Single Top Production

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Flavour Physics at LHC RunII
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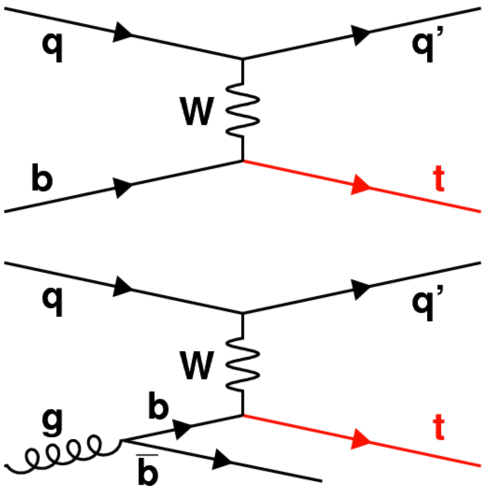
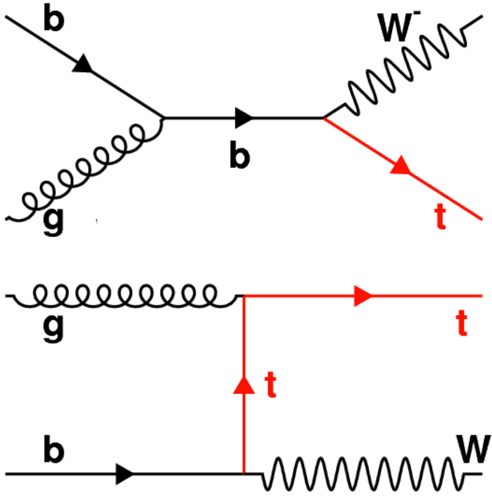
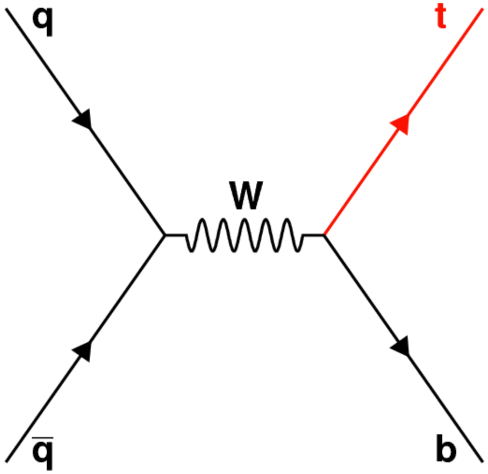
Single Top Production

- Three main production mechanisms:







- t-channel:

σ (8TeV) = $87.7^{+3.4}_{-1.9}$ pb

σ (13TeV) = $217.0^{+9.1}_{-7.7}$ pb

Golden channel

- tW-channel:

σ (8TeV) = 22.4±1.5 pb

σ (13TeV) = 71.7±3.8 pb

Observed at LHC

- s-channel:

σ (8TeV) = 5.6±0.2 pb

σ (13TeV) = 10.3±0.4 pb

Challenging at LHC

Why Studying it?

- Direct probe of EKW production via charged current:
  - Probe of Wtb vertex and measurement of CKM matrix element V_{tb} from the measured cross section
- Sensitive to beyond standard model (BSM) physics:
  - Wtb anomalous couplings and FCNC
- Allows for refinement and tests of different physics aspects of top quark modeling in MC simulations:
  - Constrain PDFs and tune MC generators
- Background for many physics searches in Higgs and SUSY analyses

In This Talk

- Single top production in the t-channel:
  - Inclusive and differential cross sections
  - Wtb vertex: polarization and anomalous couplings
- Other production mechanisms:
  - Associated production with a W boson
  - Single top production in the s-channel
  - Associated production with a Z boson and FCNC
- Summary

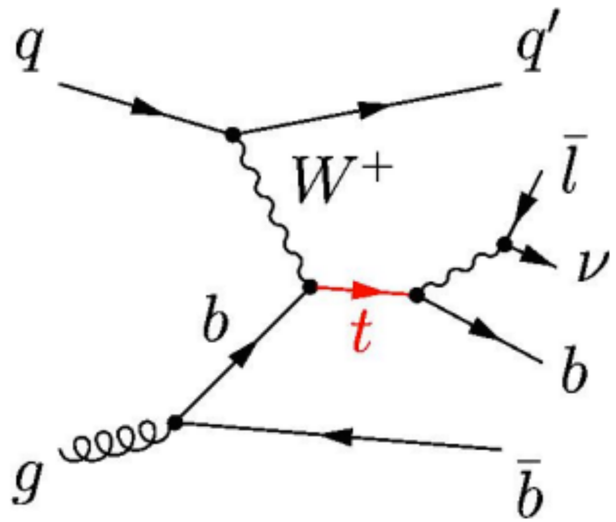
(For more results see ATLAS and CMS public pages)

Single Top Production in the t-Channel

- Inclusive and differential cross sections
- Wtb vertex: polarization and anomalous couplings

t-Channel Signature

- Experimental signature of single top t-channel production:



1 high-p_T and forward jet

1 isolated and high-p_T lepton

Missing E_T (MET) from the neutrino

1 high-p_T and central b-jet

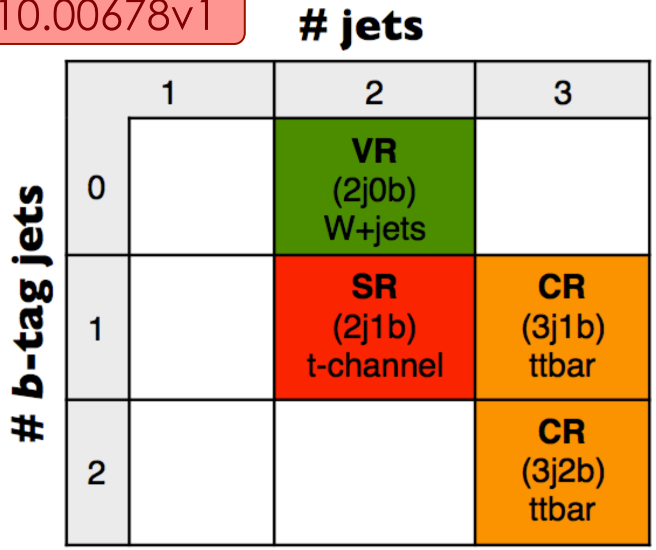
1 additional soft b-jet with high | η |
(not always detected)

- Main backgrounds:
  - top pair production
  - W+jets production

Inclusive Cross Section (13 TeV)

arXiv:1610.00678v1

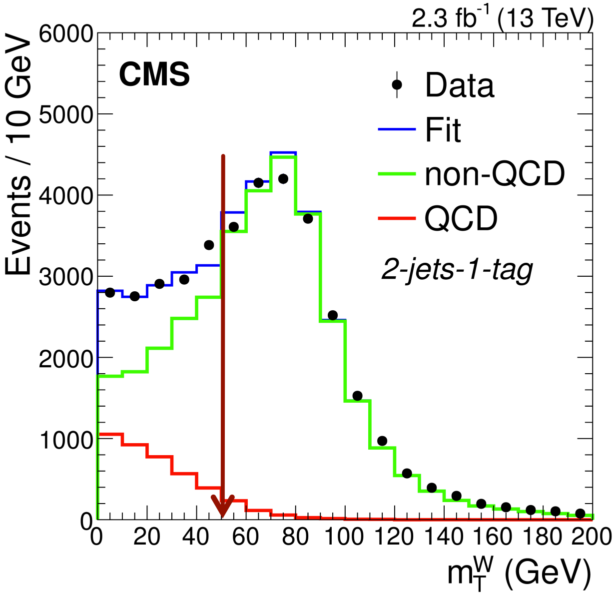
- Signal region definition:
  - One isolated muon with p_T>22 GeV
  - 2 jets with p_T>40 GeV and | η |<4.7, one of which must be b-tagged
  - m_T^W>50 GeV



jets

# b-tag jets	1	2	3
0		**VR** (2j0b) W+jets	
1		**SR** (2j1b) t-channel	**CR** (3j1b) ttbar
2			**CR** (3j2b) ttbar

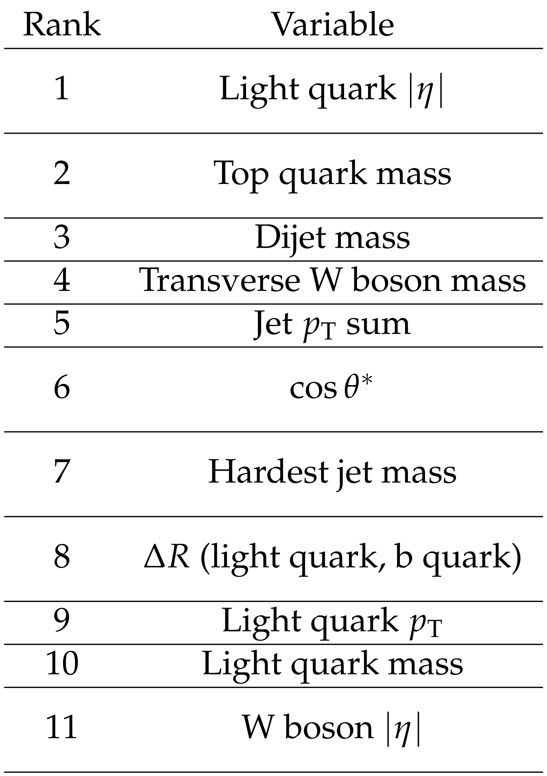
- Analysis strategy:
  - Neural network to discriminate signal to background
  - Simultaneous fit in signal and control regions to constrain dominant W+jets and ttbar backgrounds
  - QCD background extrapolated from events with m_T^W<50 GeV



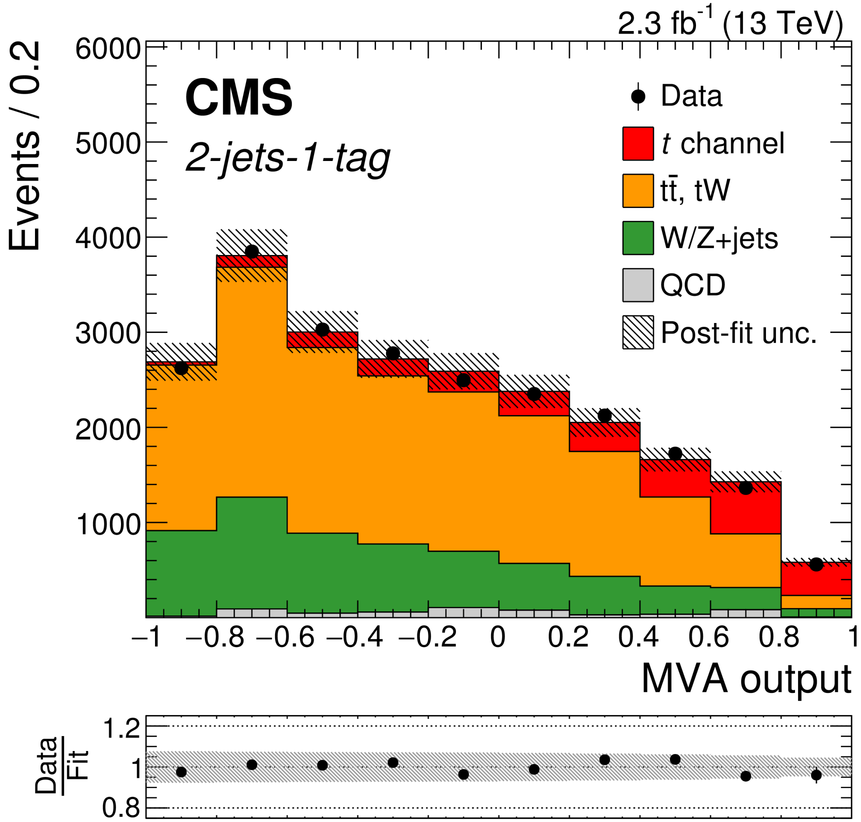
Inclusive Cross Section (13 TeV)

arXiv:1610.00678v1

- Neural network trained in the signal region (2 jets, 1 tag) by using 11 input variables:



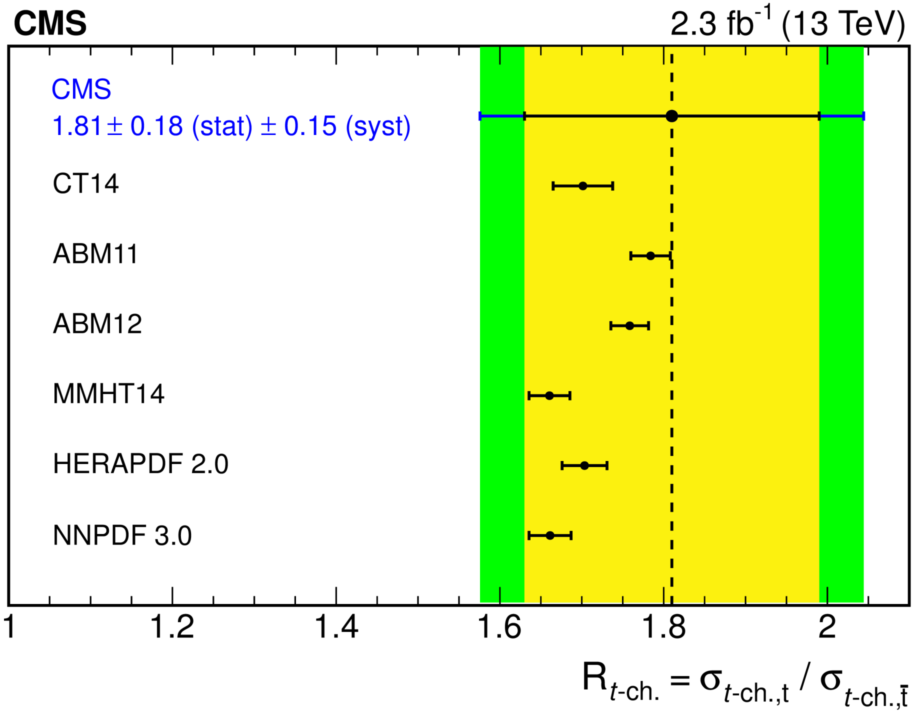
Rank	Variable
1	Light quark $\|\eta\|$
2	Top quark mass
3	Dijet mass
4	Transverse W boson mass
5	Jet p_T sum
6	$\cos\theta^*$
7	Hardest jet mass
8	ΔR (light quark, b quark)
9	Light quark p_T
10	Light quark mass
11	W boson $\|\eta\|$



$t/\bar{t}$ Cross Section Ratio (13 TeV)

arXiv:1610.00678v1

- Measured single top quark production cross section and top quark to antitop quark cross section ratio are:
  - $\sigma_{t,t\text{-channel}} = 150 \pm 8\ (\text{stat}) \pm 9\ (\text{exp}) \pm 18\ (\text{theo}) \pm 4\ (\text{lumi})$ pb
    $= 150 \pm 22$ pb
  - $R_{t\text{-channel}} = 1.81 \pm 0.18\ (\text{stat}) \pm 0.15\ (\text{syst})$
- The cross section ratio is sensitive to PDFs:
  - With future data, it could used to put constraint on them



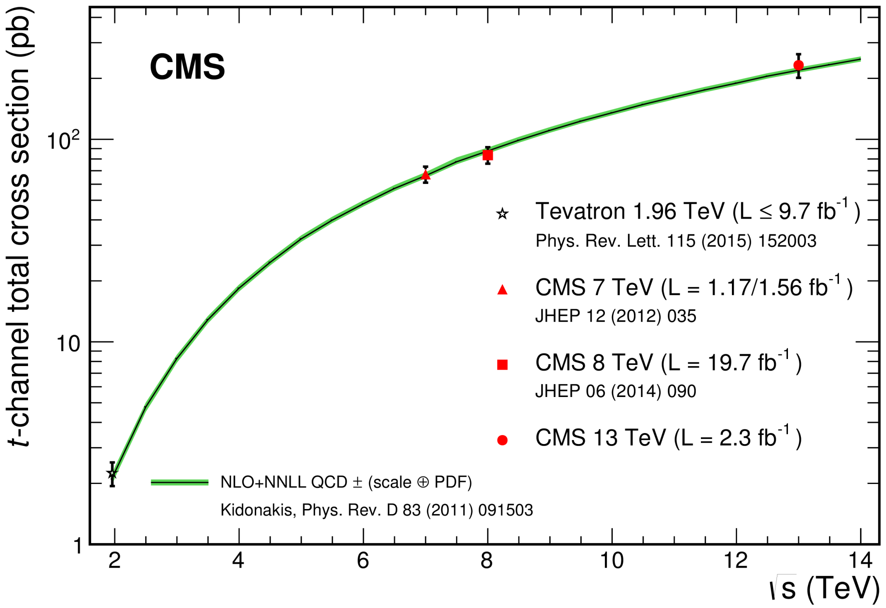
Inclusive Cross Section (13 TeV)

arXiv:1610.00678v1

- Measured production cross section:
  - $\sigma^{\text{measured}}_{\text{t-channel}} = 232 \pm 13\ (\text{stat}) \pm 12\ (\text{exp}) \pm 26\ (\text{theo}) \pm 6\ (\text{lumi})\ \text{pb}$

    $= 232 \pm 31\ \text{pb}$
  - Dominant systematics from signal and ttbar modeling (~9%), and factorization and renormalization scales (~6%)

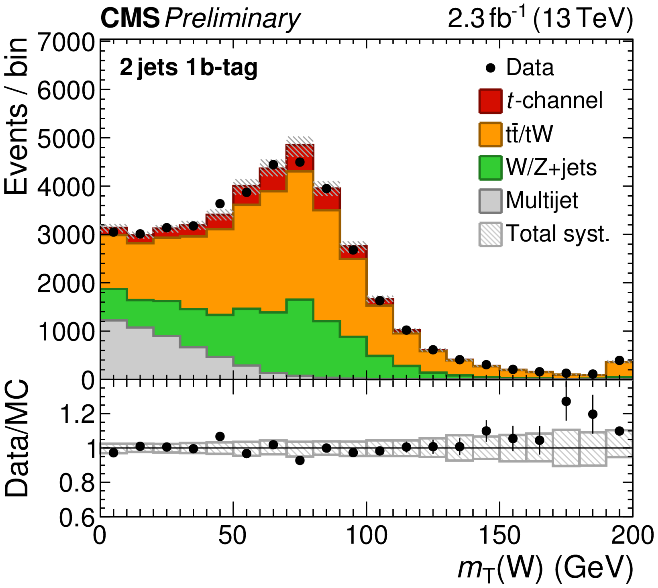
- Good agreement with theoretical predictions:
  - $\sigma^{\text{NLO}}_{\text{t-channel}} = 217.0^{+6.6}_{-4.6}\ (\text{scale}) \pm 6.2\ (\text{PDF}+\alpha_S)\ \text{pb}$
- Assuming $|V_{td}|, |V_{ts}| << |V_{tb}|$:
  - $|f_{LV}V_{tb}| = 1.03 \pm 0.07 (\text{epx}) \pm 0.02 (\text{th.})$
  - Where f_{LV} accounts for a possible anomalous Wtb coupling

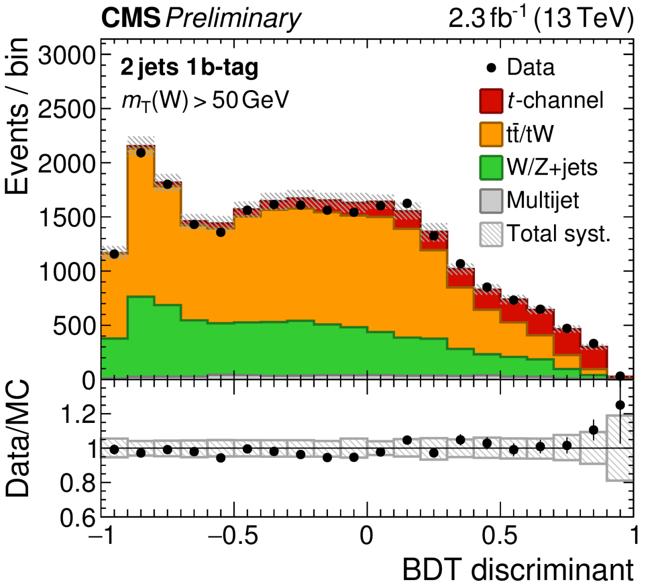


Differential Cross Section (13 TeV)

CMS-PAS-TOP-16-004

- Aim to measure the signal yields as a function of top quark p_T and rapidity y
- Same signal and control regions as in the inclusive cross section measurement
- BDT discriminant build from five observable chosen to small correlation with top quark p_T and rapidity
- Simultaneous fit in signal and control regions to a likelihood combining:
  - m_T^W for events with m_T^W<50 GeV, to constrain QCD background
  - BTD discriminant otherwise, sensitive to signal and other backgrounds

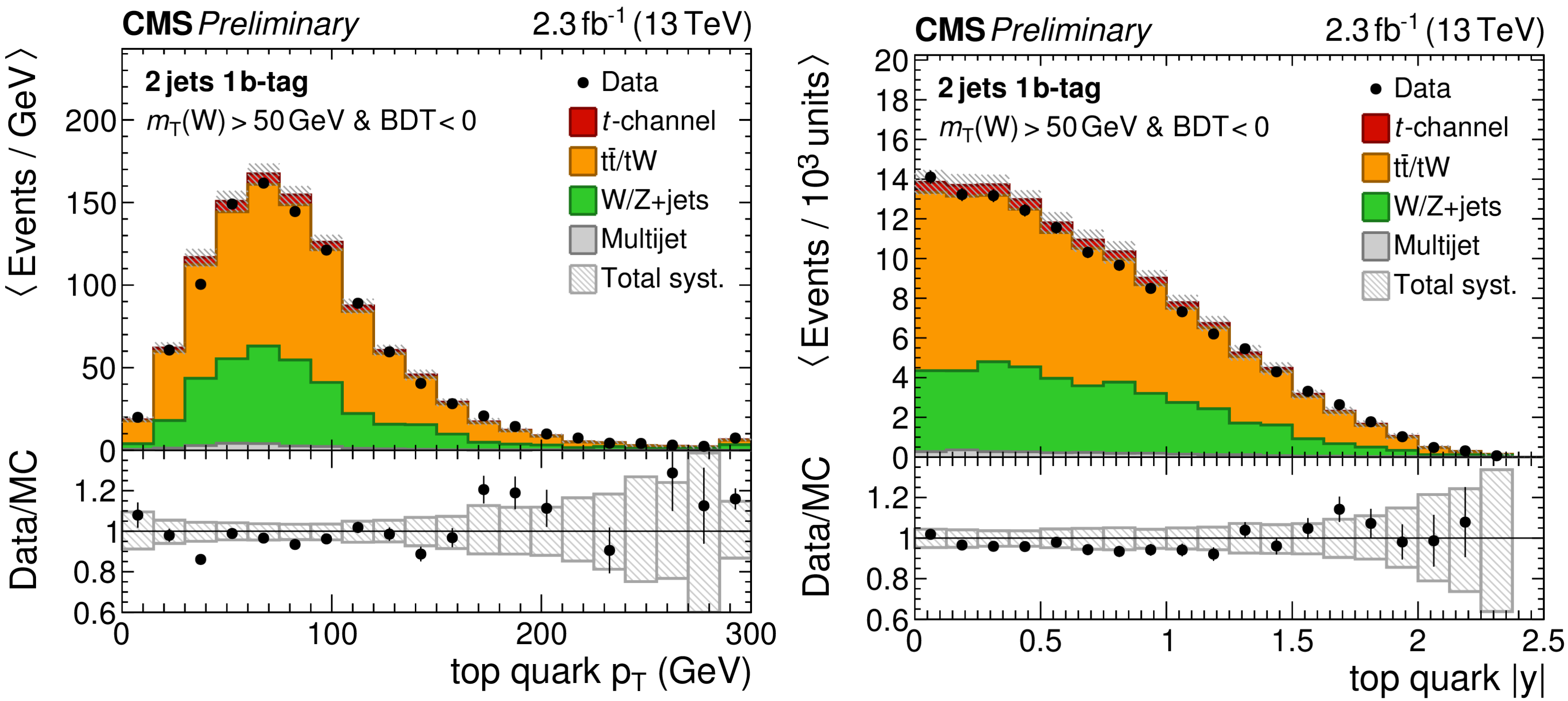




Differential Cross Section (13 TeV)

CMS-PAS-TOP-16-004

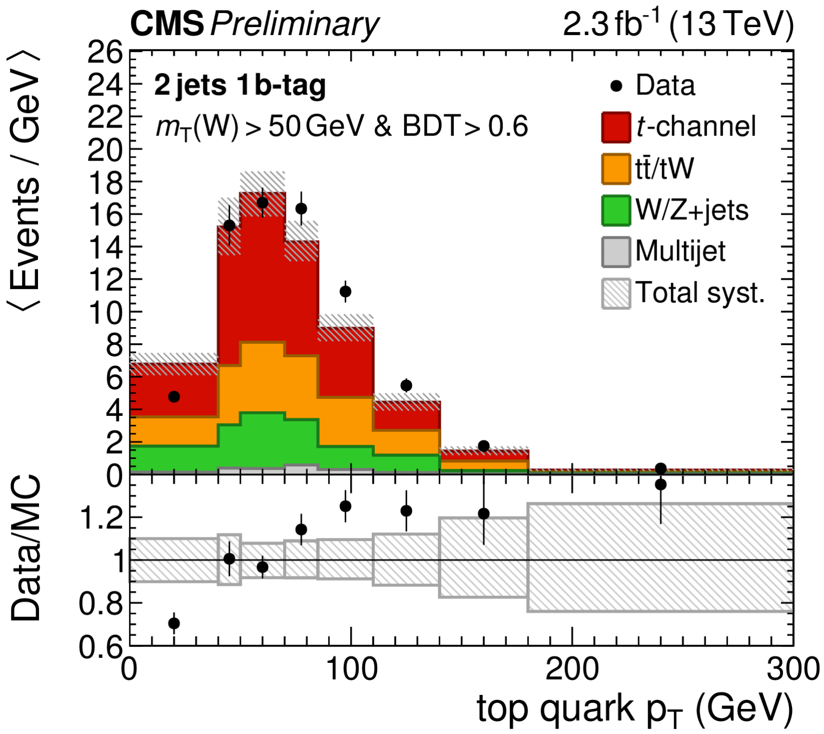
- Post-fit distributions in a signal-depleted region:
  - $m_T^W > 50$ GeV
  - BDT<0.6
  - Good agreement between data and MC

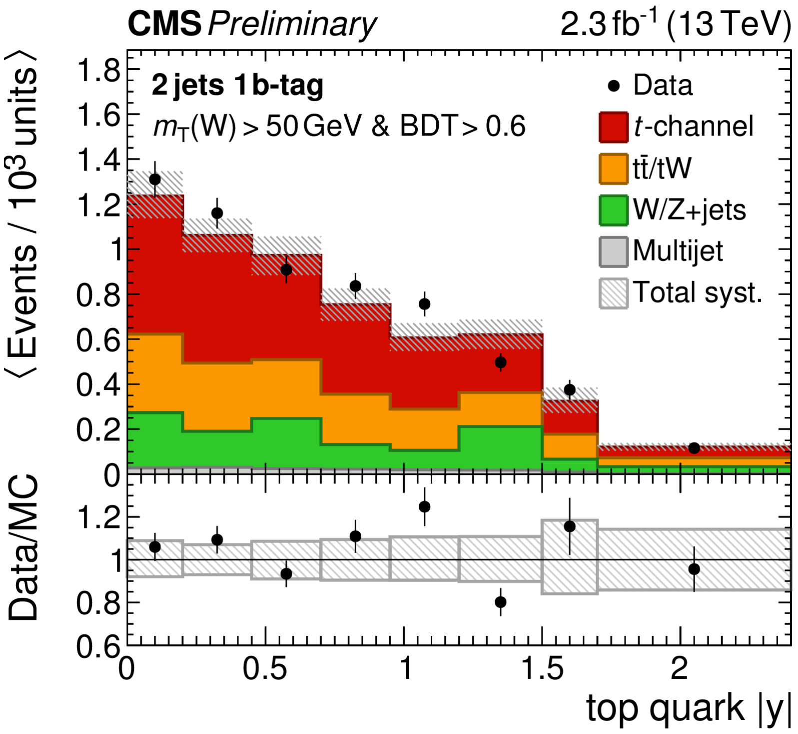


Differential Cross Section (13 TeV)

CMS-PAS-TOP-16-004

- Post-fit distributions in a signal-enhanced region:
  - $m_T^W > 50$ GeV
  - BDT>0.6
  - p_T spectrum in data somewhat harder than in MC

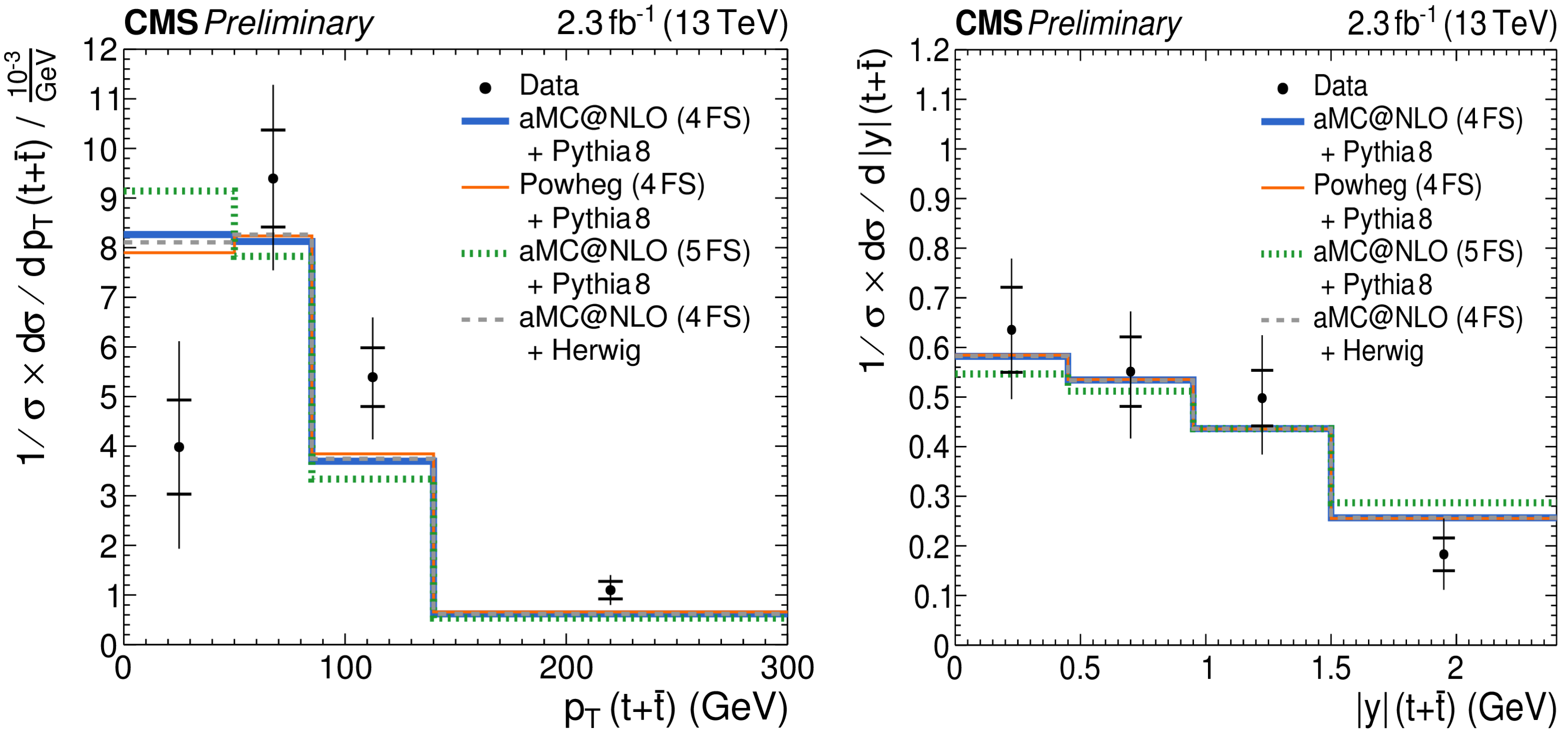




Differential Cross Section (13 TeV)

CMS-PAS-TOP-16-004

- Observed distributions are unfolded to parton level:
  - Differential cross sections normalized to the in-situ measured inclusive cross section of the t-channel single top production
  - Data are described by theoretical prediction within the current uncertainties



Wtb Vertex

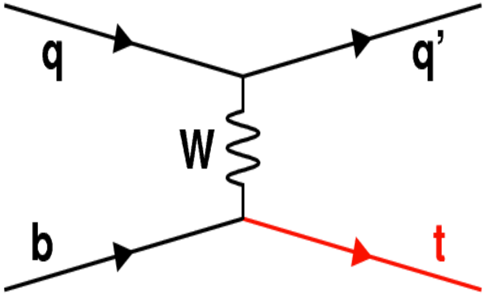
- Probing the W_{tb} vertex is a powerful test for new physics
- Most general form of the W_{tb} Lagrangian in the effective operator formalism:

$$\mathcal{L}^{\text{anom.}}_{\text{tWb}} = -\frac{g}{\sqrt{2}}\bar{\text{b}}\gamma^{\mu}(V_{\text{L}}P_{\text{L}} + V_{\text{R}}P_{\text{R}})\text{t}W^{-}{}_{\mu} - \frac{g}{\sqrt{2}}\bar{\text{b}}\frac{i\sigma^{\mu\nu}q_{\nu}}{m_{\text{W}}}(g_{\text{L}}P_{\text{L}} + g_{\text{R}}P_{\text{R}})\text{t}W^{-}{}_{\mu} + \text{h.c.},$$

- Within the SM, $V_L=V_{tb}\approx 1$, while V_R, g_L and g_R vanish at tree level
- Anomalous couplings can be investigated in single top quark events through two main strategies:
  - Measurement of top quark polarization and W boson helicity
  - Direct searches through comparison on sensible observables in data to simulated samples generated with anomalous couplings

Top Polarization (8 TeV)

JHEP 04 (2016) 073



- In t-channel production, the SM predicts the top quark to be highly polarized alone the direction of the spectator quark q', which recoils against the top, as a consequence of the V-A structure of the W_{tb} coupling
- Measuring top quark spin asymmetry:

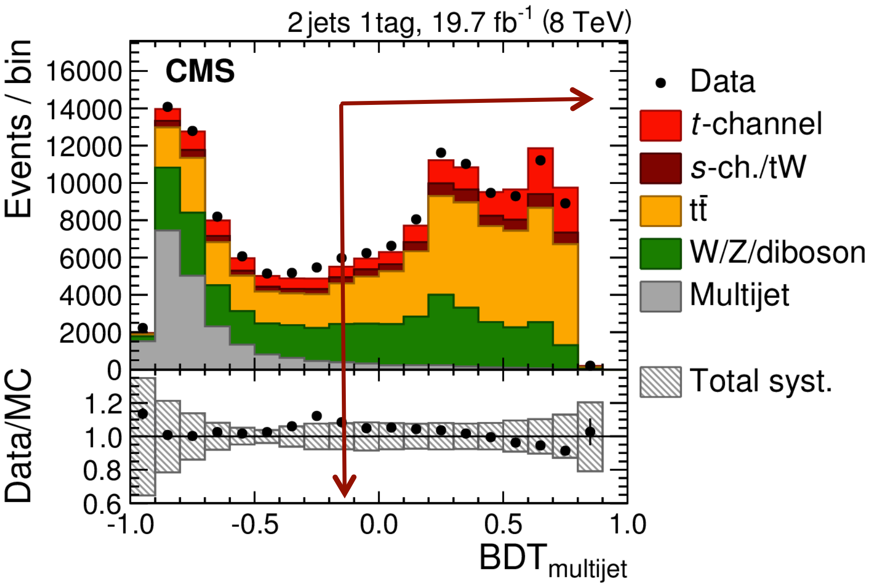
$$\boxed{A_X \equiv \frac{1}{2} P_t \, \alpha_X = \frac{N(\uparrow) - N(\downarrow)}{N(\uparrow) + N(\downarrow)}}$$

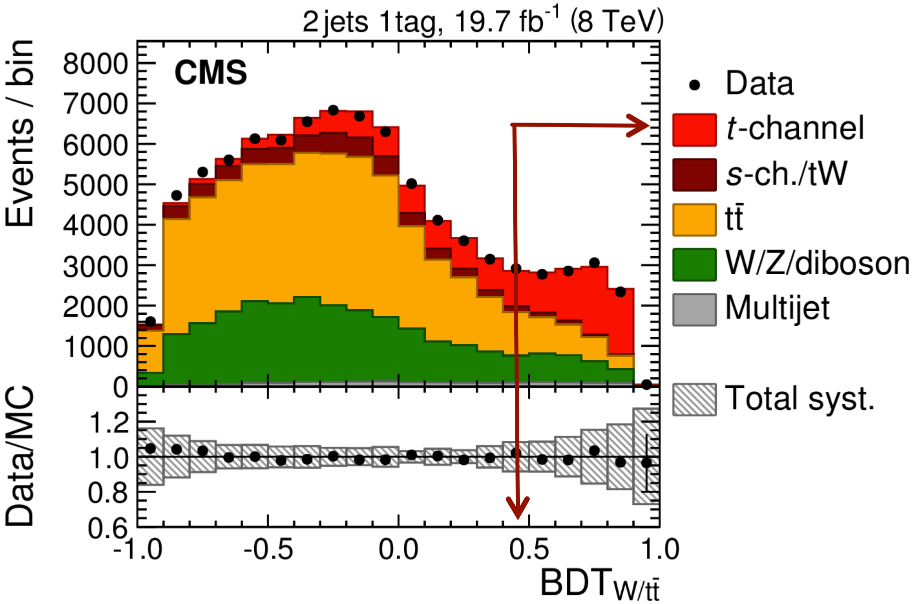
  - P_t: top quark polarization in production
  - α_X: degree of angular correlation of one of the top quark decay product with respect to the top quark spin (spin-analyzing power)
  - $N(\uparrow)$ $(N(\downarrow))$: number of times in which the top decay product is aligned (antialigned) with the momentum of the spectator quark

Top Polarization (8 TeV)

JHEP 04 (2016) 073

- Event selection:
  - One isolated muon with pT>26 GeV
  - 2 jets with p_T>40 GeV, one of which must be b-tagged ("2jets 1tag" region)
  - "3jets 2tags" and "2jets 0tags" used as control regions
- Use two BDTs to reject multijet and W/ttbar backgrounds:





Top Polarization (8 TeV)

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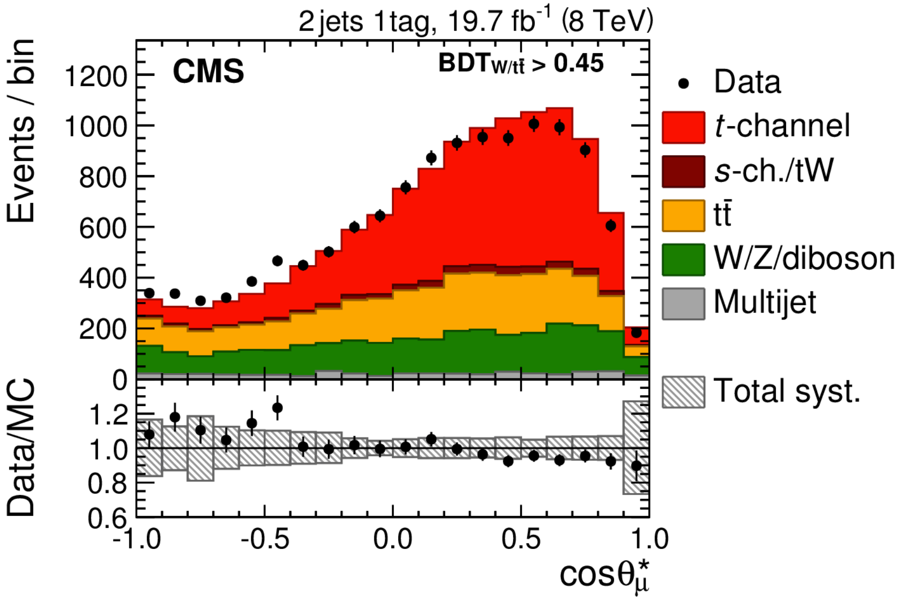
- Top quark spin asymmetry A_X extracted by the observed distribution of the angle θ_X between a top decay product and the spectator quark:

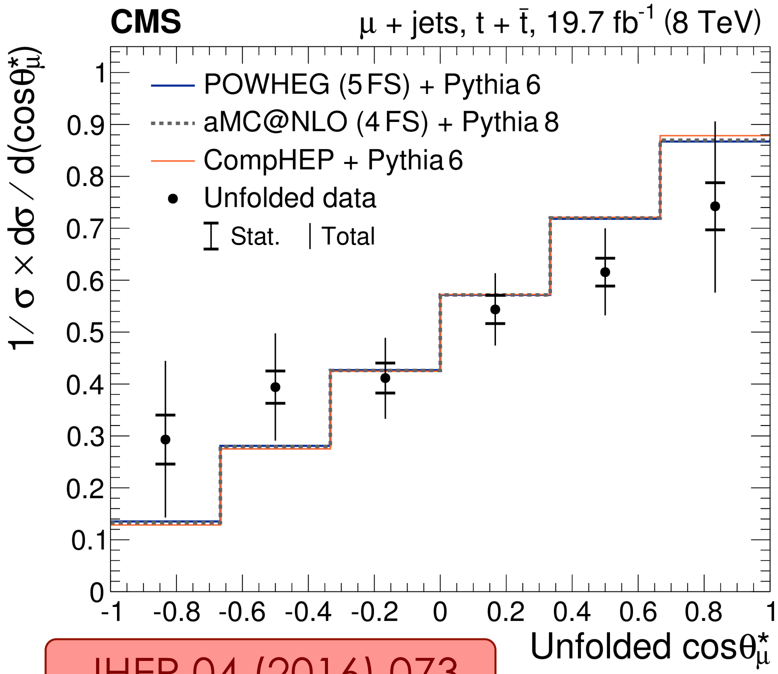
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_X^*} = \frac{1}{2}(1 + P_t^{(\vec{s})}\alpha_X\cos\theta_X^*) = \left(\frac{1}{2} + A_X\cos\theta_X^*\right)$$

- Choosing the muon as decay product, in the signal region:
  - Signal and background components extracted by fitting the $\mathrm{BDT}_{W/t\bar{t}}$ distribution in the “2jets 1tag” and “3jets 2tags” regions



Top Polarization (8 TeV)

- After background subtraction, the observed distribution for $\cos\theta_X$ is unfolded to parton level to correct for detector effects



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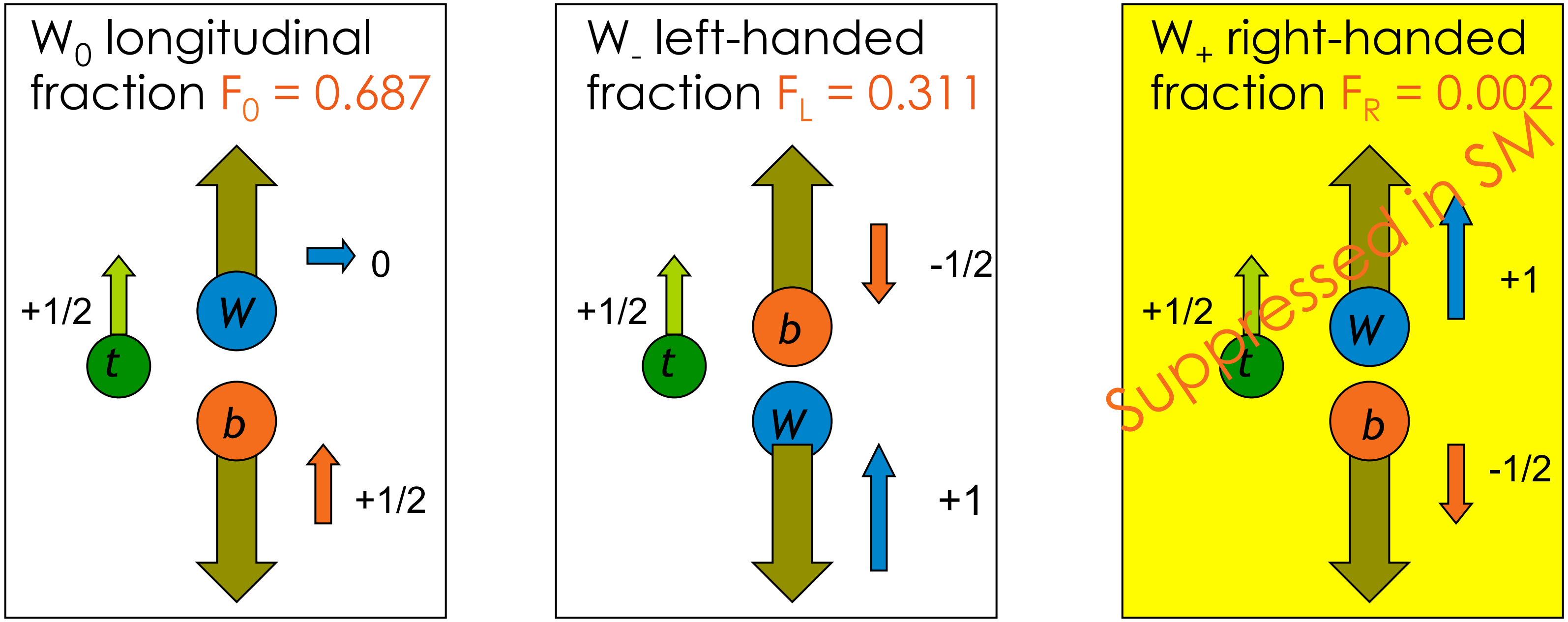
- Fitting for the top quark spin asymmetry:

$$A_\mu(t) = 0.29 \pm 0.03\ (\text{stat}) \pm 0.10\ (\text{syst}) = 0.29 \pm 0.11$$
$$A_\mu(\bar{t}) = 0.21 \pm 0.05\ (\text{stat}) \pm 0.13\ (\text{syst}) = 0.21 \pm 0.14$$
$$A_\mu(t+\bar{t}) = 0.26 \pm 0.03\ (\text{stat}) \pm 0.10\ (\text{syst}) = 0.26 \pm 0.11$$

Compatible with a *p*-value of 4.6% (2.0 σ) with the SM prediction of 0.44 (NLO)

W Helicity (8 TeV)

- V-A character of top decay probed by W boson helicity



W_0 longitudinal fraction $F_0 = 0.687$

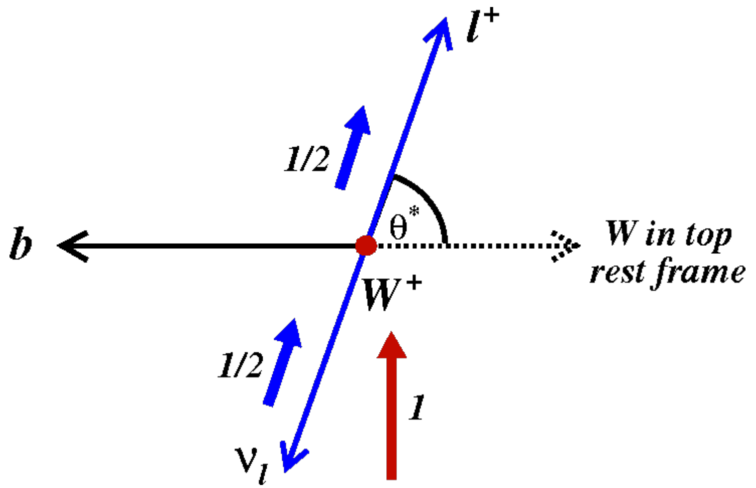
W_- left-handed fraction $F_L = 0.311$

W_+ right-handed fraction $F_R = 0.002$

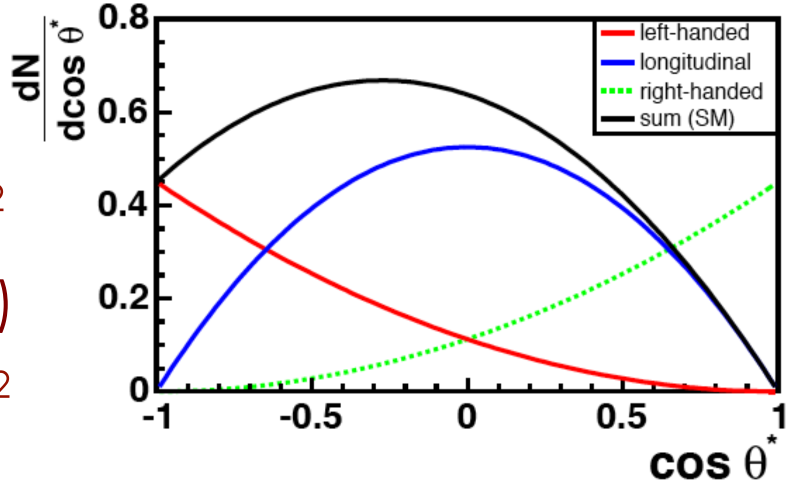
Suppressed in SM

W Helicity (8 TeV)

- The helicity angle θ^*_l is defined as the angle between the W boson momentum in the top quark rest frame and the momentum of the down-type decay fermion in the W boson rest frame

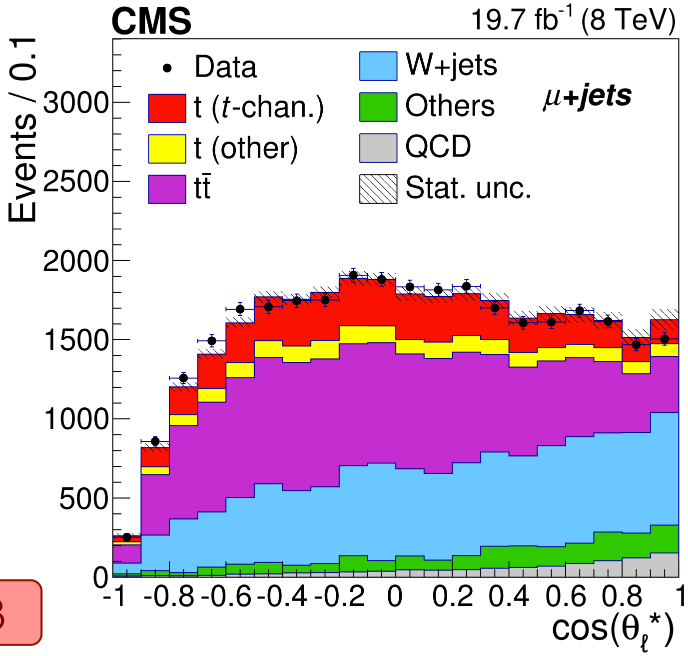


- Components of the probability distribution function of $\cos(\theta^*_l)$:
  - Left-handed ~$3/8(1-\cos\theta^*)^2$
  - Longitudinal ~ $3/4(1-\cos^2\theta^*)$
  - Right-handed ~$3/8(1+\cos\theta^*)^2$



W Helicity (8 TeV)

- Looking inclusively to events with a single reconstructed top
  - Signal from both single top and ttbar production
- Event selection:
  - One isolated muon (electron) with p_T>267 (30) GeV
  - Two jets with p_T>40 GeV, of which one b-tagged
  - Large missing E_T and m_T^W>50 GeV
- Reconstructed cos(θ^*_l) in simulations fitted to observed distribution:
  - Helicity fractions and W+jets normalization left as free parameters
  - MC events weighted by a factor relating generator level variable to detector level ones



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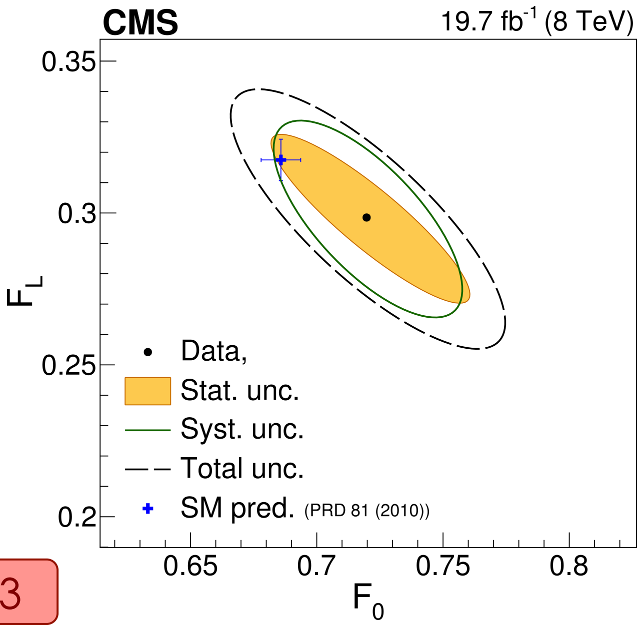
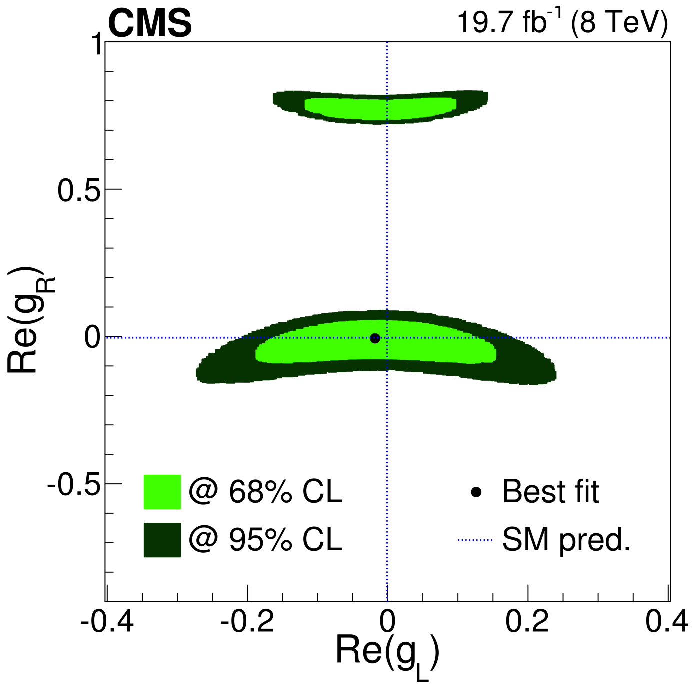
W Helicity (8 TeV)

- Measured W helicities are consistent with the SM expectations:
  - $F_L = 0.298 \pm 0.028$ (stat) ± 0.032 (syst)
  - $F_0 = 0.720 \pm 0.039$ (stat) ± 0.037 (syst)
  - $F_R = -0.018 \pm 0.019$ (stat) ± 0.011 (syst)





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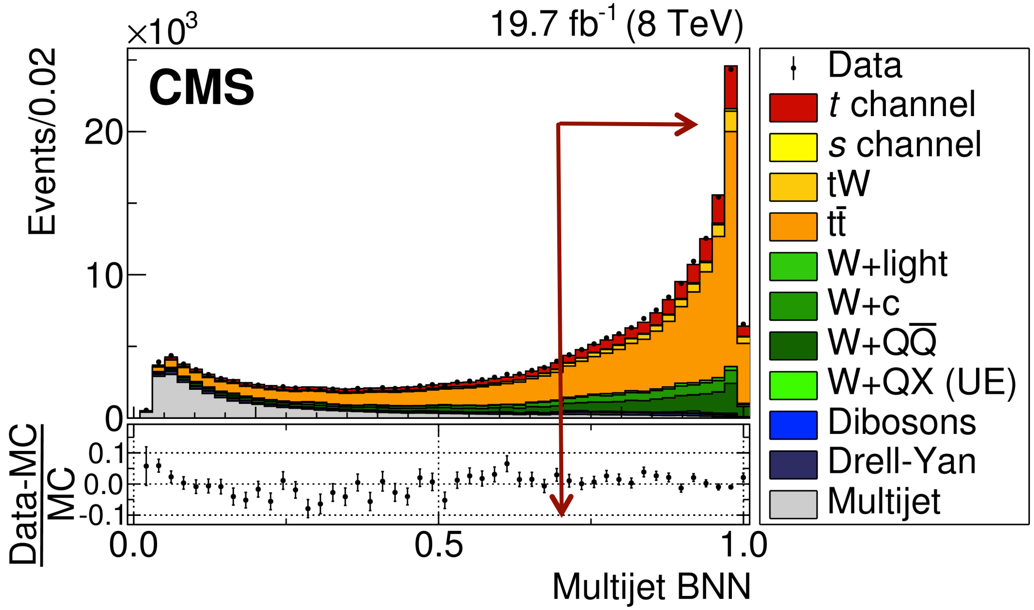
- Results are used as input to TopFit to compute exclusion limits on the tensor couplings g_L and g_R of the W_{tb} vertex
  - Assuming $V_L = 1$ and $V_R = 0$

Anomalous Couplings (7 & 8 TeV)

JHEP 02 (2017) 028

- Event selection:
  - One isolated muon with p_T> 20 (26) GeV in 7 (8) TeV analysis
  - Two or three jetes with p_T>30 GeV(40 GeV for the leading one)
  - At least one jet passing and one failing the b-tag requirement
- To suppressed multijet background, a Bayesian Neural Network (BNN) discriminator is built



Anomalous Couplings (7 & 8 TeV)

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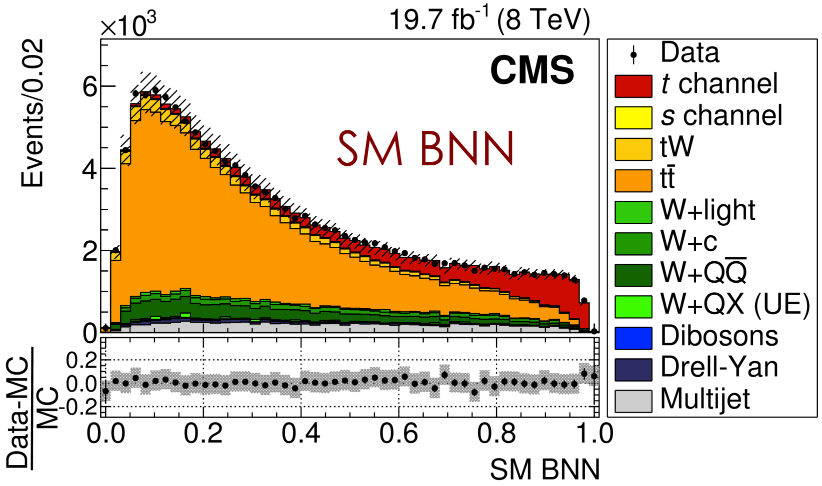
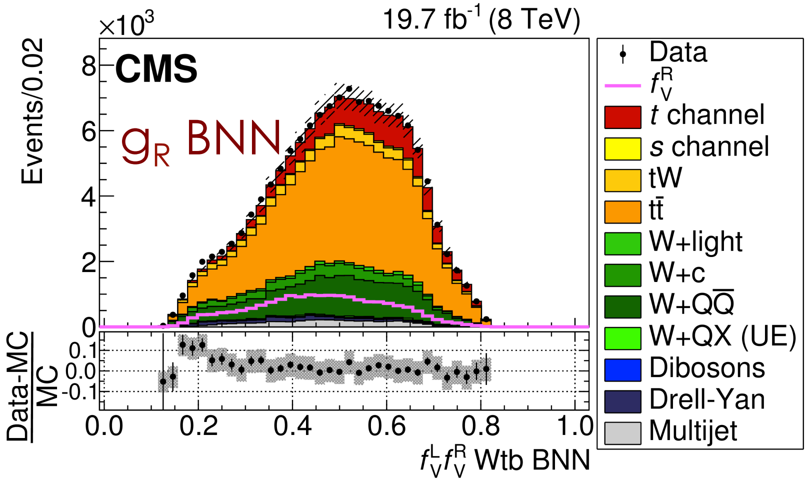
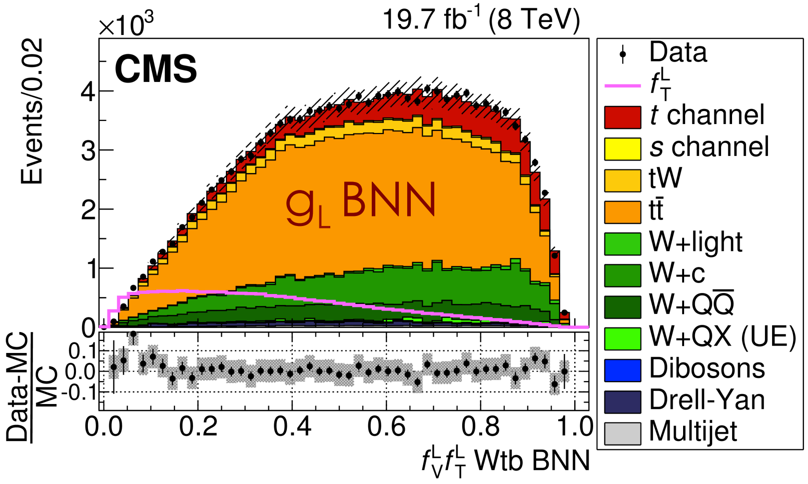
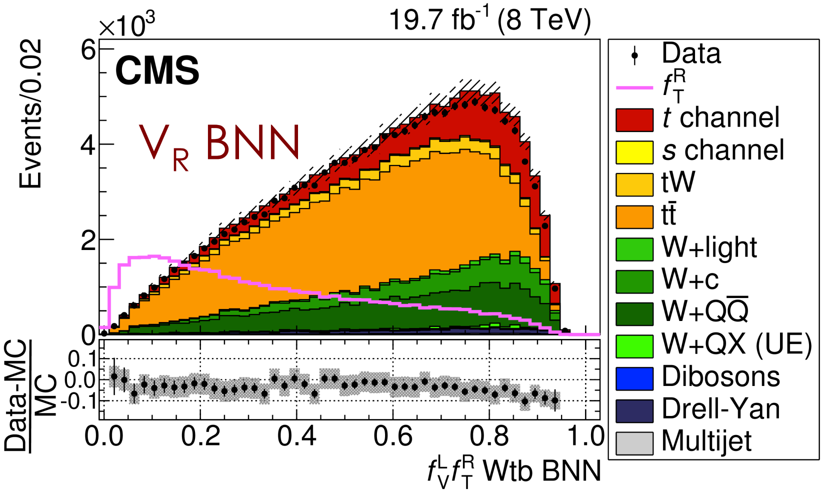
- BNN discriminators built to distinguish signal from backgrounds, and SM signal from contributions from anomalous couplings





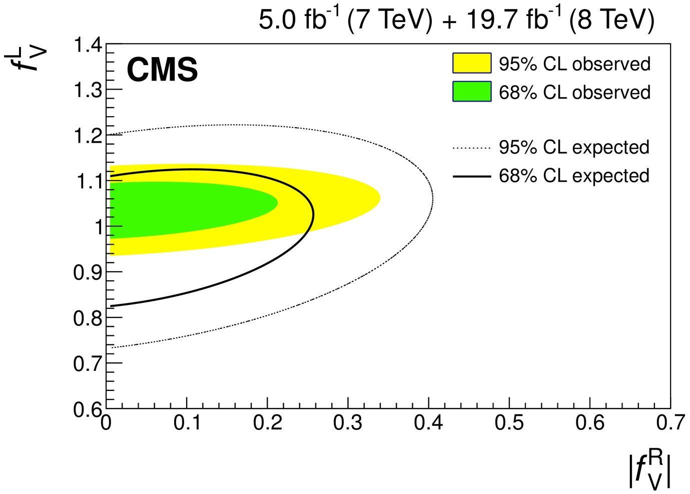


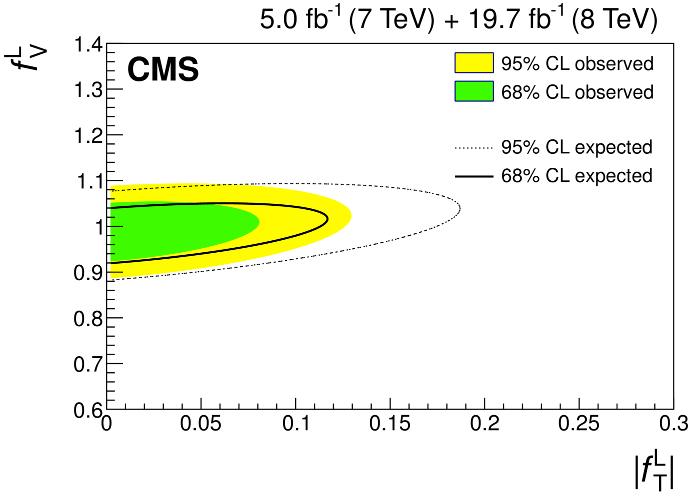


Anomalous Couplings (7 & 8 TeV)

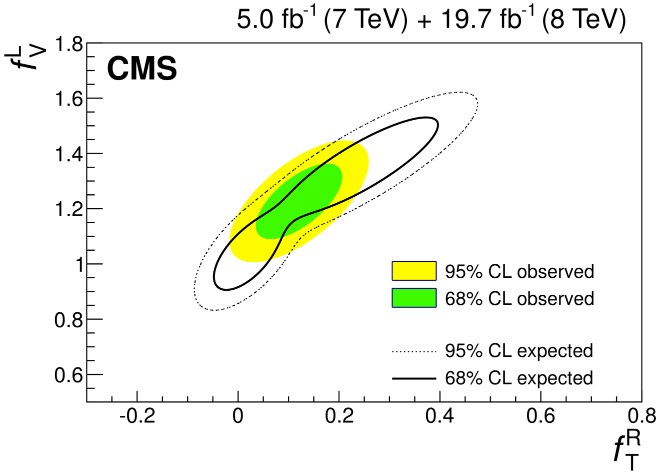
JHEP 02 (2017) 028

- The SM BNN and one of the W_{tb} BNN are simultaneously fit to data to derive exclusion limits in couplings 2D planes





- 95% CL exclusion limits on anomalous couplings:
  - $|f_V^R| < 0.16$
  - $|f_T^L| < 0.057$
  - $-0.049 < |f_T^R| < 0.048$

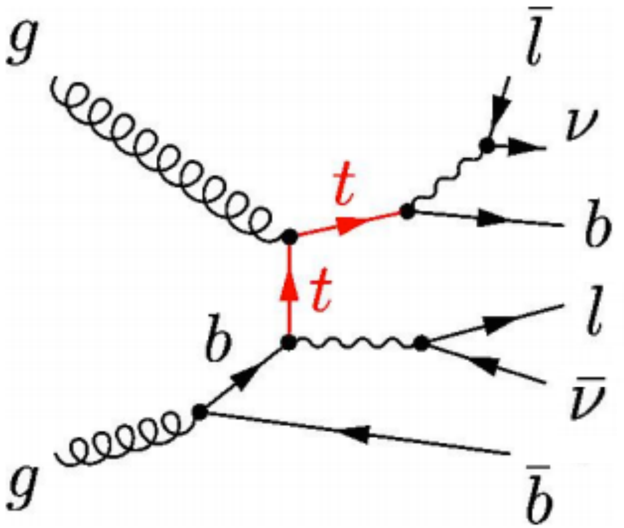


Other Single Top Production Mechanisms

- Associated production with a W boson
- Single top production in the s-channel
- Associated production with a Z boson and FCNC

tW Signature

- Experimental signature of top associated production with a W boson:



1 isolated and high-p_T lepton

Missing E_T (MET) from the neutrino

1 high-p_T and central b-jet

2nd isolated and high-p_T lepton, with opposite side with respect to the other

Other neutrino cotributing to MET

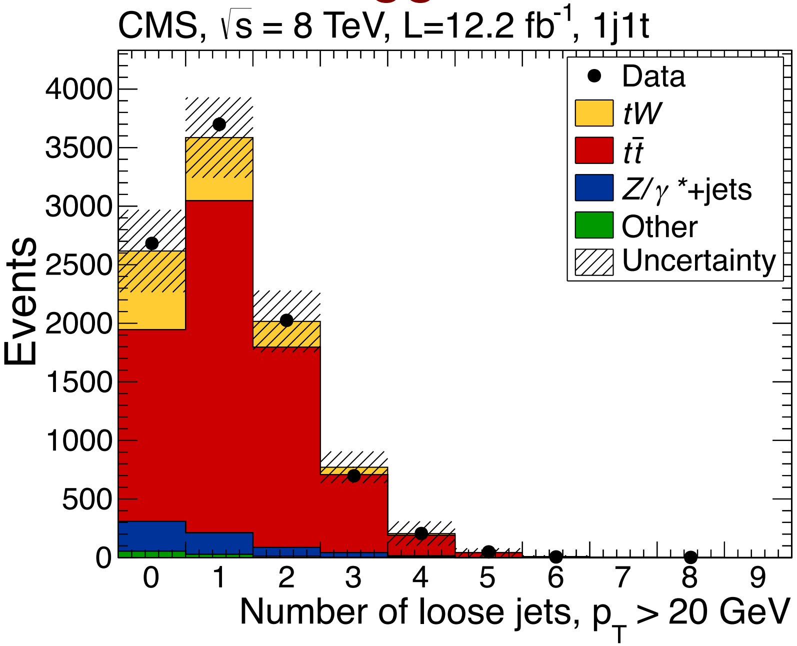
1 additional soft b-jet with high $|\eta|$ (not always detected)

- Main backgrounds:
  - top pair production

tW Cross Section (8 TeV)

Phys.Rev.Lett. 112 (2014) 231802

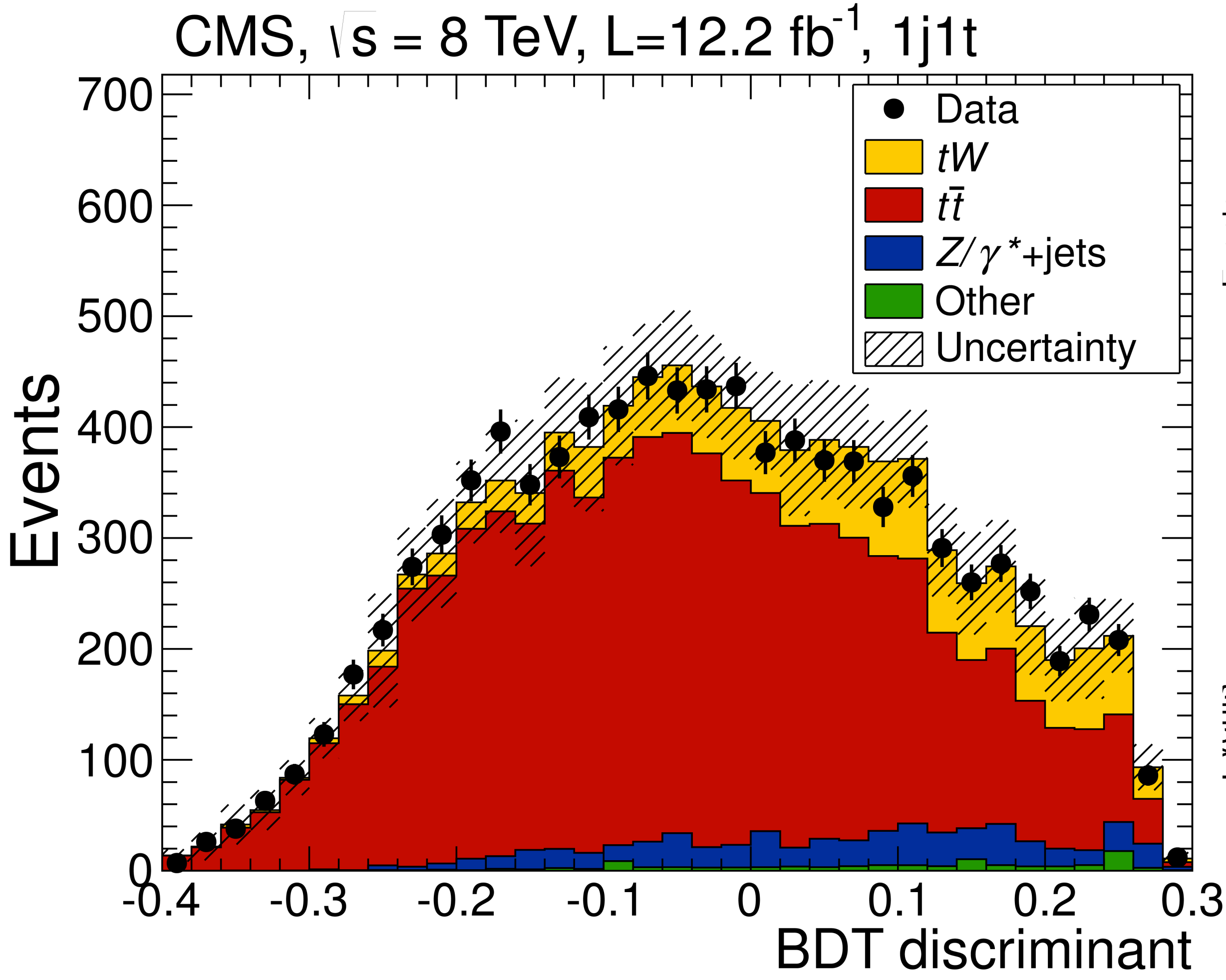
- First observation of tW associated production
- Signal region definition:
  - Two isolated opposite sign leptons with p_T>20 GeV, m_{ll}>20 GeV
  - Drell-Yan veto for the: ee and $\mu\ \mu$ channels:
    - $|m_{ll}-m_Z|$<10 GeV, Missing transverse energy MET>50 GeV
  - Exactly 1 jet with p_T>30 GeV which must be b-tagged
- BDT to separate tW from ttbar:
  - Most significant variables built from "loose" jets with pT>20 GeV
- Simultaneous fit to signal region and two control regions with 2 jets and 1 or 2 tags, respectively

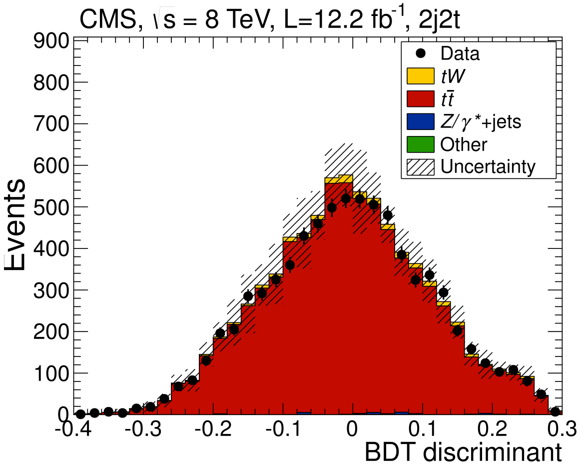


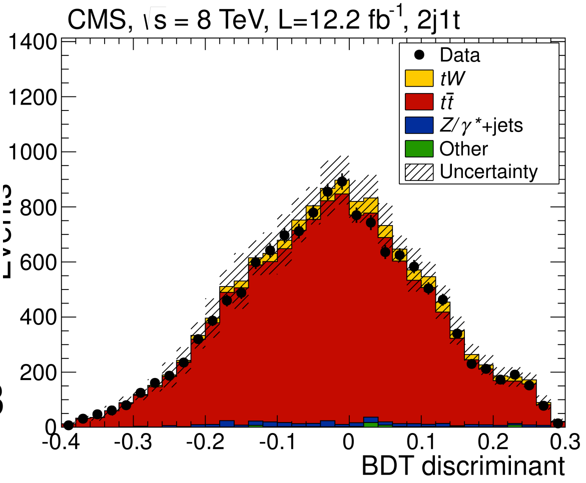
tW Cross Section (8 TeV)

Phys.Rev.Lett. 112 (2014) 231802

- Distributions of the BDT discriminator







tW Cross Section (8 TeV)

Phys.Rev.Lett. 112 (2014) 231802

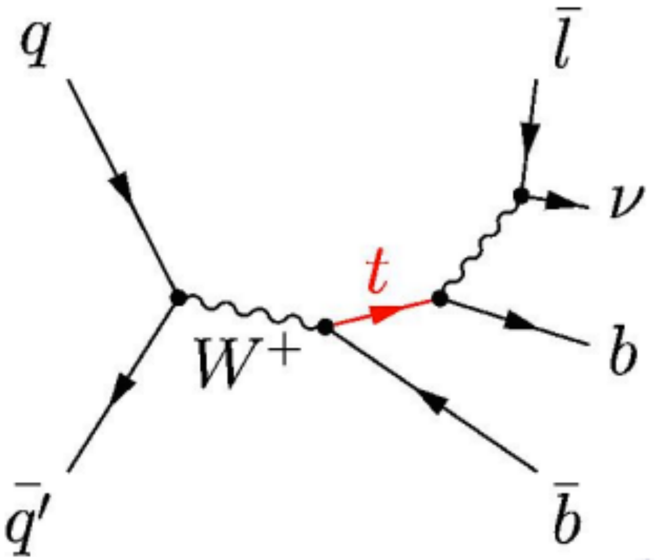
- An excess of events corresponding to a significance of 6.1 σ is observed
  - 5.4 σ significance expected from simulations
- Measured tW production cross section:
  - $\sigma_{tW} = 23.4 \pm 5.4$ pb
  - Good agreement with theoretical prediction at NNLO

$$\sigma_{tW}^{th} = 22.2 \pm 0.6\ (\text{scale}) \pm 1.4\ (\text{PDF})\ \text{pb}$$

- CKM matrix element $|V_{tb}|$ can be derived to be:
  - $|V_{tb}| = \sqrt{\sigma_{tW}/\sigma_{tW}^{th}} = 1.03 \pm 0.12\ (\text{exp}) \pm 0.04\ (\text{th})$
  - $|V_{tb}| > 0.78$ @95% CL (assuming $0 \leq |V_{tb}|^2 \leq 1$))

s-Channel Signature

- Most challenging single top production mechanism at LHC:



1 isolated and high-p_T lepton

Missing E_T (MET) from the neutrino

1 high-p_T and central b-jet

1 additional high-p_T and central b-jet

- Main backgrounds:
  - top pair production
  - Single top t-channel production
  - W+jets production

s-Channel Production (7 and 8 TeV)

JHEP 09 (2016) 027

- Signal region definition (2-jets 2-tags):
  - One isolated muon (p_T>29 GeV) or electron (p_T>30 GeV)
  - Exactly two tagged jets with p_T>40 GeV
- Analysis strategy:
  - QCD background validated in the region 2jets 0tag
  - Use of BDTs to separate signal from large ttbar and W+jets backgrounds
  - Cross section measured through a simultaneous fit to BDT distributions in the signal region and in the control regions 3jets 1tag and 3jets 2tags

	# jets	
# b-tagged jets	2	3
0	VR QCD 2jets 0tag	
1	CR t-ch.,Wjets 2jets 1 tag	
2	SR s-channel 2jets 2tags	CR ttbar 3jets 3tags

s-Channel Production (7 and 8 TeV)

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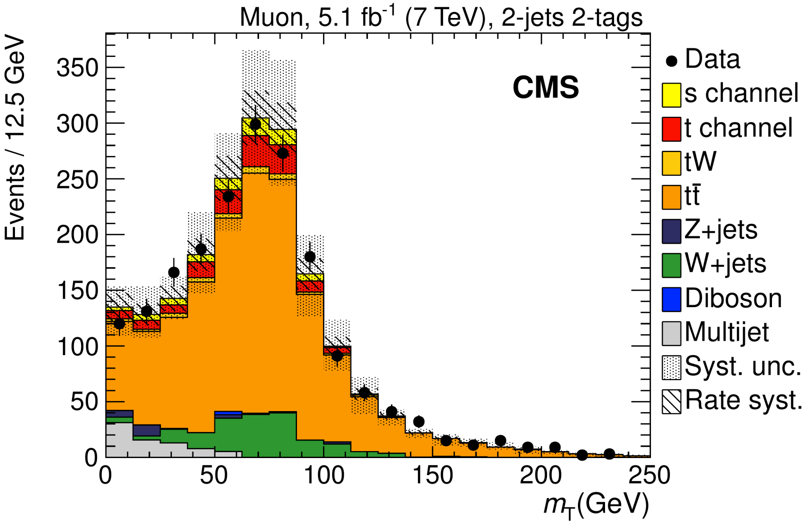
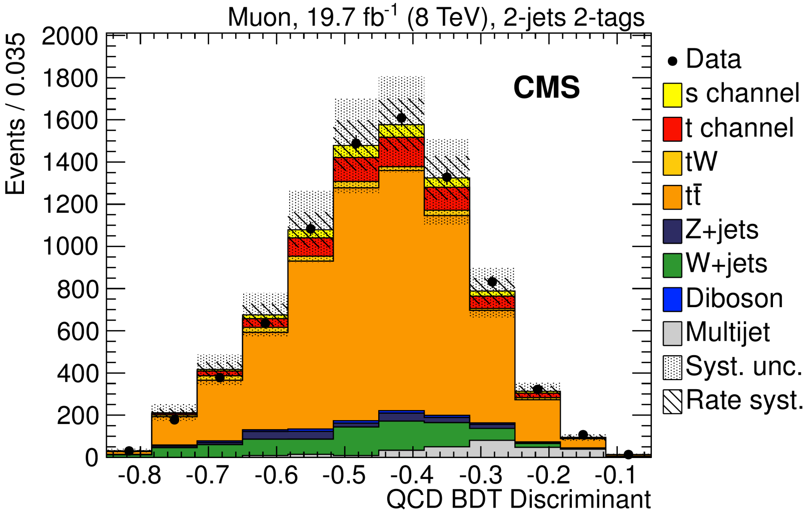
- QCD estimate at 7 TeV:
  - ML fit to m_T^W distribution in SR 2jets 2tags and CR 3jets 2tags
  - CR 2jets 1tag: ask m_T^W>50 GeV to suppress QCD contribution, cut efficiency estimated in MC



- QCD estimate at 8 TeV:
  - BDTs trained in each region to discriminate QCD from the other processes
  - ML fit to estimate the yields of QCD events



s-Channel Production (7 and 8 TeV)

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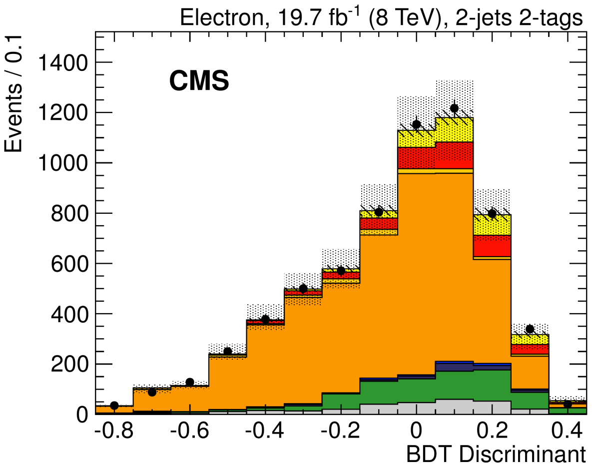
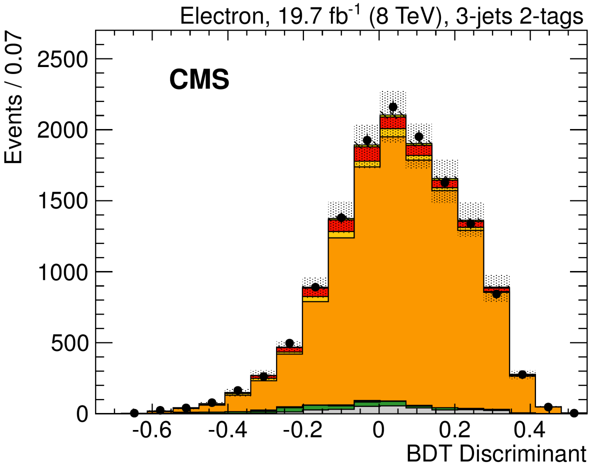
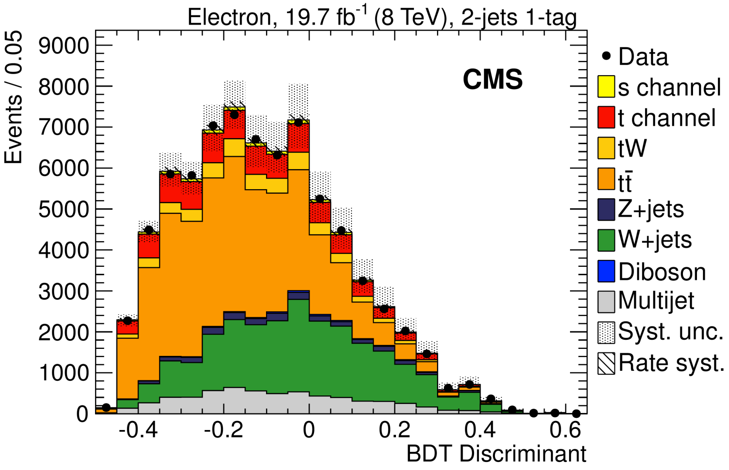
- Signal extraction based on BDT discriminants defined for the different event categories:
  - 2jets 2tags: trained to separate signal from other processes
  - 3jets 2tags: trained to separate ttbar from other processes
  - 2jets 1tag: trained to separate W+jets from other processes
  - Separate BDTs for muons at 7 and 8 TeV and electrons at 8 TeV
- Simultaneous ML fit to data in signal and control region







s-Channel Production (7 and 8 TeV)

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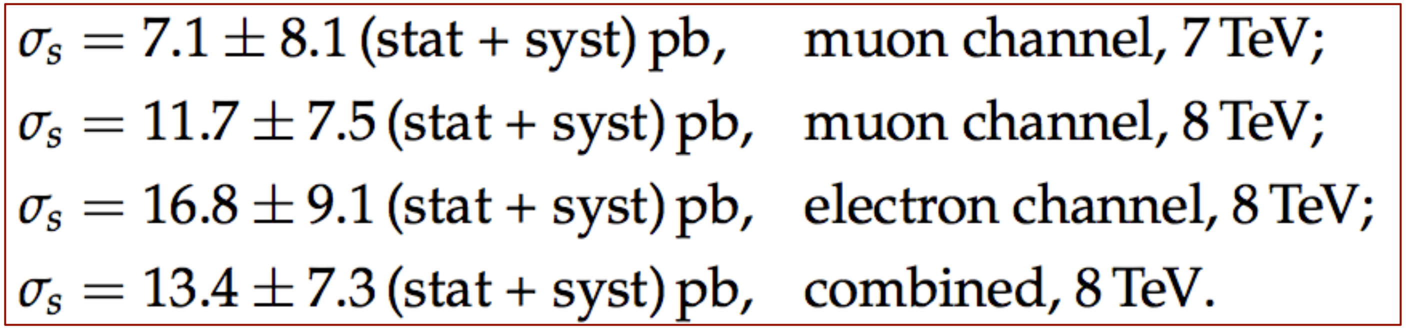
- Measured single top production cross section in the s-channel:

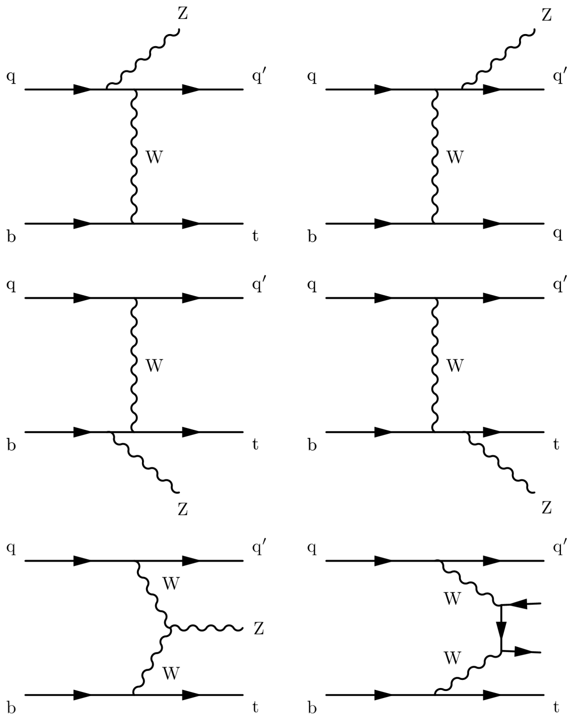


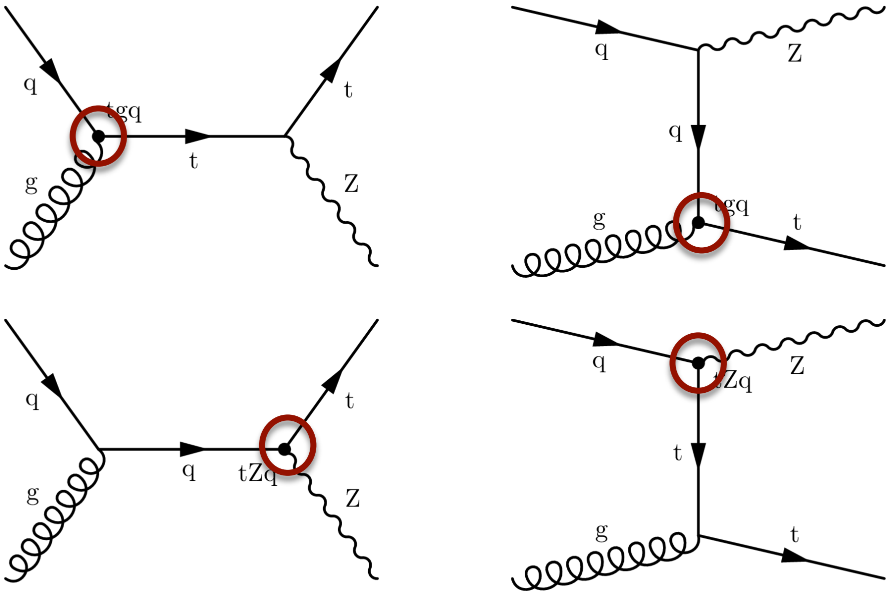
$$
\begin{aligned}
\sigma_s &= 7.1 \pm 8.1\,(\text{stat}+\text{syst})\,\text{pb}, && \text{muon channel, 7 TeV;}\\
\sigma_s &= 11.7 \pm 7.5\,(\text{stat}+\text{syst})\,\text{pb}, && \text{muon channel, 8 TeV;}\\
\sigma_s &= 16.8 \pm 9.1\,(\text{stat}+\text{syst})\,\text{pb}, && \text{electron channel, 8 TeV;}\\
\sigma_s &= 13.4 \pm 7.3\,(\text{stat}+\text{syst})\,\text{pb}, && \text{combined, 8 TeV.}
\end{aligned}
$$

  - Main systematic uncertainties from factorization and renormalization scales (~30%) and JES/JER (~35%)

- The combined fit to 7 and 8 TeV data determines the signal cross section relative to SM prediction with a best fit value $\beta_{\text{signal}} = 2.0 \pm 0.9$
- Observed (expected) significance is 2.5 (1.1) σ
- Upper limit on rate relative to SM expectation is 4.7 at 95% CL

tZq Production and FCNC

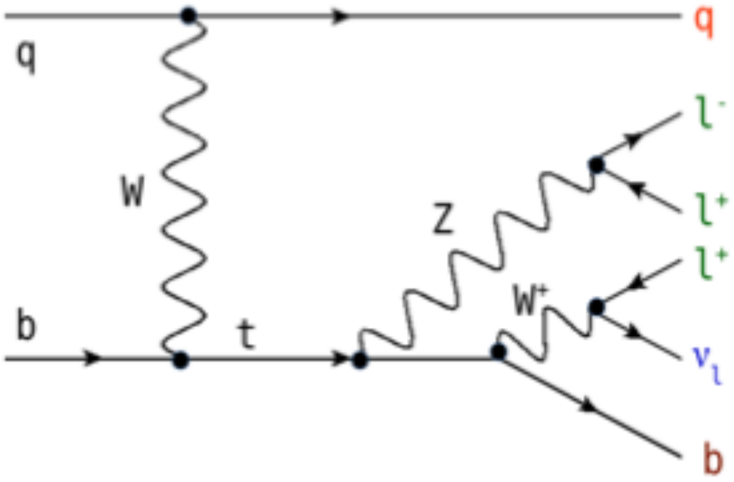




- SM tZq production:
  - Unmeasured rare standard model process
  - Irreducible background for FCNC t->Zq and tH searches
- tZ FCNC production:
  - Highly suppressed in the SM: β (t->Xq) ≈ $10^{-17} – 10^{-12}$
  - In BSM scenarios, can be enhanced up to β (t->Xq)≈10^{-3}

tZq Production (8 TeV)

arXiv:1702.01404

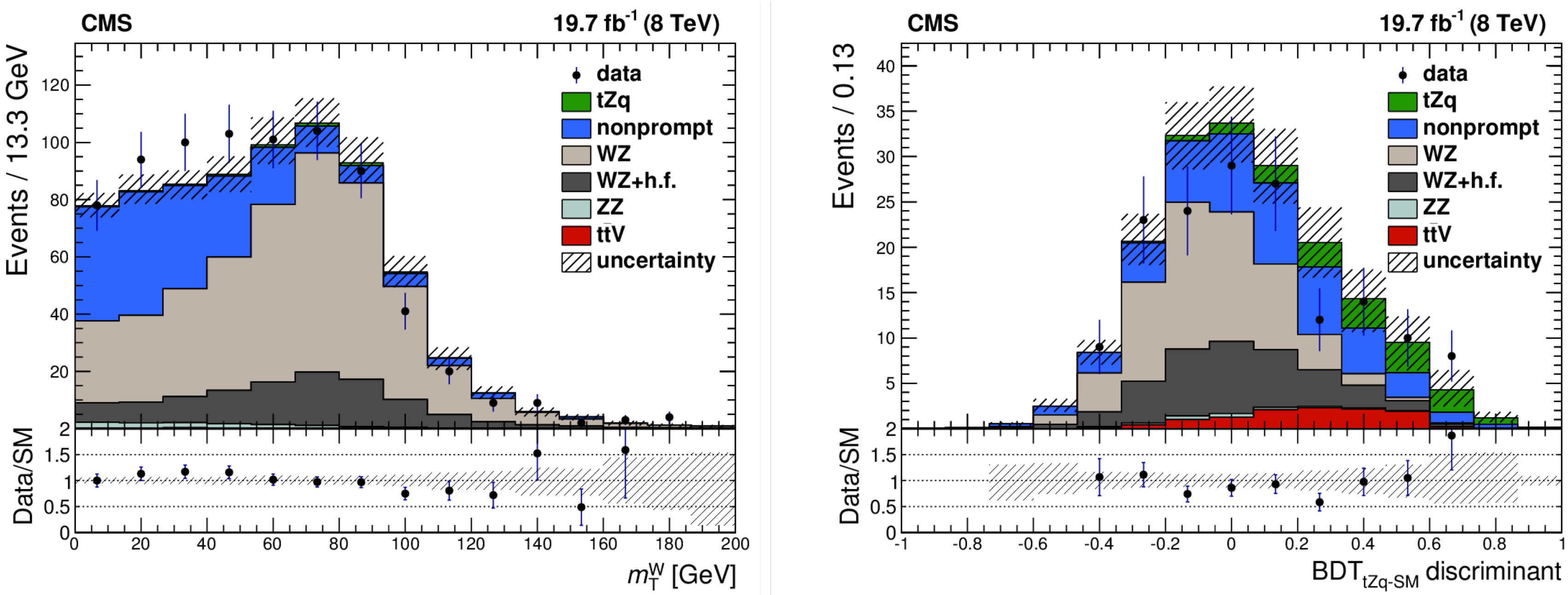


- Experimental signature:
  - Three isolate high-p_T leptons
  - Two jets
  - One b-tagged jet
  - Missing E_T from the neutrino
- Use a BDT to separate signal from ttZ and WZ backgrounds
- Backgrounds estimate:
  - WZ and non-prompt leptons from m_T^W fit in a control region with b-tag veto
    - Non-prompt templates obtained inverting isolation criteria
  - Rest of backgrounds from simulation

tZq Production (8 TeV)

arXiv:1702.01404

- Simultaneous fit to BDT in signal region and m_T^W in control region

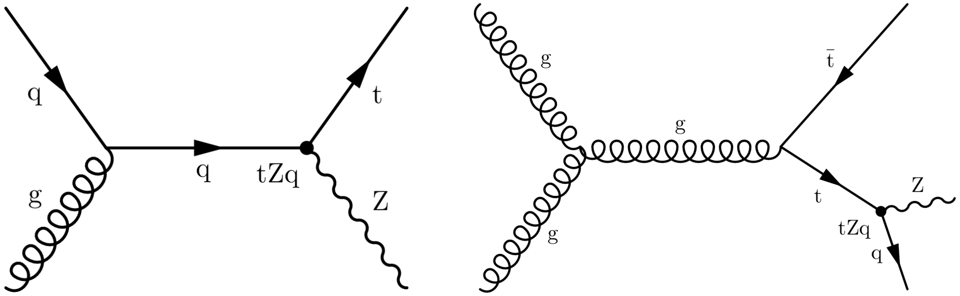


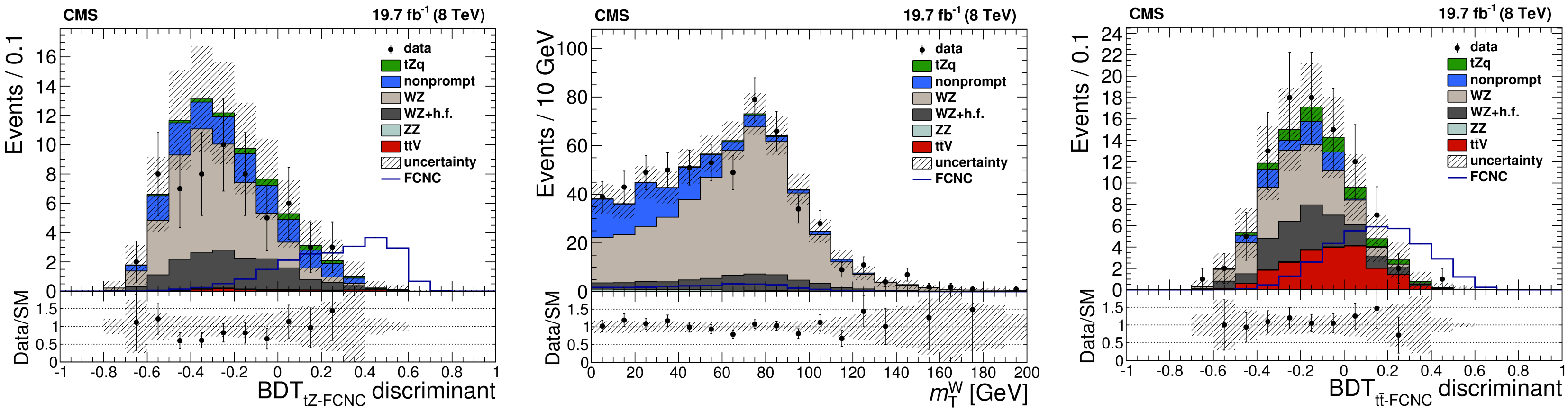
- Observed yield compatible with SM expectations:
  - σ (pp->tZq->lν bllq) = 10^{+8}_{-7} fb, with a significance of 2.4σ
  - Upper limit on tZq cross section: 21 fb at 95% CL

tZq FCNC (8 TeV)

arXiv:1702.01404

- Similar strategy as the search for tZq, but two signal regions:
  - Signal region ‘tZ’ -> BDT-tZ
  - Signal region ‘tt’ -> BDT-tt
  - b-tag veto CR -> m_T^W



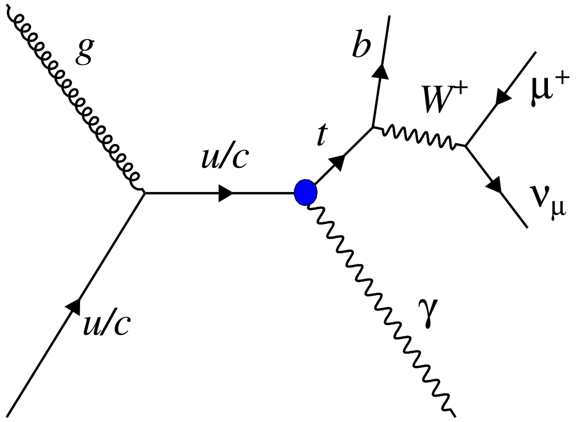


- Limits on FCNC branching ratios:

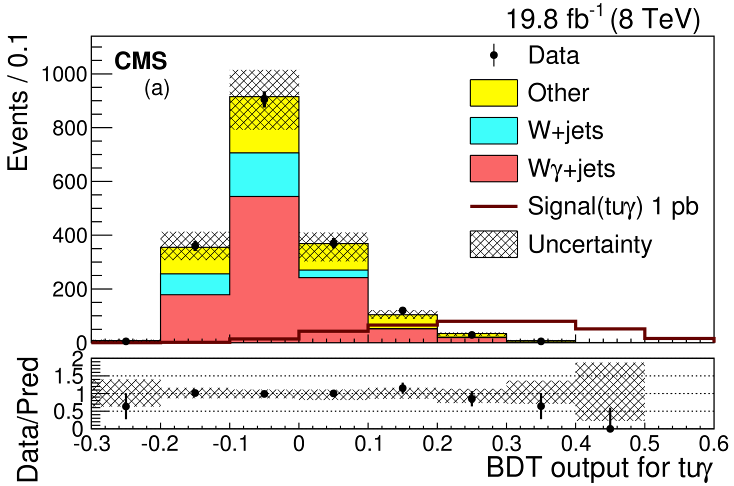
Branching fraction	Expected	68% CL range	95% CL range	Observed
$\mathcal{B}(t \to Zu)$ (%)	0.027	0.018 – 0.042	0.014 – 0.065	0.022
$\mathcal{B}(t \to Zc)$ (%)	0.118	0.071 – 0.222	0.049 – 0.484	0.049

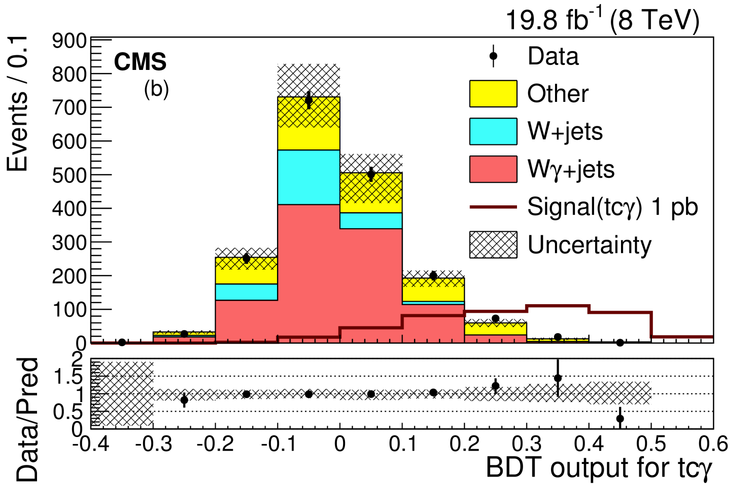
tuγ /tcγ FCNC Couplings

JHEP 04 (2016) 035



- Experimental signature:
  - Final states with a muon, a photon, large missing E_T, at least one jet with at most one being b-tagged
- Wγ +jets and W+jets estimated by a fit to a dedicated NN output
- Signal extraction through fit to BDT discriminants built separately for signal production via tuγ or tcγ couplings

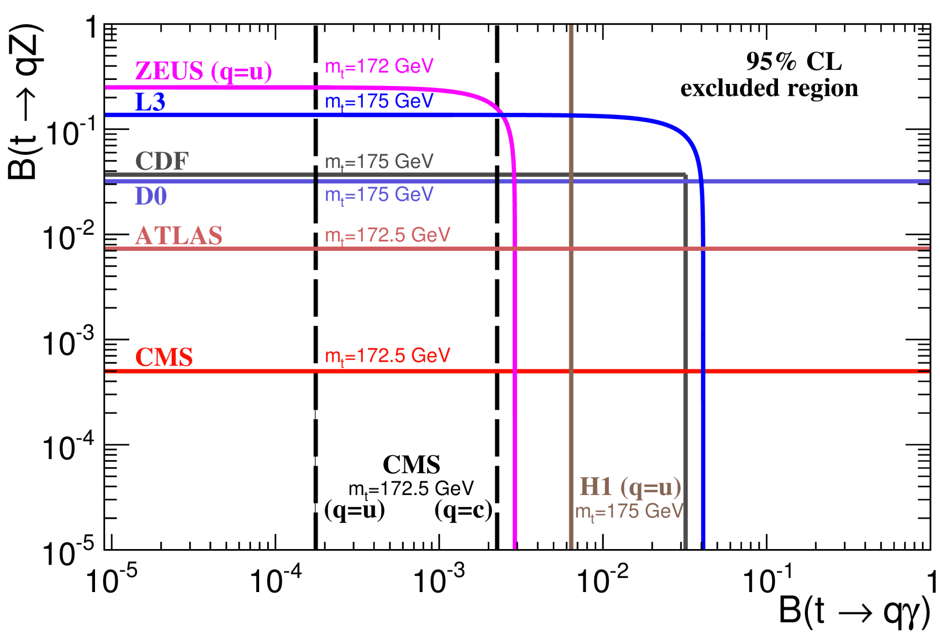




tu γ /tc γ FCNC Couplings

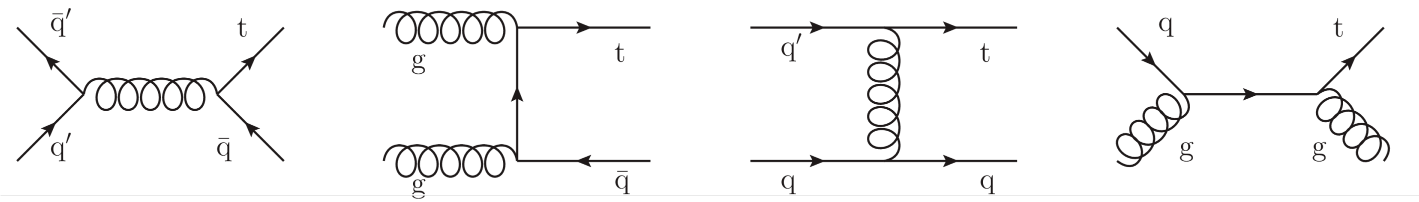
JHEP 04 (2016) 035

- No evidence of single top quark production in association with a photon is observed
- Upper limits are set on the tu γ and tc γ anomalous couplings, and translated on branching fraction of the FCNC top quark decays:
  - β (t->u γ) < 1.3 x 10^{-4}
  - β (t->c γ) < 1.7 x 10^{-3}

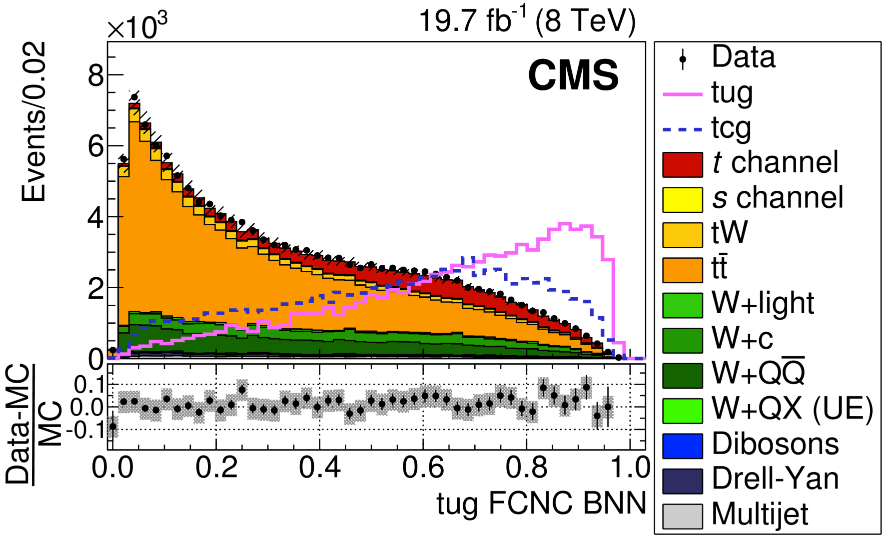


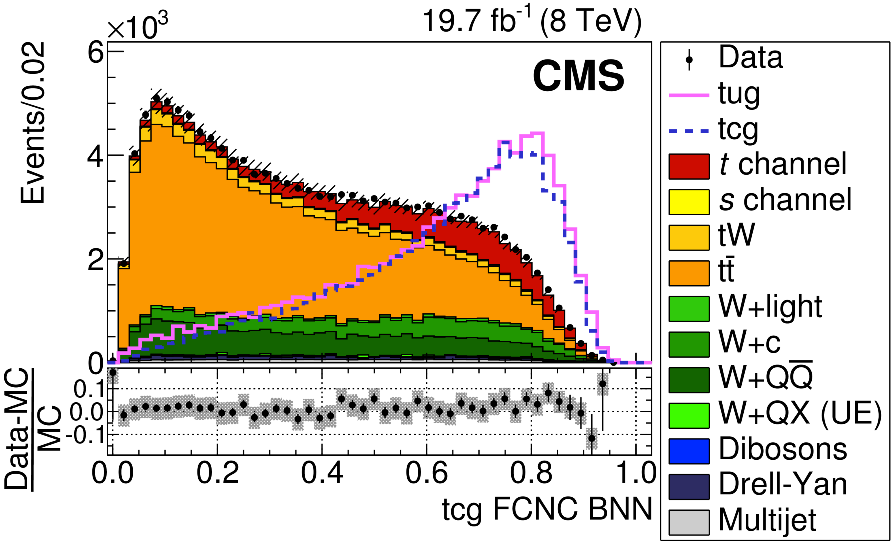
tug/tcg FCNC Couplings

JHEP 02 (2017) 028



- Same framework as for anomalous coupling searches
- Two BNNs are trained to distinguish FCNC single top production via tug/tcg couplings from SM processes

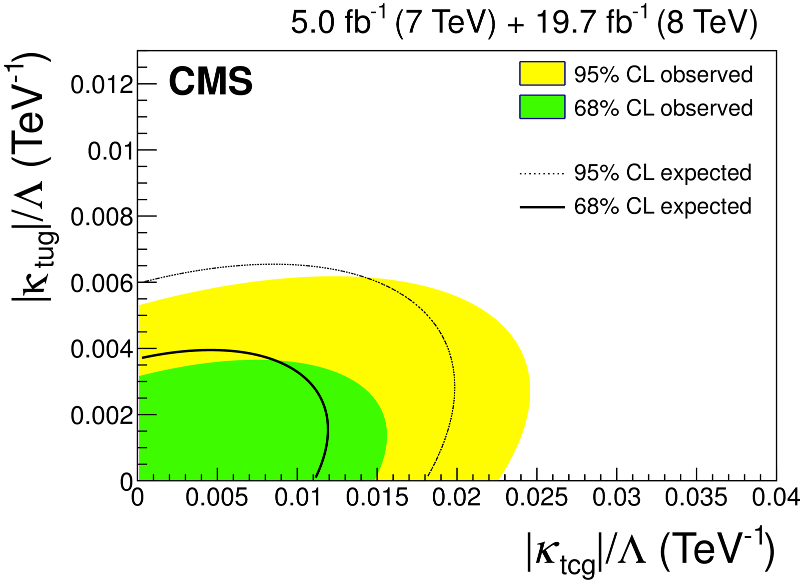




tug/tcg FCNC Couplings

JHEP 02 (2017) 028

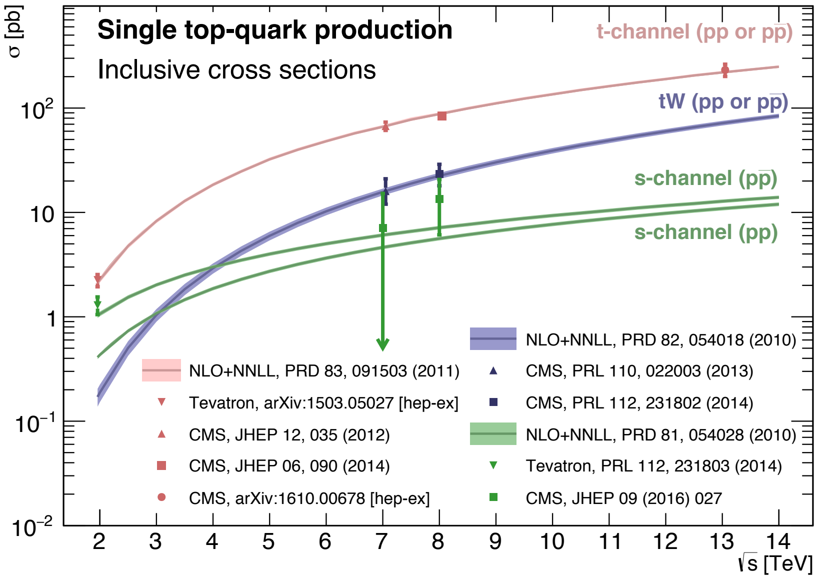
- Fitting the BNN distributions, 2D exclusion contours are set for the tug and tcg couplings
- Individual limits on one coupling are derived by integrating over the other
- These are used to establish upper limits on t -> ug and t -> cg brancing ratios

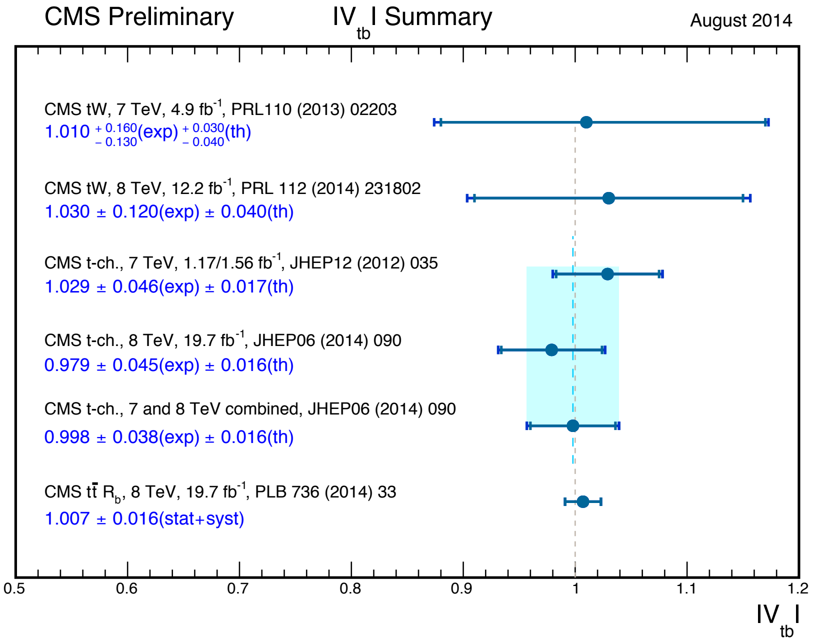


$\sqrt{s}$	$\lvert\kappa_{tug}\rvert/\Lambda$ (TeV^{-1})	$\mathcal{B}(t \to ug)$	$\lvert\kappa_{tcg}\rvert/\Lambda$ (TeV^{-1})	$\mathcal{B}(t \to cg)$
7 TeV	14 (13) $\times 10^{-3}$	24 (21)$\times 10^{-5}$	2.9 (2.4) $\times 10^{-2}$	10.1 (6.9)$\times 10^{-4}$
8 TeV	5.1 (5.9) $\times 10^{-3}$	3.1 (4.2)$\times 10^{-5}$	2.2 (2.0) $\times 10^{-2}$	5.6 (4.8)$\times 10^{-4}$
7 and 8 TeV	4.1 (4.8) $\times 10^{-3}$	2.0 (2.8)$\times 10^{-5}$	1.8 (1.5) $\times 10^{-2}$	4.1 (2.8)$\times 10^{-4}$

Summary

- A wealth of results on the electromagnetic production of the top quark being produced at the LHC





- Increasing precision on inclusive and differential cross section probe theoretical prediction
- Nature of V_{tb} coupling extensively tested

Summary

- Many searches for FCNC: no sign so far, but some channels will soon reach sufficient precision to start rejecting BSM models