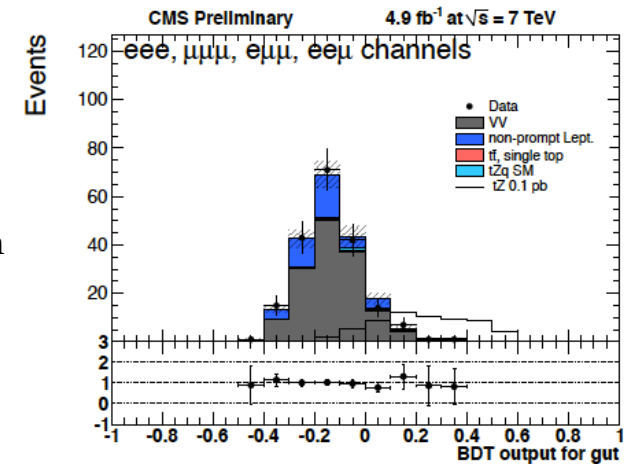


- Searches for FCNC in production:



probed also by FCNC searches in  $tt$  events  
[See Oliver's talk!](#)

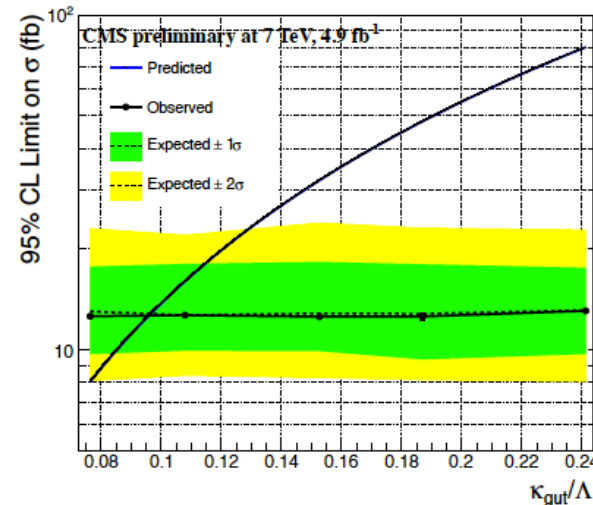
Integrated luminosity =  $4.9 \text{ fb}^{-1}$



- $tqg$  coupling best investigated in single top production since the decay topology  $t \rightarrow qg$  can't be differentiated from multijets background

- **Selection:** three leptons with  $p_T > 20 \text{ GeV}$ , more than 1 jet with  $p_T > 30 \text{ GeV}$

- Exclusion limits on the effective couplings in the Lagrangian calculated with Profile Likelihood Ratio on a BDT discriminant





- **t-channel**: established observation at 7 and 8 TeV, **precision measurements**

- Inclusive cross section
- Top charge asymmetry
- Top polarization



differential measurements,  
top mass measurement

- **tW associated production**: evidence at 7 TeV and observation at 8 TeV

- **s-channel**: **upper limit** set on the cross section at 8 TeV



combination with 7 TeV data  
(for which S/B ratio is more favorable)

- **W helicity**: helicity fractions in agreement with the SM expectations



combination with measurements  
in  $t\bar{t}b\bar{a}r$  channels

- **FCNC**: limits on  $tZ$  associated production



# Backup



- Selection**

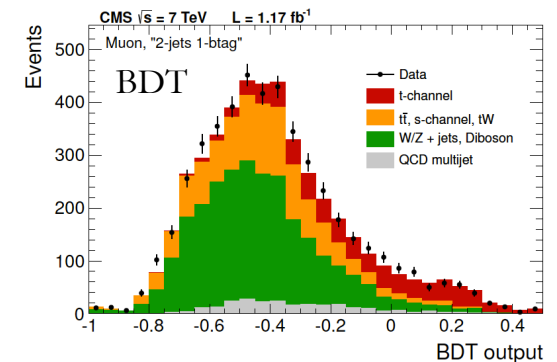
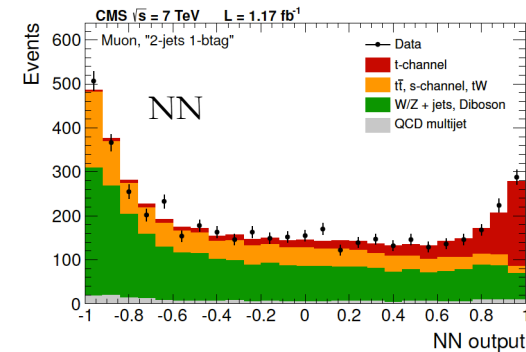
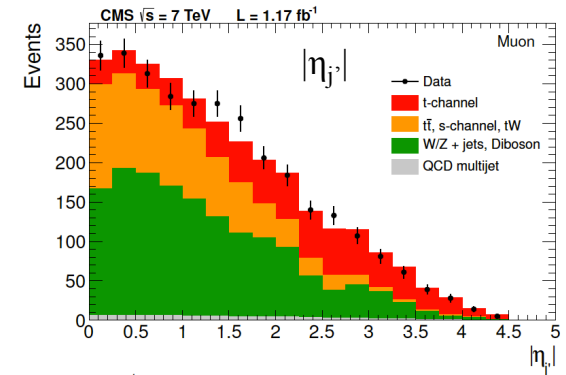
- exactly one lepton with  $p_T > 20/30$  GeV (muon/electron)
- at least two jets (anti- $k_T$ ) with  $p_T > 30$  GeV + b-tagging
- $m_T(W) > 40$  GeV ( $\mu$ );  $MET > 25$  GeV (e)

- Template fit** analysis  $|\eta_j|$

- Fit to the pseudorapidity of the recoil jet in the signal region  $130 < m_{top} < 220$  GeV
- Data-driven W+jets shape
- Low model dependence

- Boosted Decision Trees** and **Neural Network** analyses

- Most precise measurement
- Exploit the knowledge of electroweak top quark production
- Experimental and cross section uncertainties constrained by data using exclusive phase space regions (2j1t, 3j1t, 4j1t, 2j2t, 3j2t, 4j2t)



Integrated luminosity = 1.17/1.56 fb<sup>-1</sup> (muons/electrons)

Cross section measured by **individual analyses**:

$$|\eta_j|: \sigma_{\text{t-channel}} = 70.0 \pm 6.0(\text{stat}) \pm 6.5(\text{syst}) \pm 3.6(\text{th}) \pm 1.5(\text{lumi}) \text{ pb}$$

$$\text{NN}: \sigma_{\text{t-channel}} = 68.1 \pm 4.1(\text{stat}) \pm 3.4(\text{syst})^{+3.3}_{-4.3}(\text{th}) \pm 1.5(\text{lumi}) \text{ pb}$$

$$\text{BDT}: \sigma_{\text{t-channel}} = 66.6 \pm 4.0(\text{stat}) \pm 3.3(\text{syst})^{+3.9}_{-3.3}(\text{th}) \pm 1.5(\text{lumi}) \text{ pb}$$

**Analyses combination** performed using BLUE method\*:

$$\begin{aligned} \sigma_{\text{t-channel}} &= 67.2 \pm 3.7(\text{stat.}) \pm 3.0(\text{syst.}) \pm 3.5(\text{theor.}) \pm 1.5(\text{lumi.}) \text{ pb} \\ &= \mathbf{67.2 \pm 6.1 \text{ pb}} \end{aligned}$$

Assuming the CKM matrix elements  $|V_{td}|, |V_{ts}| \ll |V_{tb}|$  and allowing for the presence of an anomalous form factor  $f_{L_V}$  in the  $Wtb$  coupling:

$$|f_{L_V} \cdot V_{tb}| = \sqrt{\sigma/\sigma_{\text{th}}} = 1.020 \pm 0.046(\text{exp.}) \pm 0.017(\text{th.}), \text{ constrained } |V_{tb}| > 0.92 \text{ at } 95\% \text{ CL}$$

Integrated luminosity = 4.9 fb<sup>-1</sup>

## • Selection

- exactly two opposite-charge isolated leptons (ee, eμ, μμ) with p<sub>T</sub> > 20 GeV
- exactly one jet (anti-k<sub>T</sub>) with p<sub>T</sub> > 30 GeV, b-tagged
- veto events with 81 < m<sub>ll</sub> < 101 GeV
- min (MET, tracker MET) > 30 GeV

• **Fit to a BDT multivariate discriminant** simultaneously in the signal region (1j1t) and in control regions (2j1t, 2j2t), background dominated.

• **Main systematic uncertainties:** jet energy scale, matching thresholds

## • Results

$$\sigma_{tW} = 16^{+5}_{-4} \text{ pb}$$

$$|V_{tb}| = 1.01^{+0.16}_{-0.13} \text{ (exp.) } ^{+0.03}_{-0.04} \text{ (th.)}$$

constrained  $|V_{tb}| > 0.79$  at 90% CL

Significance = 4.0σ (3.6<sup>+0.8</sup><sub>-0.9</sub> σ expected)

SM expectation

$$\sigma_{tW} = 15.6 \pm 0.4 \pm 1.1 \text{ pb}$$

