Single top quark production with CMS

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On behalf of CMS Collaboration

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Outline

- Introduction
- Cross - section measurements
  - ☛ t - channel
  - ☛ tW - channel
  - ☛ s - channel
- Properties measurement
  - ☛ top polarization
  - ☛ W helicity
  - ☛ Anomalous couplings
- Summary

Single Top @ LHC

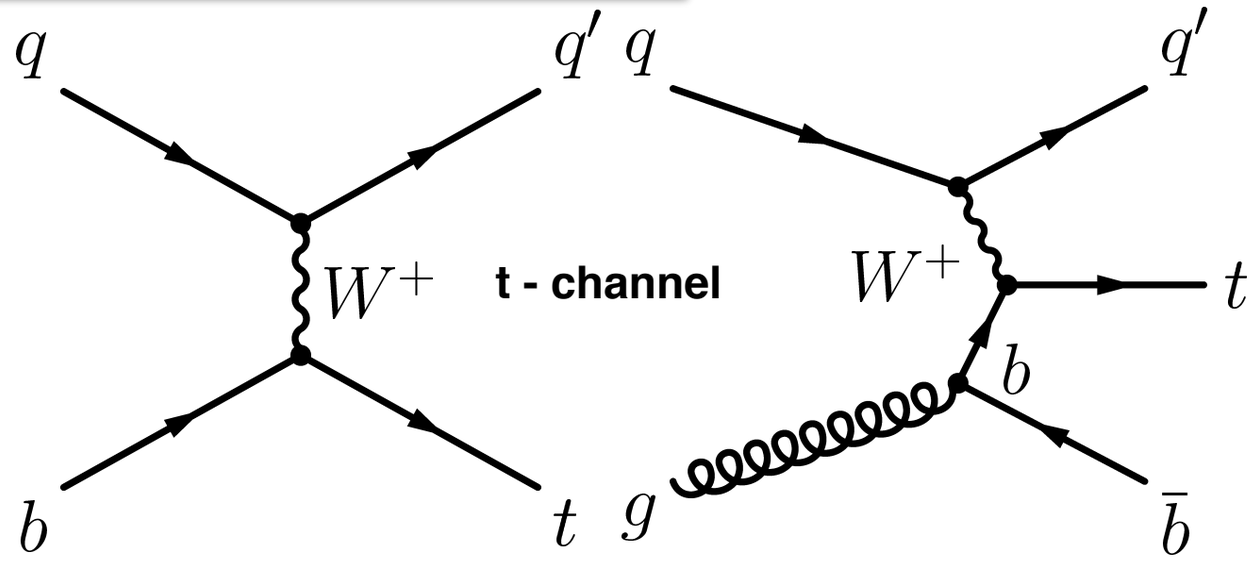
- Single top production in pp collisions at LHC can be characterized via 3 modes

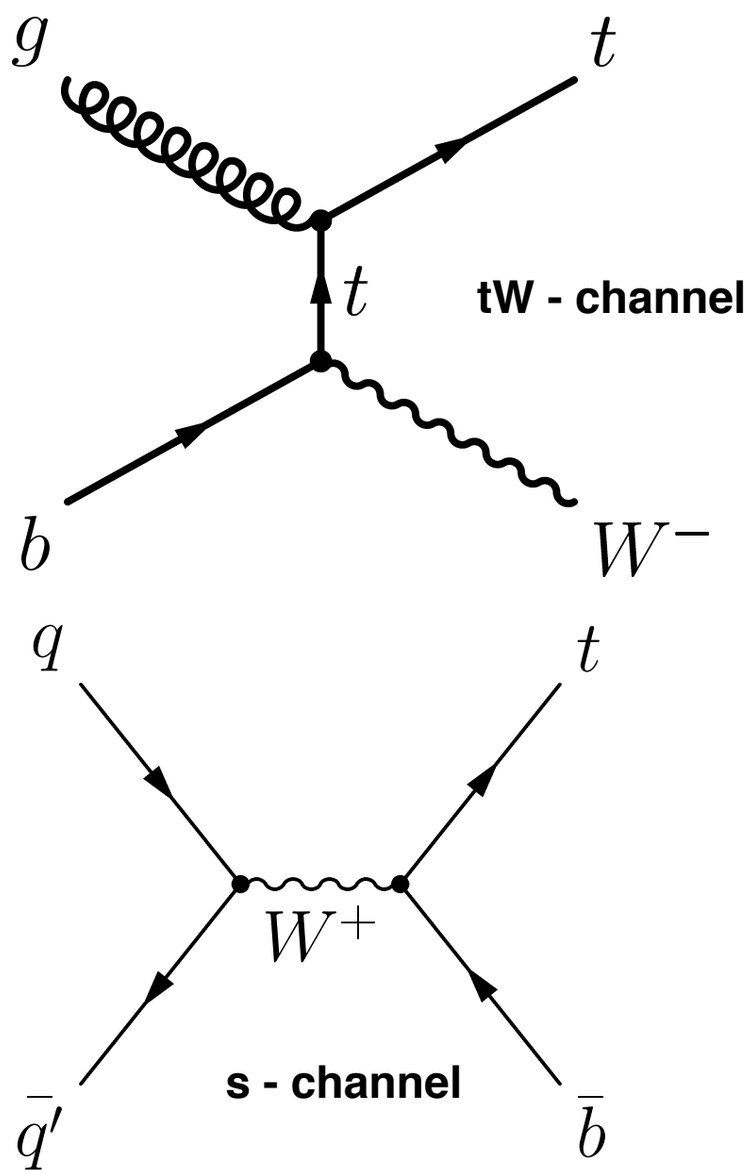
  ➛ t - channel
  ➛ tW - channel
  ➛ s - channel

- t-Channel has highest cross-section, followed by tW-channel and s-channel respectively

- Single top quark production is one of the important electroweak processes at LHC

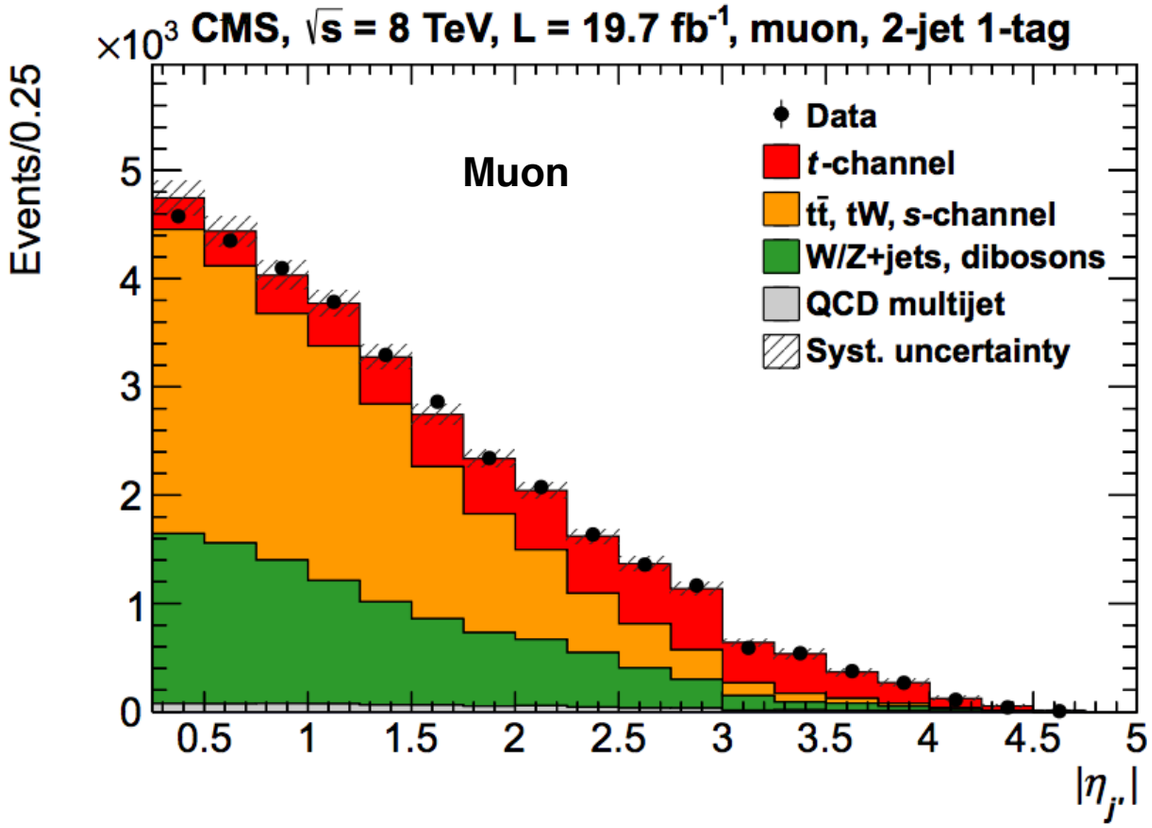
  ➛ direct probe to the charged current interaction via tWb coupling
  ➛ allows measurement of $|V_{tb}|$, study of top quark polarization
  ➛ sensitive to b-quark PDF
  ➛ sensitive to new physics like anomalous couplings (FCNC), 4th generation, charged Higgs ($H^{\pm}$) interaction etc.

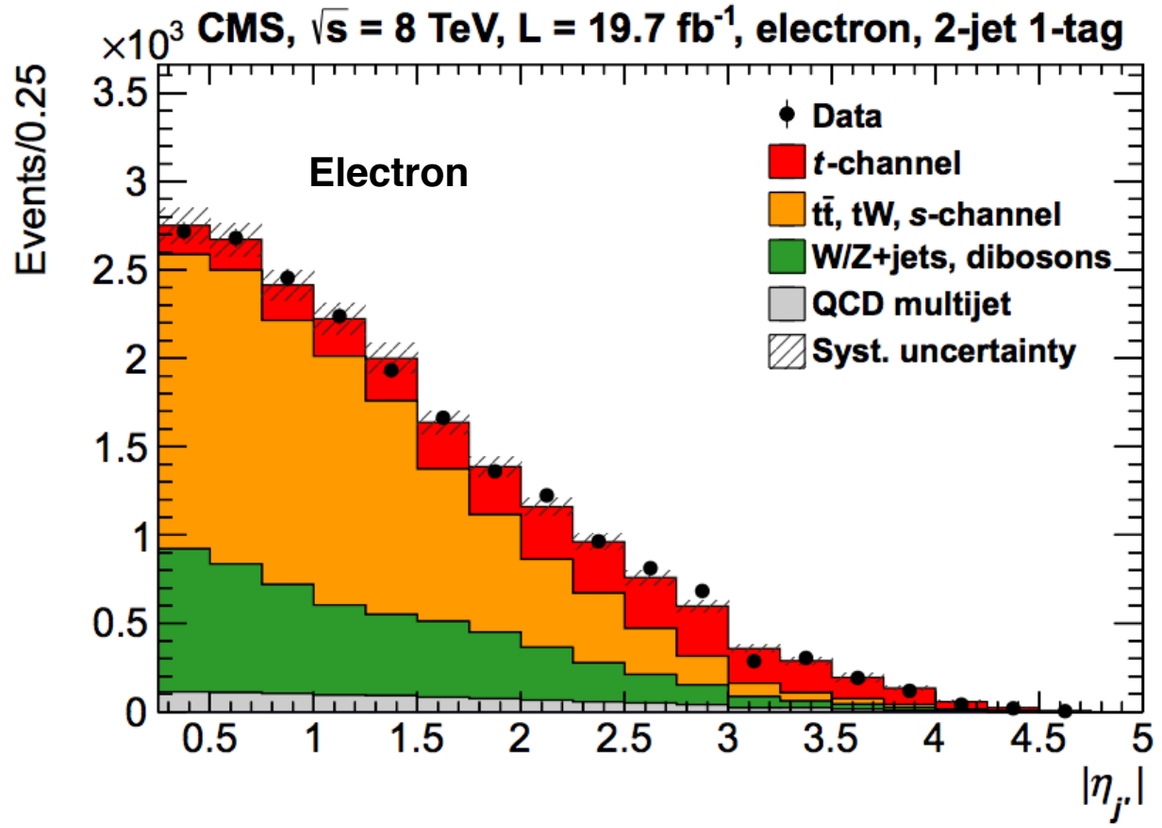




Cross - section measurements

t - channel cross-section @ 8 TeV





- Experimental Signature:
  - ➛ isolated lepton (muon/ electron)
  - ➛ light quark jet with high $|\eta_{j'}|$
  - ➛ central high - p_T b-jet
  - ➛ missing transverse energy
- Major Systematics: signal modeling, JES

$\sigma_{t\text{-}ch}$ (8 TeV)=83.6 ± 2.3 (syst.) ± 7.4 (syst.) pb
$R_{t\text{-}ch}$ (8 TeV) = 1.95 ± 0.10(stat.) ± 0.19 (syst.)
Under SM assumption:
$|V_{tb}|$ (8 TeV)= 0.998 ± 0.038 (exp.) ± 0.016 (theo.)

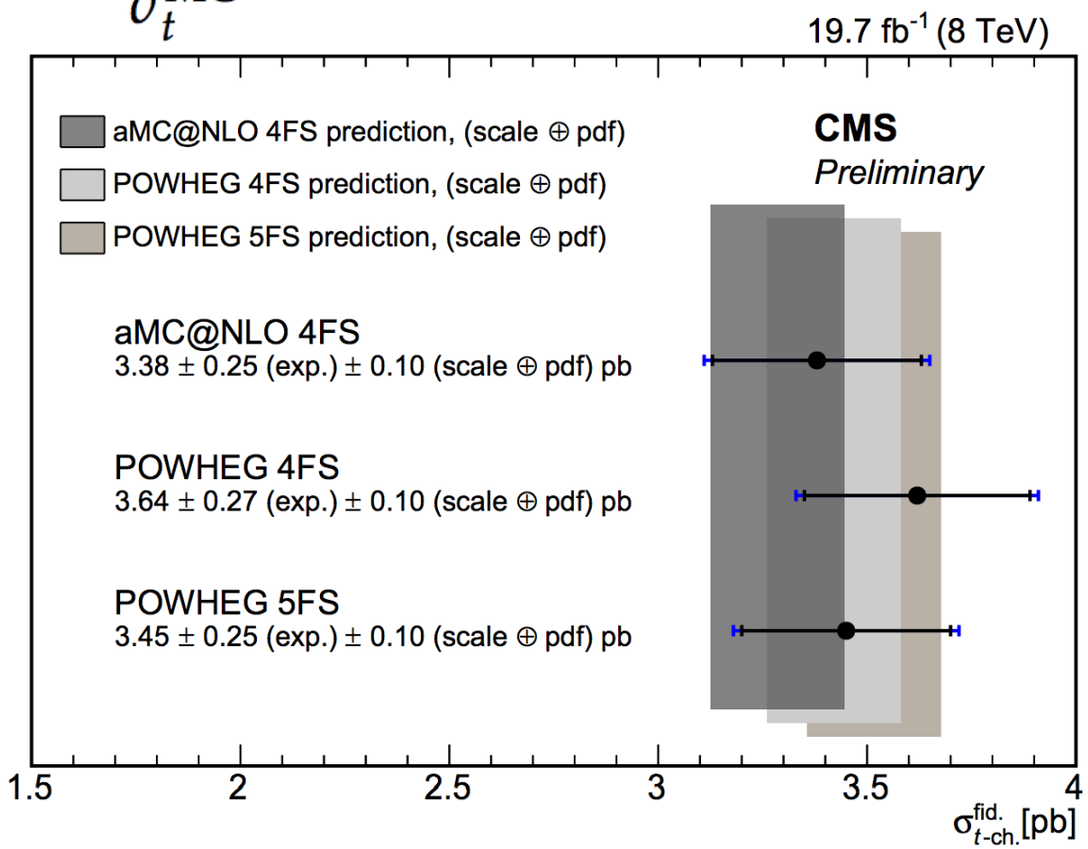
- Main Backgrounds: $t\bar{t}$, W+Jets, QCD multijet
- Typical 2J1T selection (2 jets, one of them b-tagged)
- Template fit to $|\eta_{j'}|$ or MVA discriminant
- Background estimation:
  - ➛ Correct $t\bar{t}$ shape/normalization using 3J2T events
  - ➛ Take W+Jets shape from m_{top} SB (< 130 GeV or > 220 GeV) / use 3J1T events
  - ➛ Data-driven QCD from $M_{T,W}$ or $\not{E}_T$ (inverting lepton isolation)

JHEP 06 (2014) 090

t - channel fiducial cross-section measurement @ 8 TeV

$$\sigma^{\text{fid}}_{t\text{-ch}} = \sigma_{t\text{-ch}} \cdot A^{\text{fid}}, \quad A^{\text{fid}} = \frac{\sigma^{\text{fid,MC}}_{t\text{-ch}}}{\sigma^{\text{MC}}_{t}}$$

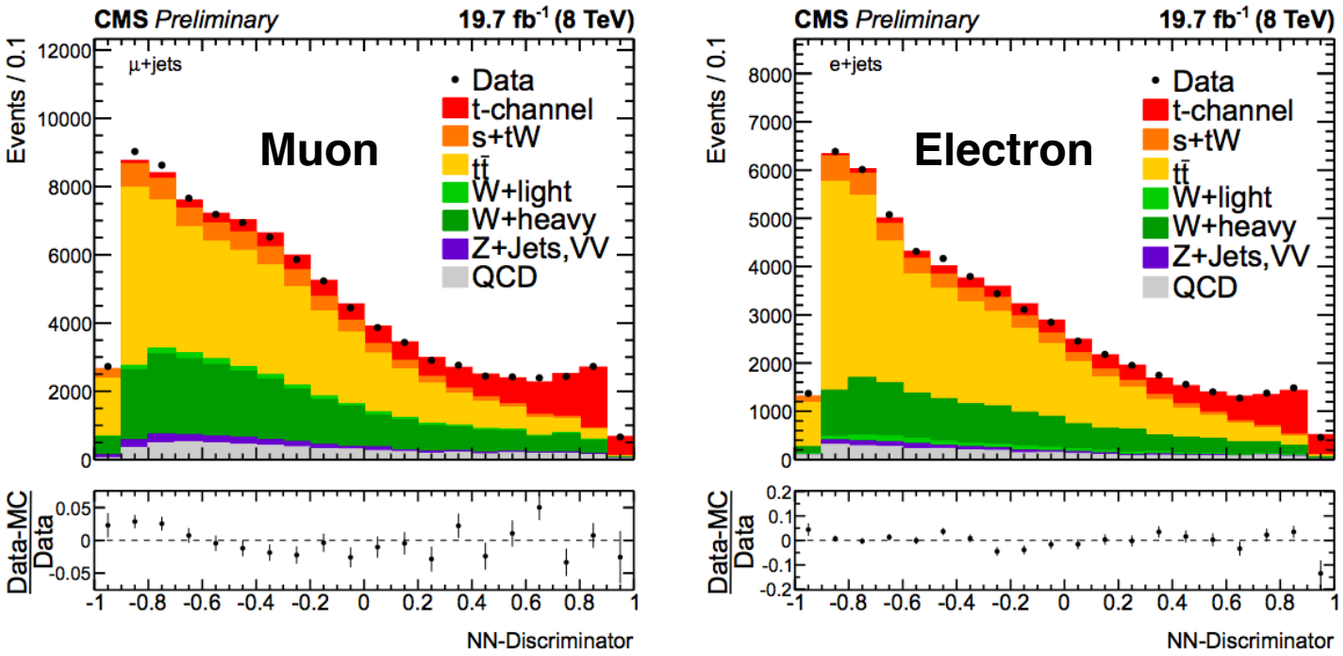
- Define a fiducial volume with selections cuts on MC truth objects close to cuts applied on reconstructed objects
- Restriction of the measurement to a well defined fiducial volume
  - ➔ reduces final result dependency on estimated acceptance-based extrapolation



Object	Kinematic cuts at detector level	Cuts at particle level	number required
Tight Muon	$p_{\text{T}} > 26$, $\lvert\eta\rvert$ <2.1, $I_{\text{rel}} < 0.12$	$p_{\text{T}} > 30$, $\lvert\eta\rvert < 2.4$	exactly 1 (or 1 Ele)
Tight Electron	E_{T} >30 , $\lvert\eta\rvert < 2.4$, $I_{\text{rel}} < 0.1$	$p_{\text{T}} > 30$, $\lvert\eta\rvert < 2.4$	exactly 1 (or 1 Mu)
Veto Muon	$p_{\text{T}} > 10$, $\lvert\eta\rvert$ <2.4 , $I_{\text{rel}} < 0.2$	-	0
Veto Electron	E_{T} >20 , $\lvert\eta\rvert$ <2.4 , $I_{\text{rel}} < 0.15$	-	0
Jets	$p_{\text{T}} > 40$, $\lvert\eta\rvert < 4.7$	$p_{\text{T}} > 40$, $\lvert\eta\rvert < 5.0$	exactly 2
B-tagging	1 jet is tagged	$\lvert\eta\rvert < 2.4$, b-hadron	exactly 1
m_{T} (muons)	$m_{\text{T}} > 50$	-	-
$\not{E}_{\text{T}}$ (electrons)	$\not{E}_{\text{T}} > 45$	-	-

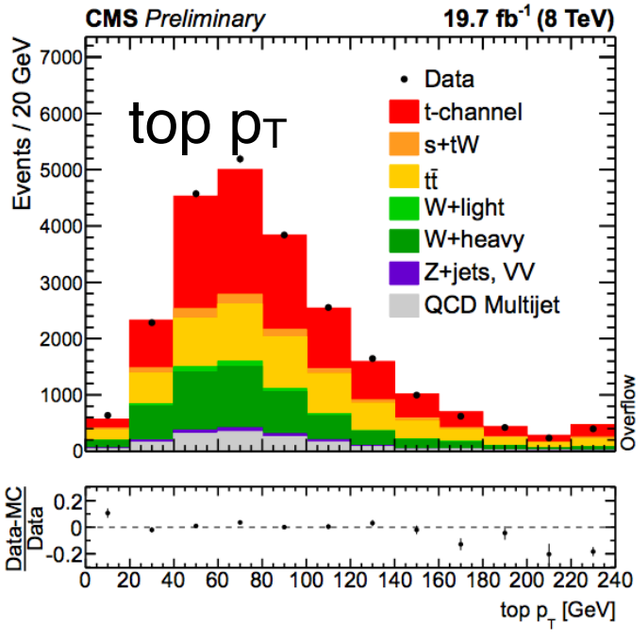
CMS PAS TOP-15-007

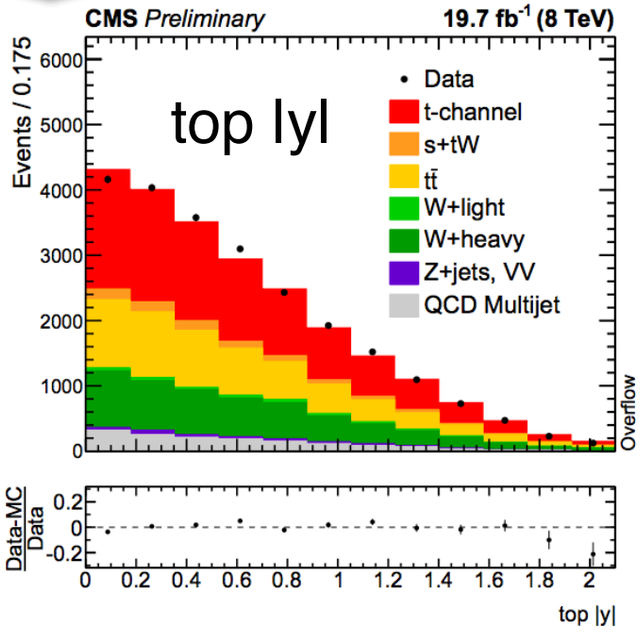
t - channel differential cross-section @ 8 TeV

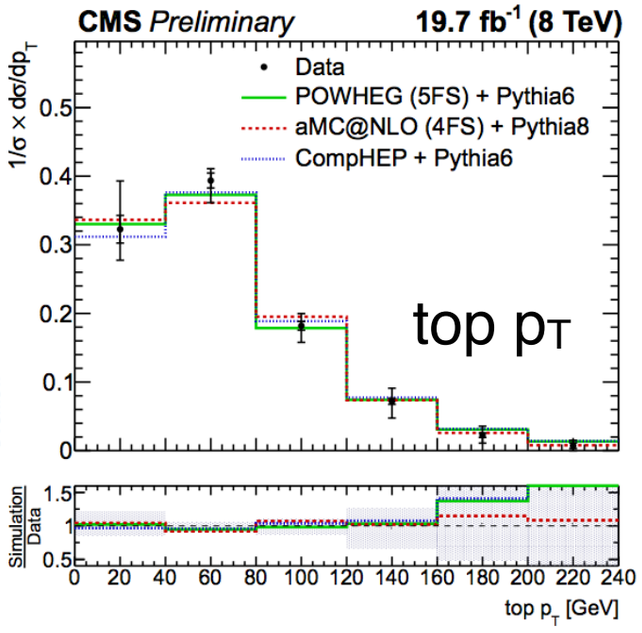


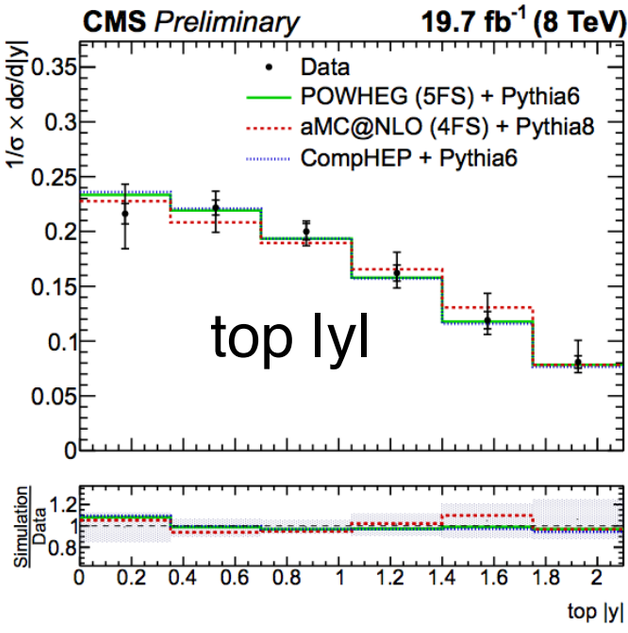
NN discriminator cut > 0.3 (0.4) for μ (e)

- 2J1T event selection
- NN trained with variables uncorrelated to top p_T and lyl
- Cut on NN output to obtain signal enriched sample
- Unfold background subtracted data to compare with MC prediction
- Largest uncertainties: JES, $\not{E}_T$, renorm. scale, $t\bar{t}$ and W+ heavy flavor modeling
- aMC@NLO 4FS + Pythia8 gives better description in the tail of p_T





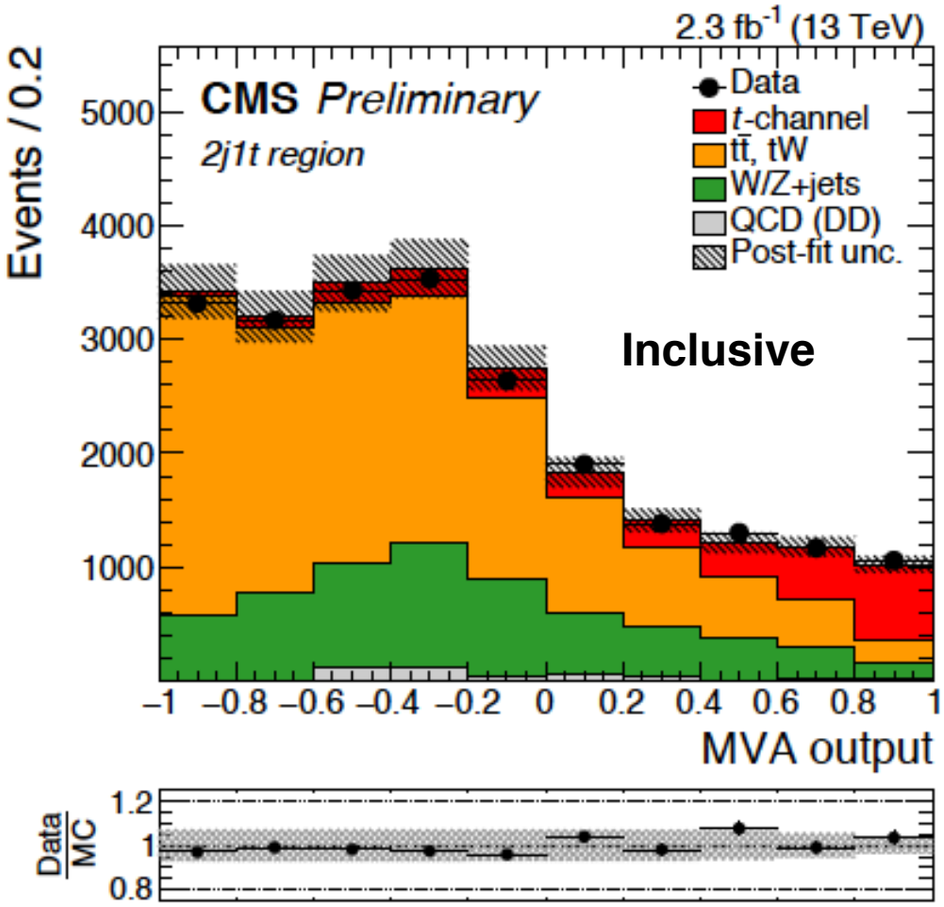


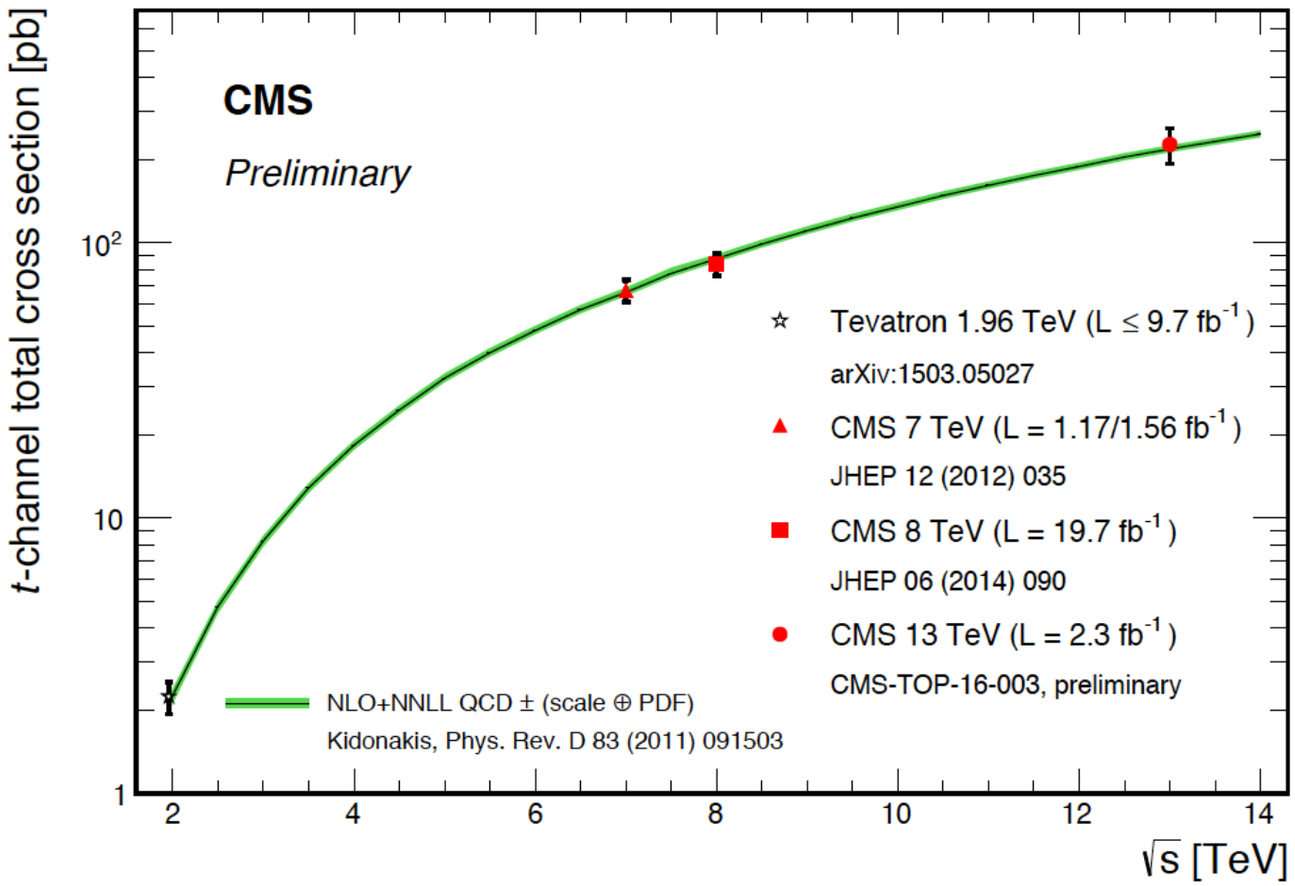


CMS PAS TOP-14-004

t - channel cross-section @ 13 TeV

New





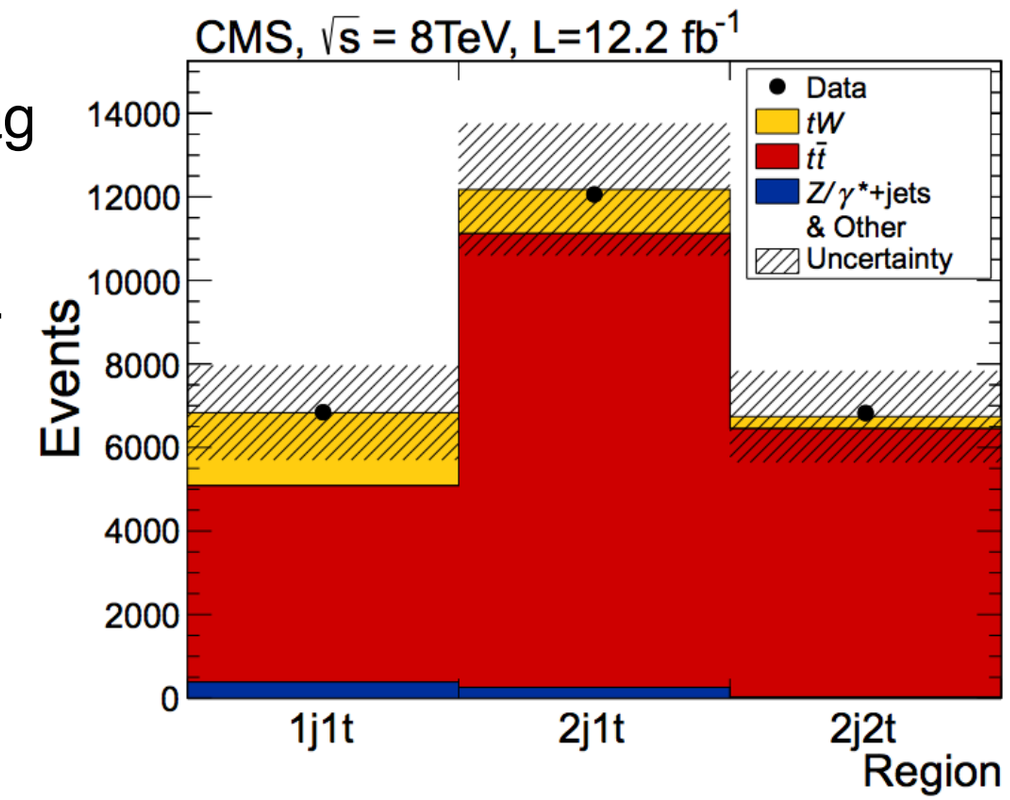
- Simultaneous fit to MVA output in 2J1T, 3J1T and 3J2T events
- Experimental systematics are mostly introduced as nuisance parameters
- Theoretical uncertainties are evaluated using pseudo-experiments
- Main uncertainties: Signal modeling, PDF, JES

$\sigma_{t\text{-}ch}$ (13 TeV) = 227.8 ± 9.1 (stat.) ± 14.0 (exp) +28.7 / -27.7(th.) ± 6.2 (Lumi) pb
$R_{t\text{-}ch}$ (13 TeV) = 1.75 ± 0.16(stat.) ± 0.21 (syst.)
Under SM assumption: $|V_{tb}|$ (13 TeV) = 1.02 ± 0.07 (exp.) ± 0.02 (th.)

CMS PAS TOP-16-003

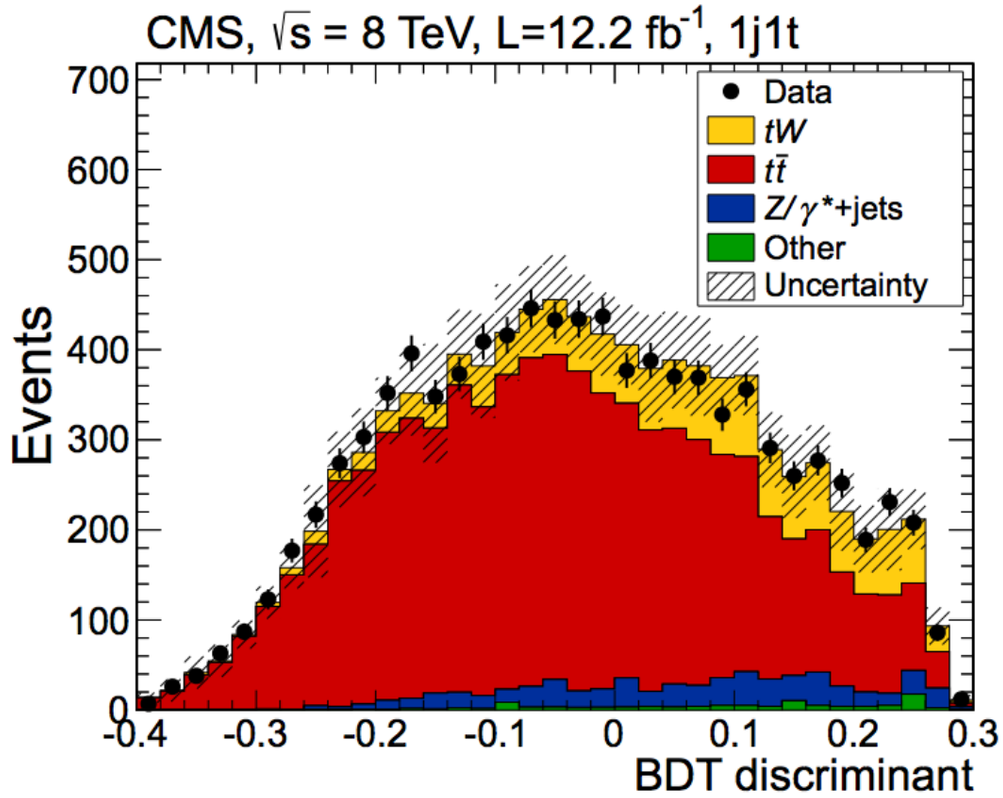
tW - channel observation

- ee, eμ, μμ final state
- Events categorized in bins of #of jets and # of b-tag
- Signal region: 1J1T
- Dominant background: $t\bar{t}$
  ➛ controlled by simultaneous fit to 2J1T and 2J2T
- Fit BDT discriminant to extract cross-section
- **σ_{meas} = 23.4 ± 5.4 pb**
- **6.1σ** significance ➛ **First observation**
- **$|V_{tb}|$ = 1.03 ± 0.12 (exp.) ± 0.04 (th.)**



Largest systematic uncertainties

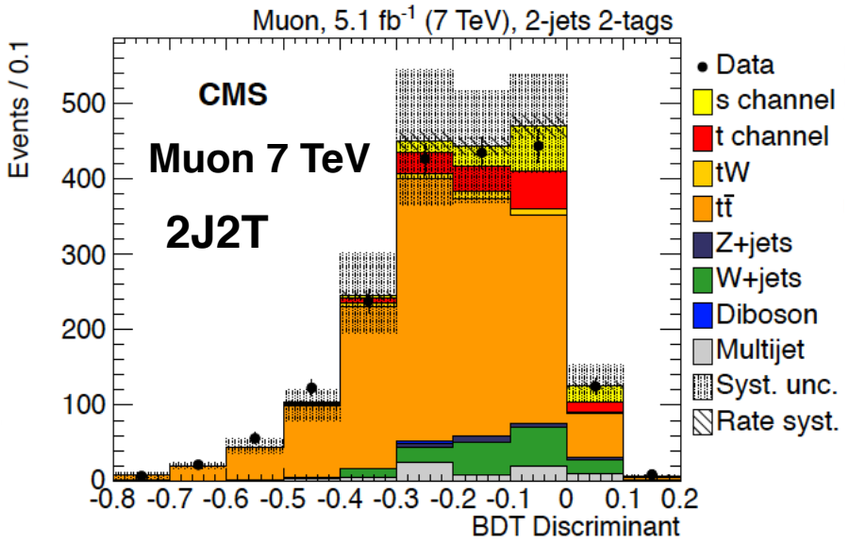
Systematic uncertainty	$\Delta\sigma/\sigma$
ME/PS matching thresholds	14%
Renormalization/factorization scale	12%
Top-quark mass	9%
Fit statistical	8%
Total	24%

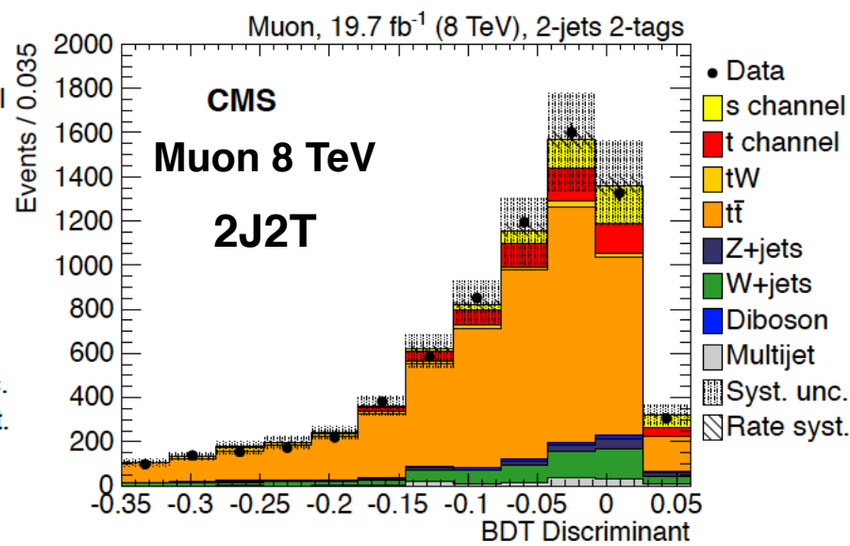


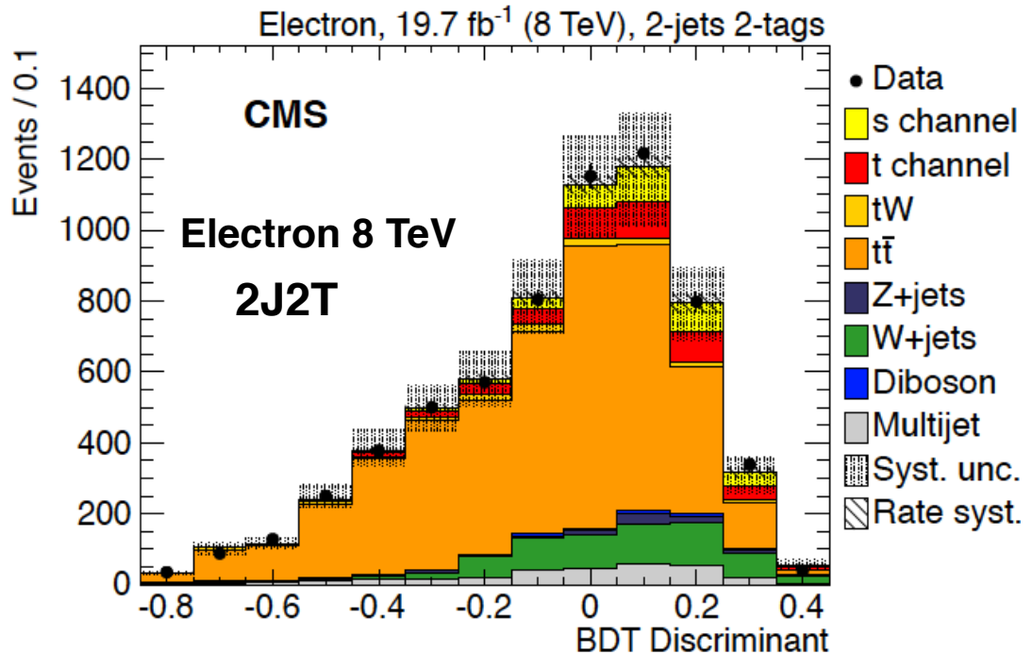
PRL 112 (2014) 23180

s - channel production

- Lepton + 2 b-jet final state
- Tiny signal in comparison with backgrounds
- Dominant backgrounds : $t\bar{t}$, t-channel single top, W+bb
- BDTs trained in 2J2T and 3J2T
  - ☛ s-channel vs rest in 2J2T
  - ☛ $t\bar{t}$ vs rest in 3J2T
- Likelihood fit to BDTs
- Largest systematic uncertainties:
  - ☛ Theory modeling: renorm. scale, ME-PS
  - ☛ JES, JER, $\not{E}_T$





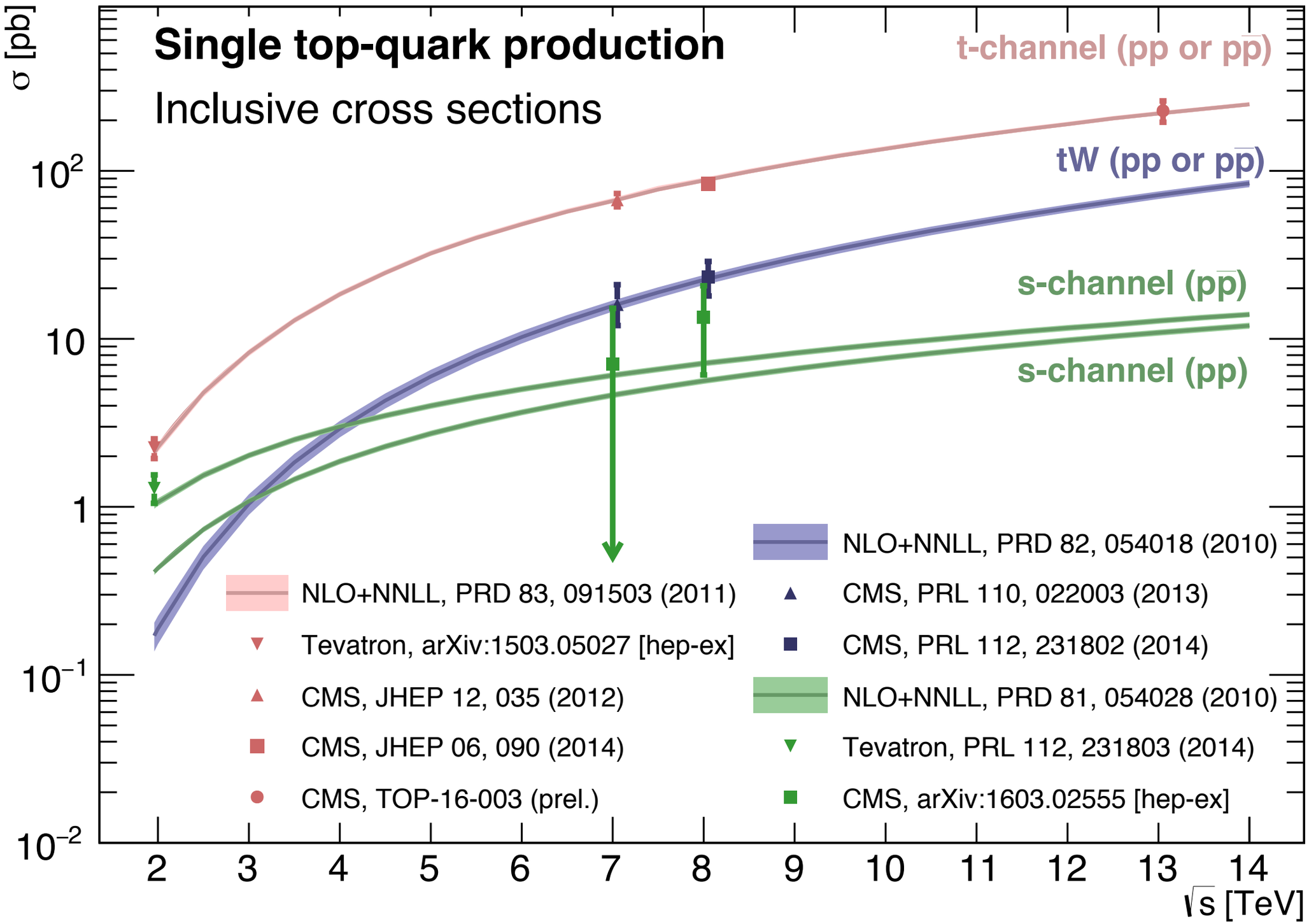


$\sigma_s = 7.1 \pm 8.1\,(\text{stat} + \text{syst})\,\text{pb}$, muon channel, 7 TeV;
$\sigma_s = 11.7 \pm 7.5\,(\text{stat} + \text{syst})\,\text{pb}$, muon channel, 8 TeV;
$\sigma_s = 16.8 \pm 9.1\,(\text{stat} + \text{syst})\,\text{pb}$, electron channel, 8 TeV;
$\sigma_s = 13.4 \pm 7.3\,(\text{stat}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

Channel	Observed UL	Expected UL—SM signal	Expected UL—no signal
μ, 7 TeV	31.4 pb	25.4 [19.0, 36.6] pb	20.2 pb
μ+e, 8 TeV	28.8 pb	20.5 [13.4, 26.7] pb	15.6 pb
7+8 TeV	4.7	3.1 [2.1, 4.0]	2.2

arXiv:1603.02555, submitted to JHEP

Summary of Single Top cross-section measurements in CMS

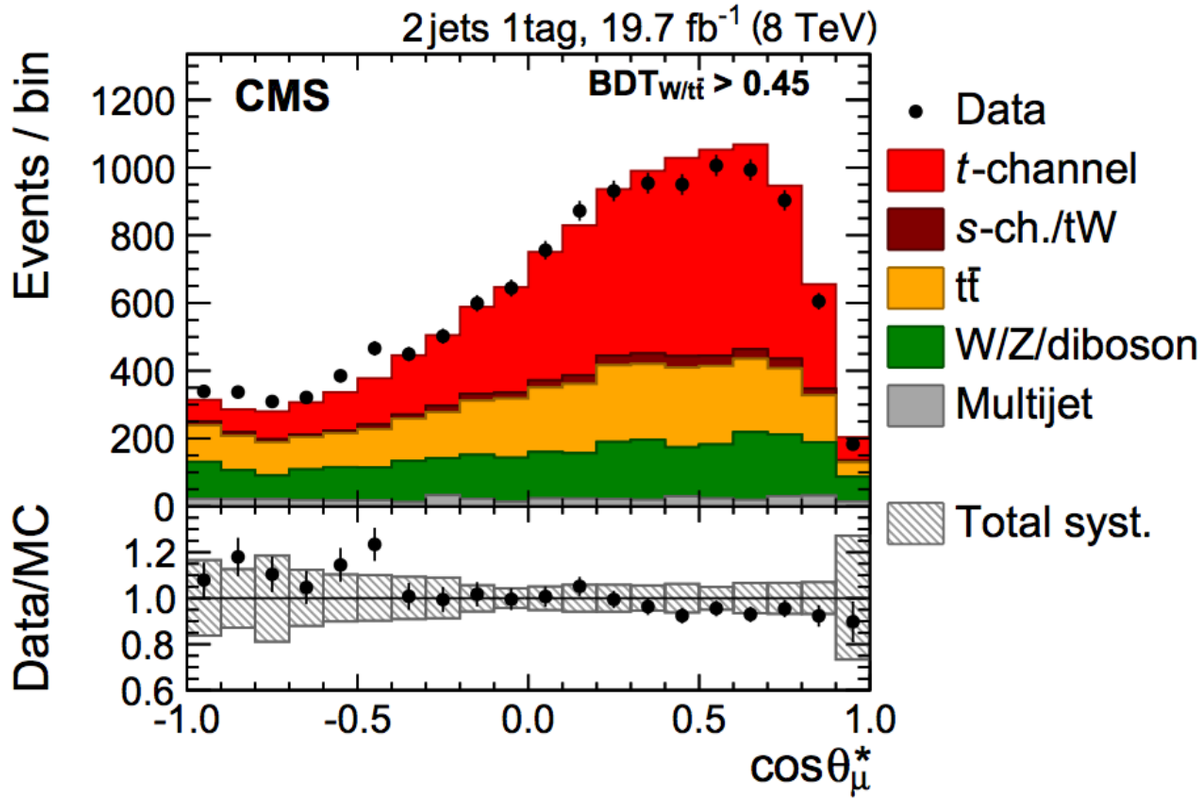


Properties measurement

Top polarization in t - channel

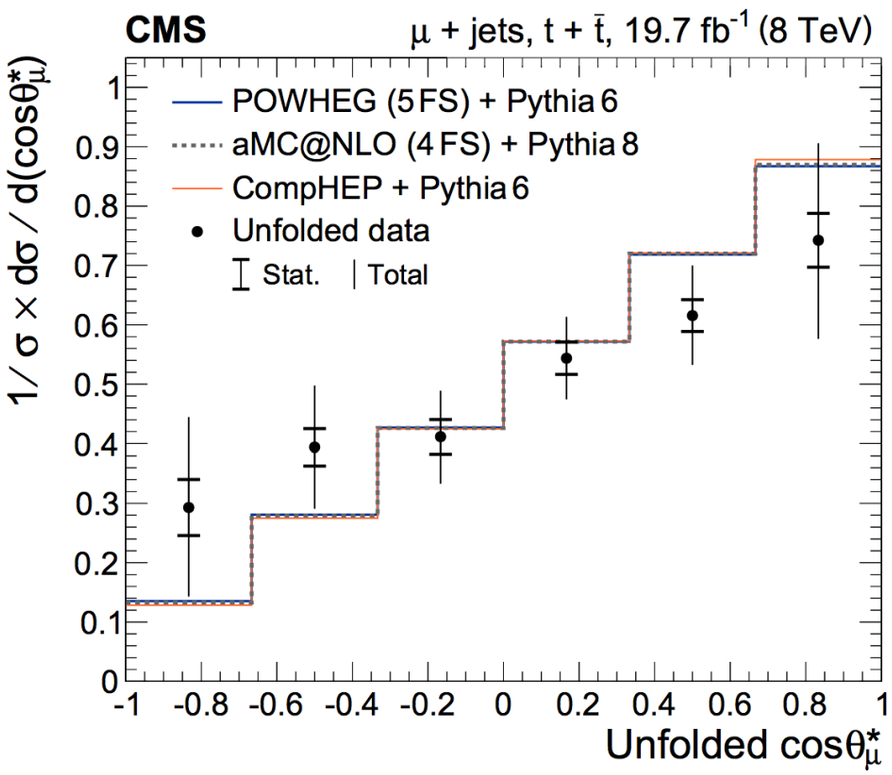
$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta^*_X} = \frac{1}{2}(1 + P_t^{(\vec{s})}\alpha_X\cos\theta^*_X) = \left(\frac{1}{2} + A_X\cos\theta^*_X\right) \quad A_X \equiv \frac{1}{2}P_t\,\alpha_X = \frac{N(\uparrow) - N(\downarrow)}{N(\uparrow) + N(\downarrow)}$$

- θ_X^* = Angle between muon and light quark in top rest frame
- P_t : Top polarization , $\alpha_X = 1$ in SM
- 2J1T event selection
- Fit BDT discriminant to determine signal and background normalization
- Cut on BDT output to select signal enriched region
- Unfolding to correct for detector effects



A_μ^{meas} = 0.26 ± 0.03 (stat.) ± 0.10 (syst) = 0.26 ± 0.11
A_μ^{SM} = 0.44
=> Measured value ~2σ away from SM prediction

- JES, JER, W+ heavy flavor jets modeling, Q^2 scale, PDF etc. are the main source of uncertainties

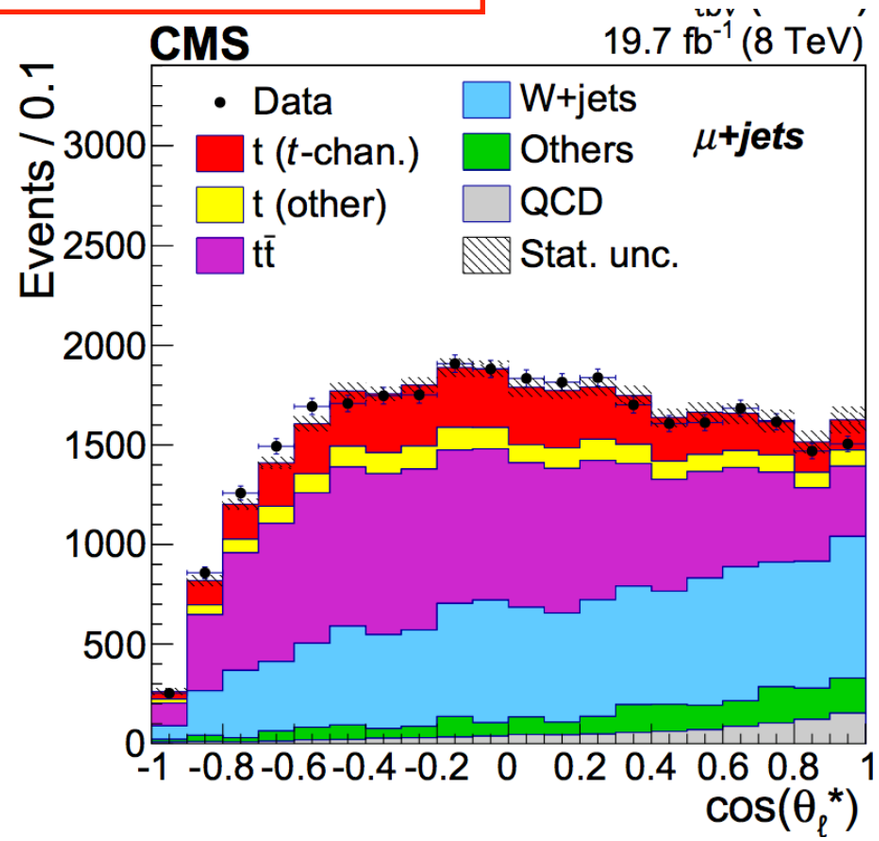


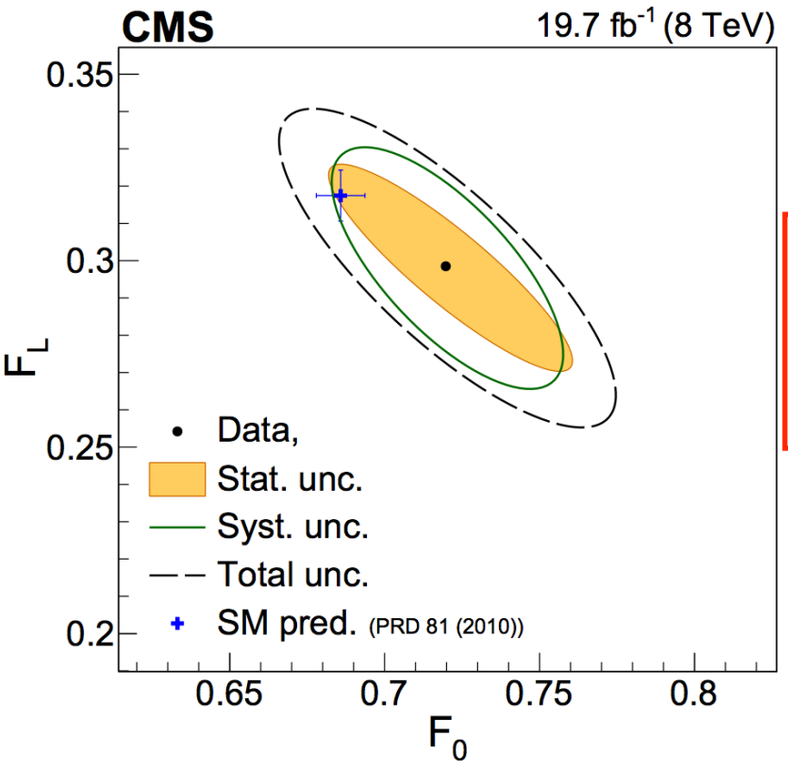
arXiv:1511.02138 , accepted by JHEP

W - helicity measurement

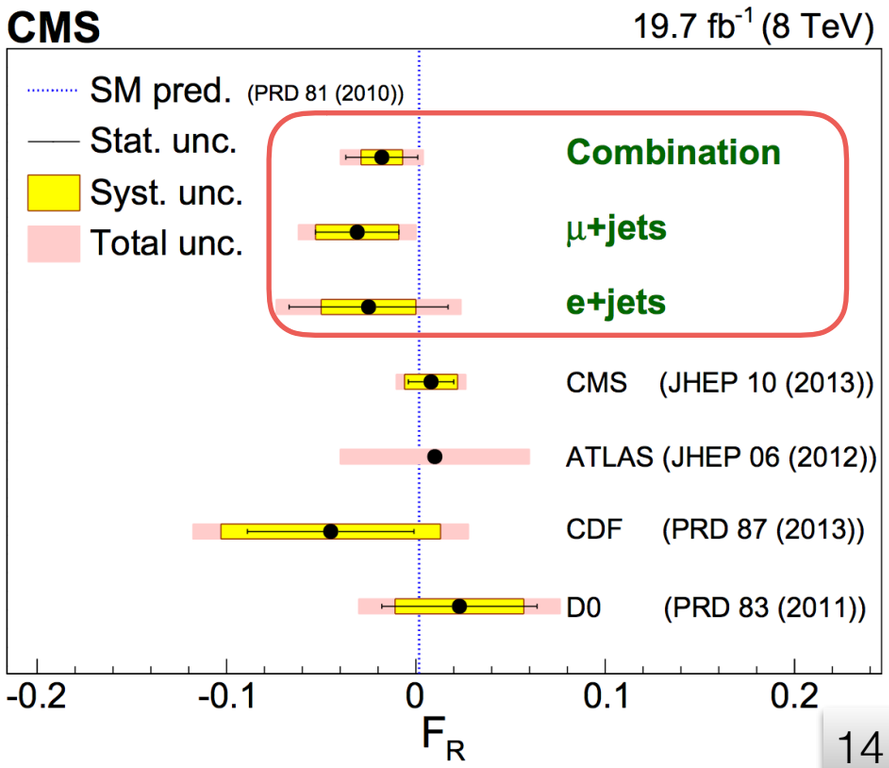
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*_\ell} = \frac{3}{8}(1-\cos\theta^*_\ell)^2 F_L + \frac{3}{4}\sin^2\theta^*_\ell F_0 + \frac{3}{8}(1+\cos\theta^*_\ell)^2 F_R$$

- θ_ℓ^* : Angle between W in top rest frame and ℓ in W rest frame
- F_L, F_0 to be extracted from ML fit to $\cos\theta_\ell^*$ and F_R from $\Sigma F_i = 1$
- POWHEG simulation for SM: $F_L = 0.3$, $F_0 = 0.7$, $F_R = 0$
- Set limits on anomalous vector and tensor couplings in tWb vertex
- 2J1T selection applied
- All processes with t ➛bW considered as signal
- F_L, F_0 and W+Jets normalization are kept free to float, all other normalizations fixed to t-channel cross-section measurement
- Signal modeling is the dominant uncertainty



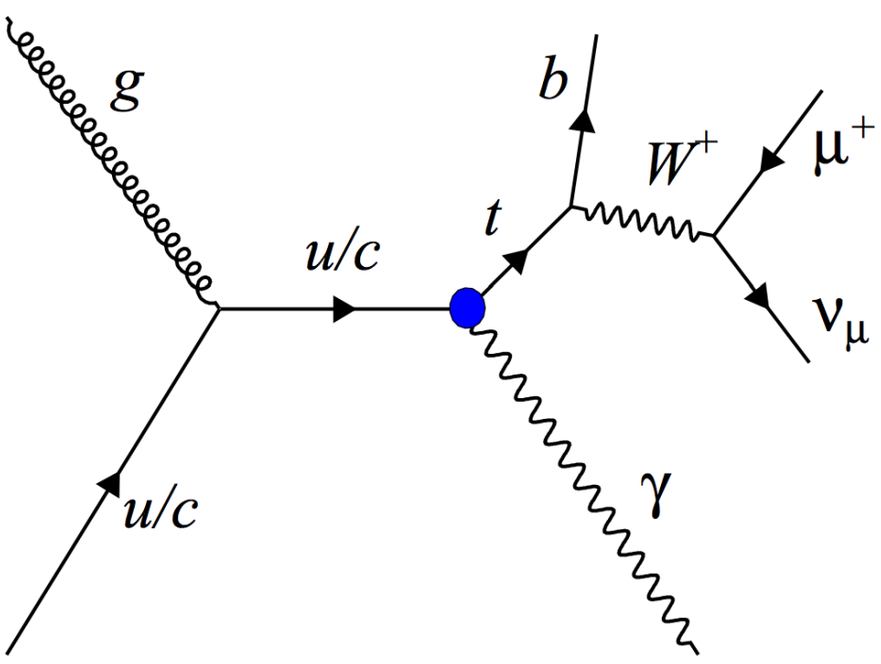


$$F_L = 0.298 \pm 0.028\,(\text{stat}) \pm 0.032\,(\text{syst}),$$
$$F_0 = 0.720 \pm 0.039\,(\text{stat}) \pm 0.037\,(\text{syst}),$$
$$F_R = -0.018 \pm 0.019\,(\text{stat}) \pm 0.011\,(\text{syst})$$

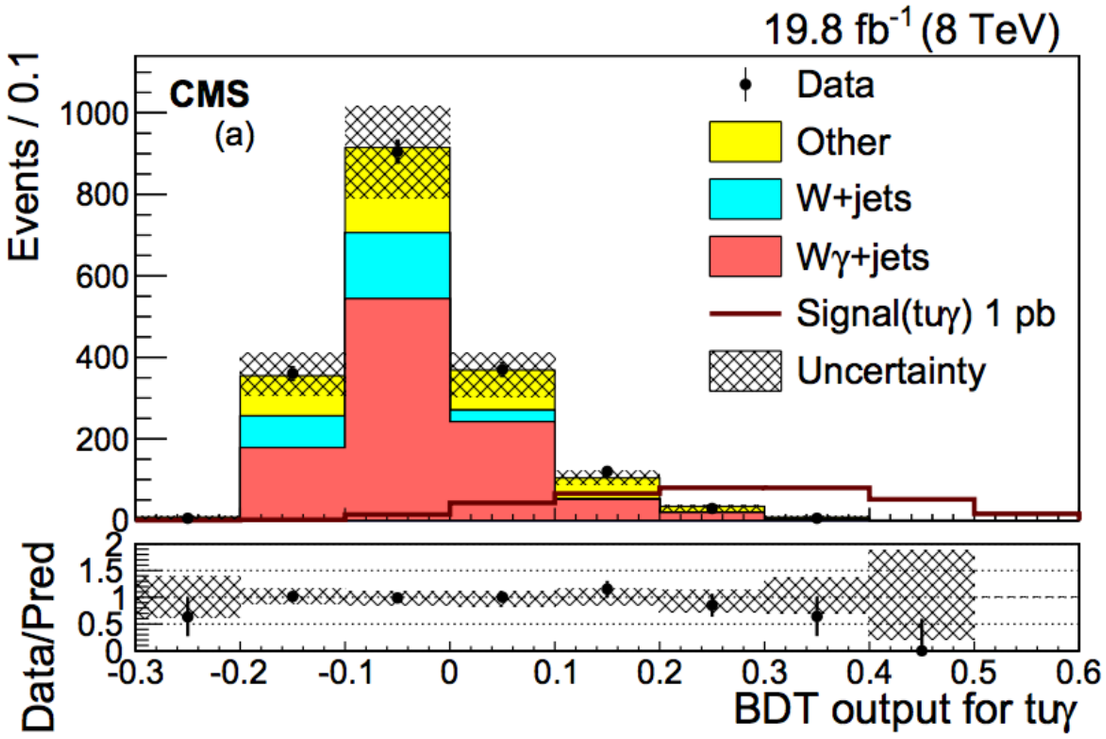


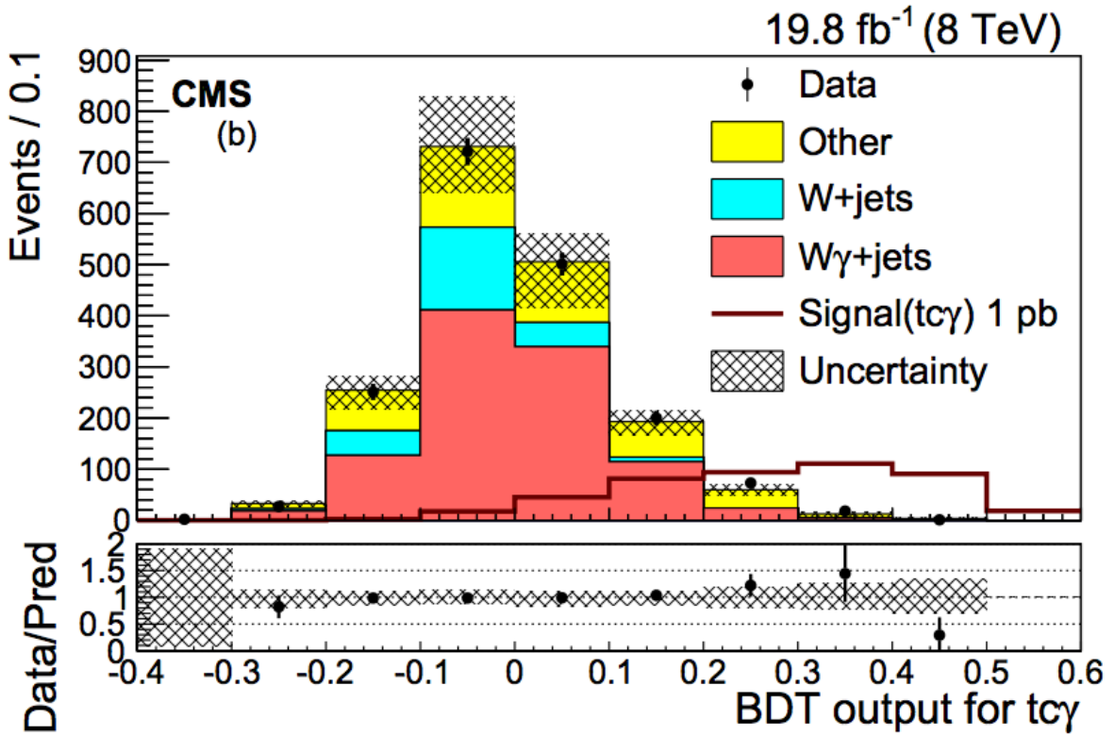
JHEP 01 (2015) 053

Search for anomalous tγ-coupling in single top events



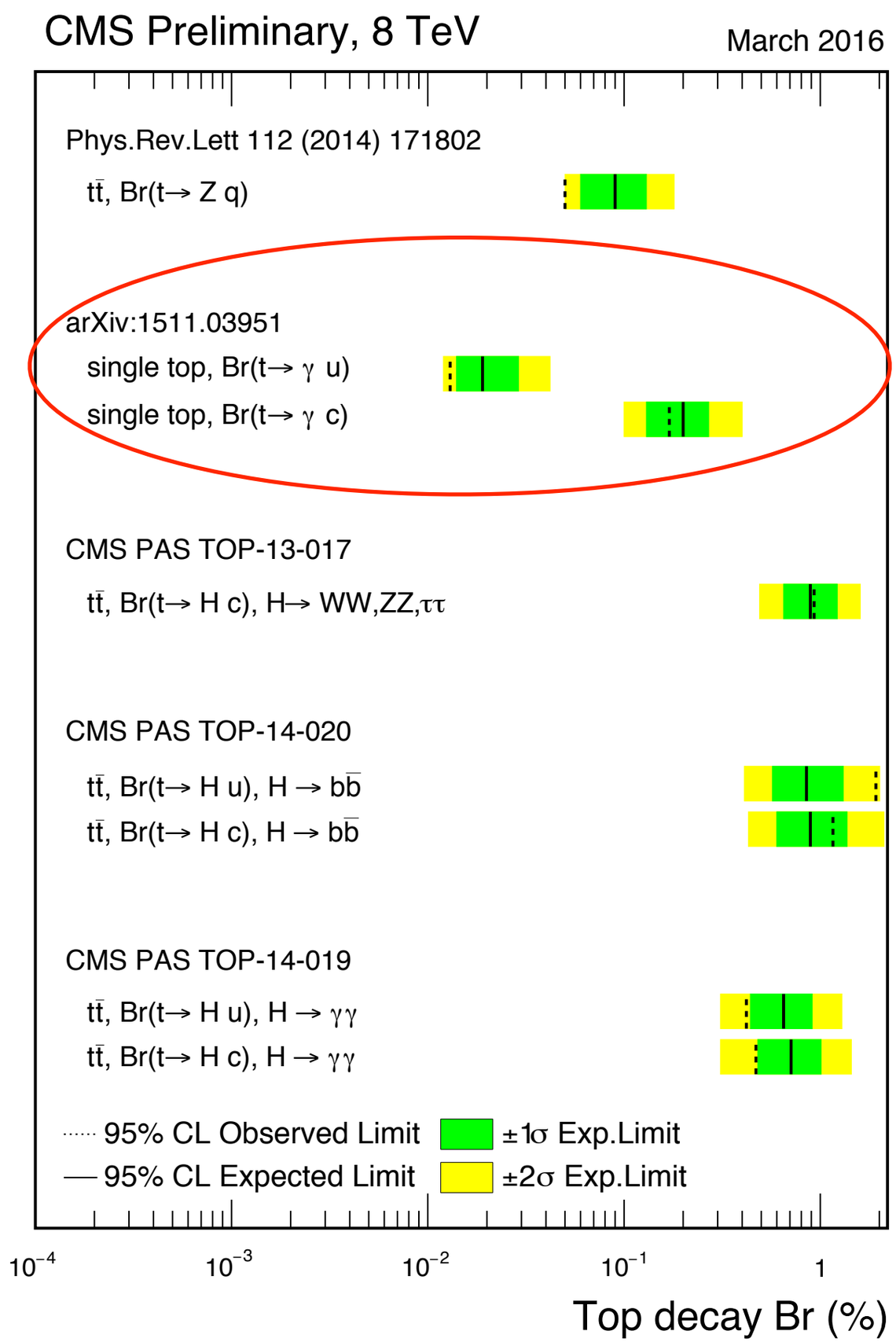
- Isolated muon, isolated energetic photon, one b-jet & $\not{E}_T$ in the final state
- Main backgrounds: Wγ + Jets and W+Jets
  - ➛ controlled by ML fit of NN output to data where W+Jets shape is obtained from CR defined by 0-tag and loose shower-shape criteria
- BDT discriminator is fitted to data to extract limits
- **B(t ➛uγ) < 1.3 x 10^{-4} & B(t ➛cγ) < 1.7 x 10^{-3}** @ 95% CL
- Most stringent limits currently available

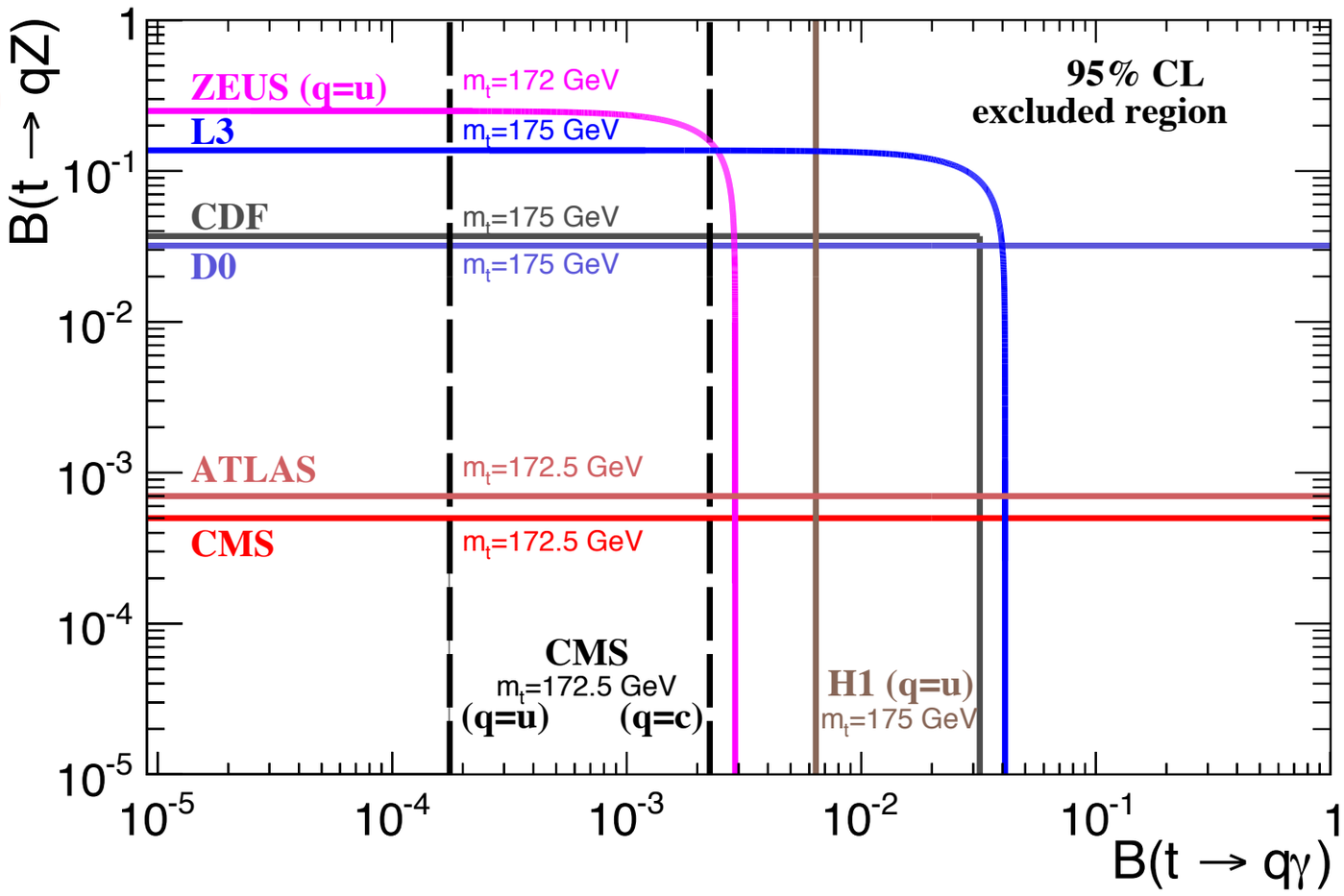




JHEP 04 (2016) 035

Summary of FCNC searches in top decay





JHEP 04 (2016) 035

Summary & Outlook

- Precise measurement of t - channel cross -section at $\sqrt{s}$ = 13 TeV has been performed and preliminary result in agreement with SM within uncertainties

- Current measurements are mostly dominated by uncertainties of theoretical origin

  ➛ Need better understanding of MC generators

- A precise tW - channel measurement is expected with Run2 data

- Push hard for s-channel observation at $\sqrt{s}$ = 13 TeV

- LHC combination of single top cross-sections with Run1 data is in progress

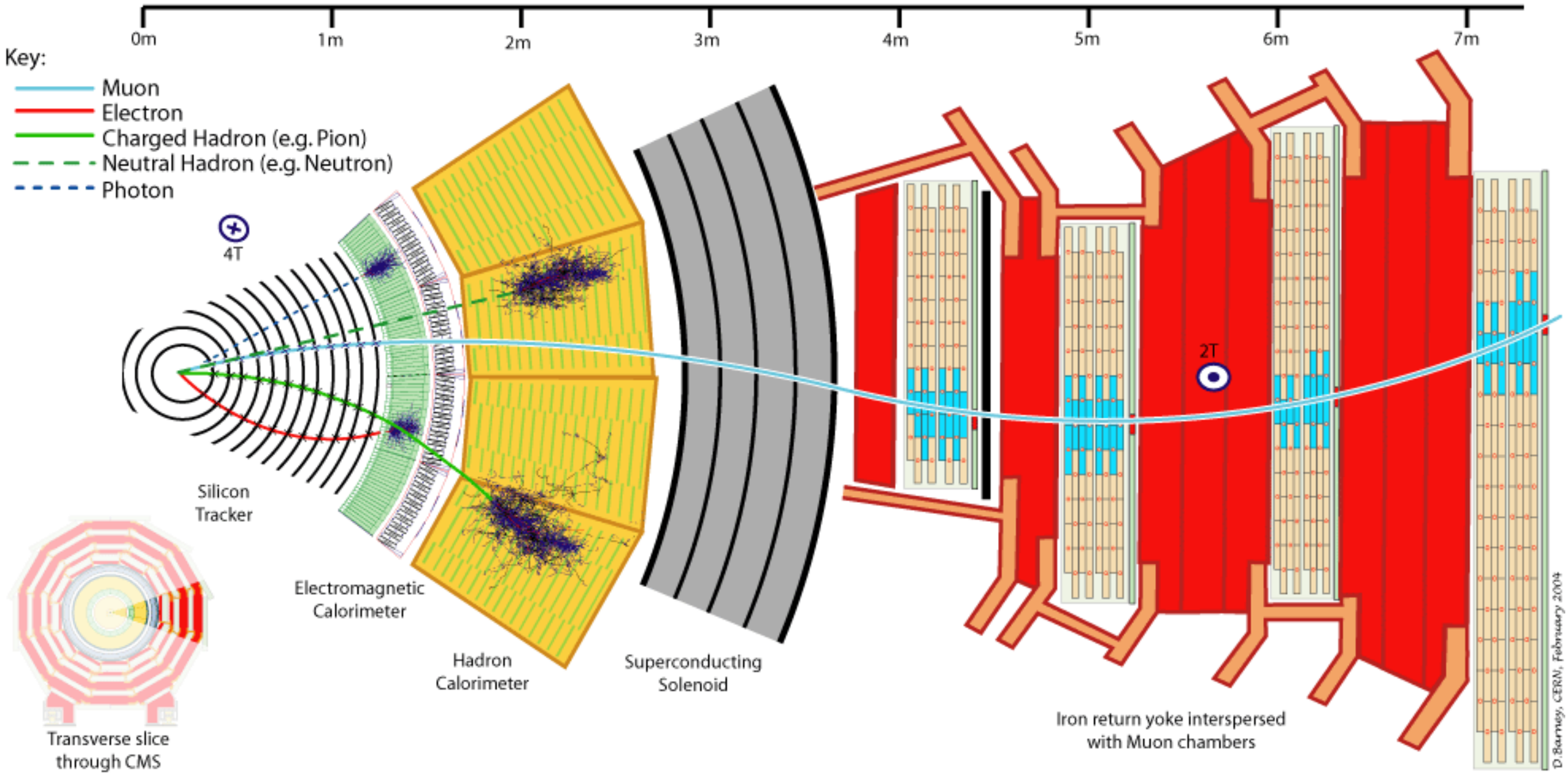
- Improve limits for anomalous coupling measurements

- Eagerly waiting for exciting results / surprises that Run2 of LHC has to offer

Thank You

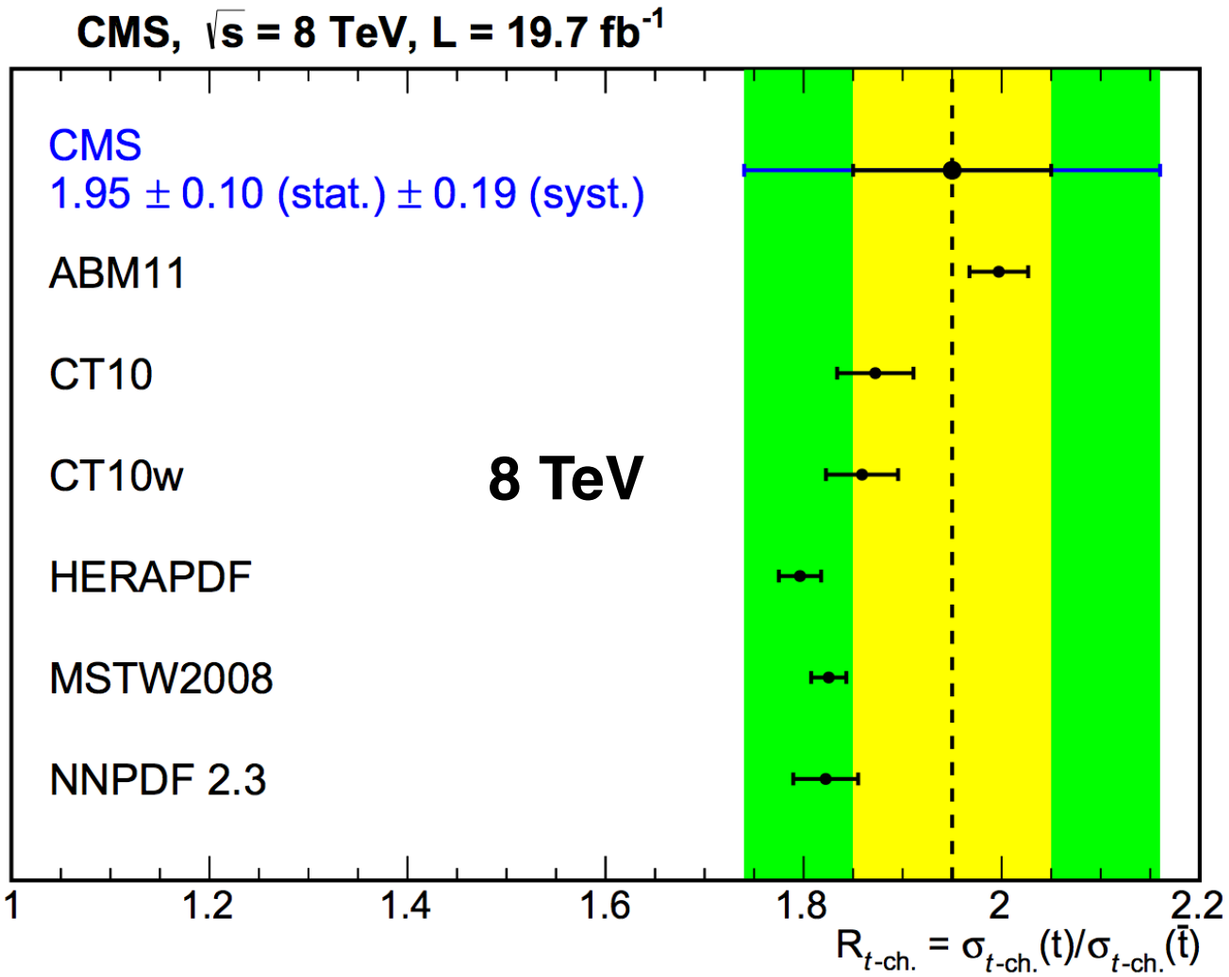
Back Up

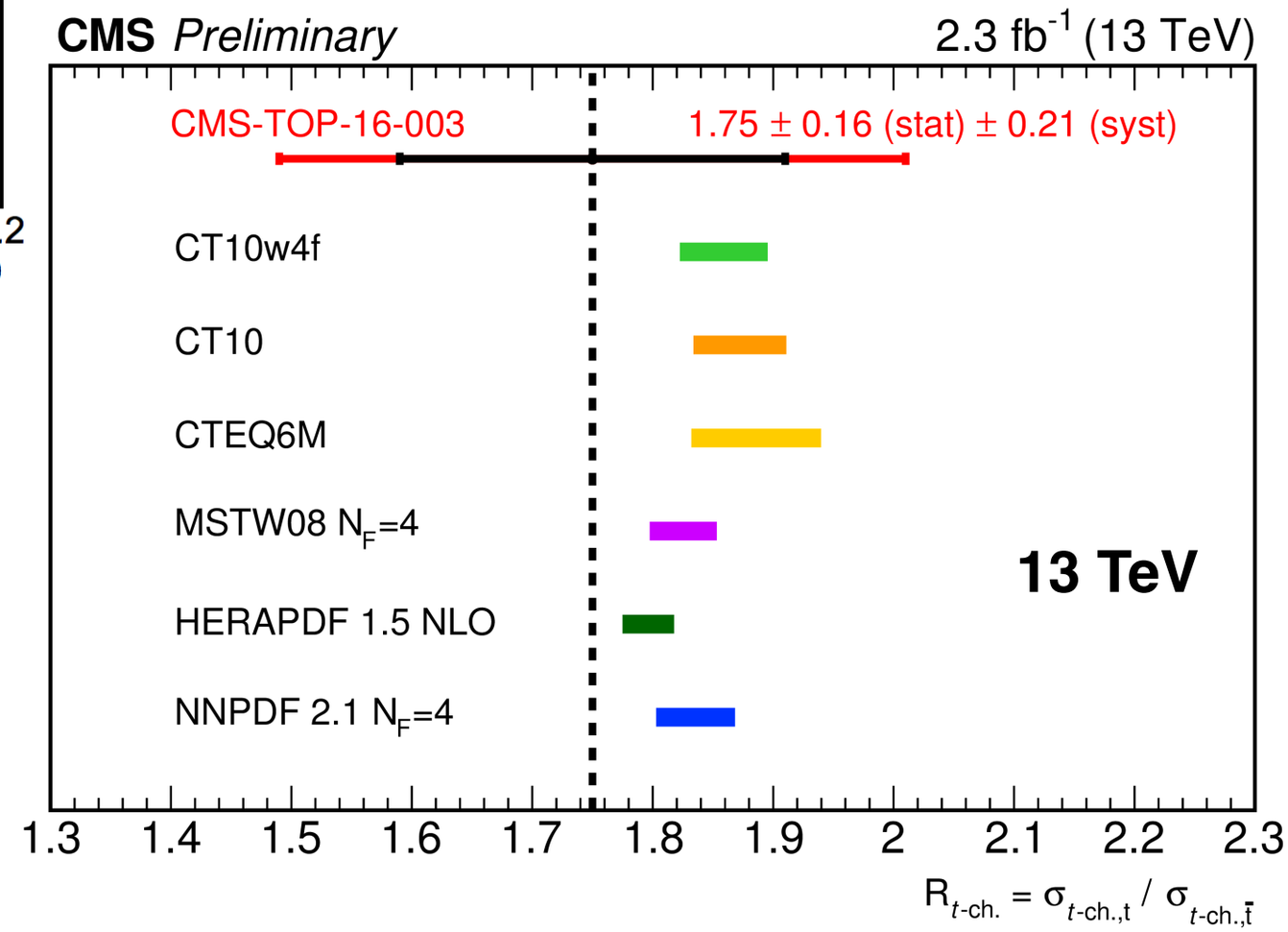
Overview of CMS detector



Almost all single top analyses require information from all detector subsystems to reconstruct jets (central and forward), leptons and $\not\!\!E_T$

$R_{t\text{-ch}}$ Summary





t-channel@13 TeV: Uncertainty Table

uncertainty source	$\Delta\sigma_{t-\text{ch.},t+\bar{t}}/\sigma^{\text{obs}}_{t-\text{ch.},t+\bar{t}}$	$\Delta\sigma_{t-\text{ch.},t}/\sigma^{\text{obs}}_{t-\text{ch.},t}$	$\Delta\sigma_{t-\text{ch.},\bar{t}}/\sigma^{\text{obs}}_{t-\text{ch.},\bar{t}}$
uncertainty of the fit (stat. + prof. unc.)	±6.8%	±7.4%	±11.9%
statistical uncertainty	±4.0%	±4.7%	±7.6%
profiled uncertainties	±5.5%	±5.7%	±9.2%
MC statistics	±2.8%	±3.4%	±4.0%
pileup	-0.2/+0.1%	-0.5/+0.4%	-0.1/+0.7%
experimental uncertainty	-6.2/+6.2%	-6.7/+6.7%	-10.0/+10.0%
Signal modeling	±7.9%	±10.1%	±8.2%
$t\bar{t}$ modeling	±4.3%	±3.9%	±4.6%
W+jets modeling	-2.1/+1.7%	-1.6/+1.1%	-2.8/+2.3%
Q^2 scale t-channel	-5.7/+7.0%	-7.1/+5.1%	-6.1/+6.9%
Q^2 scale $t\bar{t}$	-2.7/+4.1%	-2.5/+4.0%	-3.9/+3.4%
Q^2 scale tW	-0.3/+0.5%	-0.4/+0.3%	-1.1/+0.4%
Q^2 scale W+jets	-2.7/+3.0%	-2.5/+4.2%	-5/+2.4%
PDF uncertainty	-3.0/+2.6%	-3.1/+3.2%	-3.7/+4.2%
top p_T modeling	±0.1%	±0.1%	±0.2%
total theory uncertainties	-12.1/+12.6	-13.8/+13.6	-13.5/+13.4%
luminosity	±2.7%	±2.7%	±2.7%
total uncertainty	-14.5/+14.8%	-16.3/+16.1%	-18.6/+18.6%

An Estimate of relative contribution of different profiled uncertainty sources

uncertainty source	$\Delta\sigma_{t-\text{ch.},t+\bar{t}}/\sigma^{\text{obs}}_{t-\text{ch.},t+\bar{t}}$	$\Delta\sigma_{t-\text{ch.},t}/\sigma^{\text{obs}}_{t-\text{ch.},t}$	$\Delta\sigma_{t-\text{ch.},\bar{t}}/\sigma^{\text{obs}}_{t-\text{ch.},\bar{t}}$
JES	±4.9%	±5.6%	±3.7%
JER	±0.7%	±0.2%	±1.5%
b-tagging efficiency	±2.3%	±2.1%	±1.6%
mis-tagging efficiency	±0.8%	±1.2%	±0.4%
lepton reconstruction/trigger	±2.5%	±2.0%	±2.9%

t-channel@8 TeV: Uncertainty Table

Uncertainty source	$\sigma_{t\text{-ch.}}$ (%)
Statistical uncertainty	$\pm$ 2.7
JES, JER, MET, and pileup	$\pm$ 4.3
b-tagging and mis-tag	$\pm$ 2.5
Lepton reconstruction/trig.	$\pm$ 0.6
QCD multijet estimation	$\pm$ 2.3
W+jets, $t\bar{t}$ estimation	$\pm$ 2.2
Other backgrounds ratio	$\pm$ 0.3
Signal modeling	$\pm$ 5.7
PDF uncertainty	$\pm$ 1.9
Simulation sample size	$\pm$ 0.7
Luminosity	$\pm$ 2.6
Total systematic	$\pm$ 8.9
Total uncertainty	$\pm$ 9.3
Measured cross section	83.6 $\pm$ 7.8 pb

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

t-channel differential @8 TeV: Uncertainty Table

top p_T

Uncertainty / Δ [%]	Bin 1	Bin 2	Bin 3	Bin 4	Bin 5	Bin 6
JES	+12.2 -0.0	+1.0 -2.1	+0.0 -6.2	+0.0 -16.1	+0.0 -26.7	+0.0 -41.0
JER	+3.4 -0.0	+0.1 -1.0	+0.3 -1.6	+0.0 -2.2	+0.0 -11.1	+0.0 -29.6
met	+10.4 -12.1	+1.9 -2.3	+8.9 -8.5	+25.5 -23.4	+42.1 -28.0	+55.4 -31.6
PU	+2.9 -0.0	+0.0 -0.2	+0.0 -1.0	+0.0 -3.0	+0.0 -13.1	+0.0 -21.0
btagcb	+0.7 -1.1	+0.2 -0.1	+1.1 -0.9	+2.4 -1.9	+1.1 -0.6	+1.2 -0.6
btaglight	+0.2 -0.6	+0.3 -0.2	+0.1 -0.0	+0.3 -0.0	+0.9 -0.3	+0.4 -0.0
PT	+1.5 -1.0	+0.3 -1.0	+0.6 -0.3	+3.4 -2.5	+10.6 -10.3	+17.3 -18.5
mass	+2.8 -0.0	+0.7 -0.0	+0.0 -1.4	+0.0 -5.6	+0.0 -12.5	+0.0 -35.8
LEP	+1.0 -0.0	+0.7 -0.0	+0.0 -0.3	+0.0 -2.5	+0.0 -10.2	+0.0 -18.6
scale tchan	+0.0 -1.0	+0.9 -0.0	+0.0 -0.3	+0.4 -0.9	+0.8 -0.0	+13.6 -3.2
scale wjetsbc	+11.1 -0.0	+0.4 -6.7	+0.0 -5.7	+0.0 -7.5	+20.3 -0.0	+6.2 -0.0
scale ttbar	+3.8 -0.9	+1.5 -1.2	+1.5 -0.9	+0.0 -3.4	+0.0 -12.9	+0.0 -19.1
matching wjetsbc	+2.8 -1.5	+1.3 -1.3	+0.0 -3.5	+0.0 -13.1	+29.0 -0.0	+72.0 -0.0
matching ttbar	+1.7 -0.0	+0.3 -0.2	+0.5 -0.4	+0.0 -2.8	+0.0 -9.0	+0.0 -31.1
MuRes	+1.0 -0.0	+0.0 -0.5	+0.2 -0.0	+0.2 -0.0	+0.0 -3.9	+0.0 -9.4
QCD	+0.0 -1.2	+0.8 0.0	+0.0 -0.9	+1.4 0.0	+7.2 0.0	+0.0 -4.1
PDF	+0.1 -0.9	+0.0 -0.1	+0.5 -0.1	+1.8 -0.3	+3.5 -0.6	+3.8 -1.6
Total systematic uncertainty	+20.9 -12.5	+3.4 -7.7	+9.1 -12.8	+26.0 -33.4	+56.6 -49.2	+93.7 -86.1

top lyl

Uncertainty / Δ [%]	Bin 1	Bin 2	Bin 3	Bin 4	Bin 5	Bin 6
JES	+0.7 -5.1	+2.4 -2.3	+0.6 -0.2	+3.6 -2.2	+5.8 -1.9	+2.6 -0.8
JER	+0.0 -2.9	+1.9 -0.0	+0.8 -0.0	+1.4 -0.9	+1.3 -1.7	+0.0 -2.2
met	+6.1 -9.2	+4.2 -3.2	+1.9 -0.5	+5.1 -5.0	+7.3 -6.8	+7.4 -6.6
PU	+0.0 -1.5	+0.5 -0.0	+0.1 -0.2	+0.5 -0.0	+1.2 -0.0	+1.6 -0.0
btagcb	+0.0 -0.5	+1.0 -0.0	+0.4 -0.0	+0.0 -0.2	+0.0 -0.9	+0.0 -1.1
btaglight	+0.0 -0.7	+1.0 -0.0	+0.4 -0.0	+0.0 -0.4	+0.0 -1.0	+0.0 -1.2
PT	+0.3 -0.2	+0.1 -0.2	+0.0 -0.2	+0.3 -0.2	+0.4 -0.1	+0.0 -0.3
mass	+2.1 -1.1	+1.4 -0.0	+0.6 -0.6	+0.0 -1.6	+0.0 -1.8	+0.0 -1.2
LEP	+0.0 -0.2	+1.1 -0.0	+0.2 -0.0	+0.0 -0.5	+0.0 -1.2	+0.0 -0.9
scale tchan	+2.2 -0.0	+1.5 -0.0	+0.3 -0.0	+0.0 -1.2	+0.0 -3.3	+0.0 -3.3
scale wjetsbc	+9.4 -0.0	+0.0 -2.9	+0.0 -3.5	+0.8 -3.7	+3.7 -1.8	+4.5 -4.6
scale ttbar	+0.4 -1.6	+0.3 -0.4	+0.4 -0.0	+0.9 -0.0	+1.1 -0.6	+1.5 -2.3
matching wjetsbc	+0.0 -7.5	+0.0 -8.2	+1.8 -3.9	+8.3 -0.0	+16.0 -0.0	+20.8 -0.0
matching ttbar	+0.3 -0.1	+0.2 -0.2	+0.5 -0.2	+0.3 -0.0	+0.0 -0.5	+0.0 -1.1
MuRes	+1.1 -0.0	+0.4 -0.0	+0.0 -0.2	+0.0 -0.6	+0.0 -0.9	+0.0 -1.3
QCD	+0.0 -3.6	+0.0 -1.5	+0.1 0.0	+1.6 0.0	+3.7 0.0	+4.8 0.0
PDF	+0.9 -1.7	+0.4 -0.9	+0.2 -0.2	+1.1 -0.6	+2.1 -1.1	+2.1 -1.1
Total systematic uncertainty	+11.7 -14.1	+6.0 -9.7	+3.0 -5.3	+10.8 -7.1	+19.5 -8.7	+23.4 -9.7

tW - channel @ 8TeV: Uncertainty Table

Systematic uncertainty	$\Delta\sigma$ (pb)	$\Delta\sigma/\sigma$
ME/PS matching thresholds	3.3	14%
Renormalization/factorization scale	2.9	12%
Top-quark mass	2.2	9%
Fit statistical	1.9	8%
Jet energy scale	0.9	4%
Luminosity	0.7	3%
Z+jets data/simulation scale factor	0.6	3%
tW DR/DS scheme	0.5	2%
$t\bar{t}$ cross section	0.4	2%
Lepton identification	0.4	2%
PDF	0.4	2%
Jet energy resolution	0.2	1%
b-tagging data/simulation scale factor	0.2	<1%
$t\bar{t}$ spin correlations	0.1	<1%
Pileup	0.1	<1%
Top-quark p_T reweighting	0.1	<1%
E_T^{miss} modeling	0.1	<1%
Lepton energy scale	0.1	<1%
Total	5.5	24%

s - channel @ 7+8TeV: Uncertainty Table

Source	Uncertainty (%)				
	μ, 7 TeV	μ, 8 TeV	e, 8 TeV	μ + e, 8 TeV	7+8 TeV
Statistical	34	15	14	10	11
$t\bar{t}$, single top quark rate	29	15	14	12	14
W/Z+jets, diboson rate	23	11	13	12	12
Multijet rate	9	3	5	2	2
Lepton efficiency	14	1	2	1	3
Hadronic trigger	5	—	—	—	1
Luminosity	10	5	6	4	6
JER & JES	66	39	29	34	18
b tagging & mistag	34	15	14	14	16
Pileup	6	11	7	9	7
Unclustered $\not\!\!E_T$	5	8	2	6	5
μ_R, μ_F scales	54	34	31	30	28
Matching thresholds	43	11	12	7	17
PDF	12	8	7	7	9
Top quark p_T reweighting	3	5	7	6	6
Total uncertainty	115	64	54	55	47

Top polarization in t-channel@8 TeV: Uncertainty Table

	$\delta A_\mu(\mathrm{t})/10^{-2}$	$\delta A_\mu(\bar{\mathrm{t}})/10^{-2}$	$\delta A_\mu(\mathrm{t}+\bar{\mathrm{t}})/10^{-2}$
Statistical	3.2	4.6	2.6
ML fit uncertainty	0.7	1.2	0.6
Diboson bkg. fraction	<0.1	<0.1	<0.1
Z/γ^*+jets bkg. fraction	<0.1	<0.1	<0.1
s-channel bkg. fraction	0.3	0.2	0.2
tW bkg. fraction	0.1	0.7	0.2
Multijet events shape	0.5	0.7	0.5
Multijet events yield	1.9	1.2	1.7
b tagging	0.7	1.2	0.9
Mistagging	<0.1	0.1	<0.1
Jet energy resolution	2.7	1.8	2.0
Jet energy scale	1.3	2.6	1.1
Unclustered $\not{E}_\mathrm{T}$	1.1	3.3	1.3
Pileup	0.3	0.2	0.2
Lepton identification	<0.1	<0.1	<0.1
Lepton isolation	<0.1	<0.1	<0.1
Muon trigger efficiency	<0.1	<0.1	<0.1
Top quark p_T reweighting	0.3	0.3	0.3
W+jets W boson p_T reweighting	0.1	0.1	0.1
W+jets heavy-flavour fraction	4.7	6.2	5.3
W+jets light-flavour fraction	<0.1	<0.1	0.1
W+jets $\cos\theta^*_\mu$ reweighting	2.9	3.4	3.1
Unfolding bias	2.5	4.2	3.1
Generator model	1.6	3.5	0.3
Top quark mass	1.9	2.9	1.8
PDF	0.9	1.6	1.2
t-channel renorm./fact. scales	0.2	0.2	0.2
$\mathrm{t\bar{t}}$ renorm./fact. scales	2.2	3.4	2.7
$\mathrm{t\bar{t}}$ ME/PS matching	2.2	0.5	1.6
W+jets renorm./fact. scales	3.7	4.6	4.0
W+jets ME/PS matching	3.8	3.0	3.4
Limited MC events	2.1	3.2	1.8
Total uncertainty	10.5	13.8	10.5

Anomalous tγ-coupling @8 TeV: Uncertainty Table

Type	Source	tuγ (%)	tcγ (%)
Rate	Integrated luminosity	1.8	4
	Background normalization (W + jets)	5.6	3
	Background normalization (Wγ + jets)	2.5	1.1
	Other background normalizations	<1	1
Rate+Shape	Trigger efficiency	2.2	0.4
	Pileup effects	7	2.3
	Lepton identification and isolation	<1	4.4
	Photon identification and isolation	1.9	4.5
	Photon energy scale	<1	3.1
	b tagging and mistag efficiency	1.1	4
	Jet energy scale	2.9	2.2
	Jet energy resolution	2.1	3.4
	PDF	3.1	<1
	Scale	1	2.4
	Top quark mass	2.5	1

Input to Multivariate Analysis for t-channel @ 13 TeV

Rank	Variable	Description
1	light quark $\lvert\eta\rvert$	Absolute value of the pseudorapidity of the light-quark jet
2	top quark mass	Invariant mass of the top quark reconstructed from muon, neutrino, and b-tagged jet
3	dijet mass	Invariant mass of the two selected jets
4	transverse W boson mass	Transverse mass of the W boson, calculated from the muon momentum and the $\vec{\not{p}}_{\mathrm{T}}$
5	jet-p_{T} sum	Scalar sum of the transverse momenta of the two jets
6	$\cos\theta^*$	Cosine of the angle between the muon and the light-quark jet in the rest frame of the top quark
7	hardest jet mass	Invariant mass of the jet with the largest transverse momentum
8	ΔR (light quark, b quark)	Difference in R between the light-quark jet and the b-tagged jet.
9	light quark p_{T}	Transverse momentum of the light-quark jet
10	light quark mass	Invariant mass of the light-quark jet
11	W boson $\lvert\eta\rvert$	Absolute value of the pseudorapidity of the reconstructed W boson

Input variables to MVA in t-channel differential cross-section @ 8TeV

variable	rank in channel μ+jets	rank in channel e+jets	variable	rank in channel μ+jets	rank in channel e+jets
η_{lq}	1	1	C	11	12
$m_{\ell,\nu,b}$	2	2	$p_{T,lq}$	12	9
$m_{\mathrm{jet1,jet2}}$	3	3	D	13	17
$m_{\mathrm{T,W}}$	4	4	m_{jet1}	14	5
Q_{ℓ}	5	6	$E_{\mathrm{T}}^{\mathrm{miss}}$	15	14
m_{lq}	6	13	$\Delta\phi[jet2, \vec{\not{E}}_{\mathrm{T}}]$	16	16
η_{W}	7	7	m_{jet2}	17	8
$\Delta\phi[\ell, lq]$	8	11	$\Delta R[jet1, \vec{\not{E}}_{\mathrm{T}}]$	18	15
$m_{b_{top}}$	9	–	$\Delta\phi[jet2, \ell]$	–	10
$\Delta\phi[jet1, \vec{\not{E}}_{\mathrm{T}}]$	10	–	$Aplanarity$	–	18

Event shape variables:
C = 3 x ($\lambda_1\lambda_2+\lambda_2\lambda_3+\lambda_3\lambda_1$), measures 3-jet structure an the event
D = 27x($\lambda_1\lambda_2\lambda_3$), measures 4-jet structure of an event
Aplanarity = $3\lambda_3 / 2$, measures transverse momentum component out of event plane
where λ_i -s are eigen values of linearized momentum tensor

Top polarization in t-channel @ 8TeV: MVA inputs

Input variables for BDT_{W/tt^-}

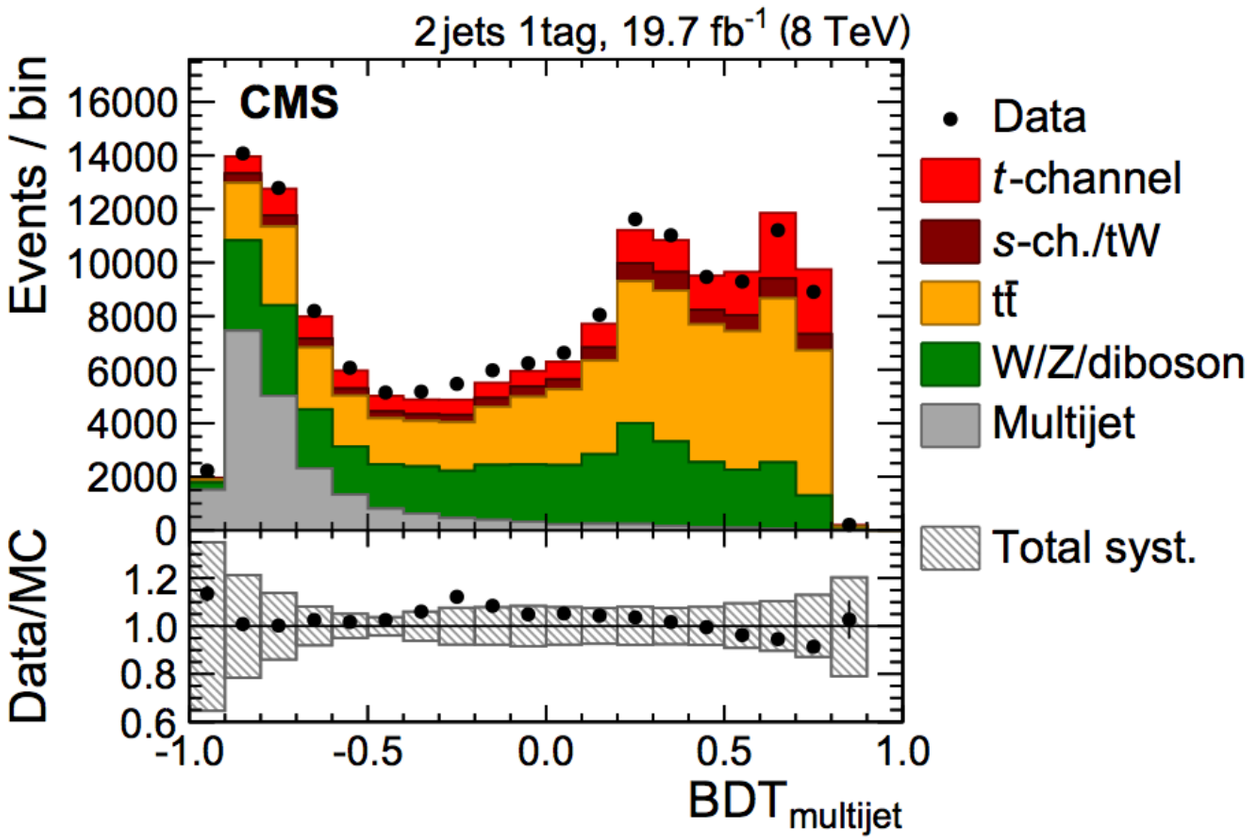
- the invariant mass of the top quark candidate, $m_{\mathrm{b}\mu\nu}$;
- the absolute pseudorapidity of the untagged jet, $|\eta_{\mathrm{j}'}|$;
- the absolute pseudorapidity of the b-tagged jet, $|\eta_{\mathrm{b}}|$;
- the invariant mass of the b-tagged jet from the summed momenta of the clustered tracks, m_{b};
- the transverse momentum of the muon, p_{T}^{μ};
- the transverse momentum of the b-tagged jet, $p_{\mathrm{T}}^{\mathrm{b}}$;
- the transverse mass of the W boson candidate, $m_{\mathrm{T}}(\mathrm{W}) = \sqrt{\left(p_{\mathrm{T}}^{\mu} + \not{E}_{\mathrm{T}}\right)^2 - \left(p_x^{\mu} + \not{p}_{\mathrm{T},x}\right)^2 - \left(p_y^{\mu} + \not{p}_{\mathrm{T},y}\right)^2}$;
- the missing transverse energy, $\not{E}_{\mathrm{T}}$;
- the total invariant mass of the top quark candidate and the untagged jet system, $\hat{s}$;
- the transverse momentum of the hadronic final-state system, $H_{\mathrm{T}} = (\vec{p}_{\mathrm{b}} + \vec{p}_{\mathrm{j}'})_{\mathrm{T}}$.

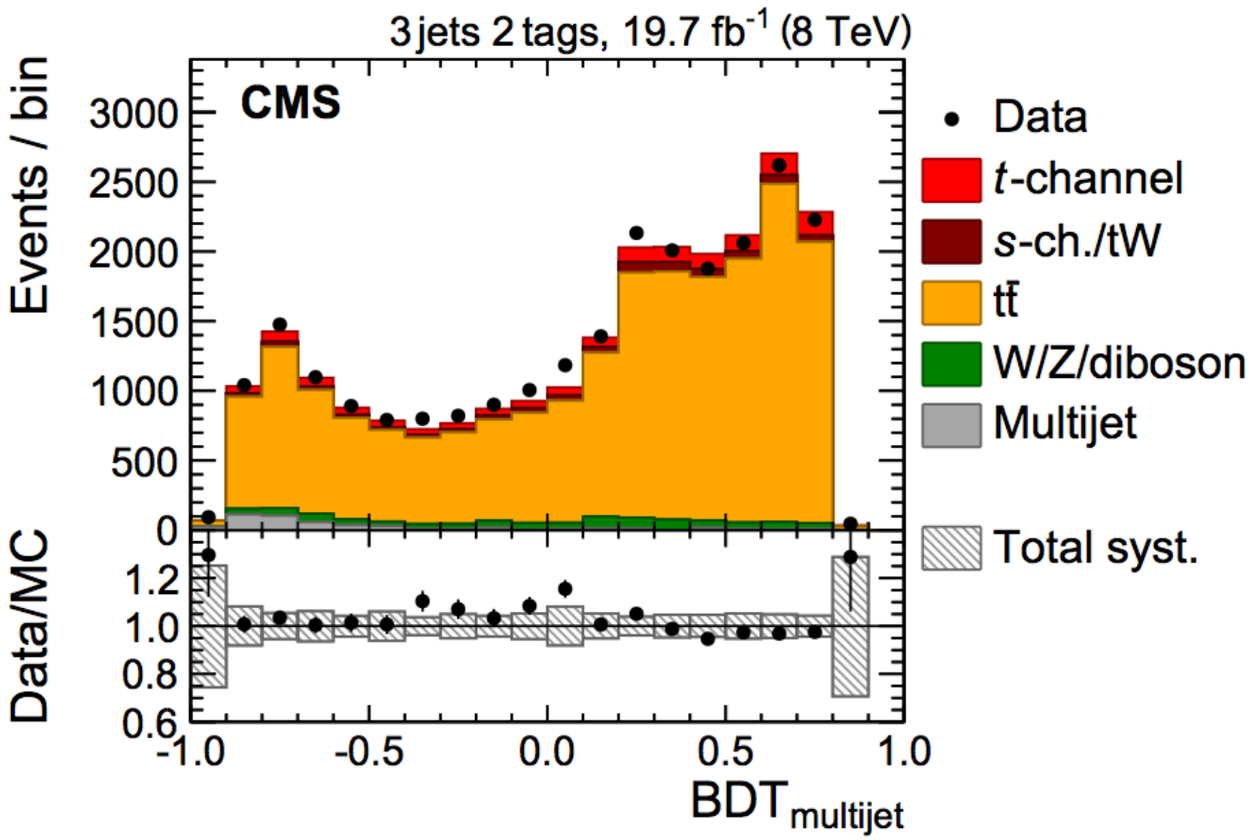
Input variables for $BDT_{Multijet}$

- the missing transverse energy, $\not{E}_{\mathrm{T}}$;
- the invariant mass of the top quark candidate, $m_{\mathrm{b}\mu\nu}$;
- the absolute pseudorapidity of the top quark candidate, $|\eta_{\mathrm{b}\mu\nu}|$;
- the transverse momentum of the b-tagged jet, $p_{\mathrm{T}}^{\mathrm{b}}$;
- the event isotropy, defined as $(\mathcal{S}_{\max} - \mathcal{S}_{\min})/\mathcal{S}_{\max}$ with $\mathcal{S} \equiv \sum_i^{\mu,\mathrm{jets}} |\vec{n} \cdot \vec{p}_i|$, where the unit vector in the transverse r–ϕ plane, $\vec{n} = (\cos\phi, \sin\phi)$, can be chosen to either maximise or minimise $\mathcal{S}$.

$BDT_{Multijet} >$ -0.15 to reject QCD multijet background

Top polarization in t-channel @ 8TeV: $BDT_{Multijet}$ Distribution





tW-channel @ 8TeV: MVA inputs

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

s-channel: MVA inputs

Muon

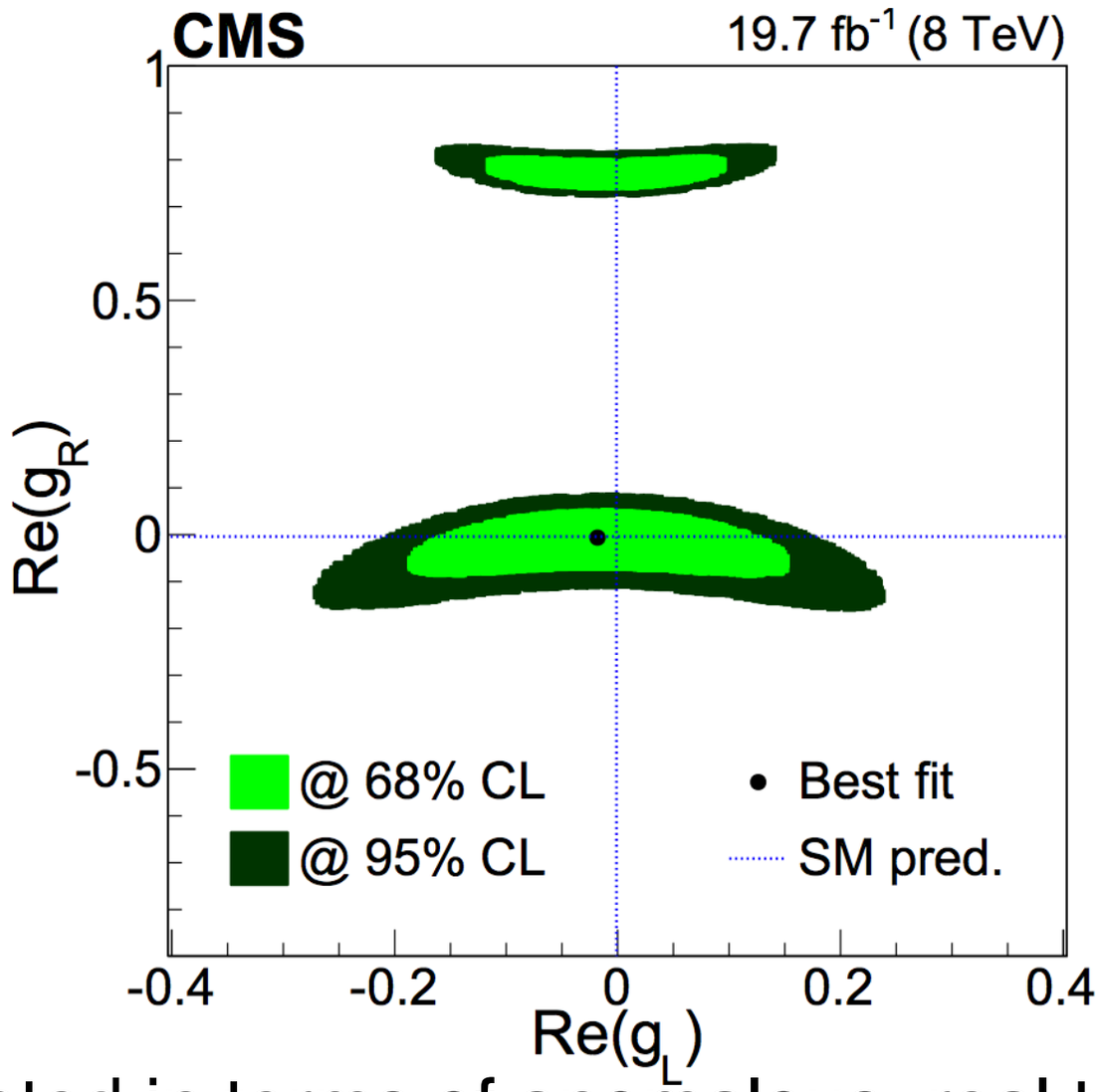
Variable	Description
$p_{\mathrm{T}}^{\mathrm{bb}}$	vector sum of p_{T} of the two b-tagged jets
$m_{\ell\nu\mathrm{b}}$-best	invariant mass of lepton, neutrino and one of the b-tagged jets reconstructed with the best-mass top method, as described in Sec.2
m_{T}	tranverse W boson mass
$M_{\ell b2}$	invariant mass of the lepton and the second-to-leading b-tagged jet
$\not{E}_{\mathrm{T}}$	missing transverse energy
$\Delta\Phi_{\mathrm{top,b'}}$	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
ΔR_{bb}	angular separation between the two b-tagged jets
H_{T}	scalar sum of p_{T} of all jets
p_{T}^{ℓ}	transverse momentum of the lepton

Electron

Variable	Description
m_{T}	tranverse W boson mass
$\Delta\Phi_{\mathrm{top,b'}}$	difference in azimuthal angle between top quark and recoiled b-tagged jet
$\not{E}_{\mathrm{T}}$	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
$p_{\mathrm{T}}^{\mathrm{bb}}$	vector sum of p_{T} of the two b-tagged jets
$\Delta R_{\mathrm{bb}}(*)$	angular separation between the two b-tagged jets
p_{T}^{ℓ}	transverse momentum of the lepton
$m_{\ell\nu\mathrm{b}}$-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
$\Delta R_{\mathrm{b}'\ell}$	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

Anomalous coupling limit from W helicity measurement

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



- Results interpreted in terms of anomalous, real tensor coupling with the assumption $V_R = 0$
- Best Fit values: $g_L = -0.017$, $g_R = -0.008$

W helicity measurement @ 8TeV: Uncertainty Table

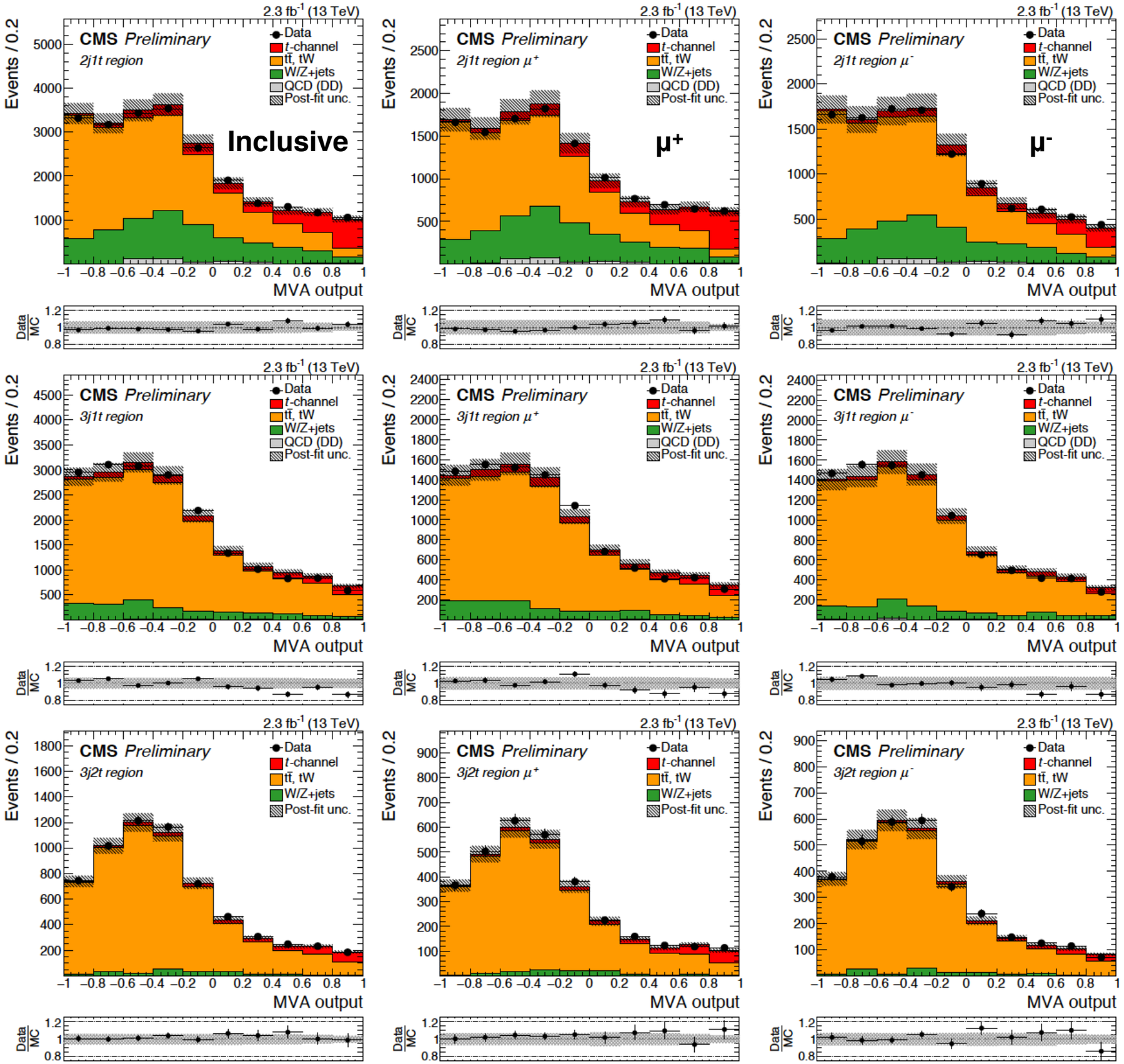
	Muon channel		Electron channel		Combination	
	ΔF_0	ΔF_L	ΔF_0	ΔF_L	ΔF_0	ΔF_L
Experimental	0.010	0.009	0.008	0.005	0.010	0.010
Modeling	0.025	0.017	0.025	0.022	0.025	0.020
Normalization	0.002	0.008	0.012	0.014	0.011	0.012
SM W helicities	0.007	0.004	0.005	0.003	0.007	0.004
MC sample size	0.026	0.012	0.025	0.015	0.020	0.012
tWb in prod.	0.014	0.016	0.010	0.018	0.011	0.014
Total	0.041	0.030	0.040	0.036	0.037	0.032

Post Fit Plots t-channel @ 13TeV

2J1T

3J1T

3J2T



t-channel theory cross - section

7 TeV					
Mode	**Central value**	**Scale uncert.**	**PDF+alphaS uncert.**	**Total uncert.**	**Mass uncert.**
top	41.80	+1.24 -0.82	+1.28 -1.28	+1.78 -1.52	+0.42 -0.42
anti-top	22.02	+0.67 -0.43	+1.08 -1.08	+1.27 -1.16	+0.24 -0.23
top + anti-top	63.89	+1.92 -1.25	+2.19 -2.19	+2.91 -2.52	+0.65 -0.65
8 TeV					
Mode	**Central value**	**Scale uncert.**	**PDF+alphaS uncert.**	**Total uncert.**	**Mass uncert.**
top	54.87	+1.64 -1.09	+1.60 -1.60	+2.29 -1.94	+0.52 -0.52
anti-top	29.74	+0.92 -0.59	+1.39 -1.39	+1.67 -1.51	+0.30 -0.30
top + anti-top	84.69	+2.56 -1.68	+2.76 -2.76	+3.76 -3.23	+0.82 -0.82
13 TeV					
Mode	**Central value**	**Scale uncert.**	**PDF+alphaS uncert.**	**Total uncert.**	**Mass uncert.**
top	136.02	+4.09 -2.92	+3.52 -3.52	+5.40 -4.57	+1.11 -1.11
anti-top	80.95	+2.53 -1.71	+3.18 -3.18	+4.06 -3.61	+0.71 -0.70
top + anti-top	216.99	+6.62 -4.64	+6.16 -6.16	+9.04 -7.71	+1.81 -1.81

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SingleTopRefXsec

tW , s - channel theory cross - section

7 TeV			
Mode	**Central value**	**Scale uncert.**	**PDF uncert.**
top + antitop	15.74	+0.40 -0.40	+1.10 -1.14
8 TeV			
Mode	**Central value**	**Scale uncert.**	**PDF uncert.**
top + antitop	22.37	+0.60 -0.60	+1.40 -1.40
13 TeV			
Mode	**Central value**	**Scale uncert.**	**PDF uncert.**
top + antitop	71.7	+1.80 -1.80	+3.40 -3.40

tW - channel

s - channel

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SingleTopRefXsec

7 TeV					
Mode	**Central value**	**Scale uncert.**	**PDF+alphaS uncert.**	**Total uncert.**	**Mass uncert.**
top	2.76	+0.08 -0.07	+0.08 -0.08	+0.11 -0.10	+0.06 -0.06
anti-top	1.52	+0.04 -0.04	+0.07 -0.07	+0.08 -0.08	+0.04 -0.04
top + anti-top	4.29	+0.12 -0.10	+0.14 -0.14	+0.19 -0.17	+0.10 -0.10
8 TeV					
Mode	**Central value**	**Scale uncert.**	**PDF+alphaS uncert.**	**Total uncert.**	**Mass uncert.**
top	3.34	+0.09 -0.08	+0.09 -0.09	+0.13 -0.12	+0.07 -0.07
anti-top	1.90	+0.05 -0.04	+0.08 -0.08	+0.10 -0.09	+0.05 -0.04
top + anti-top	5.24	+0.15 -0.12	+0.16 -0.16	+0.22 -0.20	+0.12 -0.12
13 TeV					
Mode	**Central value**	**Scale uncert.**	**PDF+alphaS uncert.**	**Total uncert.**	**Mass uncert.**
top	6.35	+0.18 -0.15	+0.14 -0.14	+0.23 -0.20	+0.14 -0.13
anti-top	3.97	+0.11 -0.09	+0.15 -0.15	+0.19 -0.17	+0.09 -0.09
top + anti-top	10.32	+0.29 -0.24	+0.27 -0.27	+0.40 -0.36	+0.23 -0.22