Single top quark production with CMS

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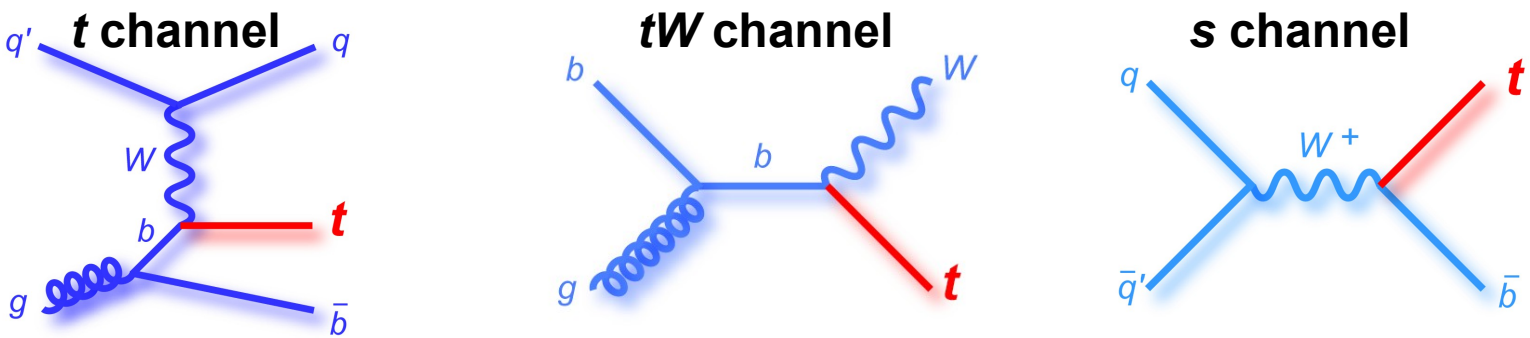
on behalf of the CMS collaboration

Pheno 2014, May 5-7
University of Pittsburgh

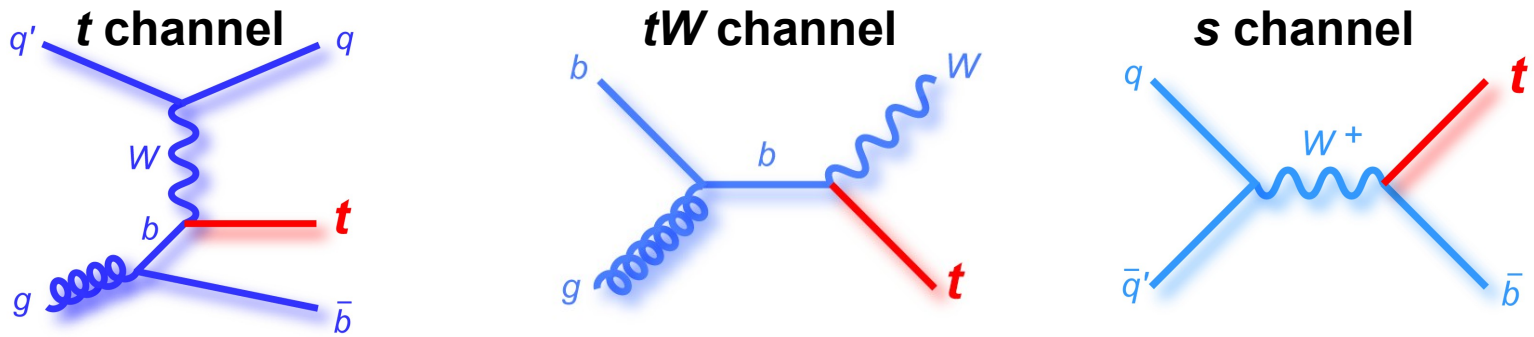
Single top physics



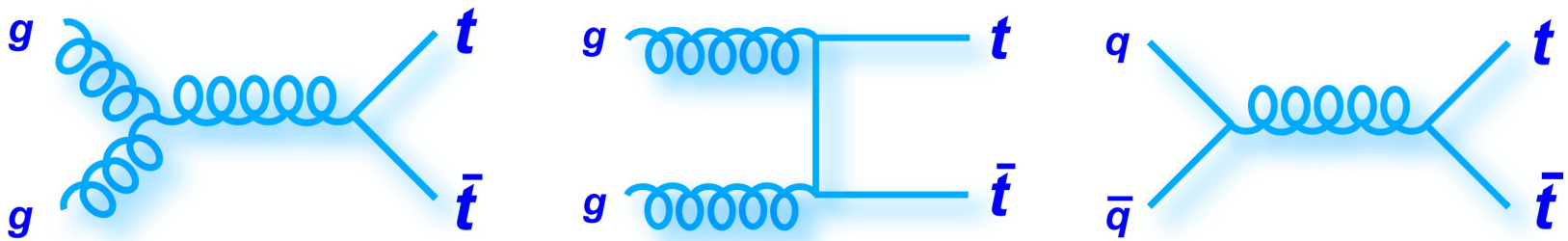
- Check of the standard model electroweak physics with the top quark
- Many **SM measurements** possible:
  - Cross sections, polarization, W helicity, Vtb, etc.
- Sensitive to many models of **new physics**:
  - New particles (W', charged Higgs, etc.)
  - FCNC, Anomalous couplings
- Background to many searches (Higgs, SUSY, etc.)

Top production at LHC

Single top electroweak production



Top pair strong production (background)



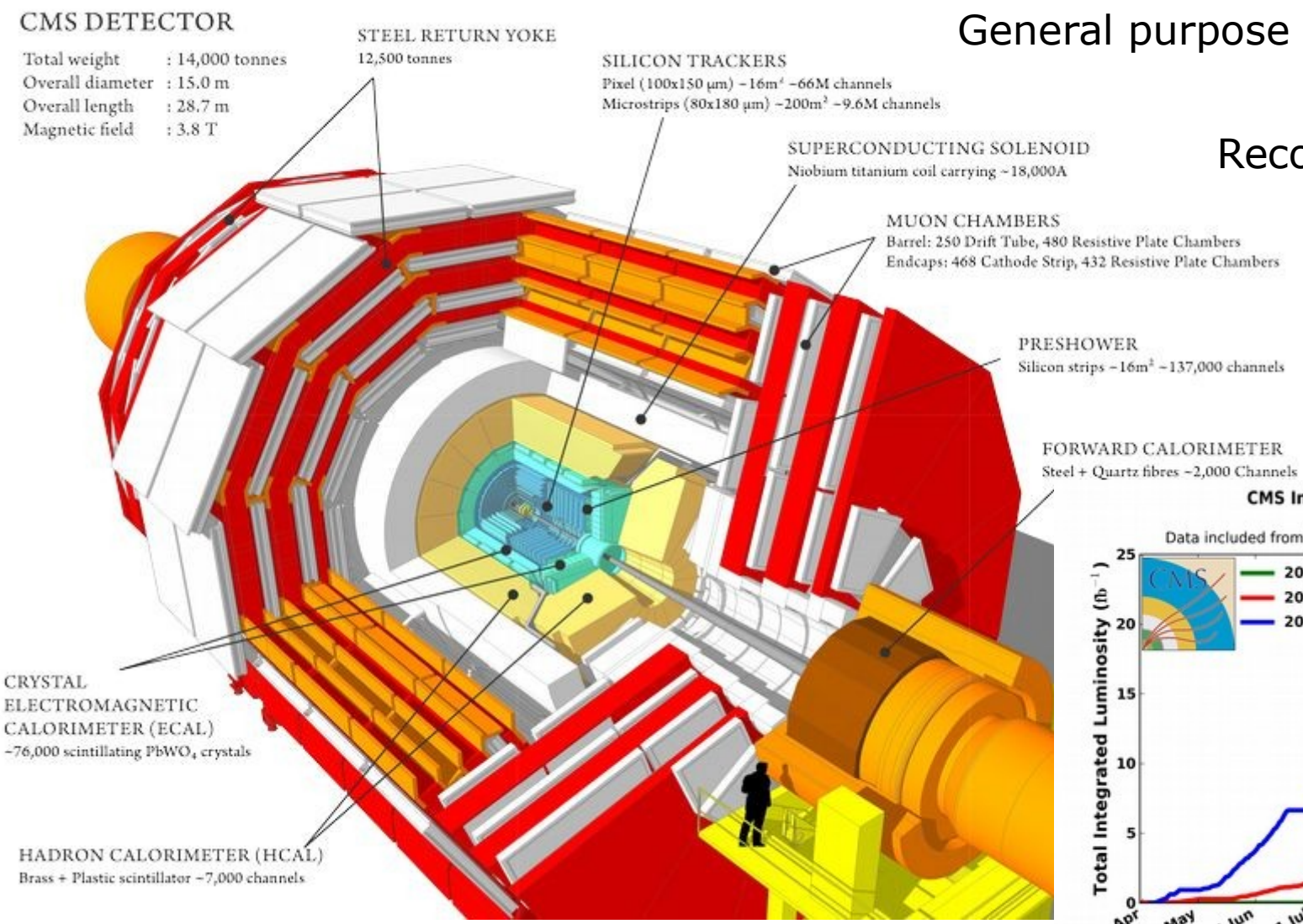
		t ch.	tW ch.	s ch.	$t\bar{t}$
Tevatron ($p\bar{p}$)	1.96 TeV	2.08 pb	0.22 pb	1.05 pb	7.16 pb
LHC (pp)	7 TeV	65.9 pb	15.6 pb	4.56 pb	172 pb
	8 TeV	87.2 pb	22.2 pb	5.55 pb	249 pb

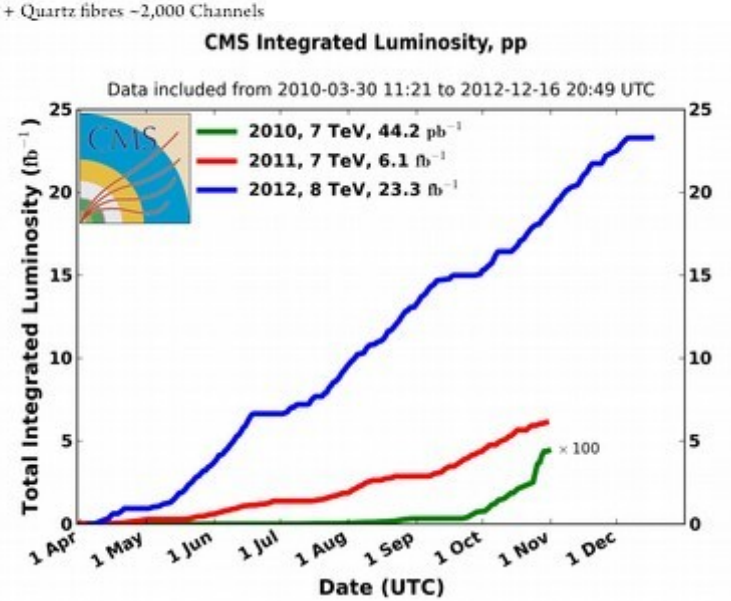
N.Kidonakis: arXiv:1210.7813, arXiv:0909.0037 Czakon, et al:PRL110(2013)252004

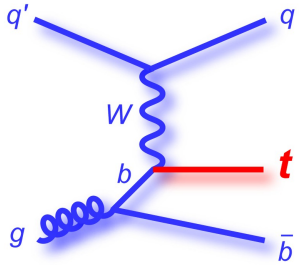
Compact Muon Solenoid (CMS)

General purpose detector at the LHC

Recorded ~5 fb^{-1} at 7 TeV
and ~20 fb^{-1} at 8 TeV







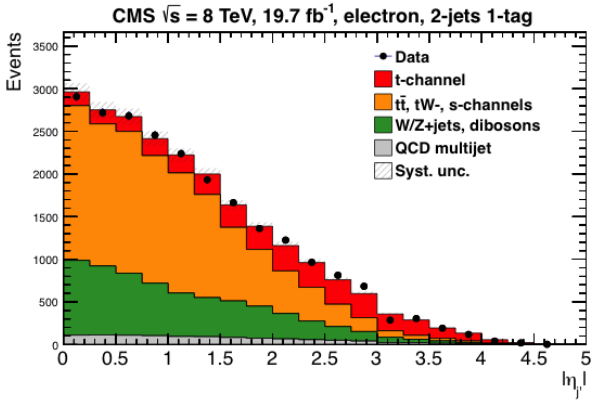
t-channel Cross Section

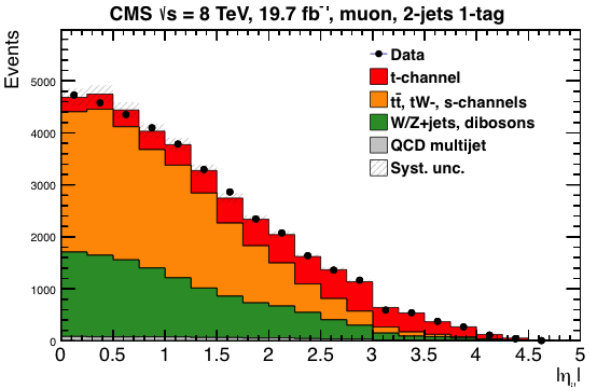
- Using full 8 TeV dataset, L=19.7 fb^{-1}
- Looking in the lepton + jets final state
  - Signal region: one e or μ, 2jets-1tag, in top mass window ($130 < m_{lvb} < 220$ GeV)
- Fit to the pseudorapidity of the light jet $|\eta_{j'}|$
- Background shapes for W+jets and $t\bar{t}$ estimated from control regions in data (side band in m_{lvb} and 3jets-2tag)

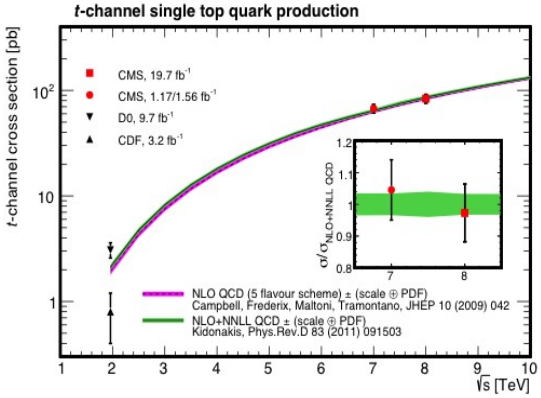
$$\sigma_{t\text{-channel}} = 83.6 \pm 2.3\ (\text{stat.}) \pm 7.4\ (\text{syst.})\ \text{pb}$$

$$\sigma^{\text{th.}}_{t-\text{channel}} = 87.2^{+2.8}_{-1.0}(\text{scale})^{+2.0}_{-2.2}(\text{PDF})\,\text{pb}$$

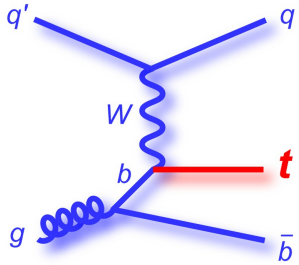
$$R_{8/7} = 1.24 \pm 0.08\ (\text{stat.}) \pm 0.12\ (\text{syst.})$$







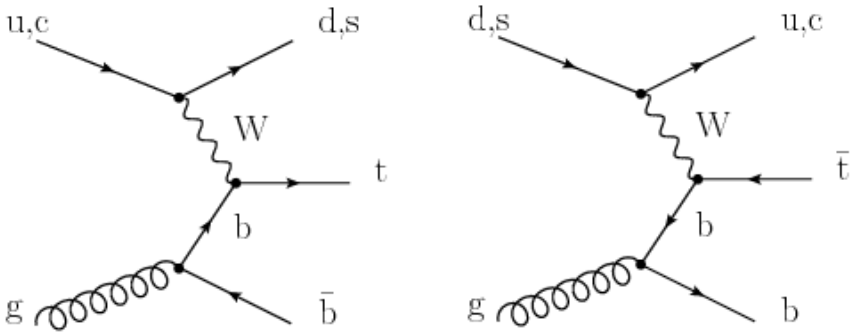
arXiv:1403.7366 (submitted to JHEP)



Charge Ratio

Expect a difference in the cross section of top vs antitop quarks due to relative abundance of u and d quarks in the proton.

Measurement of the ratio of top to antitop is approaching the sensitivity to discriminate between different PDF models of the proton



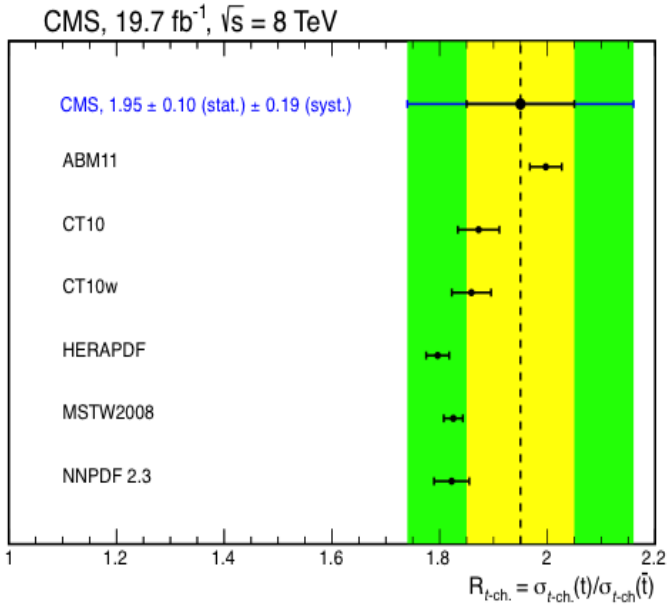
σ_{top} = 53.8±1.5(stat.)±4.4(syst.) pb

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

$\sigma_{antitop}$ = 27.6±1.3(stat.)±4.4(syst.) pb

$$\sigma_{antitop}^{th.} = 30.7 \pm 0.7(\text{scale})^{+0.9}_{-1.1}(\text{PDF})\,\text{pb}$$

$R_{t\text{-}ch} = \sigma_{top}/\sigma_{antitop}$ = 1.95±0.1(stat.)±0.19(syst.) pb



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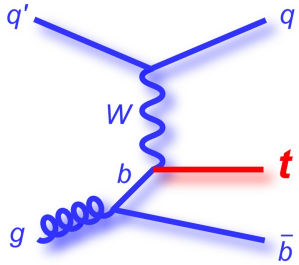
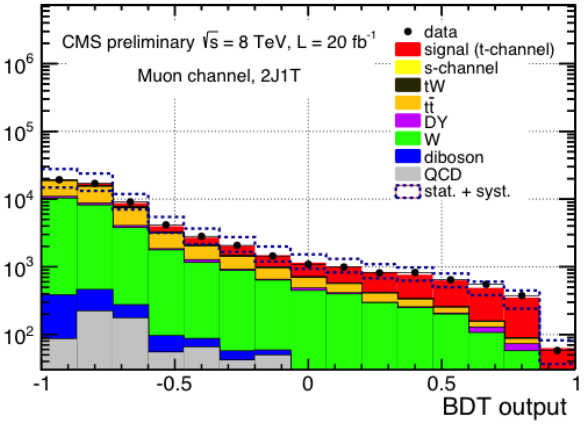


Top polarization

- Measuring the top polarization of in the t-channel, selecting events based on a BDT discriminant in order to obtain more pure sample
- Spin of the top quark is aligned with the recoiling light jet
- Polarization is measured from unfolded $\cos(\theta^*_l)$ distribution (angle between lepton and light jet in top quark rest frame)
- Combine e and μ channels with BLUE



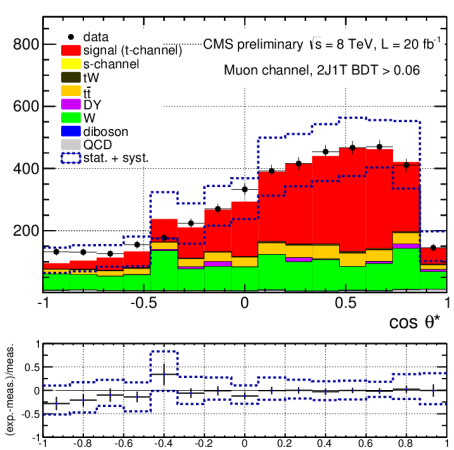
$$A_l \equiv \frac{1}{2} \cdot P_t \cdot \alpha_l \qquad A_l = \frac{N(\cos\theta^*_{unfolded} > 0) - N(\cos\theta^*_{unfolded} < 0)}{N(\cos\theta^*_{unfolded} > 0) + N(\cos\theta^*_{unfolded} < 0)}$$

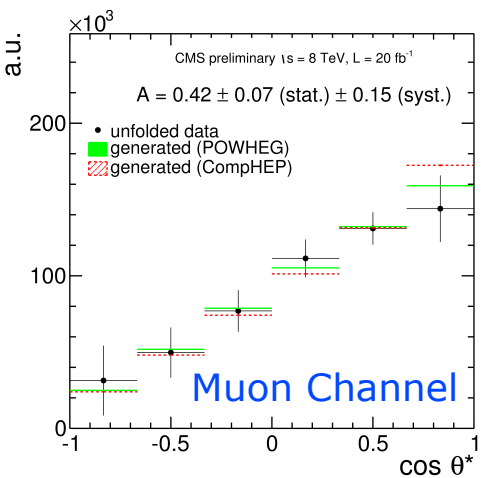
Top spin asymmetry:

A_ℓ = 0.41±0.06(stat)±0.16(syst)

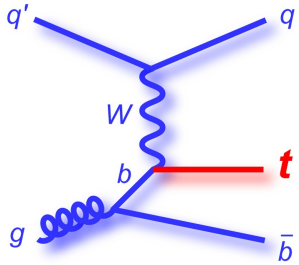
Top Polarization: Assuming $\alpha_l = 1$

P_ℓ = 0.82±0.12(stat)±0.32(syst)





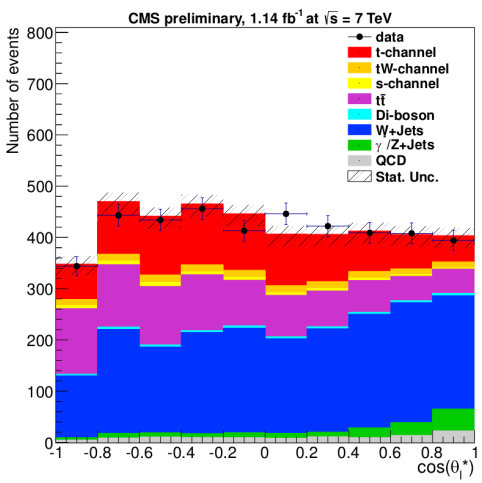
CMS-PAS-TOP-13-001

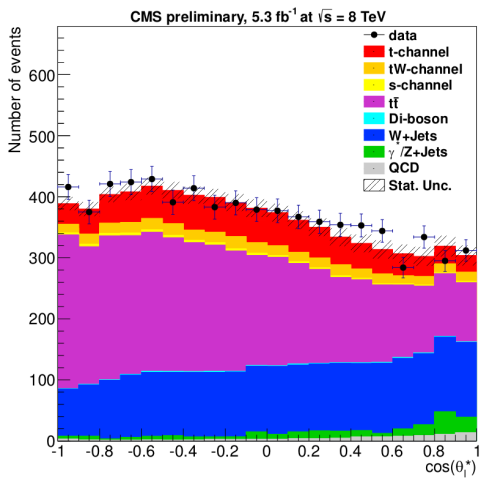


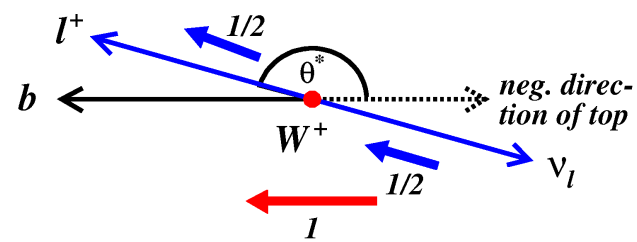
W-helicity

- Measured using t-channel events
  - Combination of 7 and 8 TeV data (1.14 and 5.3 fb^{-1}), in muon+jets channel
- W boson can have longitudinal, left or right-handed helicity states
  - SM couplings predict helicity fractions of F_0=0.687, F_L=0.311, F_R=0.0017
- Can be extracted from angular distribution of decay products

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

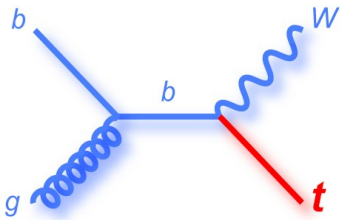






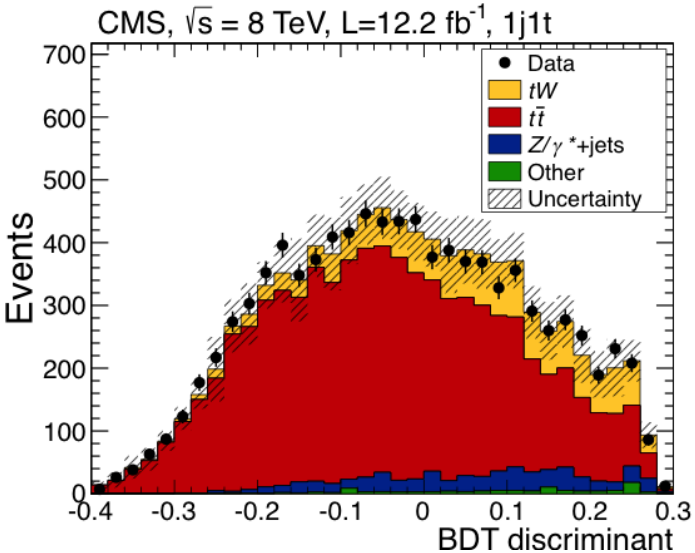
F_L = 0.293±0.069(stat)±0.30(syst)
F_0 = 0.713±0.114(stat)±0.023(syst)
F_R = -0.006±0.057(stat)±0.027(syst)

CMS-PAS-TOP-12-020



tW channel

- Analysis performed at 8 TeV, L=12.2 fb^{-1}
- Second largest single top cross section at the LHC, inaccessible at the Tevatron
- Evidence reported at 7 TeV by both ATLAS and CMS
- Dilepton final state, main challenge is $t\bar{t}$ background
  - Signal Region: two leptons, 1jet-1tag
  - Control Region: Two jets, 1 or 2 tags
- Uses Boosted Decision Tree to separate tW from $t\bar{t}$
- Fit to BDT discriminant in signal and control regions

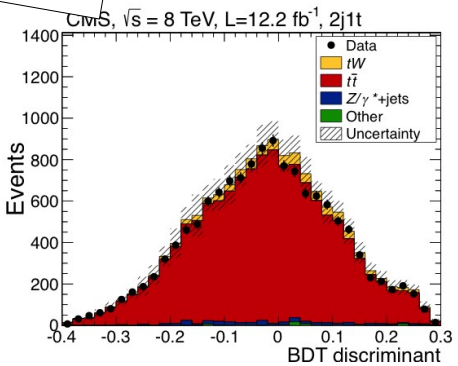


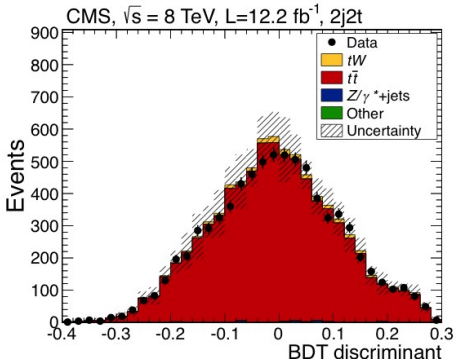
First Observation

tW signal observed with a significance of 6.1σ (5.4±1.4σ expected)

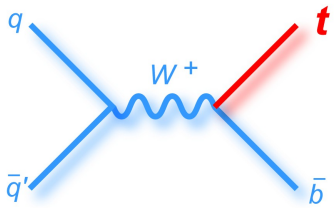
$$\sigma_{tW} = 23.4 \pm 5.4 \text{ pb}$$

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





arXiv:1401.2942 (accepted for pub. in PRL)

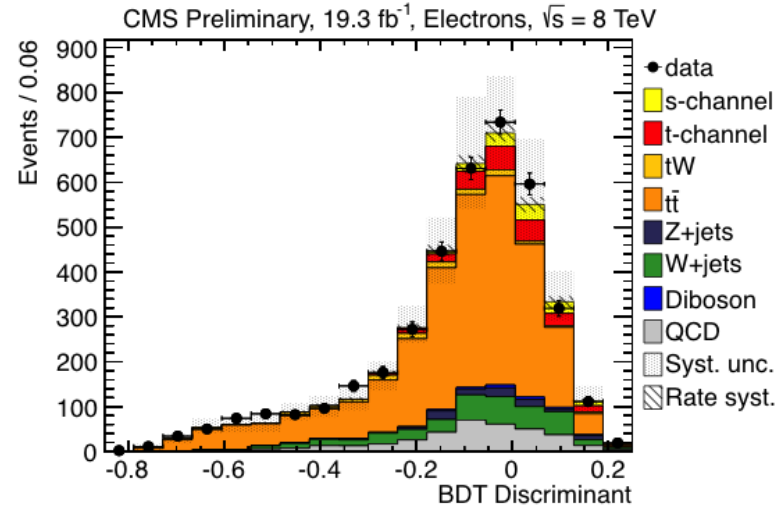


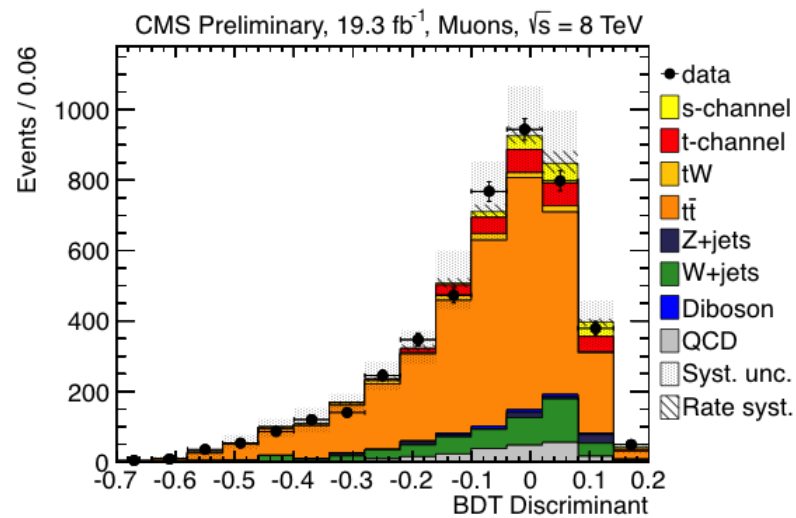
s channel

- Performed using 12.2 fb^{-1} of data at 8 TeV
- Smallest single top cross-section at the LHC:

$$\sigma^{th.}_{s-ch.} = 5.55 \pm 0.08(\text{scale}) \pm 0.21(\text{PDF})\,\text{pb}$$

- Lepton + jets signature:
  - Signal region: one e or μ, MET, and 2 b-tagged jets
- Main background: tt, W+jets, multijet
- Uses a BDT to separate s-channel signals from backgrounds





$\sigma_{s\text{-ch.}}$ = 6.2±5.4(exp.)±5.9(th.) pb
= 6.2+8.0-5.1 pb (Feldman-Cousins)
Upper limit of 2.1 $\sigma_{s\text{-ch.}}$ < 11.5 pb = 2.1xσ_{SM}
Observed (expected) signif. 0.7σ (0.9σ)

CMS PAS TOP-13-009

$|V_{tb}|$ measurement

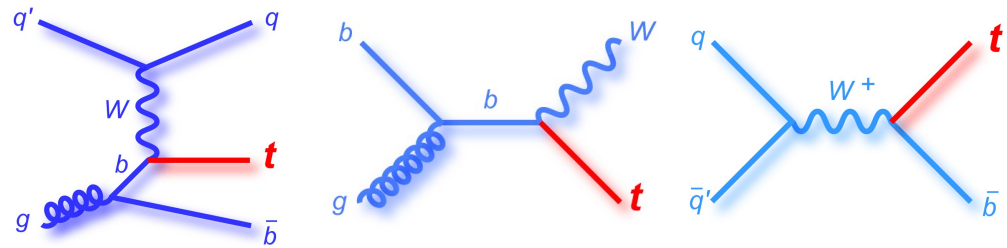
- Single top events provide the ability to directly probe the Wtb vertex, and measure $|V_{tb}|$
  - $|V_{tb}| = (\sigma/\sigma_{th})^{1/2}$, assuming $|V_{tb}| \gg |V_{ts}|,|V_{td}|$

- **tW-channel:**
  - **7 TeV:** $|V_{tb}| = 1.01^{+0.16}_{-0.13}(\text{exp.})^{+0.03}_{-0.04}(\text{th.})$
  - **8 TeV:** $|V_{tb}| = 1.03 \pm 0.12(\text{exp.}) \pm 0.04(\text{th.})$
- **t-channel:**
  - **7 TeV:** $|V_{tb}| = 1.020 \pm 0.046(\text{exp.}) \pm 0.017(\text{th.})$
  - **8 TeV:** $|V_{tb}| = 0.979 \pm 0.045(\text{exp.}) \pm 0.016(\text{th.})$
  - **7+8 TeV:** $|V_{tb}| = 0.998 \pm 0.038(\text{meas.}) \pm 0.016(\text{th.})$

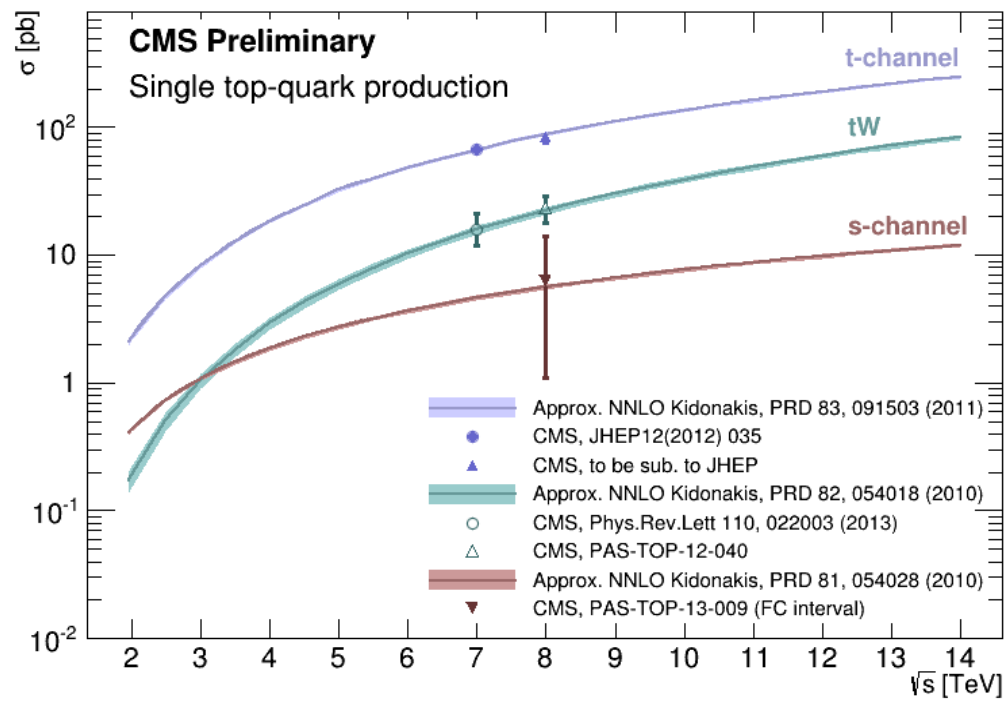
tW: 7 TeV: PRL 110, 022003 (2013)
8 TeV: arXiv:1401:2942 (→ PRL)

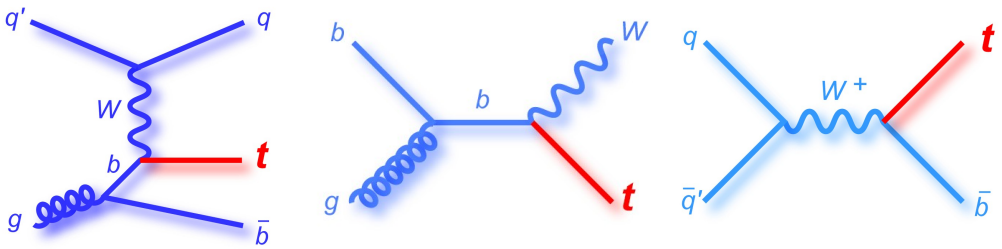
t-ch.: 7 TeV: JHEP 12 (2012) 035
8 TeV: arXiv:1403.7366 (→ JHEP)

Summary

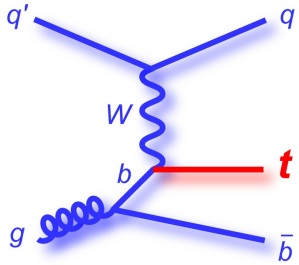


- Many exciting single top results from CMS
- t-channel: LargestCross section measurement
- tW-channel: First observation of the process found in 8 TeV data
- s-channel: Very small cross section at the LHC, first result using 8 TeV
- The t-channel used for measurement of top properties:
  - $|V_{tb}|$ measurement
  - W-helicity fractions
  - Top polarization





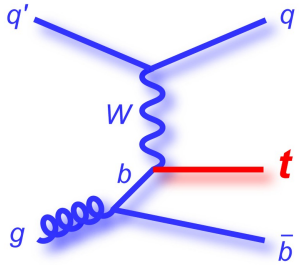
Backup Slides



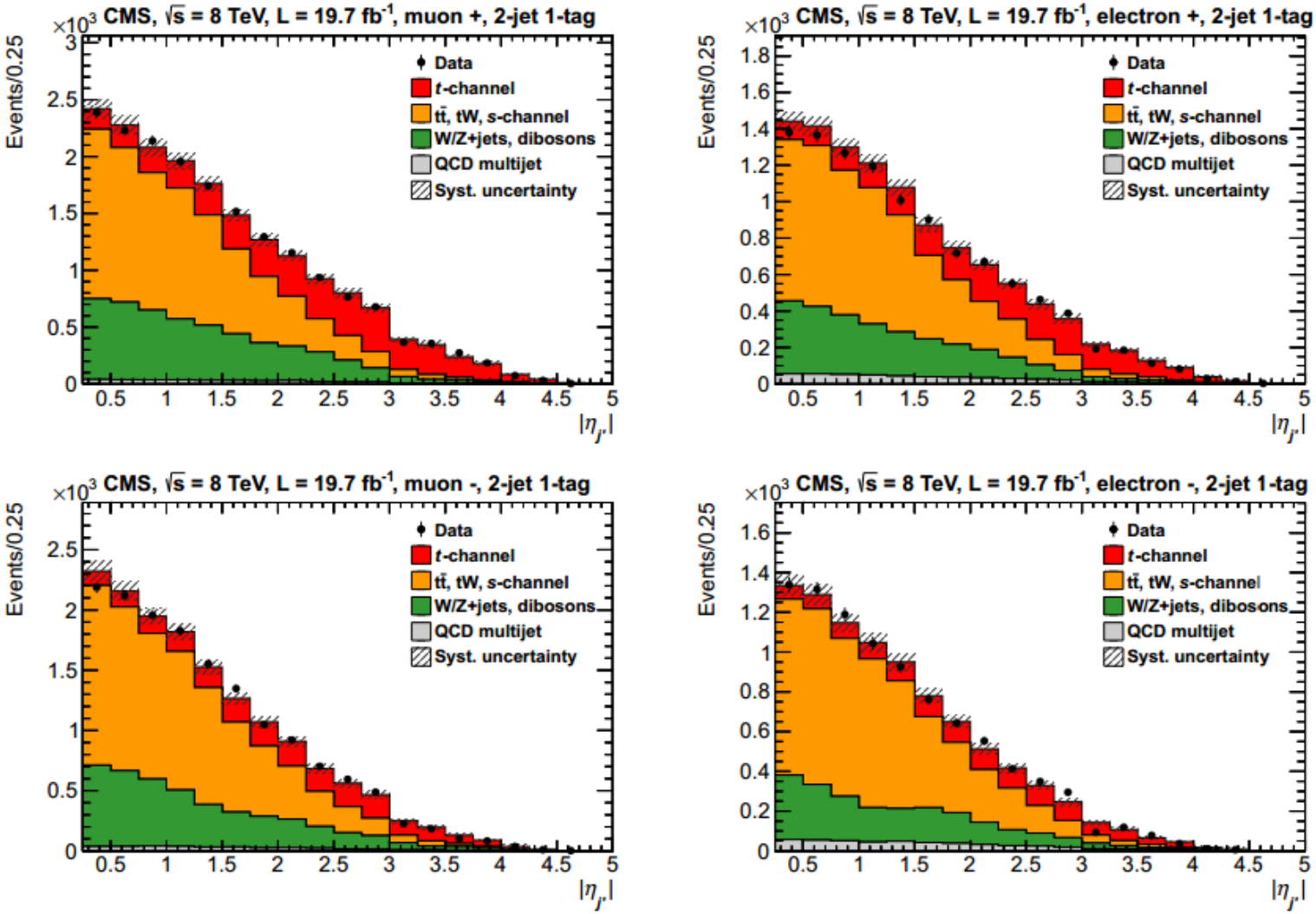
t-channel

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

arXiv:1403.7366 (submitted to JHEP)



Charge Ratio



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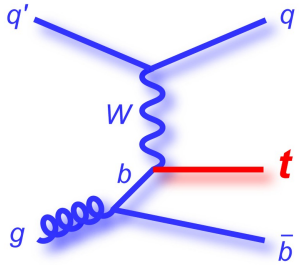
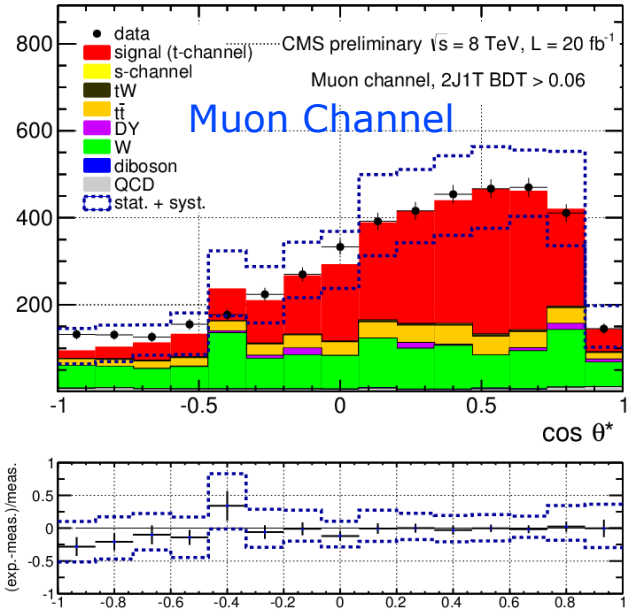
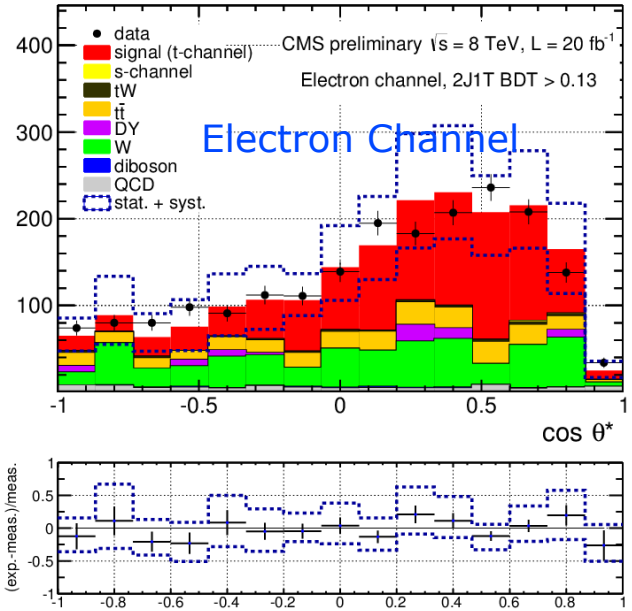
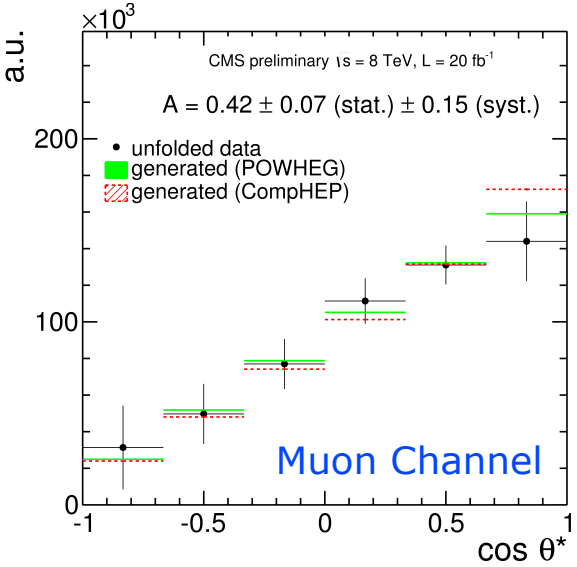
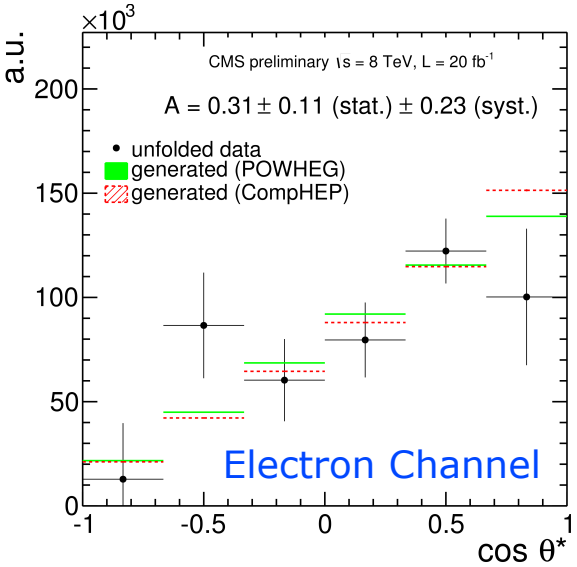


Top polarization







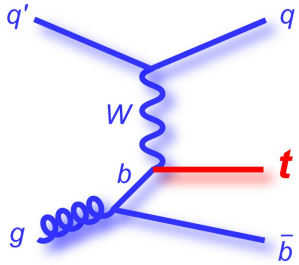


Top spin asymmetry:

e: A_ℓ = 0.42±0.07(stat)±0.15(syst)

μ: A_ℓ = 0.31±0.11(stat)±0.23(syst)

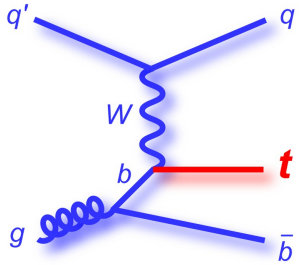
CMS-PAS-TOP-13-001



Top polarization

Systematic Uncertainties

Uncertainty source	δA_l^μ	δA_l^e
generator	0.025	0.009
Q^2 scale t-channel	0.024	0.055
Q^2 scale, $t\bar{t}$	0.015	0.005
Q^2 scale, W+jets	0.036	0.038
top quark mass	0.058	0.042
W+jets shape	0.016	0.007
W+jets flavour	0.005	0.008
top p_T, $t\bar{t}$	0.010	0.025
matching, $t\bar{t}$	0.028	0.052
matching, W+jets	0.025	0.038
PDF	0.013	0.014
JES	0.074	0.074
JER	0.016	0.179
unclustered $\not{E}_T$	0.013	0.006
lepton ID and isolation	0.001	0.002
lepton trigger	0.001	0.002
pileup	0.015	0.002
b tagging	0.007	0.009
mistagging	0.001	0.003
lepton weight	0.001	0.009
anti-isolation range of QCD	0.010	0.053
QCD fraction	0.092	0.028
background fractions	0.007	0.018
unfolding bias	0.002	0.003
total systematics	0.15	0.23
statistical	0.07	0.11
total	0.17	0.26



W-helicity

Results 7 TeV

F_L = 0.293±0.069(stat)±0.30(syst)
F_0 = 0.713±0.114(stat)±0.023(syst)
F_R = -0.006±0.057(stat)±0.027(syst)

Results 8 TeV

F_L = 0.293±0.069(stat)±0.30(syst)
F_0 = 0.713±0.114(stat)±0.023(syst)
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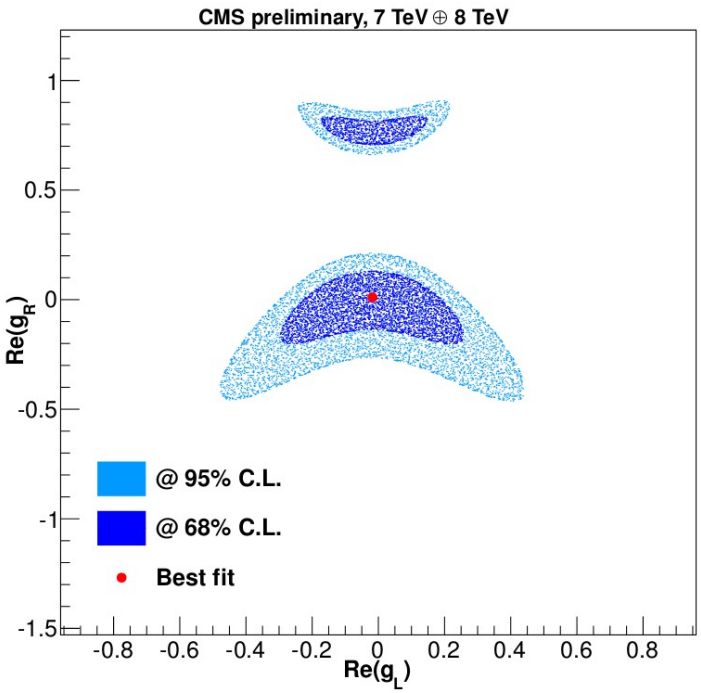
Anomalous Couplings



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

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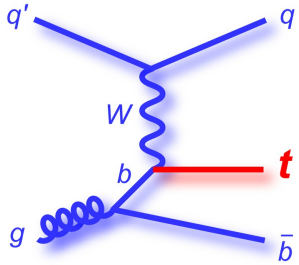


W-helicity

Systematic Uncertainties

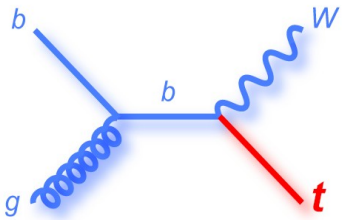
Separated by Energy

	$\sqrt{s} = 8$ TeV		$\sqrt{s} = 7$ TeV	
Systematic source	ΔF_L	ΔF_0	ΔF_L	ΔF_0
JES	0.006	0.006	0.020	0.020
JER	0.008	0.003	0.015	0.010
unclustered energy	0.013	0.003	0.015	0.015
pileup	0.002	0.003	0.004	0.000
b-flavored scale factor	0.004	0.006	0.009	0.009
non-b-flavored scale factor	0.004	0.007	0.002	0.001
single-top generator	0.008	0.014	0.004	0.004
Q^2 scale	0.009	0.012	0.040	0.007
m_{top}	0.005	0.006	0.010	0.010
PDF	0.005	0.005	0.000	0.000
$t\bar{t}$ normalization	0.002	0.003	0.008	0.008
QCD shape	0.002	0.002	0.004	0.004
W+jets shape	0.008	0.010	0.010	0.010
integrated luminosity	0.003	0.003	0.007	0.007
SM W-helicity reference	0.004	0.003	0.001	0.002
total systematic uncertainty (w/o generator)	0.022	0.021	0.054	0.035
total systematic uncertainty	0.024	0.026	0.054	0.035

Combined

Systematic source	ΔF_L	ΔF_0
JES	0.007	0.007
JER	0.011	0.003
unclustered energy	0.018	0.010
pileup	0.002	0.002
b-flavored scale factor	0.003	0.001
non-b-flavored scale factor	0.001	0.002
single-top generator	0.005	0.009
Q^2 scale	0.006	0.008
m_{top}	0.001	0.001
PDF	0.003	0.003
$t\bar{t}$ normalization	0.003	0.002
QCD shape	0.003	0.003
W+jets shape	0.012	0.011
integrated luminosity	0.010	0.010
SM W-helicity reference	0.002	0.001
total systematic uncertainty	0.030	0.023

CMS-PAS-TOP-12-020

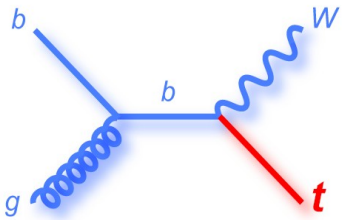


tW channel

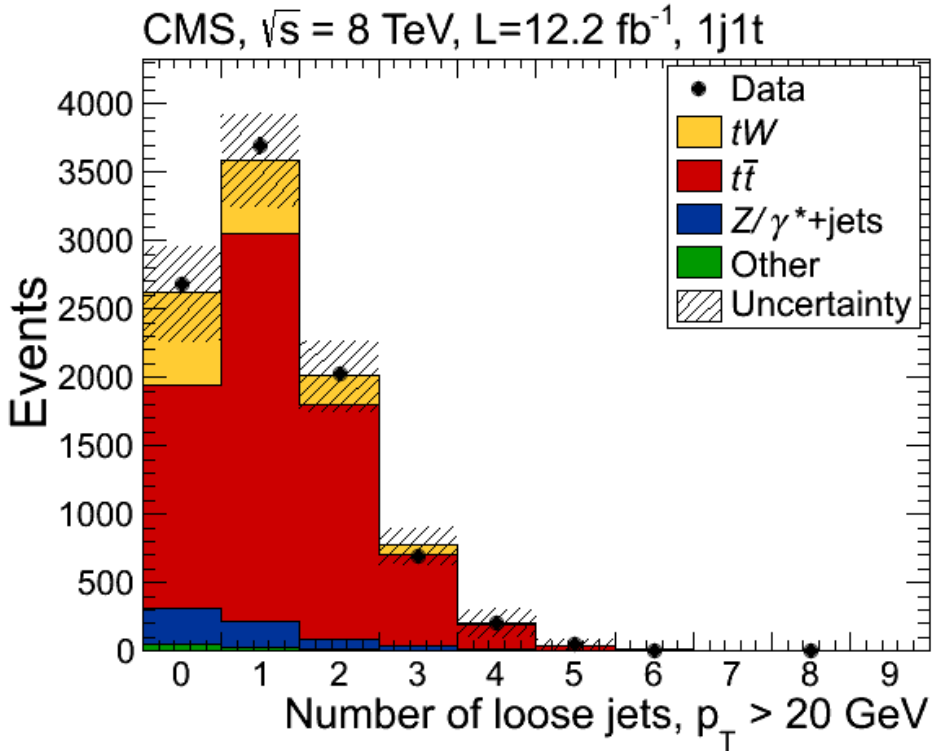
BDT input variables

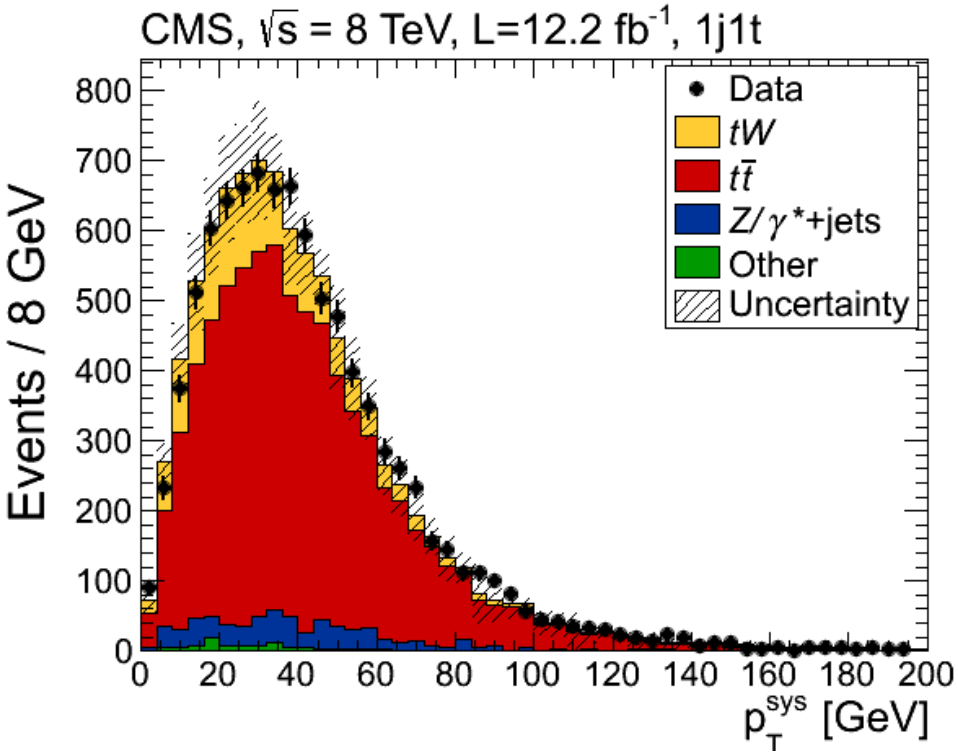
Variable Name	Description
# of loose jets	Number of loose jets, $p_{\mathrm{T}} > 20$ GeV, $\lvert\eta\rvert < 4.9$
# of central loose jets	Number of loose jets, $p_{\mathrm{T}} > 20$ GeV, $\lvert\eta\rvert < 2.4$
# of b-tagged loose jets	Number of loose jets, $p_{\mathrm{T}} > 20$ GeV, b-tagged, $\lvert\eta\rvert < 2.4$
$p_{\mathrm{T}}^{\mathrm{sys}}$	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 $E_{\mathrm{T}}^{\mathrm{miss}}$
$p_{\mathrm{T}}(jet)$	p_{T} of the leading, tight, b-tagged jet
$p_{\mathrm{T}}(loosejet)$	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 $E_{\mathrm{T}}^{\mathrm{miss}}$
Centrality(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

arXiv:1401.2942 (accepted for pub. in PRL)

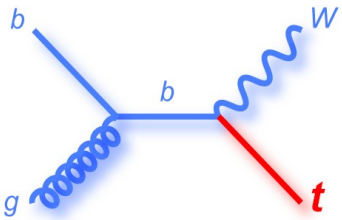


tW channel

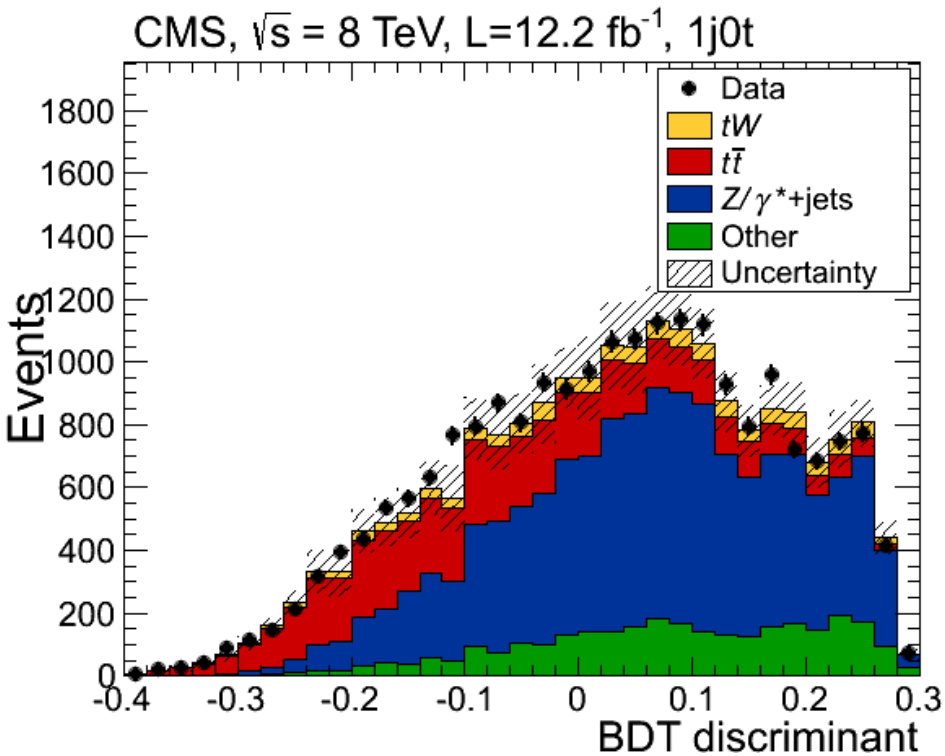


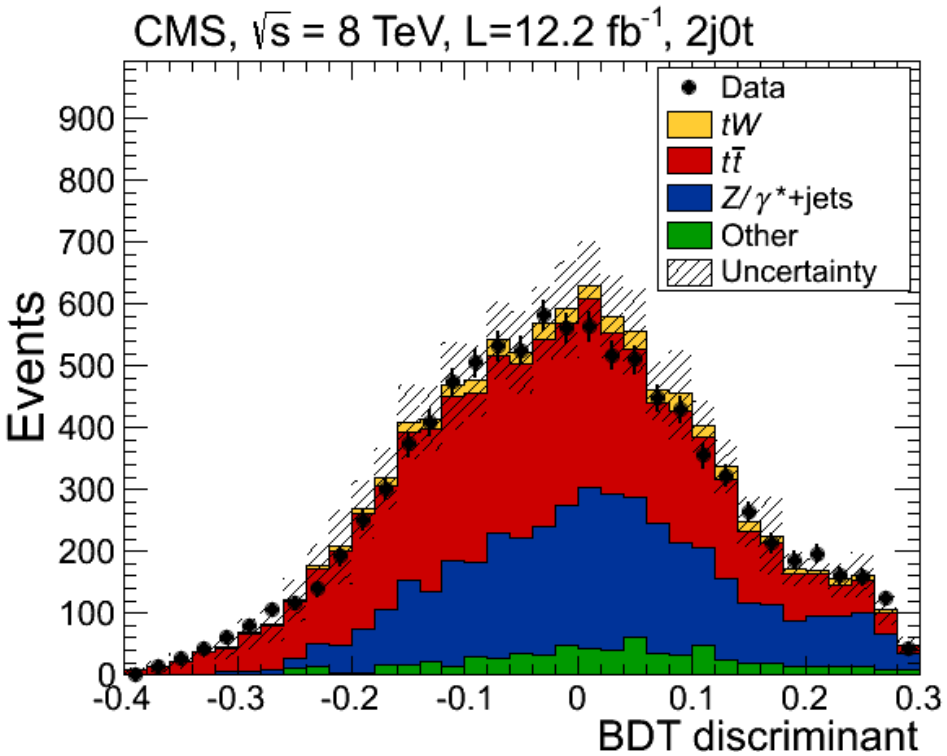


arXiv:1401.2942 (accepted for pub. in PRL)



tW channel





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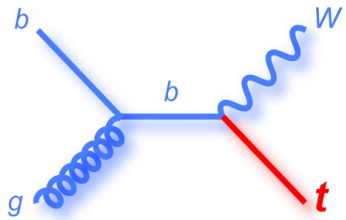
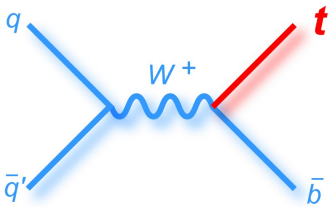


tW channel

Systematic Uncertainties

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

arXiv:1401.2942 (accepted for pub. in PRL)



s channel

Muon Channel

Variable	Description
p_T^{bb}	vector sum of p_T of the two b-tagged jets
$m_{\ell\nu b}$-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
$\not{E}_T$	missing transverse energy
$\Delta\Phi_{top,b'}$	difference in azimuthal angle between top 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

Input variables to BDT

Electron Channel

Variable	Description
m_T	tranverse W-boson mass
$\Delta\Phi_{top,b'}$	difference in azimuthal angle between top and recoiled b-tagged jet
$\not{E}_T$	missing transverse energy
$M_{\ell b2}$	invariant mass of the lepton and the second-to-leading b-tagged jet
$\cos\theta^*$	cosine of the angle between the lepton and the b-tagged jet recoiling against the top-quark, in the top rest frame
p_T^{bb}	vector sum of p_T of the two b-tagged jets
$\Delta R_{bb}(*)$	angular separation between the two b-tagged jets
p_T^{ℓ}	transverse momentum of the lepton
$m_{\ell\nu b}$-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
$\Delta R_{b'\ell}$	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

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

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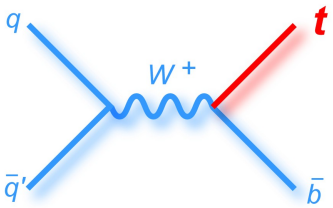

s channel

Cross Section

$$\sigma_{\text{s-ch.}} = 5.9 \pm 7.1(\text{exp.}) \pm 5.0(\text{th.})\ \text{pb} = 5.9 \pm 8.7\ \text{pb}\quad \text{muon channel}$$

$$\sigma_{\text{s-ch.}} = 6.9 \pm 5.6(\text{exp.}) \pm 6.5(\text{th.})\ \text{pb} = 6.9 \pm 8.7\ \text{pb}\quad \text{electron channel}$$

$$\sigma_{\text{s-ch.}} = 6.2 \pm 5.4(\text{exp.}) \pm 5.9(\text{th.})\ \text{pb} = 6.2 \pm 8.0\ \text{pb}\quad \text{combined}$$

Cross Section using Feldman-Cousins Approach

$$\sigma_{\text{s-ch.}} = 5.9^{+8.6}_{-5.1}\ \text{pb}\quad \text{muon channel}$$

$$\sigma_{\text{s-ch.}} = 6.9^{+8.7}_{-5.7}\ \text{pb}\quad \text{electron channel}$$

$$\sigma_{\text{s-ch.}} = 6.2^{+8.0}_{-5.1}\ \text{pb}\quad \text{combined}$$

Limits

Observed (expected with SM signal, expected with bkg. only) 95% CL upper limits

$\sigma_{\text{s-ch.}} < 12.4$ (18.4, 10.5) pb muon channel

$\sigma_{\text{s-ch.}} < 14.7$ (23.2, 15.4) pb electron channel

$\sigma_{\text{s-ch.}} < 11.5$ (17.0, 9.0) pb combined

Systematics: Largest systematic uncertainties come from factorization/ renormalization scale (83%), JES (53%), ME/PS matching (32%), unclustered MET (30%), and JER(24%)

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