Single Top quark production at CMS

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On behalf of CMS Collaboration

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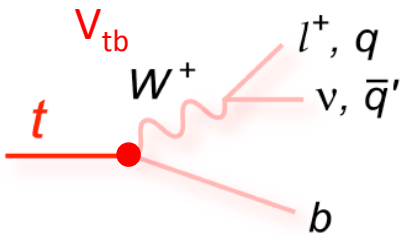
The significance of single top quark measurements

- Single top provide a direct probe of the EWK interaction, production via charge current
  - Probe of tWb vertex and measurement of CKM matrix element V_{tb} from the measured cross section

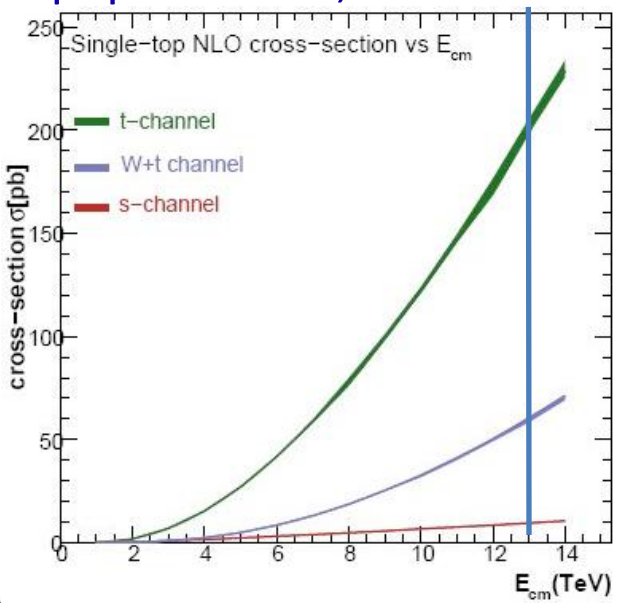


Top decays into Ws or Wd are suppressed by the square of the corresponding CKM matrix elements $|V_{ts}|$ and $|V_{td}|$.

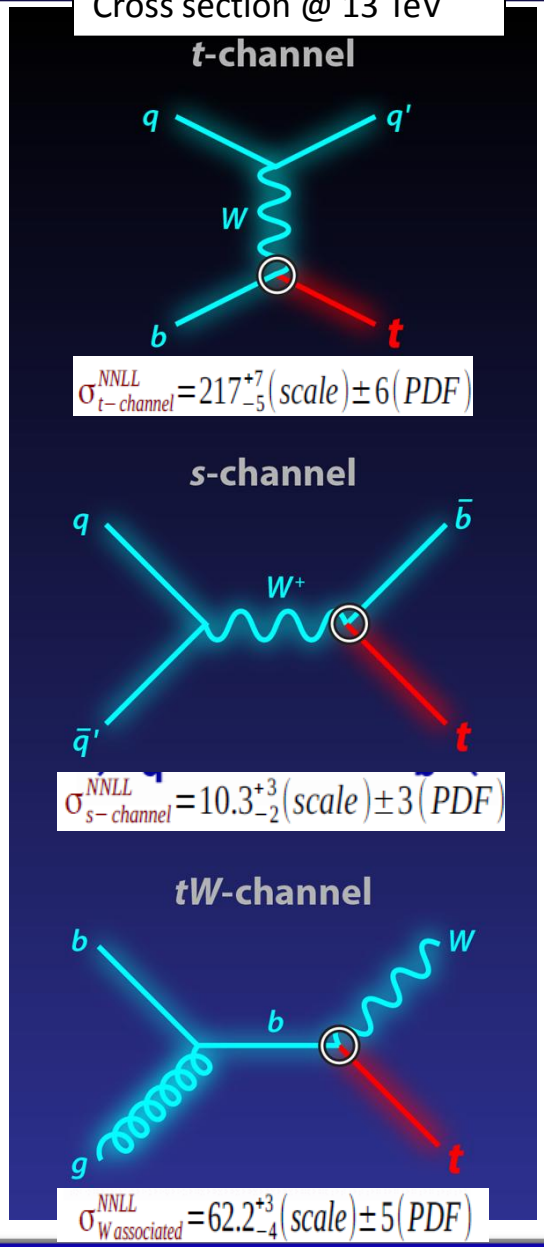
- Top quark doesn't form hadrons:
  - decays before hadronization, access to bare quark properties
  - Decay products keep spin information (spin correlations info is conserved)
    - Very important for top quark polarization studies
  - Sensitive to new physics; can change top quark anomalous couplings(FCNC)
- Important for refinement and tests of different physics aspects of top quark modeling in MC Simulations
  - Probe the PDFs
- Background for many physics searches
  - Experimental information on m_H and m_{top} gives us useful hints on the structure of the theory at very short distances

Production of Single top quark

- Discovered at Tevatron in 2009
  - Observation by CMS/ATLAS in 2011
- Three production channels
  - t-channel (2→2 and 2→3 processes at LO)
  - tW channel
  - s-channel
  - Predicted cross sections depend on PDF, choice, top quark mass, etc.

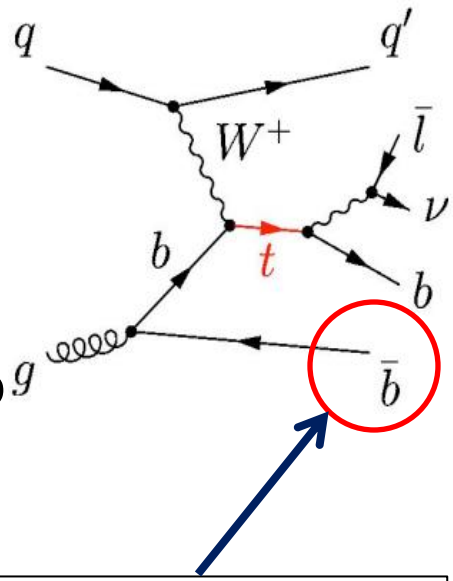


Cross section @ 13 TeV



Single top quark t-channel cross section @ 13 TeV at CMS

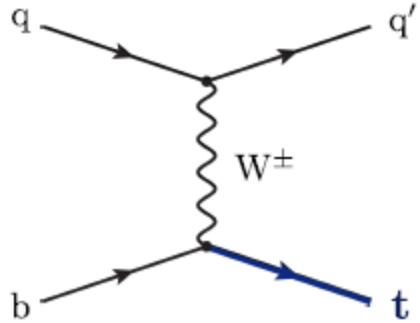
- Large production cross-section in t-channel mode
- t-channel signature (single lepton decay):
  - One isolated muon
  - Two high-pT jets (one forward and one b-tagged jet)
- Missing transverse energy (E_T^{miss}) from the neutrino



Mostly out of acceptance

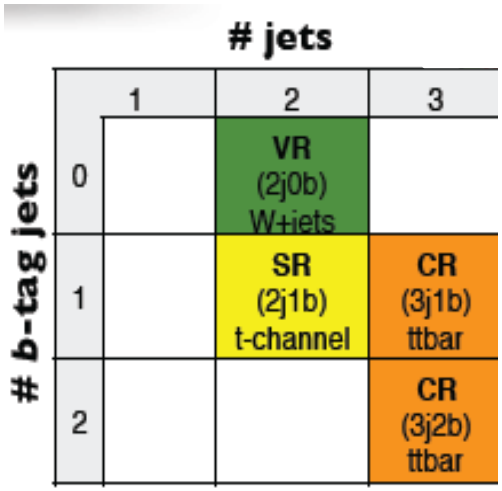
arXiv:1610.00678v1/
TOP-16-003

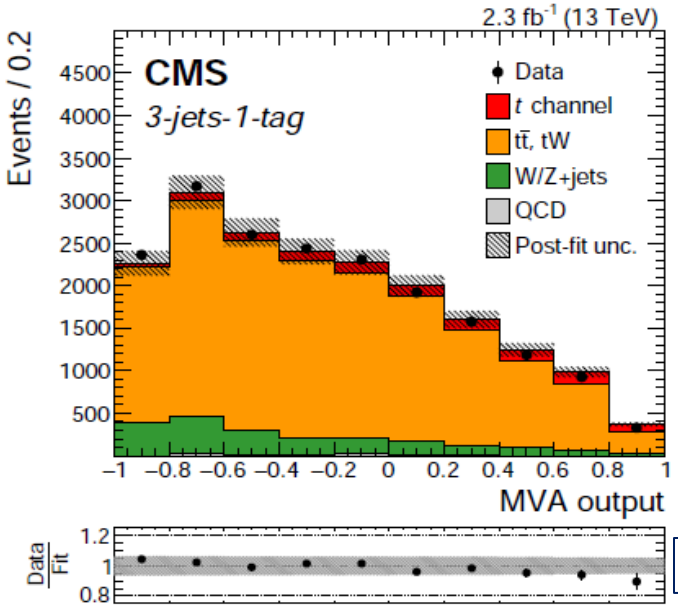
- Selection criteria:
  - One isolated μ with pT > 22 GeV and |η| < 2.1
  - 2 jets with pT > 40 GeV and |η| < 4.7
    - One of the jets must be b-tagged
    - Jet with ant-kT with R =0.5
  - m_T^W>50 GeV (low m_T^W for QCD validation)

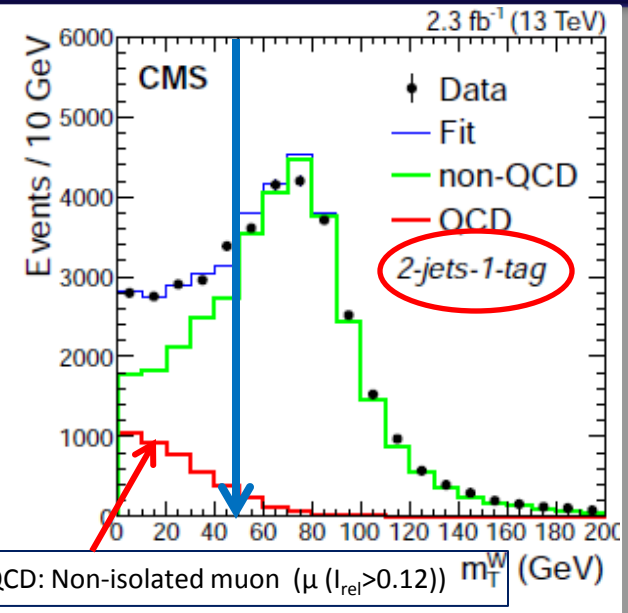


Signal region	QCD/Wjets region	ttbar region
2 jets with 1 tag	2 jets, 0 tag	3 jets, 1 or 2 tags

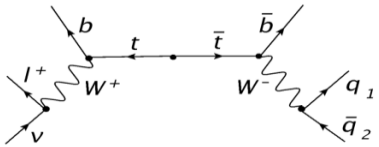
Background estimation for t-channel x-section @ 13 TeV

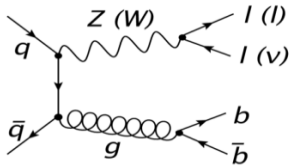






- Main backgrounds: ttbar and W+jets
  - MC samples validated in sideband control regions (3j1b,3j2b, 2j0b)
  - LH fit to both SR and CR constrain ttbar and W+jets

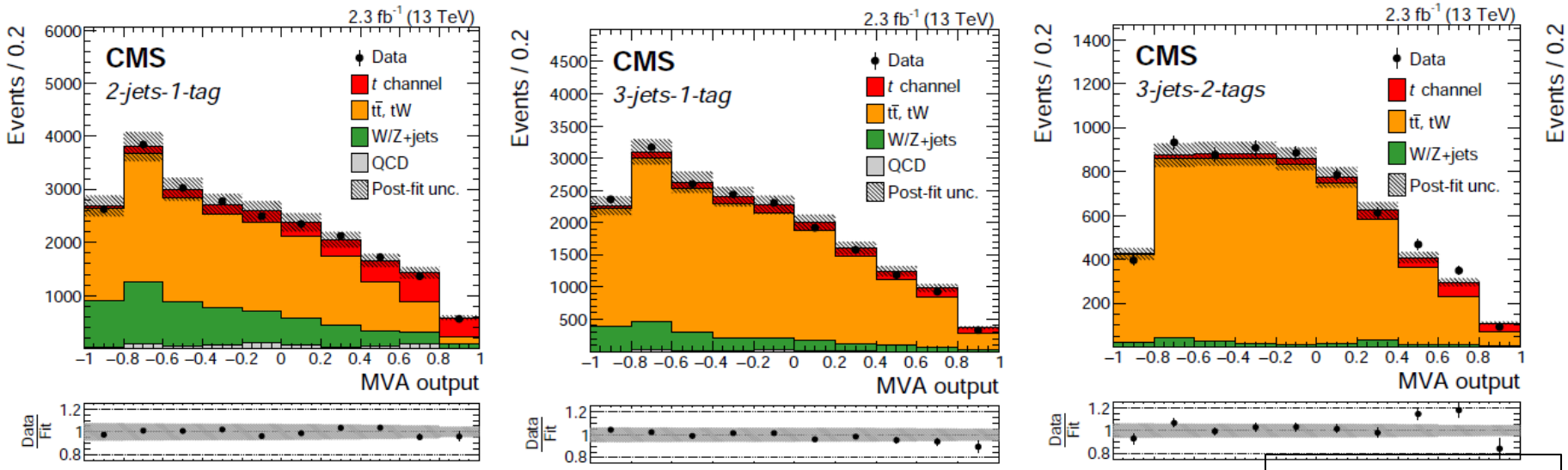




- QCD estimated from data:
  - Using m_T^W to control QCD, removing selection cut on m_T^W and perform LH fit
  - QCD contribution is then extrapolated to signal region m_T^W > 50GeV
  - Validated in 2 jet + 0 tag region where QCD is large

arXiv:1610.00678v1/
TOP-16-003

Signal extraction for t-channel @ 13 TeV



arXiv:1610.00678v1

- Artificial neural network is trained in 2jets + 1 tag region (signal region) by using 11 input variables
- Simultaneous fit is then performed in 3 regions to extract cross sections
  - Each category is then further sub-divided into +ve/-ve muons

Rank	Variable
1	Light quark $\lvert\eta\rvert$
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 $\lvert\eta\rvert$

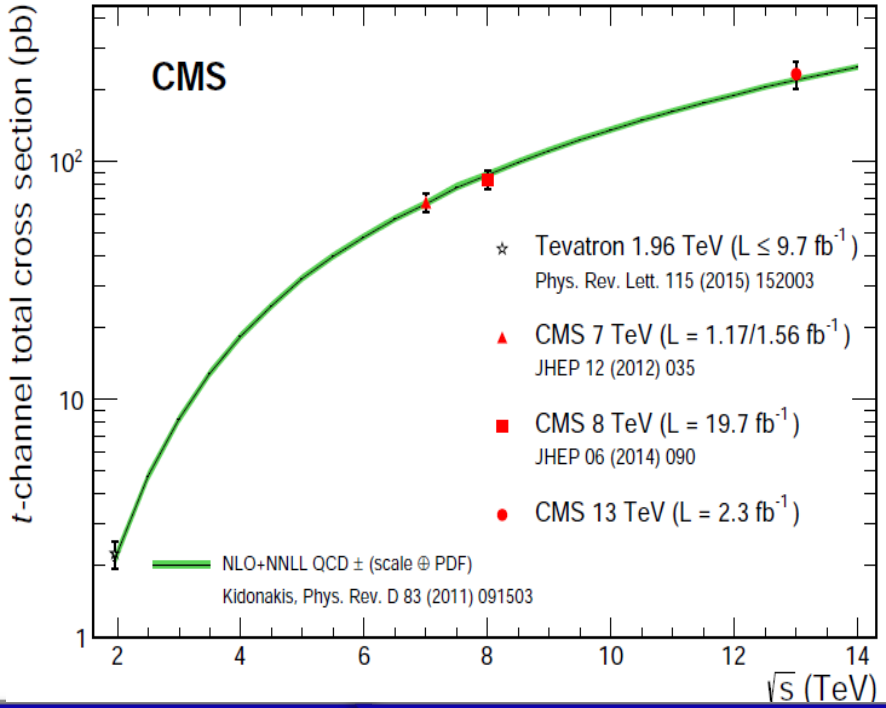
Single top quark t-channel cross-section @ 13 TeV

$$\sigma_{t\text{-ch.},t} = 150 \pm 8\,(\text{stat}) \pm 9\,(\text{exp}) \pm 18\,(\text{theo}) \pm 4\,(\text{lumi})\ \text{pb}$$
$$= 150 \pm 22\ \text{pb},$$
$$R_{t\text{-ch.}} = 1.81 \pm 0.18\,(\text{stat}) \pm 0.15\,(\text{syst}).$$
$$\sigma_{t\text{-ch.},\bar{t}} = 82 \pm 10\,(\text{stat}) \pm 4\,(\text{exp}) \pm 11\,(\text{theo}) \pm 2\,(\text{lumi})\ \text{pb}$$
$$= 82 \pm 16\ \text{pb},$$
$$\sigma_{t\text{-ch.},t+\bar{t}} = 232 \pm 13\,(\text{stat}) \pm 12\,(\text{exp}) \pm 26\,(\text{theo}) \pm 6\,(\text{lumi})\ \text{pb}$$
$$= 232 \pm 31\ \text{pb}.$$

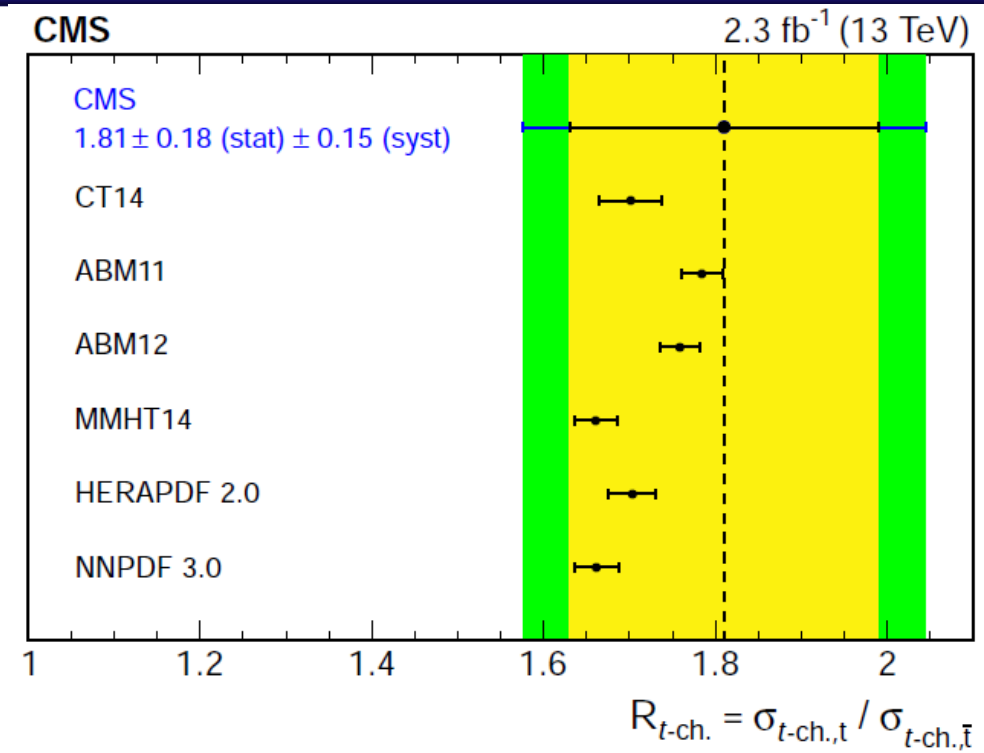
arXiv:1610.00678v1

$$\sigma^{NNLL}_{t-channel} = 217^{+7}_{-5}(scale) \pm 6(PDF)$$

- Good agreement between measurements and theory at different center of mass energies
- Dominant systematics:
  - t-channel and ttbar modelling (~9%)
  - factorisation/renormalisation scales(~6%)



Top/anti-top cross section ratio



arXiv:1610.00678v1

- $\sigma_{tch.,t}$ and $R_{tch.}$ are parameters of the fit
- The ratio is sensitive to the description of different PDF sets
- Can be used to calculate the CKM matrix element $|V_{tb}|$(assuming $|V_{tb}|>>|V_{td}|,|V_{ts}|$)
  - The presence of an anomalous Wtb coupling is taken into account by the anomalous form factor f_{LV}

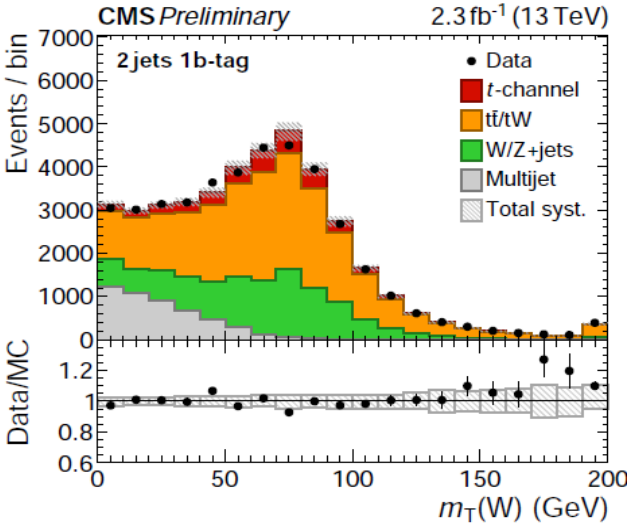
$$|f_{LV}V_{tb}| = 1.03 \pm 0.07\,(\text{exp}) \pm 0.02\,(\text{theo})$$

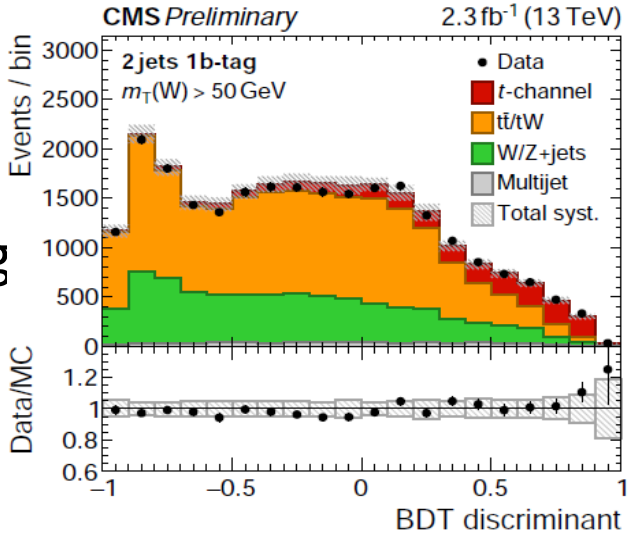
$$|f_{LV}V_{tb}| = \sqrt{\frac{\sigma_{t\text{-ch.},t+\bar{t}}}{\sigma^{th}_{t\text{-ch.},t+\bar{t}}}},$$

t-channel differential cross section @ 13 TeV

TOP-16-004

- Measured signal yields in bins of p_T and absolute rapidity ($y = \frac{1}{2} \ln \frac{E+p_z}{E-p_z}$)
- BDT discriminator :
  - Based on variables uncorrelated to top p_T and rapidity
  - No selection on m_T^W in training
  - Trained in 2jets+1 tag, used it in all regions
- Data Driven multijet estimation:
  - Low MC statistic: shape from data with same selection but non-isolated lepton $I_{rel.} > 0.2$
  - For QCD fit to m_T^W shape for $m_T^W < 50$ GeV, expect QCD at low m_T^W
- For signal extraction with $m_T^W > 50$ GeV using BDT distribution, to estimate signal and other backgrounds yields

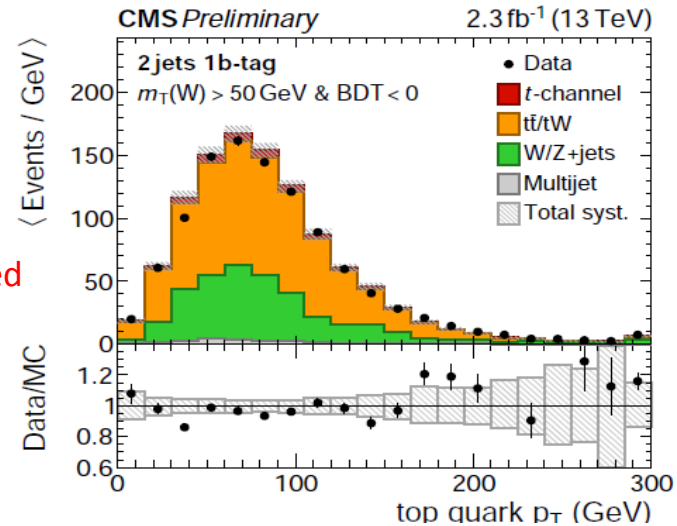


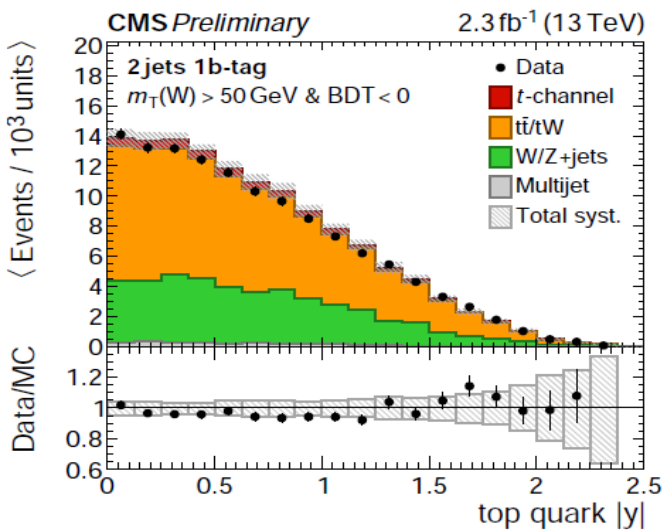


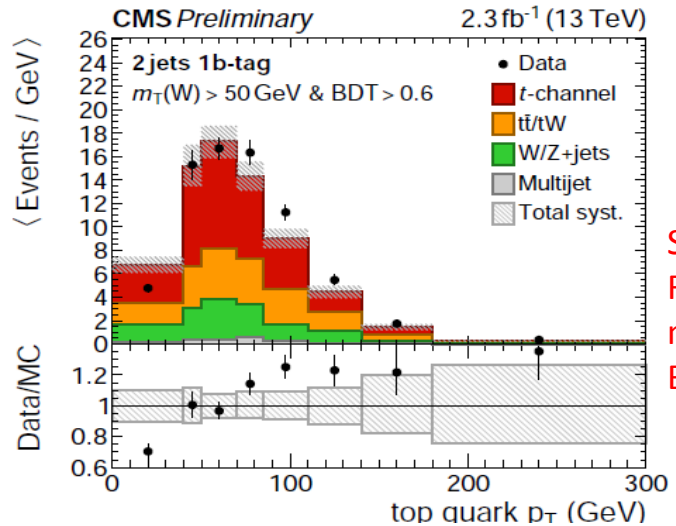
t-channel differential cross section @ 13 TeV

- Simultaneous fit in 3 regions enhances sensitivity to ttbar and reduces anti-correlation with W+jets norm.

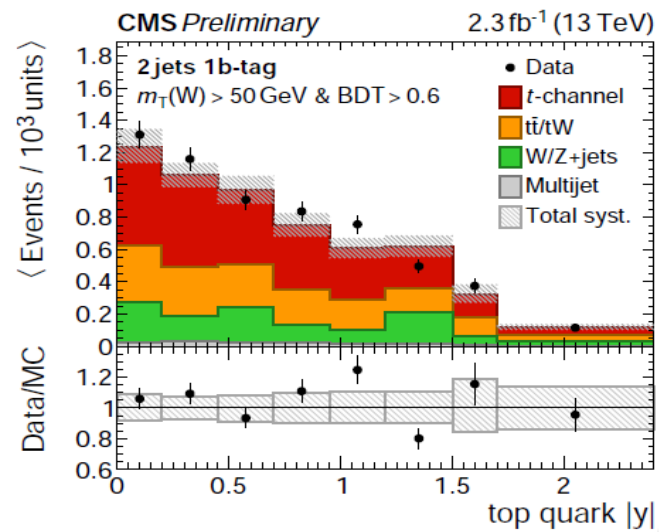
Signal depleted Region: m_T^W >50GeV , BDT<0



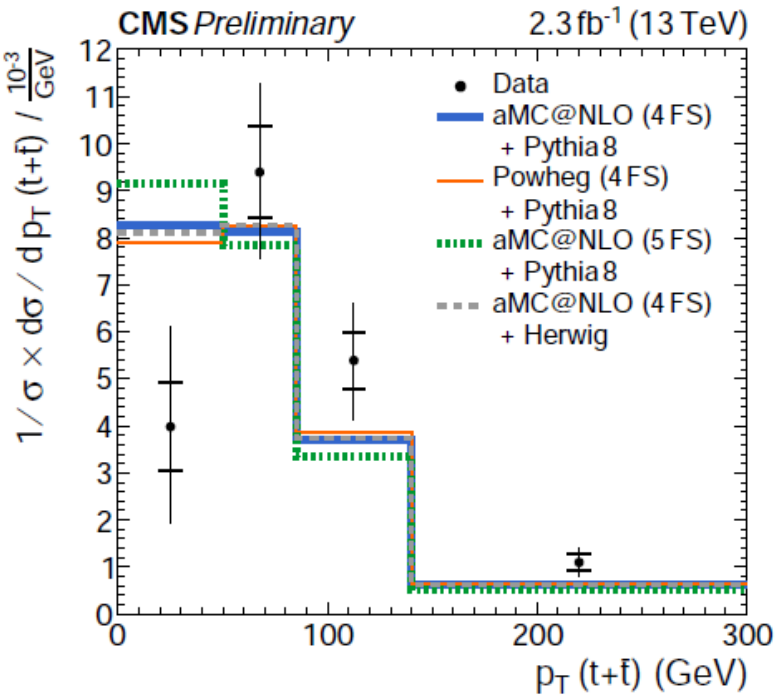


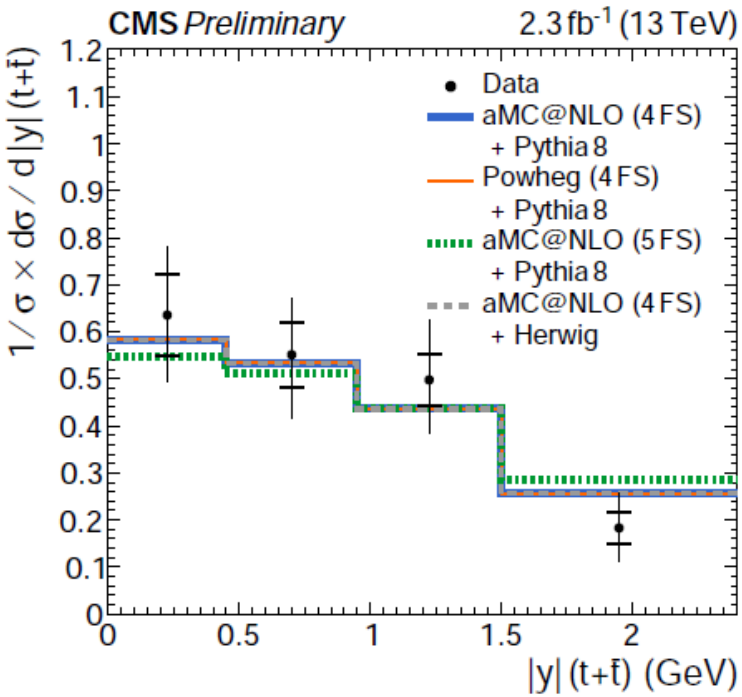


Signal enhanced Region: m_T^W >50GeV , BDT>0.6



t-channel differential cross section @ 13 TeV





- From signal region unfolded to parton level
- Data is in agreement with the theoretical predictions within uncertainties

Search for Anomalous Wtb couplings

- Single top production cross section is proportional to the size of Wtb interaction

arXiv:1610.03545v2

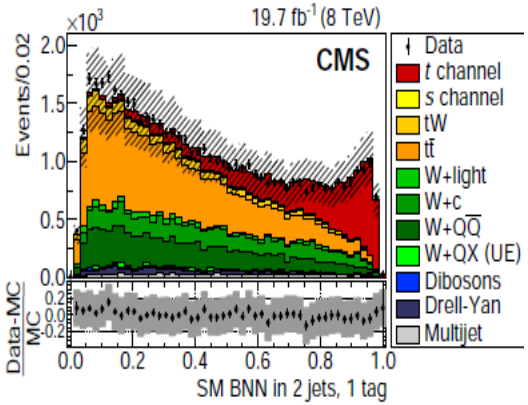
  - Provides the direct measurement of |Vtb|
  - t-channel production is sensitive to possible deviations from the SM prediction for the Wtb vertex

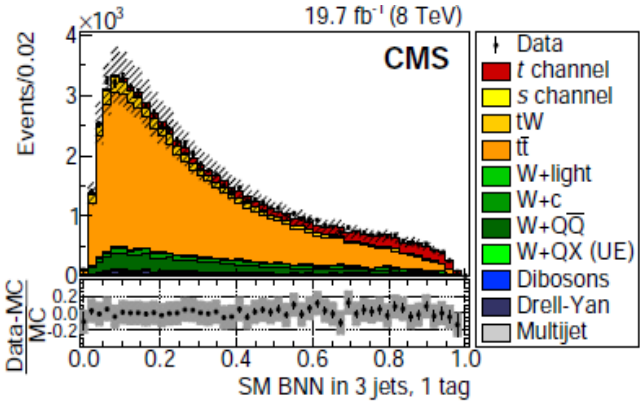
Search for single muon +one light jet + one bjet

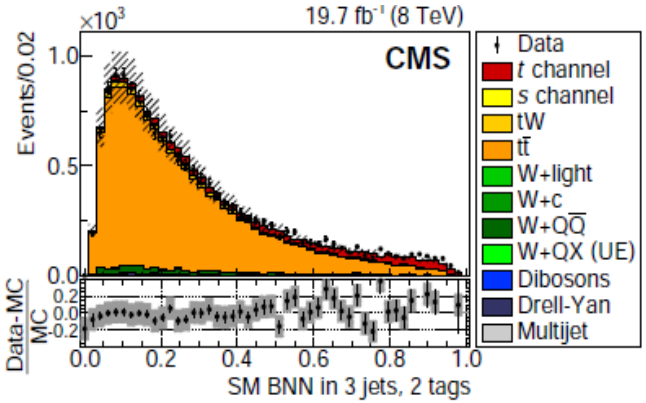
- CP-conserving Lagrangian for Wtb can be written as

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

- In SM $f_V^L = V_{tb}, f_V^R = f_T^L = f_T^R = 0.$
  - Look for differences in kinematical and angular distributions in the presence of anomalous couplings



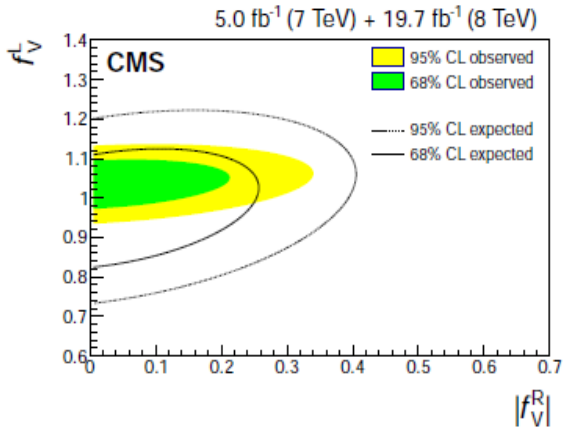


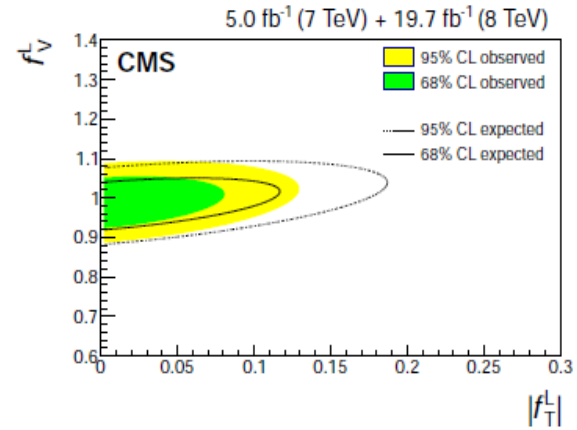


Anomalous Wtb couplings

- BNNs are trained to separate SM left-handed interactions from one of the anomalous interactions
- The SM BNN and one of the Wtb BNN discriminants are used as inputs in the simultaneous fit of the two BNN discriminants

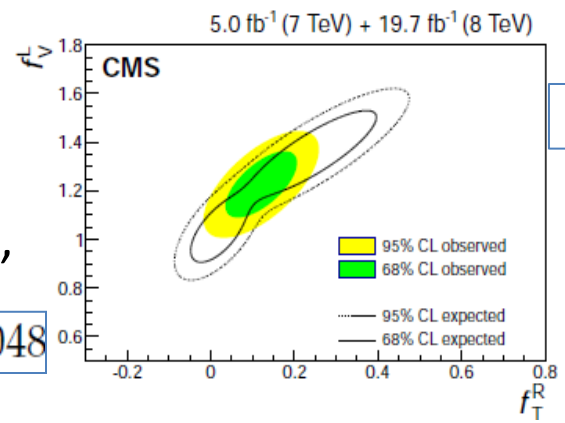
- Observed and expected exclusion limits in the two dimensional planes at 68% and 95% CL.





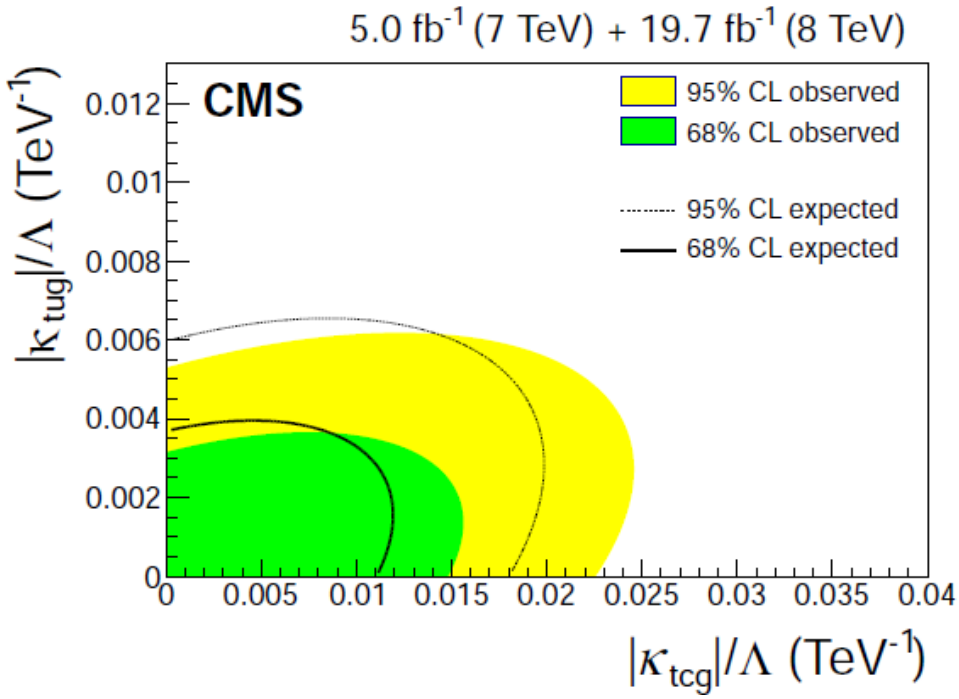
- The measured 95% CL exclusion limits on anomalous right-handed vector, and left- and right-handed tensor Wtb couplings are,

$$|f_V^R| < 0.16,\ |f_T^L| < 0.057,\ \text{and}\ -0.049 < f_T^R < 0.048$$



arXiv:1610.03545v2

Exclusion limits on tug and tcg anomalous couplings



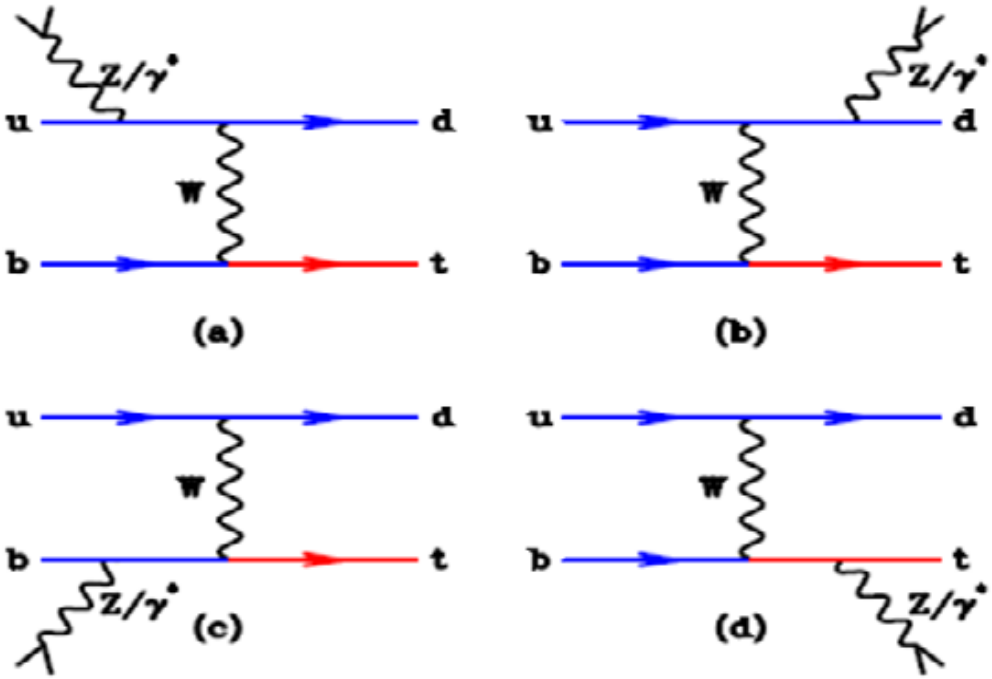
$\sqrt{s}$	$\lvert\kappa_{tug}\rvert/\Lambda$ (TeV^{-1})	$\mathcal{B}(t \to ug)$	$\lvert\kappa_{tcg}\rvert/\Lambda$ (TeV^{-1})	$\mathcal{B}(t \to cg)$
7 TeV	14 (13) $\times 10^{-3}$	24 (21) $\times 10^{-5}$	2.9 (2.4) $\times 10^{-2}$	10.1 (6.9) $\times 10^{-4}$
8 TeV	5.1 (5.9) $\times 10^{-3}$	3.1 (4.2)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

Search for associated production of a Z boson with Single Top Quark @ 8 TeV

- tqZ is an unmeasured rare standard model process.
  - Measurement confirms a predicted feature of the standard model and allow other analyses(trilepton analysis) to more accurately account for the tqZ as a background
  - irreducible background for FCNC t→Zb decay and tH searches
- Analysis techniques can be shared in common with SUSY multilepton analysis

- $\sigma(tl^+l^-q) = 8.2^{+0.59}_{-0.03}$(scale) fb based on leptonic top quark decay, and $m_{ll} > 50$ GeV using MC@NLO.

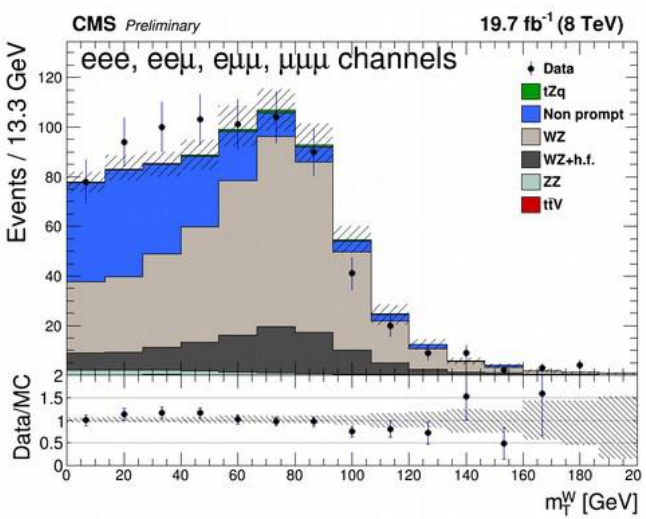
x-section enhancement w.r.t SM may be a hint of new physics

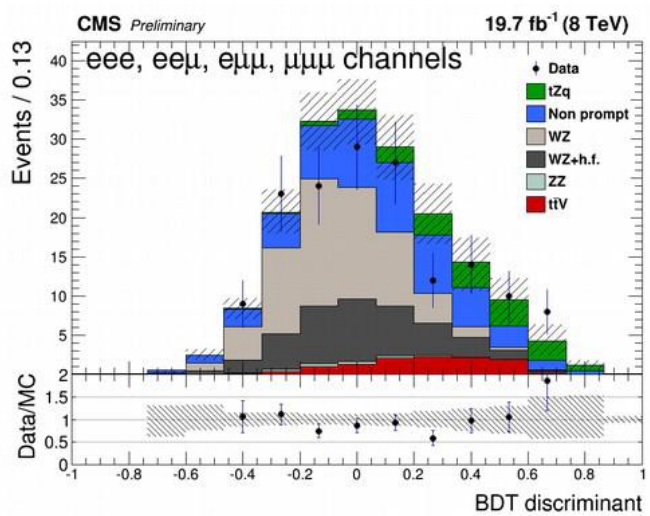


Search for SM tZq Process @ 8TeV

arXiv:1702.01404v1

- Analysis Strategy:
  - Data driven estimation for fake(from ttbar and DY) background
  - Data driven estimation for di-boson background (WZ+jets)
  - Rest of the backgrounds from simulation
  - Background is estimated from data by a fit on m_T^W distribution in the control region
    - Fake/non-prompt background templates are obtained inverting isolation criteria on third lepton
  - WZ+heavy flavor jet and WZ+light jet get free parameters in fit
- Signal Separation: BDT is trained to separate SM tZq from ttZ and WZ
- Simultaneous fit on BDT(m_T^W) distribution in signal and background region





- BDT contains variables such as the p_T and η of leptons related to top quark and Z Boson, charge asymmetry of leptons from W boson, jet properties etc

Search for SM tZq Process @ 8TeV

- Observed(expected) significances: 2.4 (1.8)σ
- Measured upper limit on tZq cross section at 95% CL. : 21 fb

Channel	Cross section (fb)
eee	0^{+9}
eeμ	11^{+13}_{-10}
$\mu\mu$e	24^{+19}_{-16}
$\mu\mu\mu$	5^{+9}_{-5}
Combined fit	10^{+8}_{-7}

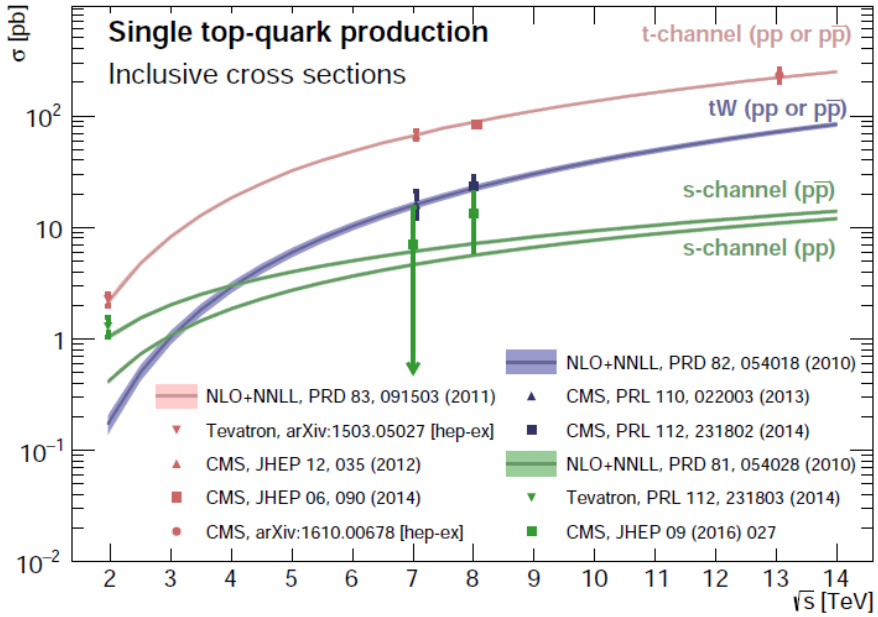
$\sigma(tl^+l^-q) = 8.2^{+0.59}_{-0.03}$(scale) fb

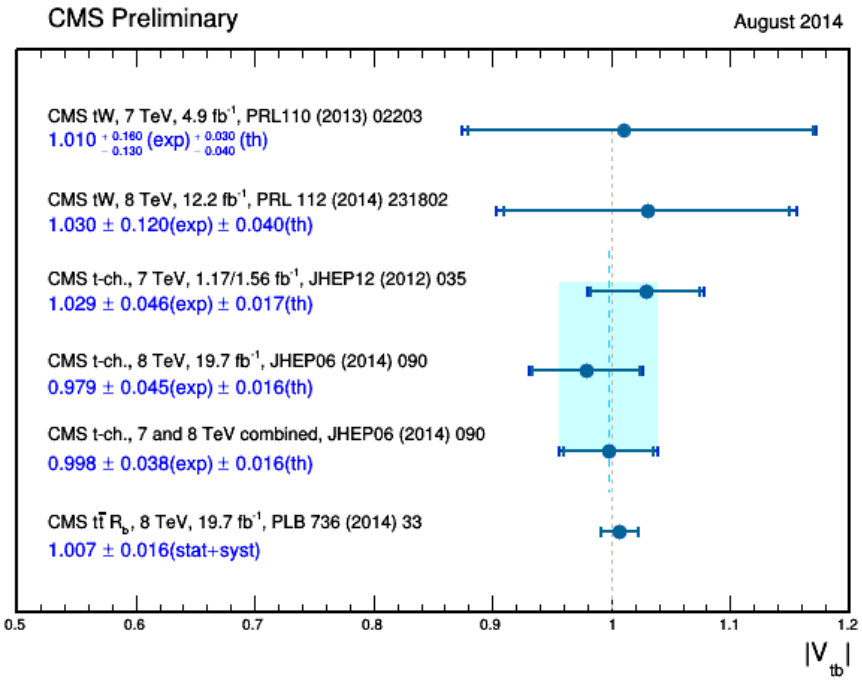
- Results confirmed by simple cut &count analysis as well

- For FCNC interpretations, see Pieter David's talk

Summary

- CMS produced a wealth of results on the electroweak production of the Top quark in different production modes at 7,8 and 13 TeV





- Measurement of V_{tb} at different CoM energies in different production modes
- First search for tqZ at 8TeV has been published
- Newer results based on the full 2016 dataset are coming soon!!

Backup

Results in this talk are based on the following measurements

- Single top quark t-channel measurement:
  - t-channel cross section at 13 TeV arXiv:1610.00678v1/TOP-16-003
  - t-channel differential cross section at 13 TeV TOP-16-004
- Single top quark s-channel measurement at 7+8 TeV JHEP09(2016)027
- Single top quark cross section in tW channel at CMS PhysRevLett.112.231802
- Single top quark produced in association with Z boson arXiv:1702.01404v1

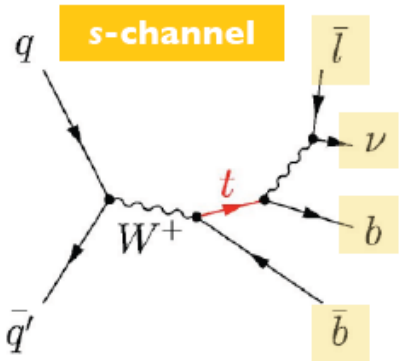
t-channel x-section relative uncertainties

Table 4: Relative impact of systematic uncertainties with respect to the observed cross sections as well as the top quark to top antiquark cross section ratio. Uncertainties are grouped and summed together with the method suggested in Ref. [45].

Uncertainty source	$\Delta\sigma_{t\text{-ch.},t+\bar{t}}/\sigma^{\text{obs}}_{t\text{-ch.},t+\bar{t}}$	$\Delta\sigma_{t\text{-ch.},t}/\sigma^{\text{obs}}_{t\text{-ch.},t}$	$\Delta\sigma_{t\text{-ch.},\bar{t}}/\sigma^{\text{obs}}_{t\text{-ch.},\bar{t}}$	$\Delta R_{t\text{-ch.}}/R_{t\text{-ch.}}$
Statistical uncert.	±5.5%	±5.3%	±11.5%	±9.7%
Profiled exp. uncert.	±5.2%	±5.7%	±4.9%	±3.3%
Total fit uncert.	±7.6%	±7.8%	±12.5%	±10.3%
Integrated luminosity	±2.7%	±2.7%	±2.7%	-
Signal modelling	±6.9%	±8.2%	±8.5%	±5.3%
$t\bar{t}$ modelling	±3.9%	±4.3%	±4.5%	±4.0%
W+jets modelling	−1.8/+2.1%	−1.6/+2.3%	−2.5/+2.3%	−1.7/+2.0%
μ_R/μ_F scale t-channel	−4.6/+6.1%	−5.7/+5.2%	−7.2/+5.1%	−0.7/+1.2%
μ_R/μ_F scale $t\bar{t}$	−3.5/+2.9%	−3.5/+4.1%	−4.7/+3.1%	−1.1/+1.0%
μ_R/μ_F scale tW	−0.3/+0.5%	−0.6/+0.8%	−1.1/+0.7%	−0.2/+0.1%
μ_R/μ_F scale W+jets	−2.9/+3.7%	−3.5/+3.0%	−4.9/+3.8%	−1.2/+0.9%
PDF uncert.	−1.5/+1.9%	−2.1/+1.6%	−1.8/+2.1%	−2.2/+2.5%
Top quark p_T modelling	±0.1%	±0.2%	±0.2%	±0.1%
Total theory uncert.	−10.7/+11.1%	−12.2/+12.1%	−13.6/+12.9%	±7.5%
Total uncert.	−13.4/+13.7%	±14.7%	−18.7/+18.2%	±12.7%

s-channel single top quark cross section @ 7, 8 TeV

- Very challenging single top quark process
- Signature :
  - Single isolated lepton (e, μ) with high pT > 30 GeV
  - Two central high p_T jets (two b-tagged jets)
  - Missing transverse energy from the neutrino
  - 2 jets, both b-tagged jets (2jets 2tags)
- analysis strategy
  - BDTs trained to separated signal from large ttbar and W+jets backgrounds
  - data-driven estimation of QCD
  - cross section estimated by performing simultaneous fit to BDT distribution in signal and control regions (2j1b, 3j2b)
- Largest syst. uncertainties: jet energy calibration, b-tagging, scale (μ_F, μ_R)



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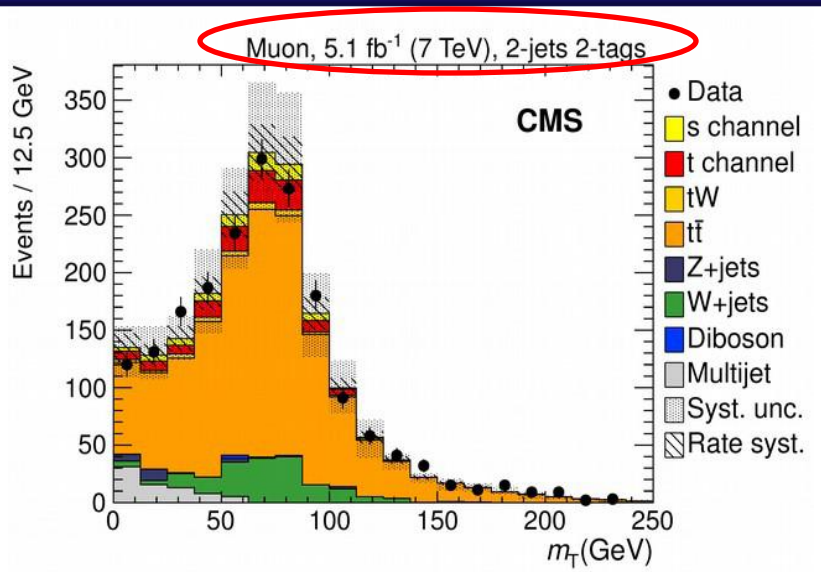
 # jets

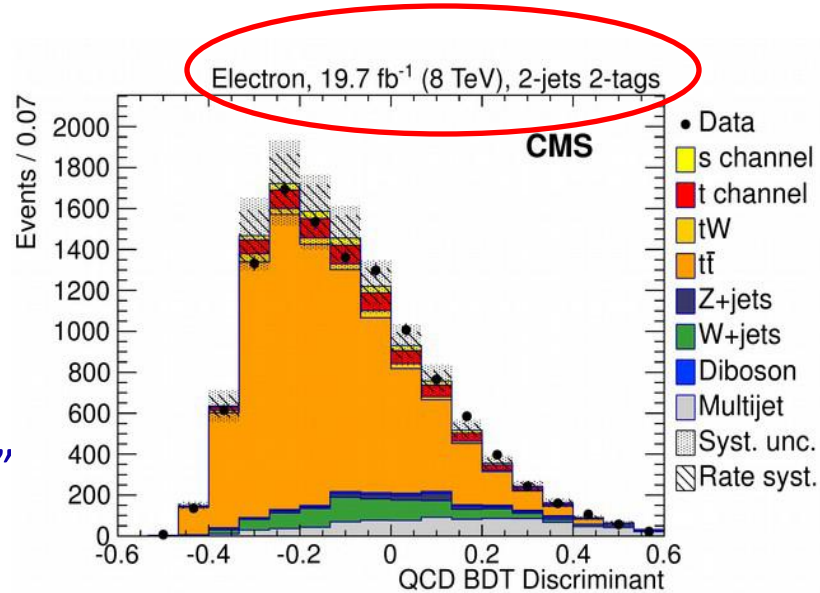
 # b-tagged jets

	1	2	3
0		CR (2j0b) QCD validation	
1		CR(2j1b) t-channel, wjets	
2		SR(2j2b) s-channel	CR(3j2b) ttbar

Background estimation for s-channel cross section @ 7, 8 TeV

- QCD estimation at 7 TeV
  - Not enough statistics to train BDT at 7 TeV
  - ML fit on m_T^W distribution (2j2btag, 3j2btag)
- 2j1btag region: cut at 50GeV to reduce QCD contamination, QCD is taken from simulation
- QCD estimation at 8 TeV
  - BDT is trained in signal/ control samples
  - Separate QCD against ttbar and W+jet, single top
  - QCD, taken from data with "ant-isolation" selection
  - Fit in the QCD enriched region





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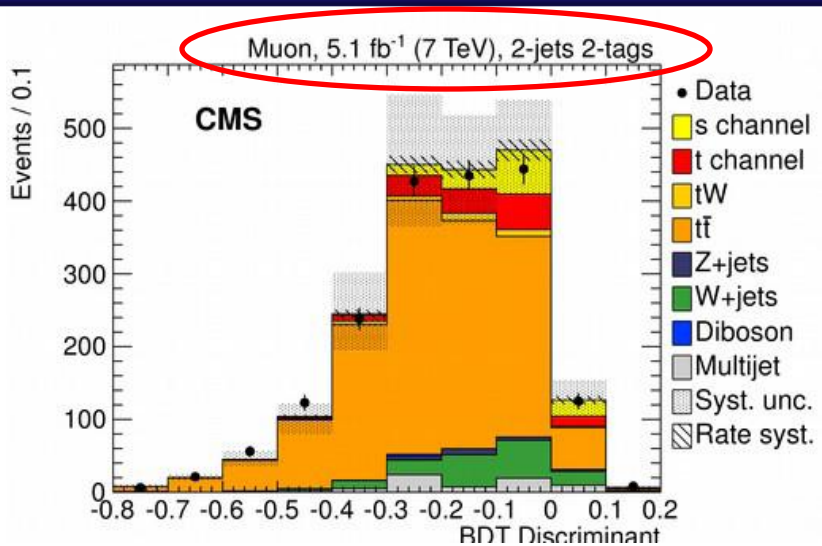
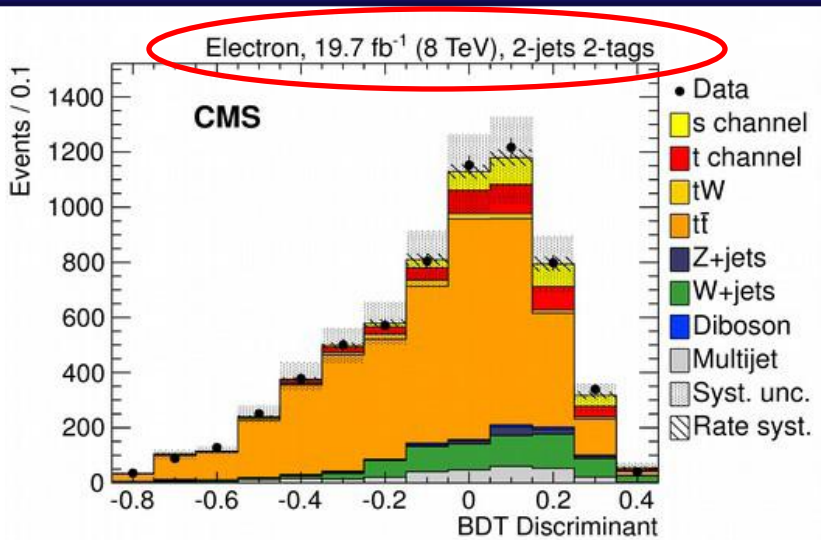
Signal extraction for s-channel cross section @ 7,8 TeV





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- Signal extraction Strategy:
  - For electron and muon at 7 and 8TeV, BDTs are trained in 2J2btag, 2J1btag and 3J2btag
  - In 2J2btag region: s-channel vs rest
  - In 3J2btag: ttbar vs rest
  - In 2J1btag: W+jets vs rest
- Simultaneous ML fit to data in signal and control regions

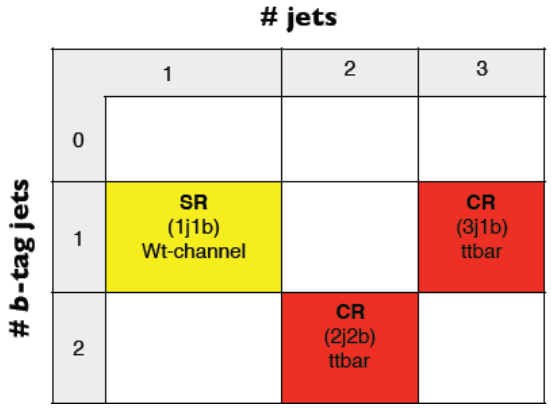
Observed significance = 2.5σ
Expected significance = 1.1σ

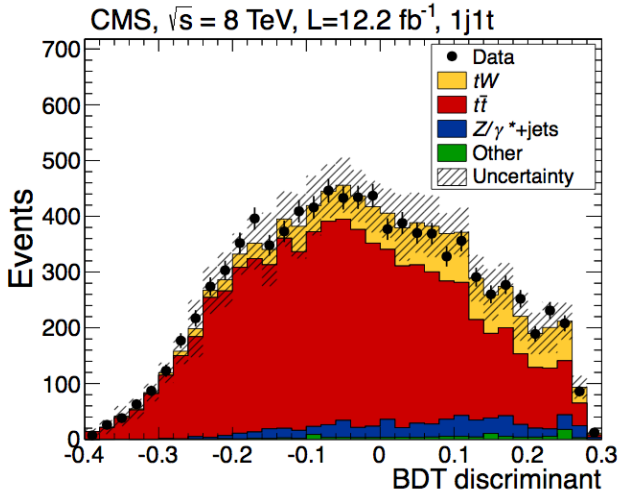
Dominant systematics:
- Factorization/renormalization scales (~30%)
- JES/JER (~35%)

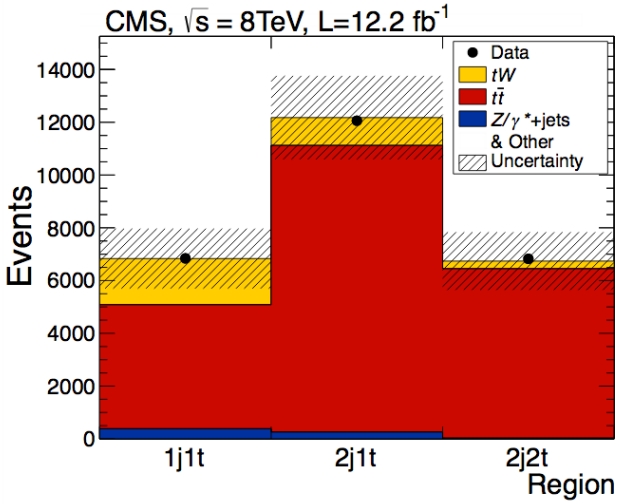
$$\sigma_s(7\text{TeV}) = 7.1 \pm 8.1(\text{stat.+syst.}), \quad \mu\text{-channel}$$
$$\sigma_s(8\text{TeV}) = 11.7 \pm 7.5(\text{stat.+syst.}), \quad \mu\text{-channel}$$
$$\sigma_s(8\text{TeV}) = 16.8 \pm 9.1(\text{stat.+syst.}), \quad e\text{-channel}$$
$$\sigma_s(8\text{TeV}) = 13.4 \pm 7.3(\text{stat.+syst.}), \quad (e+\mu)\text{-channel}$$

tW-channel cross section at 8 TeV

- First observation of tW production channel at 8 TeV
  - Analysis of events with two oppositely charged leptons
- BDT to reduce the background
  - Signal extracted from a simultaneous binned likelihood fit to BDT discriminant over the signal and background control regions, 3 independent regions







$$\sigma(\mathrm{Wt}) = 23.4 \pm 5.4\ \mathrm{pb}$$

$$|V_{tb}| = \sqrt{\sigma_{tW}/\sigma_{tW}^{th}} = 1.03 \pm 0.12\,(\mathrm{exp}) \pm 0.04\,(\mathrm{th.})$$

Observed significance is 6.1σ (5.4σ expected)

BNN input variables data/MC comparison