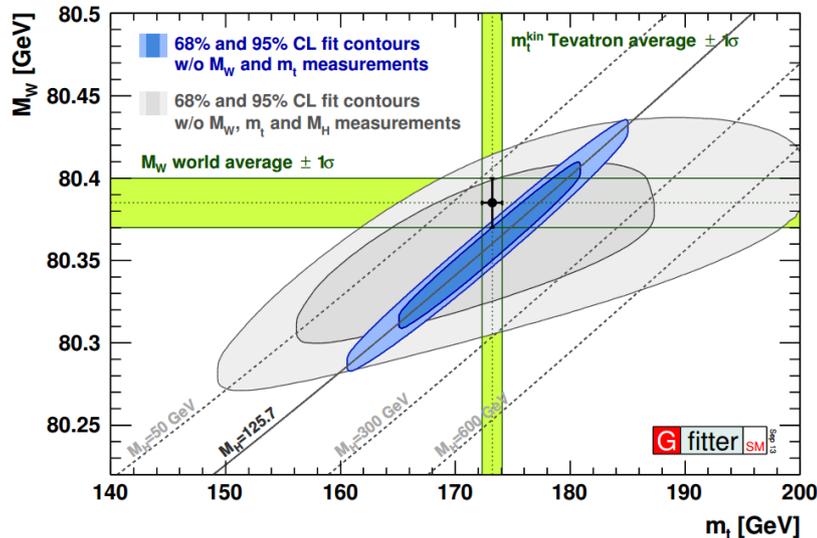
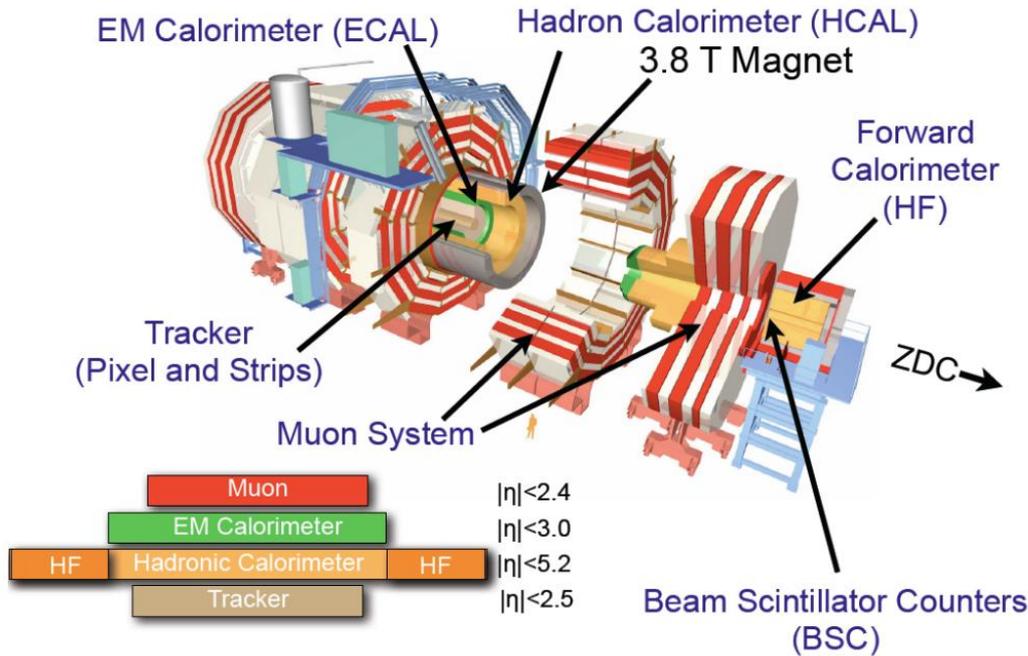


Top Physics at CMS

Igor Myagkov on behalf of CMS collaboration

- Introduction
- Top cross section
 - $t\bar{t}$, single top, $t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}b\bar{b}/t\bar{t}j$ ratio
- Top properties
 - Top mass, top-antitop mass difference, asymmetry, top polarization, W helicity, other
- Beyond the Standard Model
 - FCNC, anomalous Wtb

The CMS Detector



Igor Myagkov - Top Quark Physics at CMS, Protvino, June 2014

Integrated Luminosity:

2011 – 5 fb^{-1} at $\sqrt{s} = 7 \text{ TeV}$

2012 – 20 fb^{-1} at $\sqrt{s} = 8 \text{ TeV}$

2015 – new data taking
at $\sqrt{s} = 13 \text{ TeV}$

Top quark – heaviest SM particle
 $172.2 \pm 0.1(\text{stat.}) \pm 0.7(\text{syst.}) \text{ GeV}$ (CMS)

Yukawa coupling to the Higgs
field close to 1

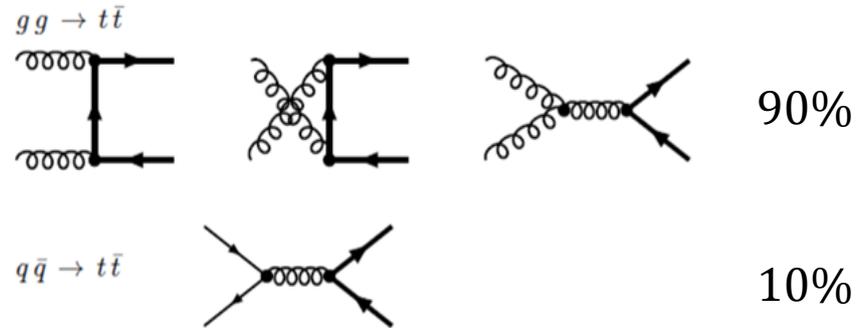
Top life time (10^{-25} s) is shorter
than the hadronization time scale
(10^{-24} s), and top quark provides a
unique possibility to study a “bare”
quark free from hadronization effects

LHC is a top quark factory
Top quark is unique and powerful
instrument to study SM physics and
search for manifestation of New Physics
beyond SM

Production Processes

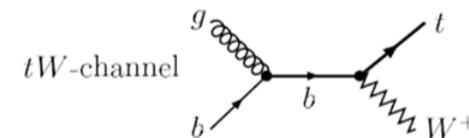
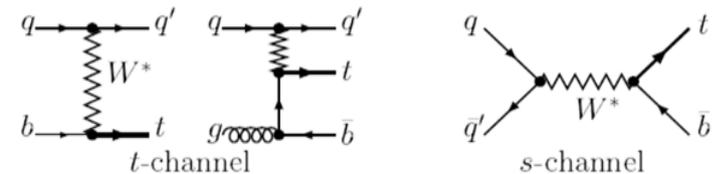
○ $t\bar{t}$ production (QCD)

	σ_{NLO} (pb)
Tevatron ($\sqrt{s} = 1.96$ TeV $p\bar{p}$)	$7.08 \pm 5\%$
LHC ($\sqrt{s} = 7$ TeV pp)	$165 \pm 6\%$
LHC ($\sqrt{s} = 8$ TeV pp)	$234 \pm 4\%$
LHC ($\sqrt{s} = 14$ TeV pp)	$920 \pm 5\%$



○ single top production (electro – weak)

	s -channel (pb)	t -channel (pb)	tW (pb)
Tevatron ($\sqrt{s} = 1.96$ TeV $p\bar{p}$)	$1.04 \pm 4\%$	$2.26 \pm 5\%$	$0.14 \pm 20\%$
LHC ($\sqrt{s} = 7$ TeV pp)	$4.6 \pm 5\%$	$64 \pm 4\%$	$15.6 \pm 8\%$
LHC ($\sqrt{s} = 8$ TeV pp)	$5.55 \pm 4\%$	$87.2^{+4}_{-3}\%$	$11.1 \pm 7\%$
LHC ($\sqrt{s} = 14$ TeV pp)	$12 \pm 6\%$	$243 \pm 4\%$	$75 \pm 10\%$



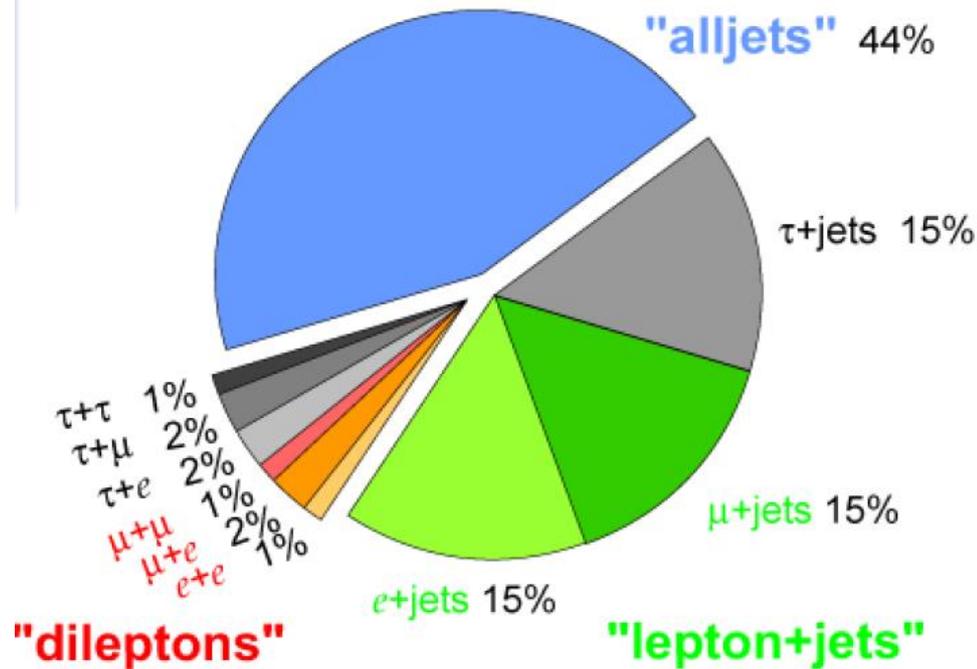
○ $t\bar{t}b\bar{b}$

○ $t\bar{t}H, t\bar{t}W^\pm, t\bar{t}Z, t\bar{t}\gamma \sim 0.1$ pb

○ t -quark production due to new interactions

Top Pair Analysis Channels

Top Pair Branching Fractions



- Dilepton

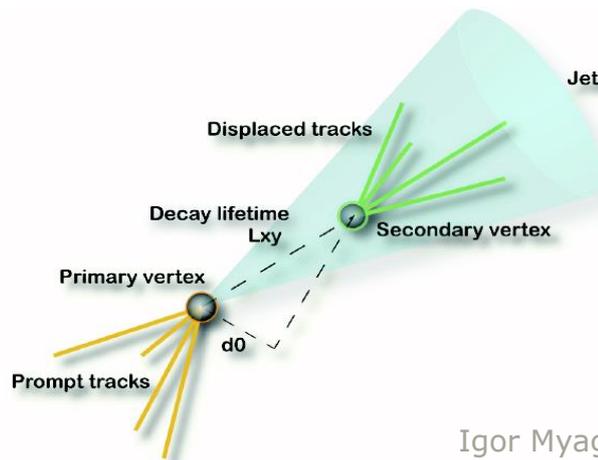
- Small rate, small backgrounds
- Main background: Drell-Yan

- Lepton + Jets

- Good rate and manageable backgrounds
- Main background: W+jets

- All-hadronic (alljets)

- Large rate, large background
- Main background: multijets



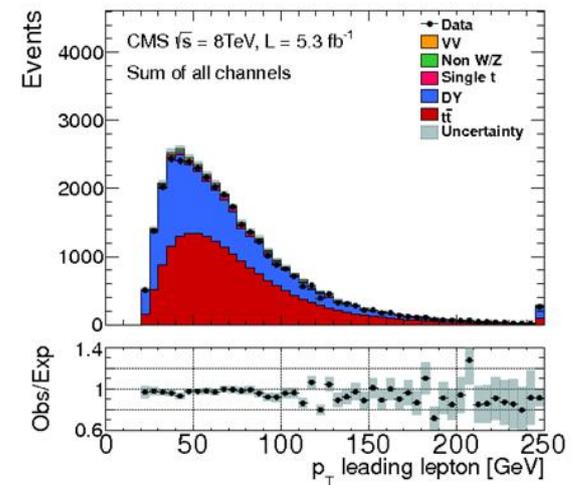
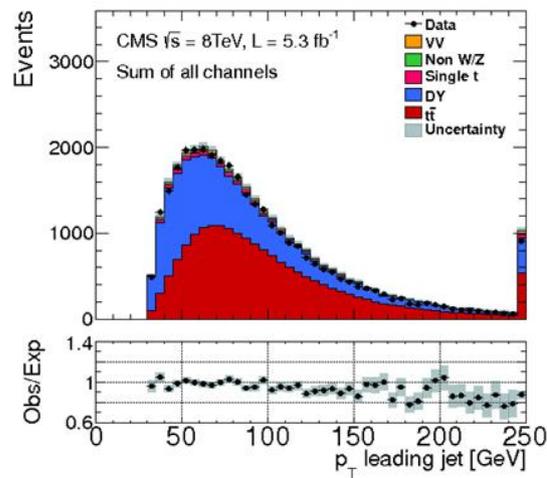
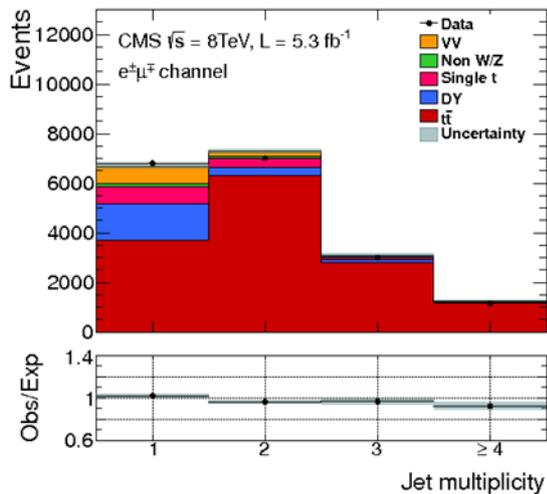
Identification of b-quarks through secondary vertex is a critical point to reduce backgrounds

Top pair production cross section in dilepton channel, pp collisions at $\sqrt{s} = 8\text{ TeV}$

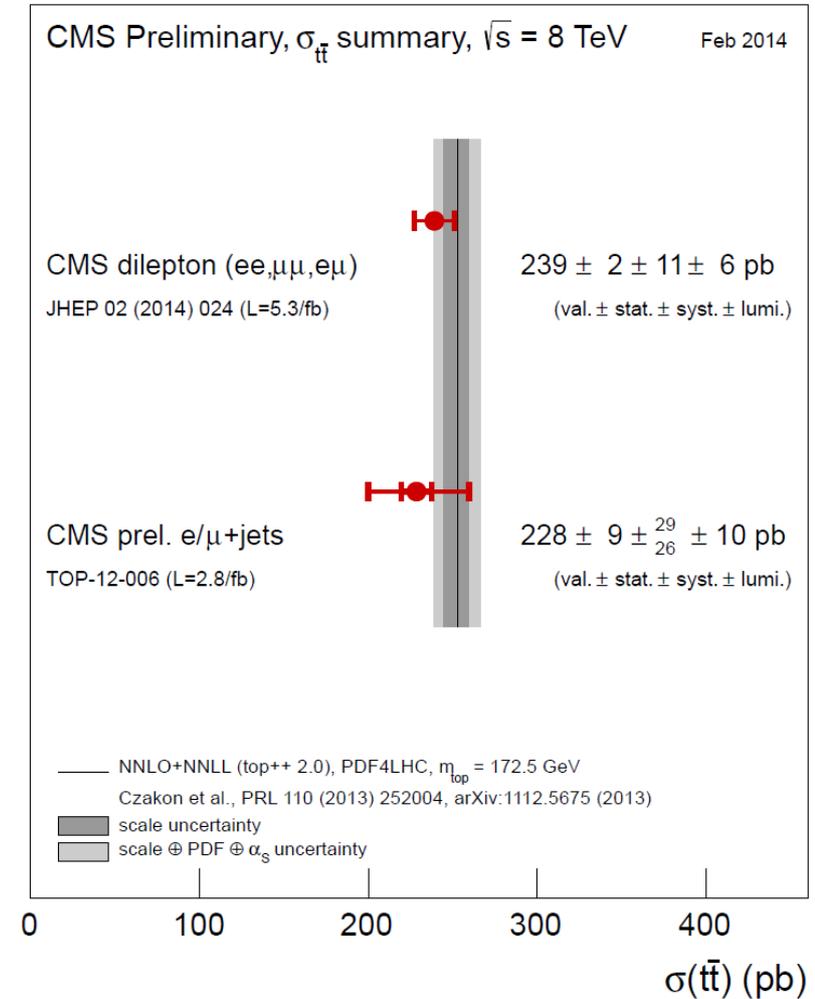
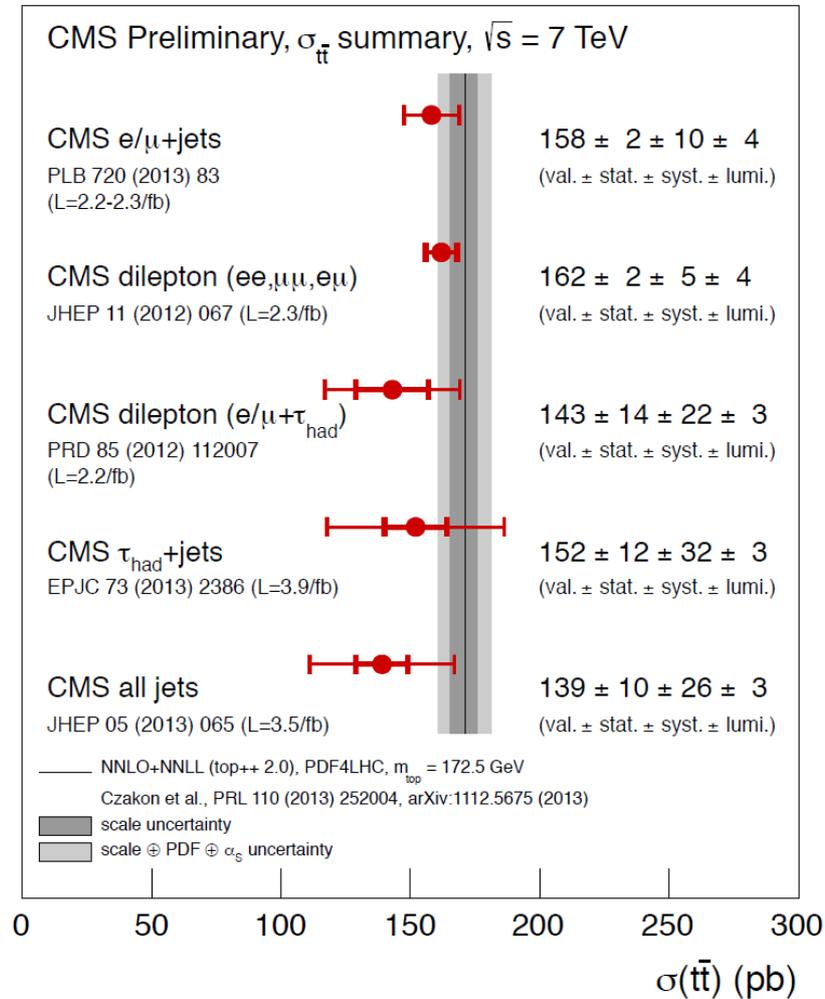
Source	Number of events		
	e^+e^-	$\mu^+\mu^-$	$e^\pm\mu^\mp$
Drell-Yan	386 ± 116	492 ± 148	194 ± 58
Non-W/Z leptons	25 ± 10	114 ± 46	185 ± 72
Single top quark	127 ± 28	157 ± 34	413 ± 88
VV	30 ± 8	39 ± 10	94 ± 21
Total background	569 ± 120	802 ± 159	886 ± 130
$t\bar{t}$ dilepton signal	2728 ± 182	3630 ± 250	9624 ± 504
Data	3204	4180	9982

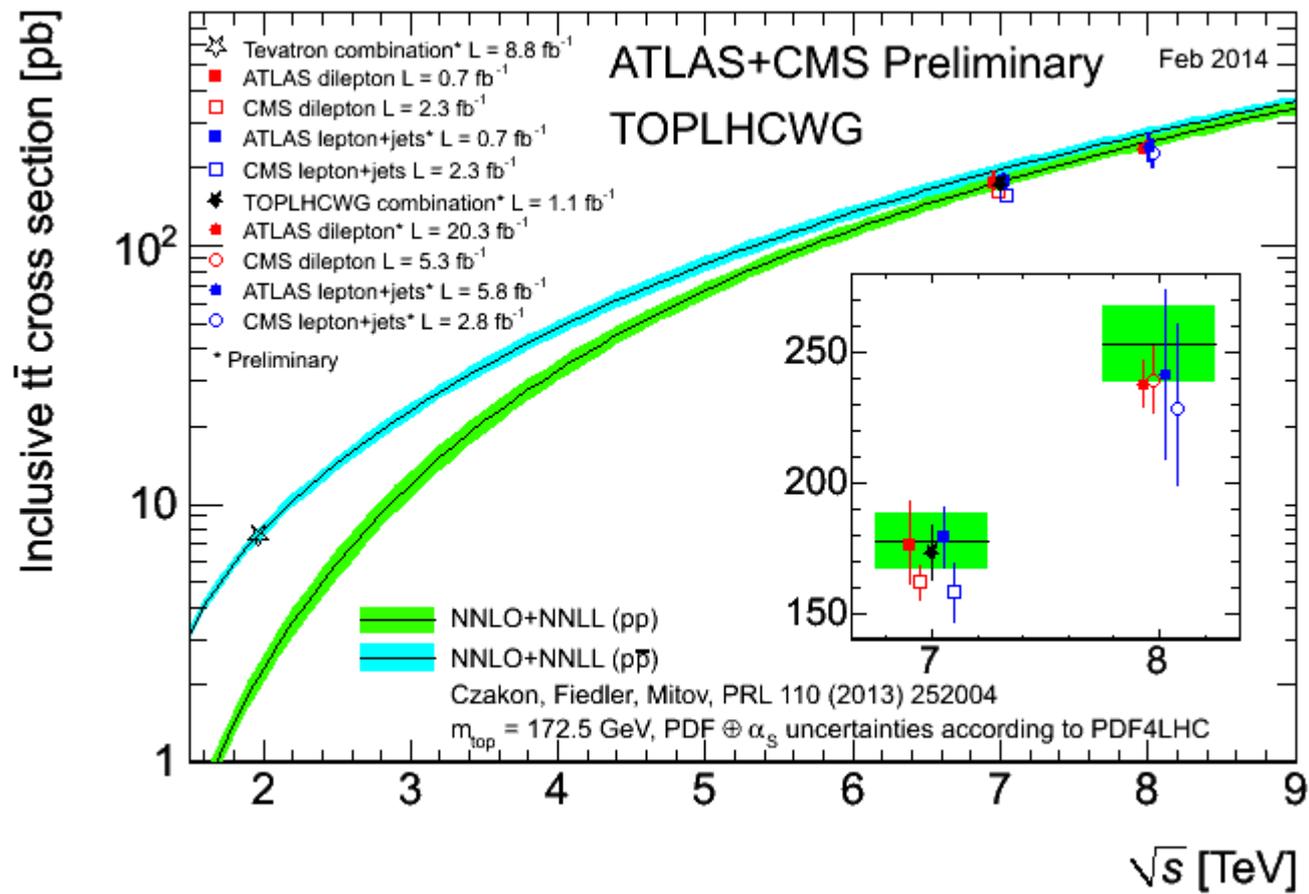
$\sigma = 239 \pm 2(\text{stat.}) \pm 11(\text{syst.}) \pm 6(\text{lum.}) \text{ pb}$

	e^+e^-	$\mu^+\mu^-$	$e^\pm\mu^\mp$
$\epsilon_{\text{total}} (\%)$	0.203 ± 0.012	0.270 ± 0.017	0.717 ± 0.033
$\sigma_{t\bar{t}} (\text{pb})$	$244.3 \pm 5.2 \pm 18.6 \pm 6.4$	$235.3 \pm 4.5 \pm 18.6 \pm 6.1$	$239.0 \pm 2.6 \pm 11.4 \pm 6.2$



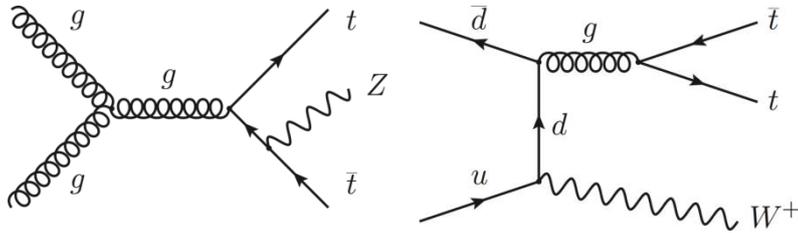
Top pair production cross section





Top pair production in association with a W or Z boson at $\sqrt{s} = 8 \text{ TeV}$

TOP-12-036

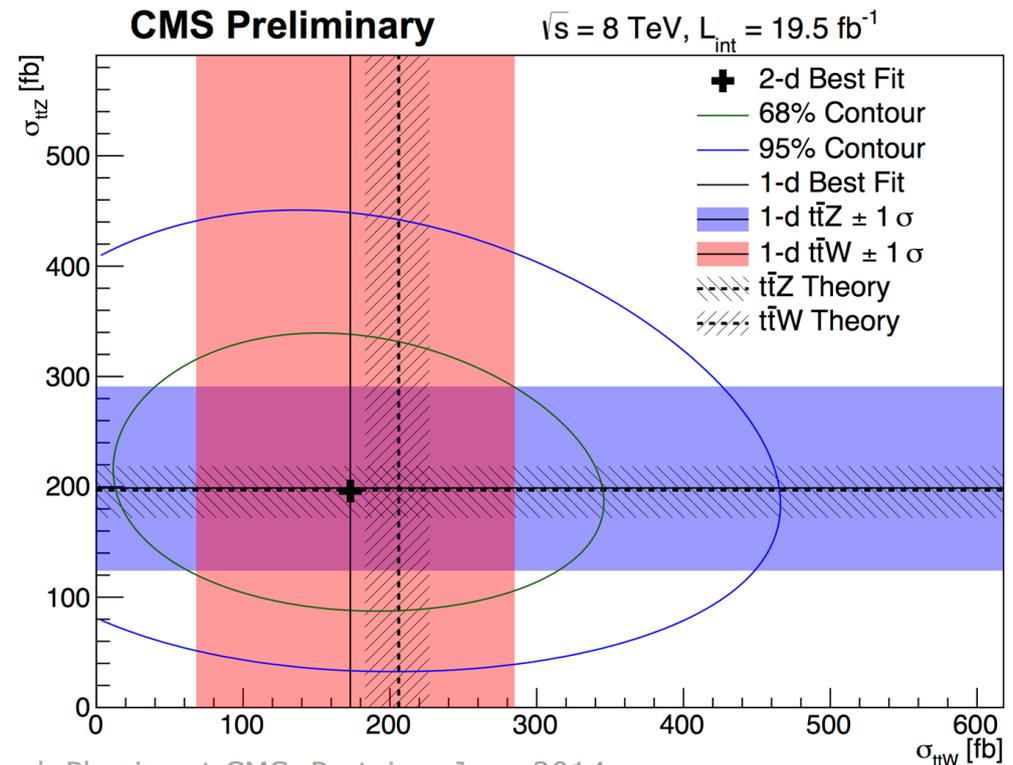


Channels used	Process	Cross section	Significance
2l	t \bar{t} W	170 $^{+90}_{-80}$ (stat.) $^{+70}_{-70}$ (syst.) fb	1.6 σ
3l+4l	t \bar{t} Z	200 $^{+80}_{-70}$ (stat.) $^{+40}_{-30}$ (syst.) fb	3.1 σ
2l+3l+4l	t \bar{t} W + t \bar{t} Z	380 $^{+100}_{-90}$ (stat.) $^{+80}_{-70}$ (syst.) fb	3.7 σ

Channels used	t \bar{t} W cross section	t \bar{t} Z cross section
2l+3l+4l	170 $^{+110}_{-100}$ (total) fb	200 $^{+90}_{-90}$ (total) fb

	Yield
Irreducible	0.8 \pm 0.4
t \bar{t} W	0.2 \pm 0.1
Non-top-quark	2.3 \pm 1.2
Misidentified lepton	1.1 \pm 0.8
Total bkg.	4.4 \pm 1.6
Observed	12
Obs. - total bkg.	7.6 \pm 1.6
t \bar{t} Z (expected)	7.8 \pm 0.9

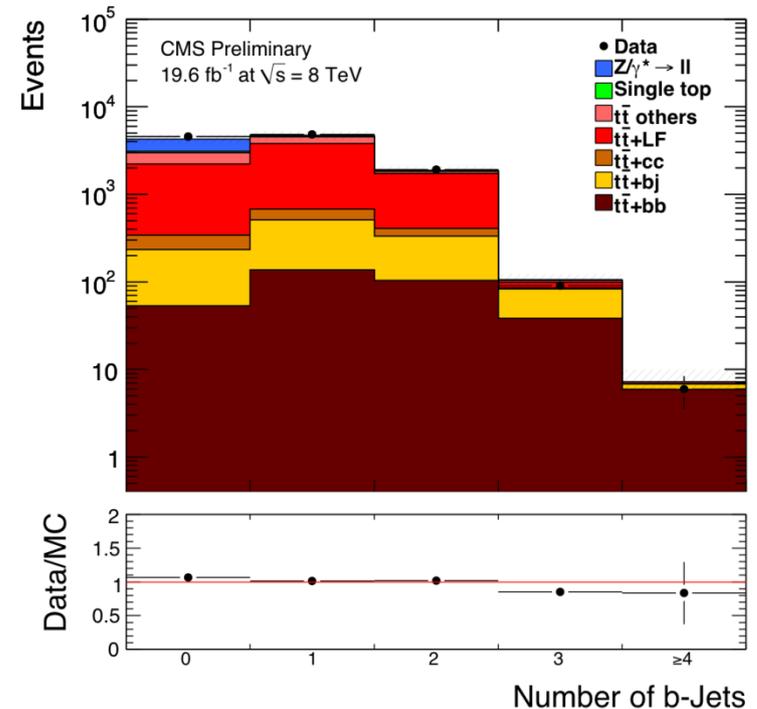
	Two b jets required	One b jet required
Misidentified lepton	0.1 \pm 0.1	0.5 \pm 0.2
ZZ	0.05 \pm 0.01	0.47 \pm 0.02
Irreducible	0.04 \pm 0.03	0.14 \pm 0.04
Total bkg.	0.2 \pm 0.1	1.1 \pm 0.2
Observed	2	2
Obs. - total bkg.	1.8 \pm 0.1	0.9 \pm 0.2
t \bar{t} Z (expected)	1.3 \pm 0.2	1.3 \pm 0.2



Cross section ratio $\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj)$ in pp collisions at $\sqrt{s} = 8 \text{ TeV}$

CMS PAS
TOP-13-010

Source	$\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj)$ (%)	$\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj)$ (%)
	Jet $p_T > 20 \text{ GeV}/c$	Jet $p_T > 40 \text{ GeV}/c$
Pile-up	1.1	2.1
JES	5.1	7.5
b-tag (heavy flavor)	10.4	11.2
b-tag (light flavor)	14.8	12.6
Background (Drell-yan)	0.8	1.0
Background (multi-jets)	0.1	0.1
Background (single-top)	0.7	0.8
Ratio of $t\bar{t}b\bar{b}$ and $t\bar{t}bj$	9.0	9.0
$t\bar{t}c\bar{c}$ contribution	4.3	5.3
MC gen. (MadGraph vs Powheg)	3.0	3.0
Q^2 scale	6.0	6.0
PS matching	3.0	3.0
Acceptance (HF fraction)	1.6	1.6
Total uncertainty	22.6	22.6



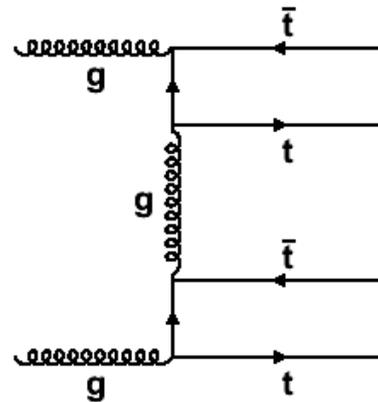
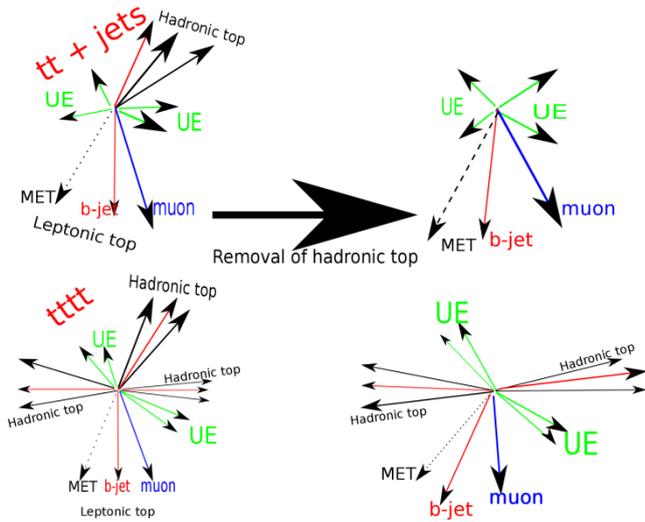
$$\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj) = 0.023 \pm 0.003(stat.) \pm \pm 0.005(syst.) \text{ at } 20 \text{ GeV}$$

$$\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj) = 0.022 \pm 0.004(stat.) \pm \pm 0.005(syst.) \text{ at } 40 \text{ GeV}$$

Process	Jet $p_T > 20 \text{ GeV}$		Jet $p_T > 40 \text{ GeV}$	
$\sigma_{t\bar{t}b\bar{b}}$ [fb] (VS)	278 ± 27 (stat.)	± 72 (syst.)	58.9 ± 12.3 (stat.)	± 15.3 (syst.)
$\sigma_{t\bar{t}jj}$ [pb] (VS)	12.2 ± 0.3 (stat.)	± 1.2 (syst.)	2.7 ± 0.1 (stat.)	± 0.3 (syst.)
$\sigma_{t\bar{t}b\bar{b}}$ [fb] (FS)	460 ± 45 (stat.)	± 120 (syst.)	159 ± 33 (stat.)	± 41 (syst.)
$\sigma_{t\bar{t}jj}$ [pb] (FS)	19.2 ± 0.5 (stat.)	± 1.9 (syst.)	6.9 ± 0.3 (stat.)	± 0.7 (syst.)

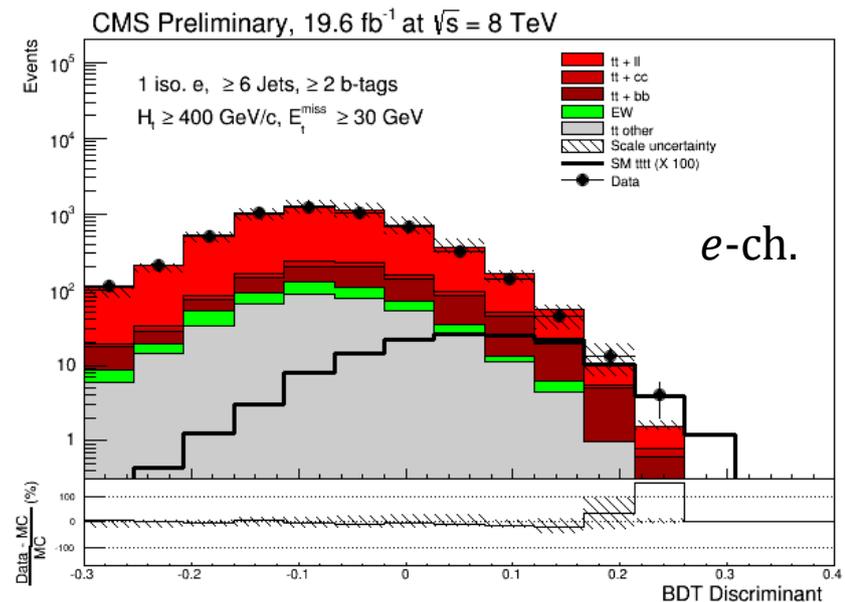
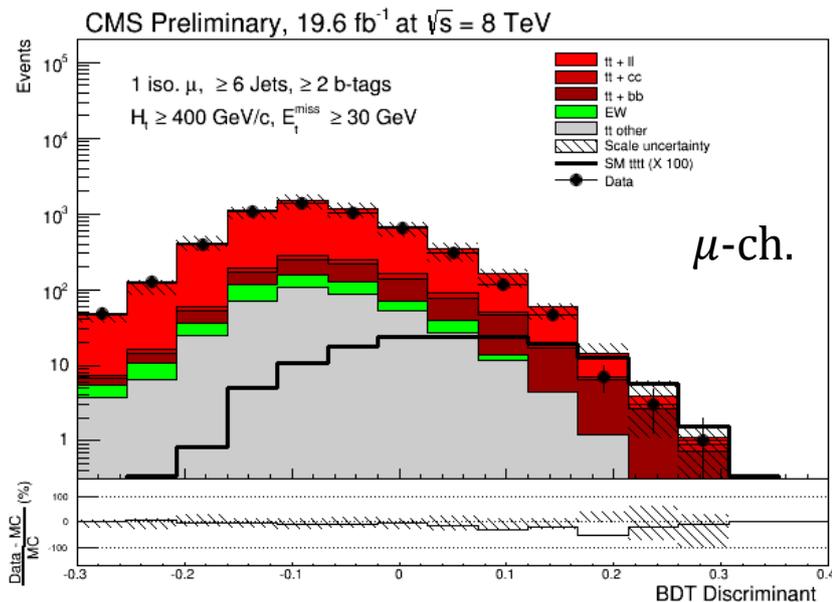
Standard model four top quark production at $\sqrt{s} = 8 \text{ TeV}$ in the lepton + jets channel

CMS PAS
TOP-13-012

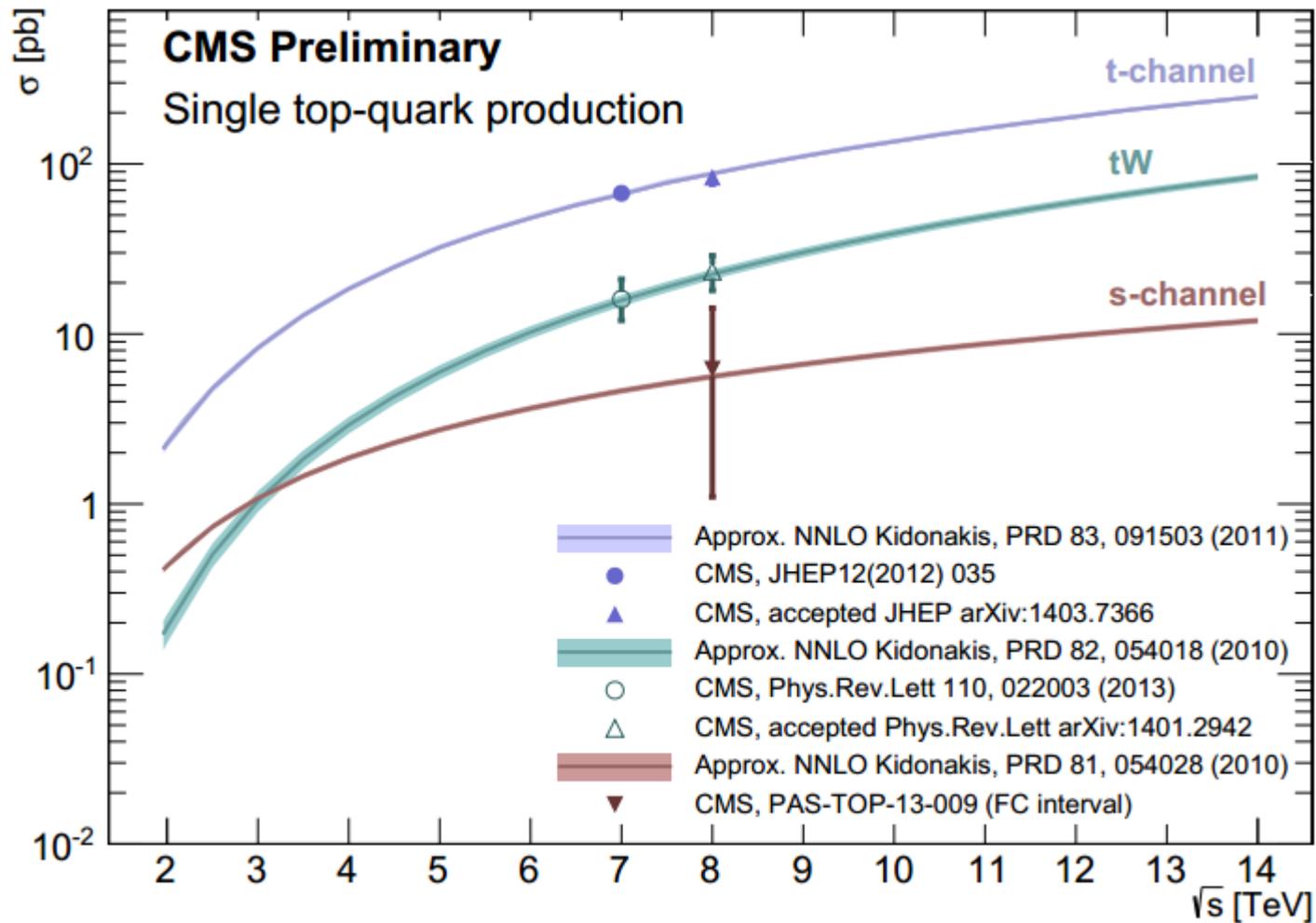


Expected upper limits:
 $42^{+18}_{-13} \text{ fb at 95\% CL}$

Observed:
 $\sigma < 63 \text{ fb at 95\% CL}$



Single Top

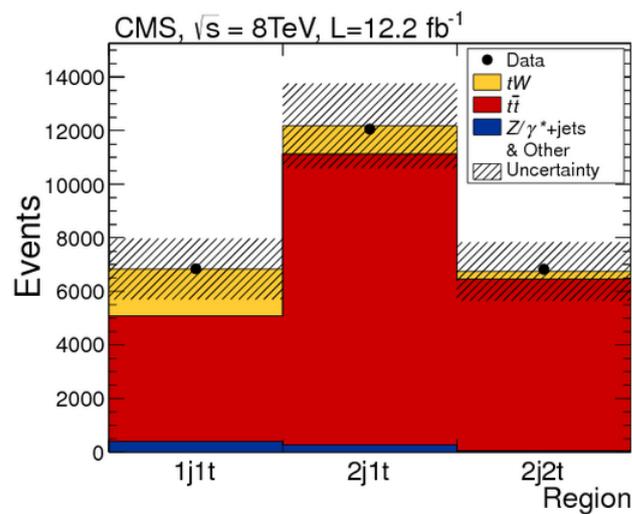
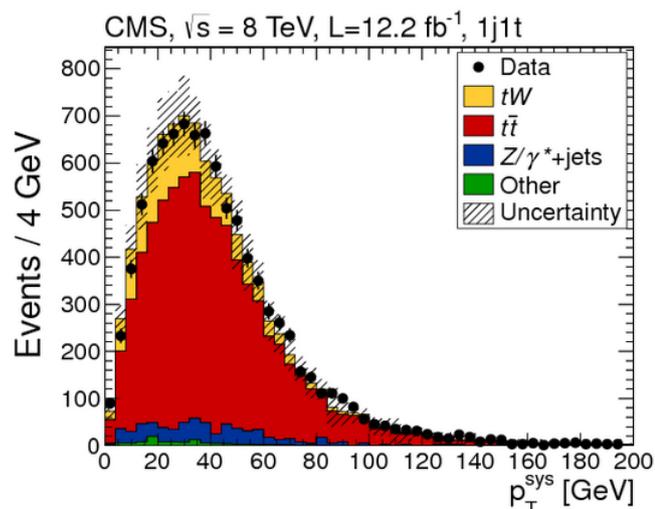


Observation of the associated production of a single top quark and a W boson in pp collisions at $\sqrt{s} = 8 \text{ TeV}$

[Phys. Rev. Lett. 112 \(2014\) 231802](#)

	1j1t	2j1t	2j2t
tW	$1500 \pm 20 \pm 130$	$790 \pm 20 \pm 80$	$220 \pm 10 \pm 30$
$t\bar{t}$	$7090 \pm 60 \pm 900$	$12910 \pm 80 \pm 1320$	$7650 \pm 60 \pm 1020$
Z/γ^* , other	$670 \pm 30 \pm 90$	$370 \pm 30 \pm 60$	$36 \pm 7 \pm 12$
Total simulation	$9260 \pm 70 \pm 1040$	$14070 \pm 90 \pm 1410$	$7910 \pm 70 \pm 1020$
Data	9353	13479	7615

TABLE I. Event yields in the signal and control regions. Yields from simulation are shown with statistical (first) and systematic (second) uncertainties.



Measured:

$$\sigma = 23.4 \pm 5.4 \text{ pb}$$

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

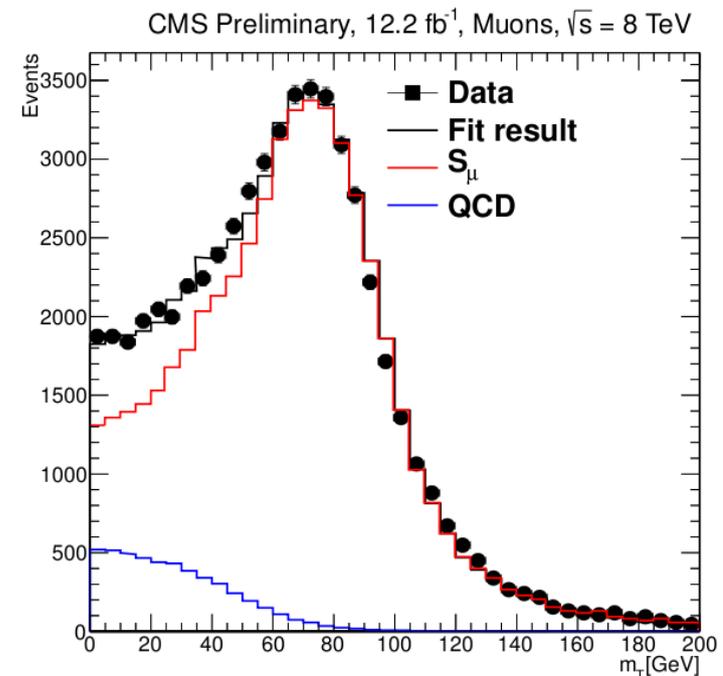
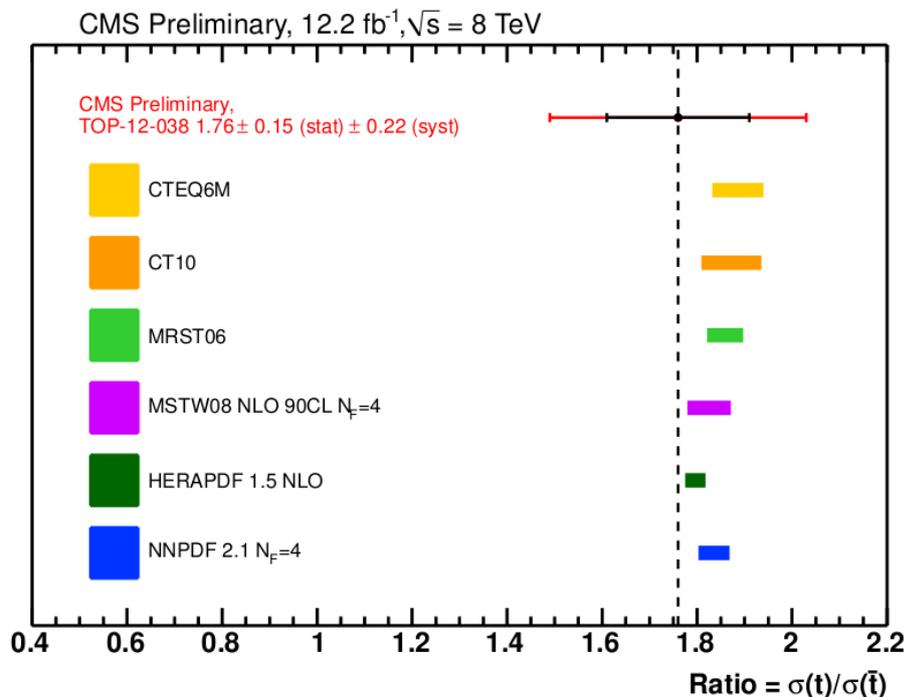
t-channel single-top production cross section and $|V_{tb}|$ CKM matrix element in pp collisions at $\sqrt{s} = 8 \text{ TeV}$

[arXiv:1403.7366](https://arxiv.org/abs/1403.7366)
Accepted by JHEP

$$\sigma(\text{t-channel, top, } 8 \text{ TeV}) = 49.9 \pm 1.9(\text{stat.}) \pm 8.9(\text{syst.}) \text{ pb}$$

$$\sigma(\text{t-channel, anti-top, } 8 \text{ TeV}) = 28.8 \pm 2.4(\text{stat.}) \pm 4.9(\text{syst.}) \text{ pb}$$

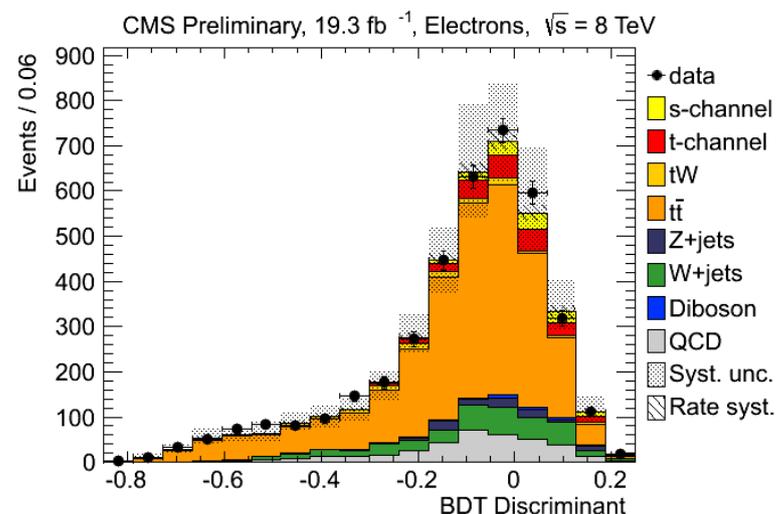
$$|R_{t\text{-channel}}| = 1.76 \pm 0.15(\text{stat.}) \pm 0.22(\text{syst.})$$



Search for single-top production in the s channel at $\sqrt{s} = 8 \text{ TeV}$

CMS PAS
TOP-13-009

Process	μ 3-jets 2-tags	μ 2-jets 2-tags	e 3-jets 2-tags	e 2-jets 2-tags
$t\bar{t}$	10043 ± 604	3144 ± 189	8010 ± 494	2483 ± 154
$W + jets$	446 ± 92	449 ± 93	370 ± 76	361 ± 77
$Z + jets$	112 ± 32	65 ± 20	97 ± 29	89 ± 27
Diboson	36 ± 8	45 ± 10	33 ± 7	37 ± 8
QCD	353 ± 74	209 ± 52	222 ± 19	363 ± 69
tW-channel	336 ± 28	102 ± 11	259 ± 22	105 ± 11
t-channel	949 ± 61	271 ± 18	750 ± 49	217 ± 15
s-channel	87 ± 5	168 ± 10	70 ± 4	131 ± 8
Total MC	12361 ± 750	4455 ± 286	9811 ± 606	3786 ± 253
Data	11979	4450	10149	3884



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

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

$$\sigma_{s\text{-ch.}} = 6.2 \pm 5.4(\text{exp.}) \pm 5.9(\text{th.}) \text{ pb} = 6.2 \pm 8.0 \text{ pb} \text{ combined} \quad 0.7\sigma$$

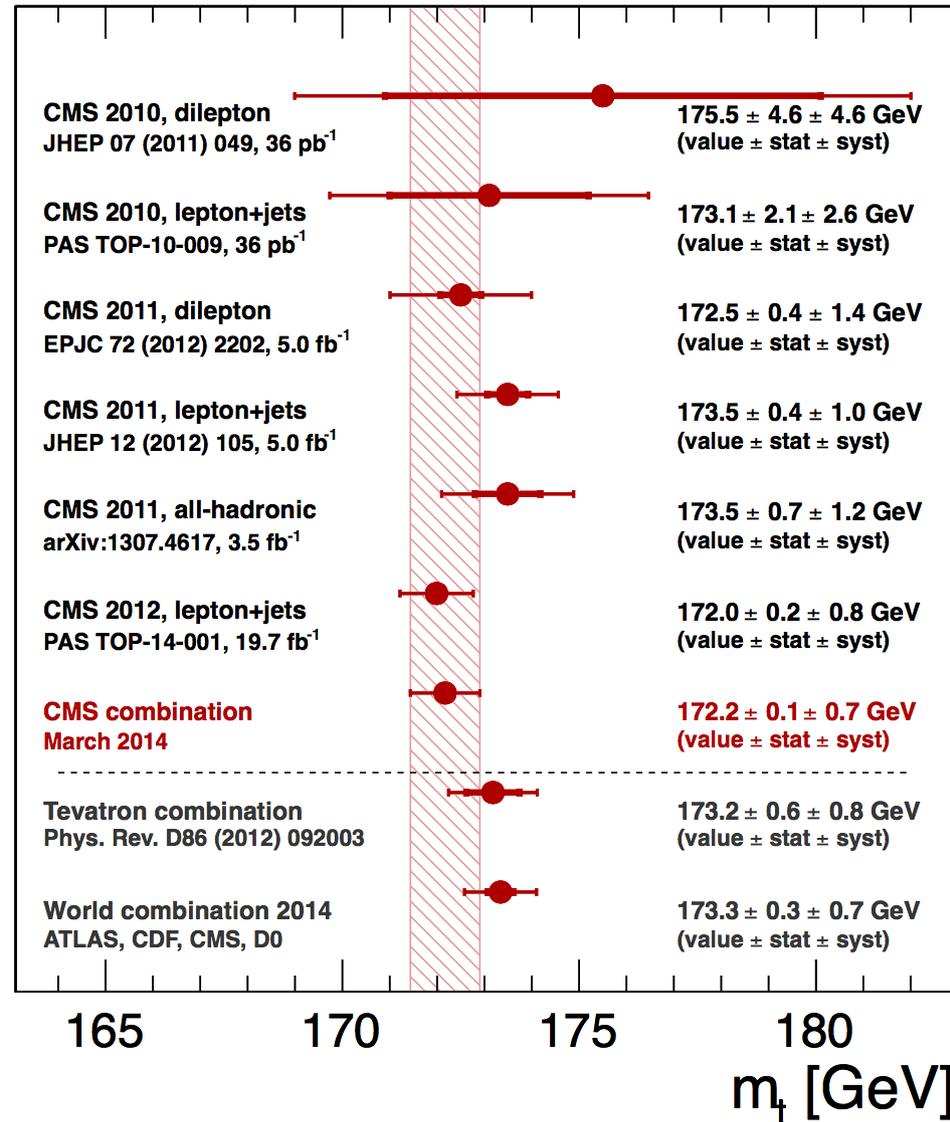
$$\sigma_{s\text{-ch.}} < 12.4 \quad (18.4, 10.5) \text{ pb} \text{ muon channel}$$

$$\sigma_{s\text{-ch.}} < 14.7 \quad (23.2, 15.4) \text{ pb} \text{ electron channel} \quad \textit{at 95\% C.L.}$$

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

Top mass

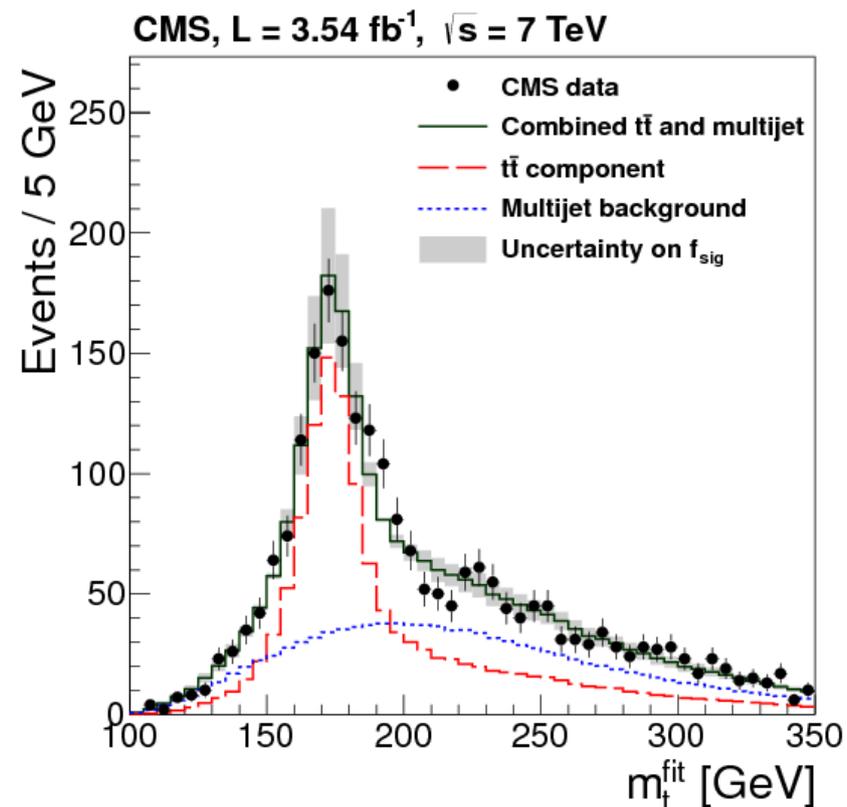
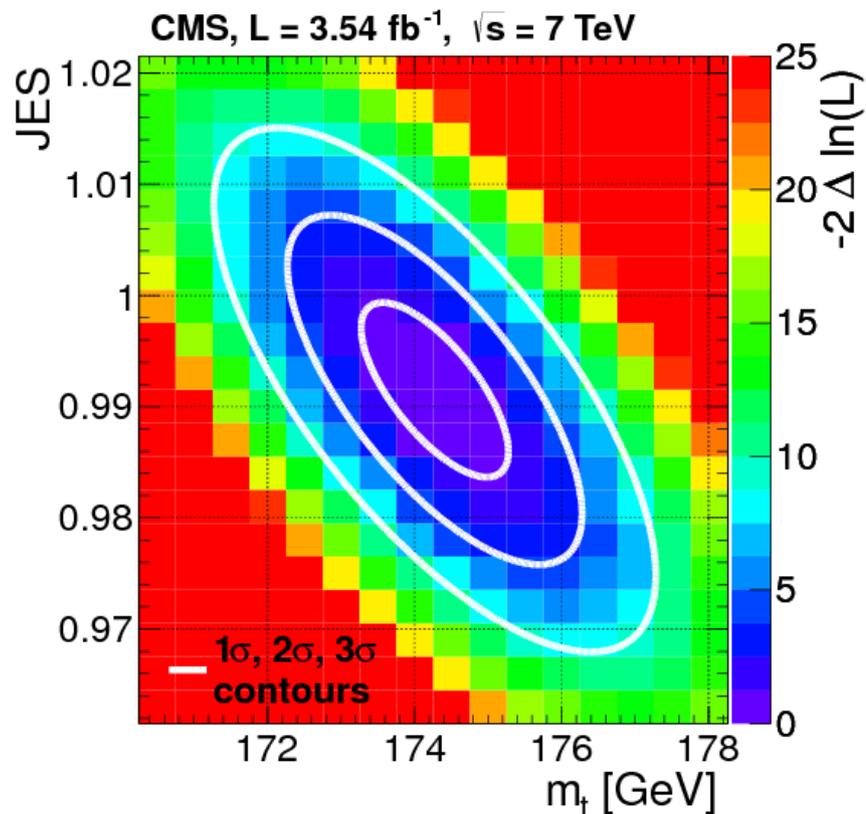
CMS Preliminary



Measurement of the top-quark mass in all-jets events in pp collisions at $\sqrt{s} = 7 \text{ TeV}$

Eur. Phys. J. C74
(2014) 2758

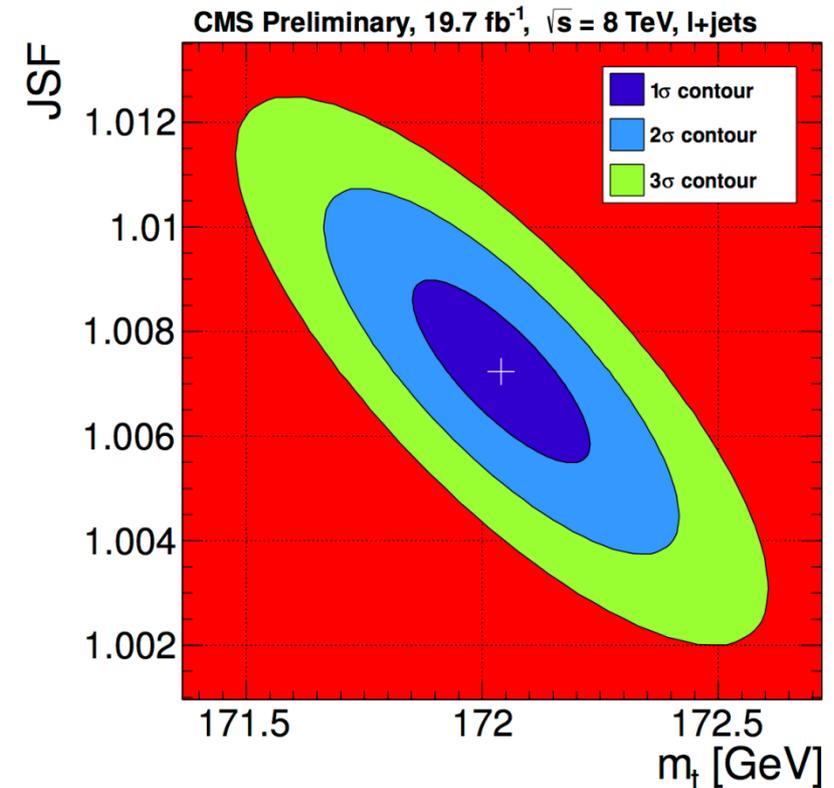
Measured: $173.49 \pm 0.69(\text{stat.}) \pm 1.21(\text{syst.}) \text{ GeV}$
Combination: $173.54 \pm 0.33(\text{stat.}) \pm 0.96(\text{syst.}) \text{ GeV}$



Measurement of the top-quark mass in $t\bar{t}$ events with lepton+jets final states in pp collisions at $\sqrt{s} = 8 \text{ TeV}$

CMS PAS
TOP-14-001

	δm_t^{2D} (GeV)	δJSF	δm_t^{1D} (GeV)
Experimental uncertainties			
Fit calibration	0.10	0.001	0.06
p_T - and η -dependent JES	0.18	0.007	1.17
Lepton energy scale	0.03	<0.001	0.03
MET	0.09	0.001	0.01
Jet energy resolution	0.26	0.004	0.07
b tagging	0.02	<0.001	0.01
Pileup	0.27	0.005	0.17
Non- $t\bar{t}$ background	0.11	0.001	0.01
Modeling of hadronization			
Flavor-dependent JSF	0.41	0.004	0.32
b fragmentation	0.06	0.001	0.04
Semi-leptonic B hadron decays	0.16	<0.001	0.15
Modeling of the hard scattering process			
PDF	0.09	0.001	0.05
Renormalization and factorization scales	0.12 ± 0.13	0.004 ± 0.001	0.25 ± 0.08
ME-PS matching threshold	0.15 ± 0.13	0.003 ± 0.001	0.07 ± 0.08
ME generator	0.23 ± 0.14	0.003 ± 0.001	0.20 ± 0.08
Modeling of non-perturbative QCD			
Underlying event	0.14 ± 0.17	0.002 ± 0.002	0.06 ± 0.10
Color reconnection modeling	0.08 ± 0.15	0.002 ± 0.001	0.07 ± 0.09
Total	0.75	0.012	1.29



$$m_t = 172.04 \pm 0.19 \text{ (stat.+JSF)} \pm 0.75 \text{ (syst.) GeV,}$$

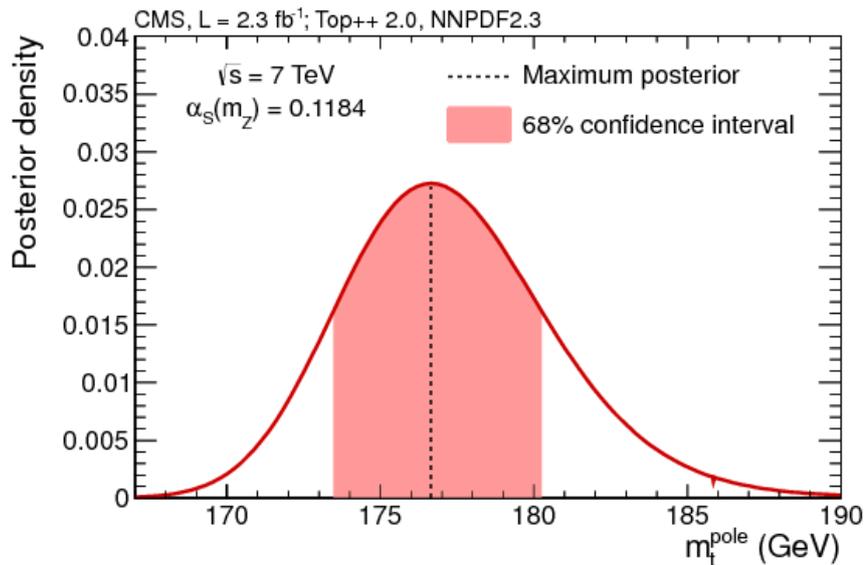
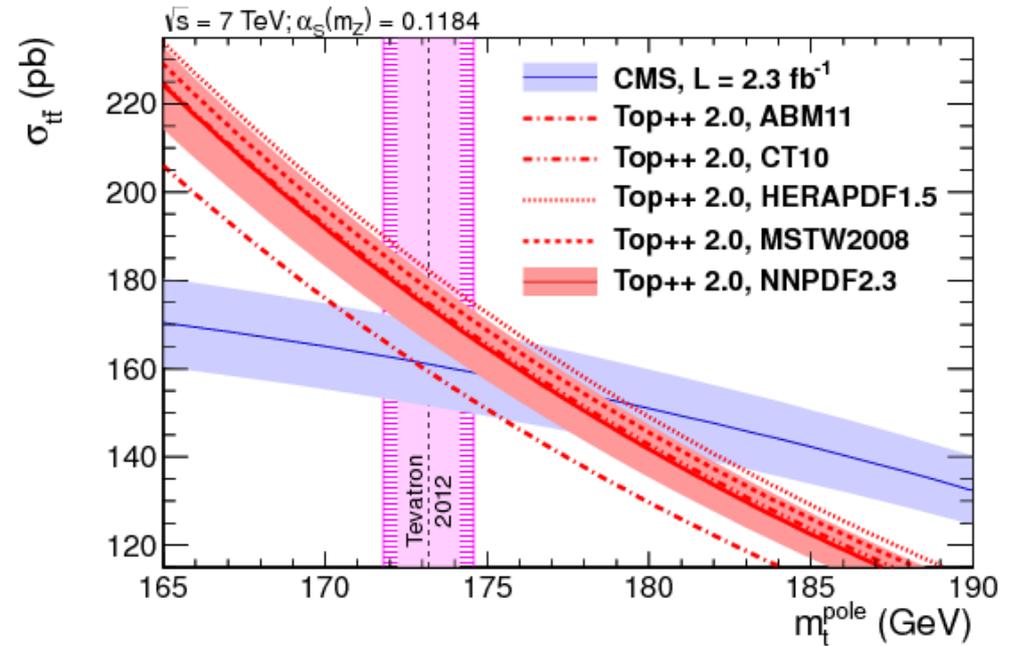
$$\text{JSF} = 1.007 \pm 0.002 \text{ (stat.)} \pm 0.012 \text{ (syst.)}$$

Top-quark pole mass and strong coupling constant from the $t\bar{t}$ production cross section in pp collisions at $\sqrt{s} = 7 \text{ TeV}$

[Phys. Lett. B 728 \(2013\) 496](#)

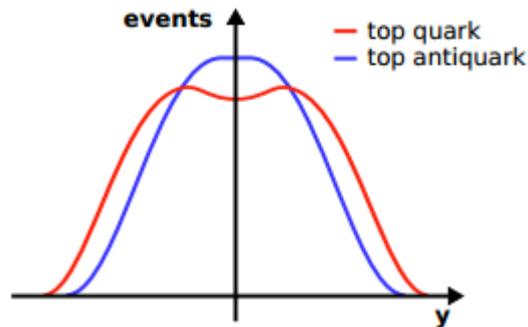
$$m_t^{\text{pole}} = 176.7^{+3.8}_{-3.4} \text{ GeV}$$

$$\alpha_S(m_Z) = 0.1151^{+0.0033}_{-0.0032}$$



Top charge asymmetry

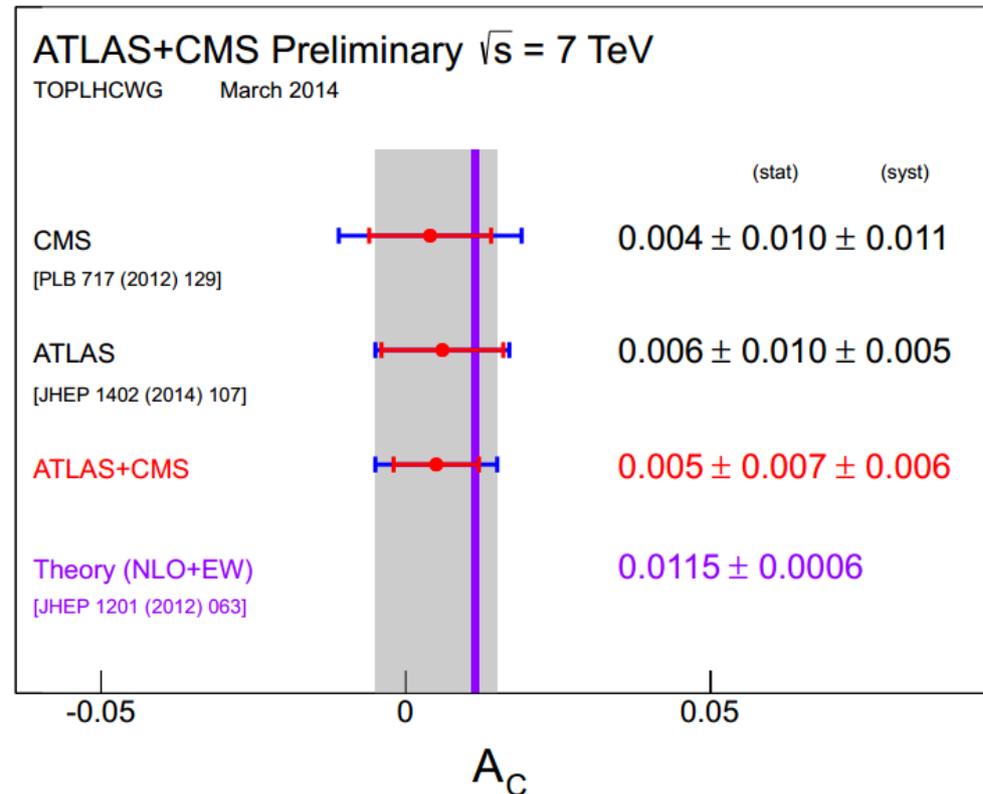
JHEP 04 (2014) 191
CMS PAS TOP-14-006



$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

$$A_C^{\text{lep}} = \frac{N(\Delta|\eta_\ell| > 0) - N(\Delta|\eta_\ell| < 0)}{N(\Delta|\eta_\ell| > 0) + N(\Delta|\eta_\ell| < 0)}$$

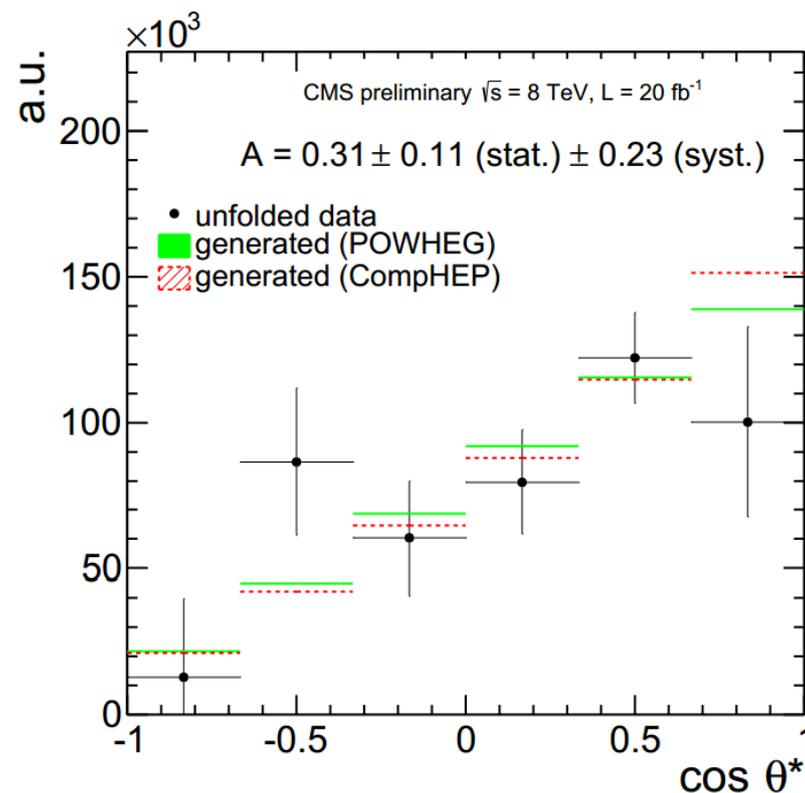
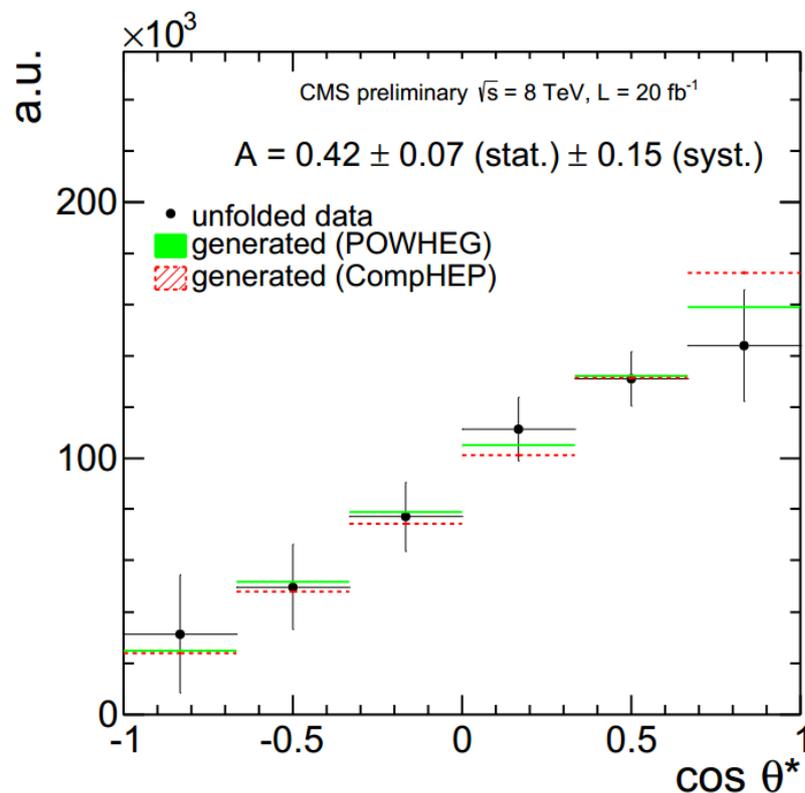
$$\Delta|y| \equiv |y_t| - |y_{\bar{t}}| \quad \Delta|\eta_\ell| = |\eta_{e^+}| - |\eta_{e^-}|$$



Variable	Data (unfolded)	MC@NLO prediction	NLO theory
A_C	$-0.010 \pm 0.017 \pm 0.008$	0.004 ± 0.001	0.0123 ± 0.0005
A_C^{lep}	$0.009 \pm 0.010 \pm 0.006$	0.004 ± 0.001	0.0070 ± 0.0003

Measurement of top-quark polarization in t-channel single-top production

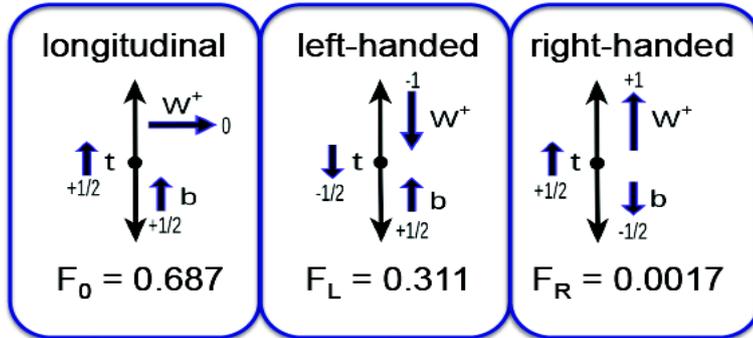
$$A_l \equiv \frac{1}{2} \cdot P_t \cdot \alpha_l = \frac{N(\uparrow) - N(\downarrow)}{N(\uparrow) + N(\downarrow)} \quad \frac{d\Gamma}{d \cos \theta_X} = \frac{\Gamma}{2} (1 + P_t \alpha_X \cos \theta_X) \equiv \Gamma \left(\frac{1}{2} + A_X \cos \theta_X \right)$$



$$A_l = 0.41 \pm 0.06 \text{ (stat.)} \pm 0.16 \text{ (syst.)} = 0.41 \pm 0.17$$

Measurement of the W-boson helicity in top-quark decays in pp collisions at $\sqrt{s}=7$ TeV

[JHEP 10 \(2013\) 167](#)



Agreement of helicity fractions with SM



Constraints on new physics contributions to Wtb vertex

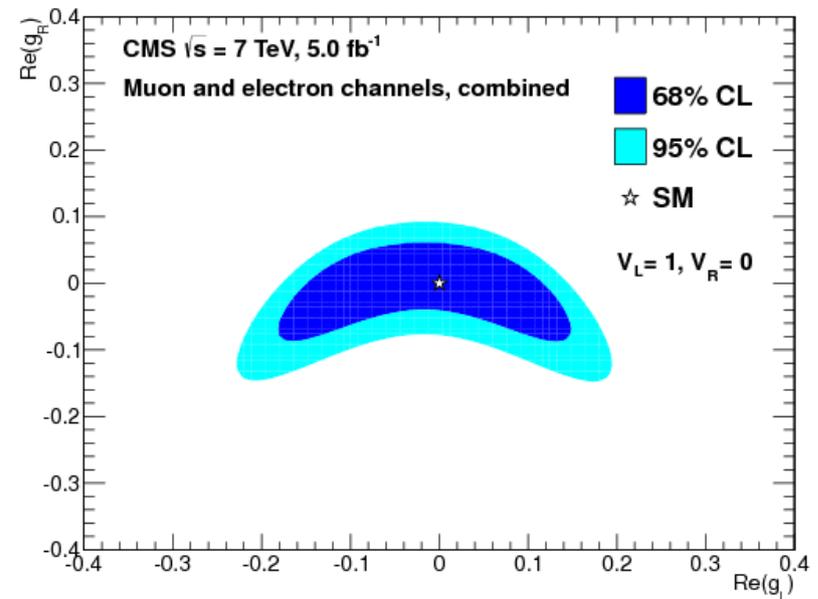
$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}} \bar{b} \gamma^\mu (V_L P_L + V_R P_R) t W_\mu^- - \frac{g}{\sqrt{2}} \bar{b} \frac{i\sigma^{\mu\nu} q_\nu}{M_W} (g_L P_L + g_R P_R) t W_\mu^- + \text{h.c.}$$

$V_{tb} = 1$ (pointing to V_L) $= 0$ in SM (pointing to V_R)

$$F_0 = 0.682 \pm 0.030 \text{ (stat.)} \pm 0.033 \text{ (syst.)}$$

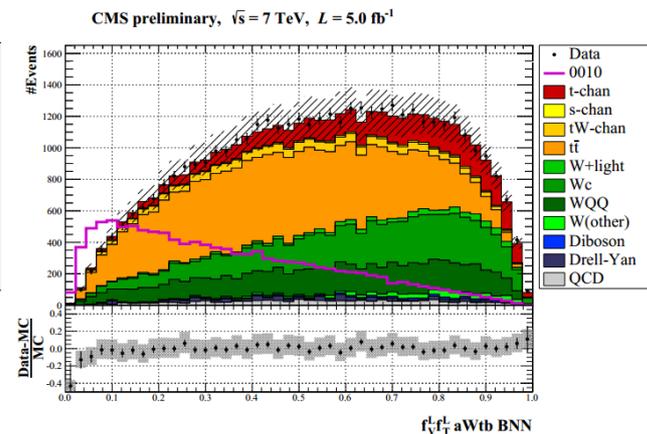
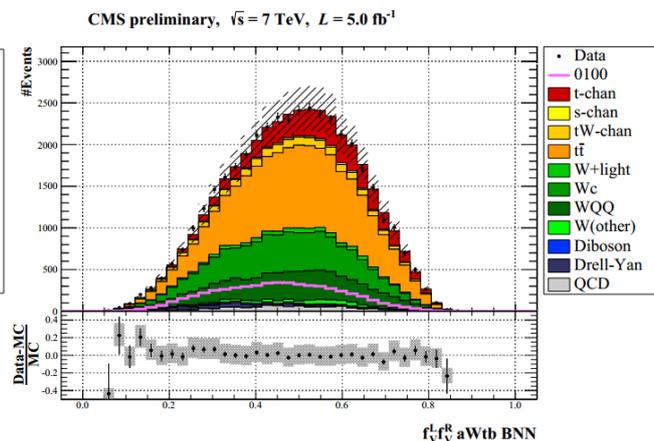
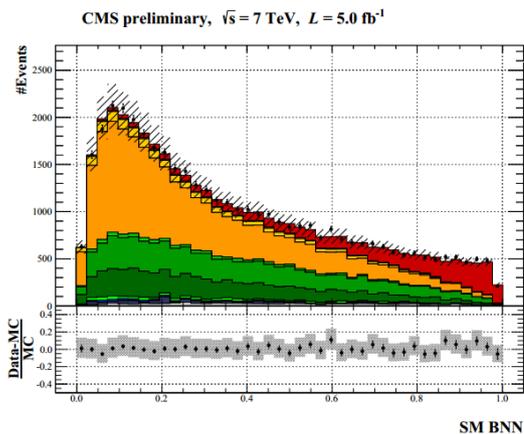
$$F_L = 0.310 \pm 0.022 \text{ (stat.)} \pm 0.022 \text{ (syst.)}$$

$$F_R = 0.008 \pm 0.012 \text{ (stat.)} \pm 0.014 \text{ (syst.)}$$



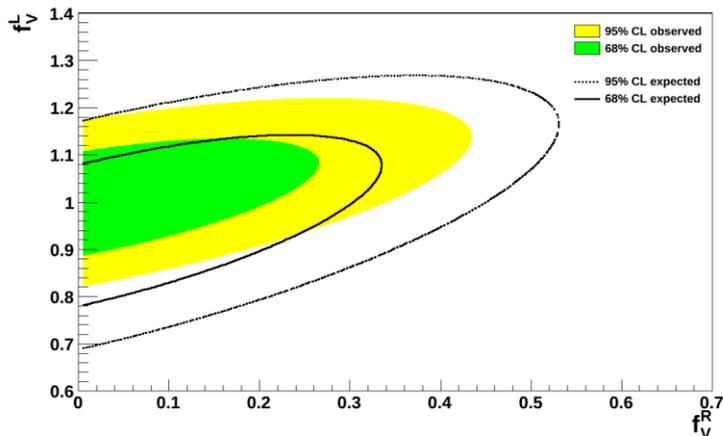
Direct search for anomalous contributions to Wtb vertex with Bayesian neural network

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



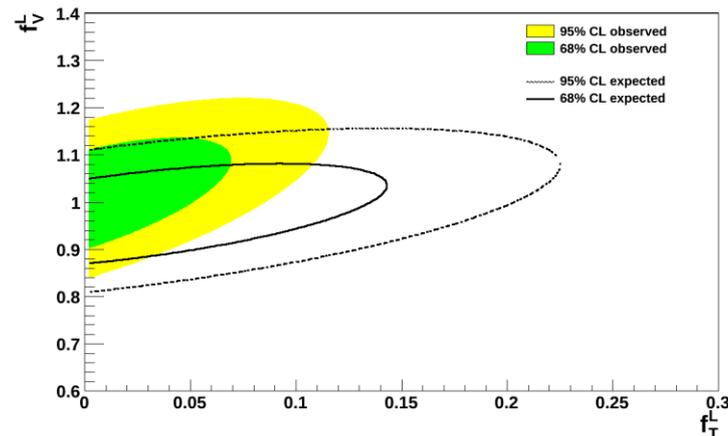
$$|f_V^R| < 0.34 \text{ at } 95\% \text{ C.L.}$$

CMS preliminary, $\sqrt{s} = 7$ TeV, $L = 5.0$ fb $^{-1}$



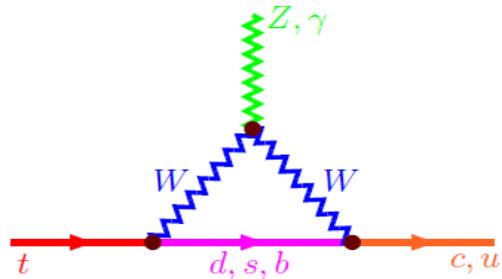
$$|f_T^L| < 0.09 \text{ at } 95\% \text{ C.L.}$$

CMS preliminary, $\sqrt{s} = 7$ TeV, $L = 5.0$ fb $^{-1}$



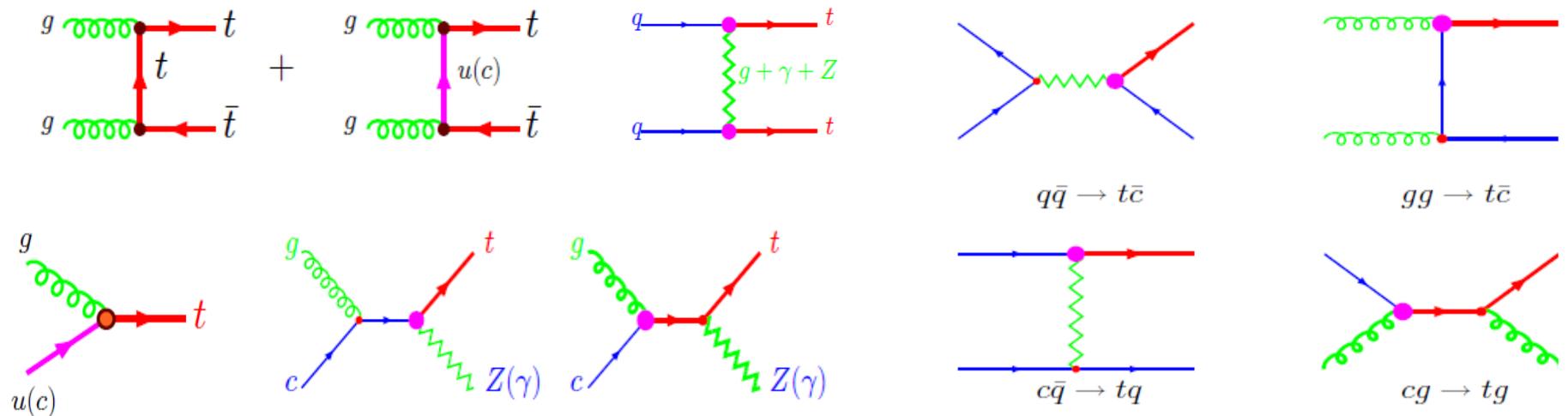
FCNC Search

Flavor Changing Neutral Currents (FCNC) $t \rightarrow qg$, $t \rightarrow q\gamma$, $t \rightarrow qZ$

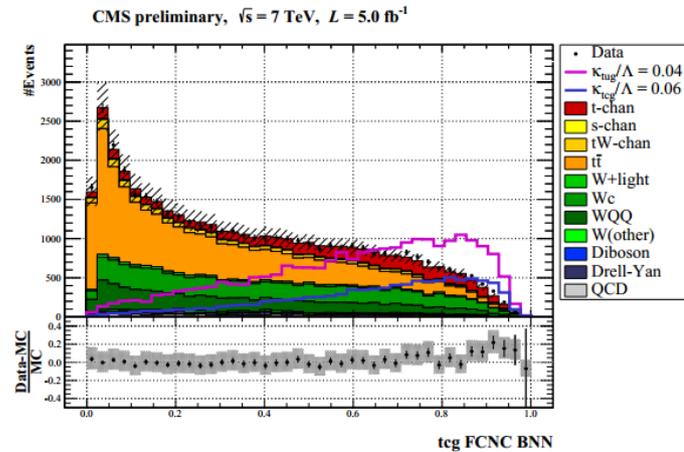
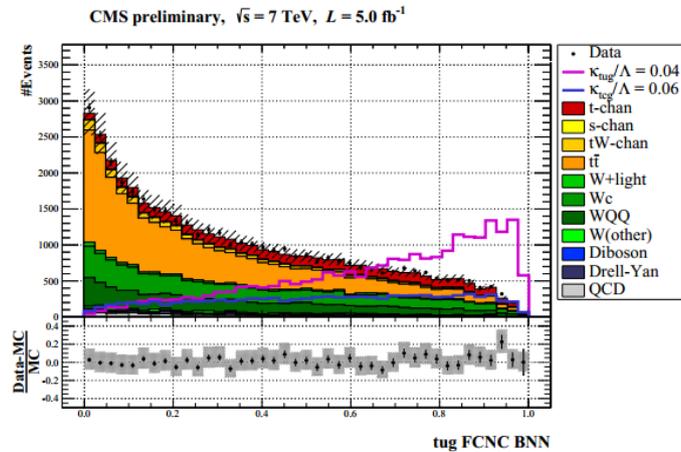


	SM	two-Higgs	SUSY
$B(t \rightarrow cg)$	$5 \cdot 10^{-11}$	10^{-6}	10^{-3}
$B(t \rightarrow c\gamma)$	$5 \cdot 10^{-13}$	10^{-6}	10^{-5}
$B(t \rightarrow cZ)$	$\sim 10^{-13}$	10^{-9}	10^{-4}

FCNC processes lead to additional contribution to $t\bar{t}$ and $t(t)$ or exotic final states



Search for FCNC tug and tcg couplings with Bayesian neural networks



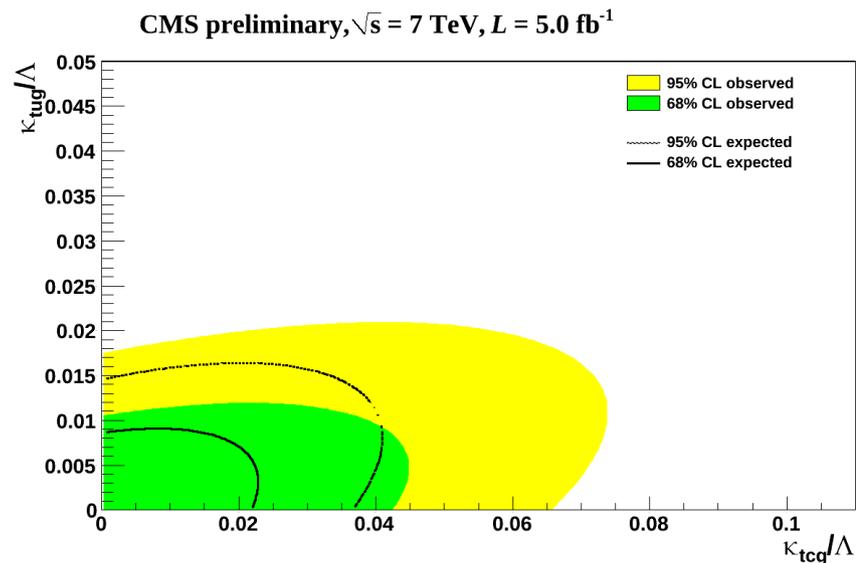
$$\frac{\kappa_{tqg}}{\Lambda} g_s \bar{f} \sigma^{\mu\nu} \frac{\lambda^a}{2} t G_{\mu\nu}^a$$

$$\kappa_{tug}/\Lambda < 1.8 \times 10^{-2} \text{ TeV}^{-1}$$

$$Br(t \rightarrow u + g) < 3.55 \times 10^{-4}$$

$$\kappa_{tcg}/\Lambda < 5.6 \times 10^{-2} \text{ TeV}^{-1}$$

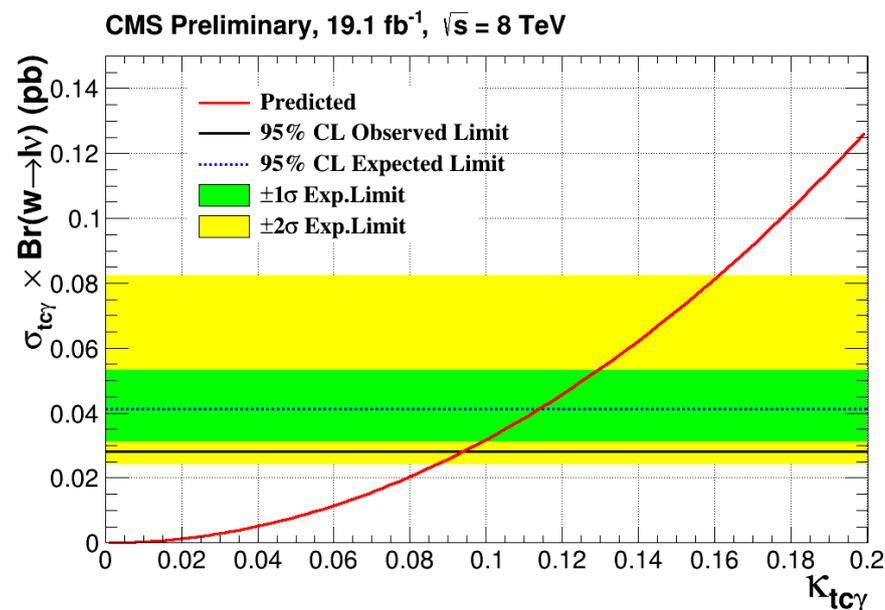
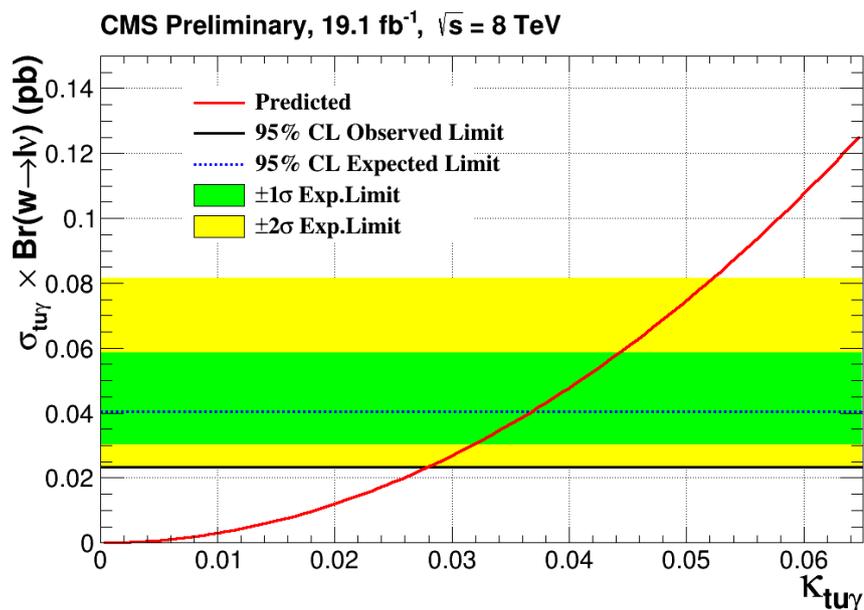
$$Br(t \rightarrow c + g) < 3.44 \times 10^{-3}$$



Search for anomalous single top quark production in association with a photon at $\sqrt{s} = 8 \text{ TeV}$

CMS PAS
TOP-14-003

	Exp. limit (LO)	Obs. limit (LO)	Exp. limit (NLO)	Obs. limit (NLO)
$\sigma_{tu\gamma} \times Br(W \rightarrow lv_l)$	0.0404 pb	0.0234 pb	0.0408 pb	0.0217 pb
$\sigma_{tc\gamma} \times Br(W \rightarrow lv_l)$	0.0411 pb	0.0281 pb	0.0410 pb	0.0279 pb
$\kappa_{tu\gamma}$	0.0367	0.0279	0.0315	0.0229
$\kappa_{tc\gamma}$	0.113	0.094	0.0790	0.0652
$Br(t \rightarrow u\gamma)$	0.0279%	0.0161%	0.0205%	0.0108%
$Br(t \rightarrow c\gamma)$	0.261%	0.182%	0.193%	0.132%

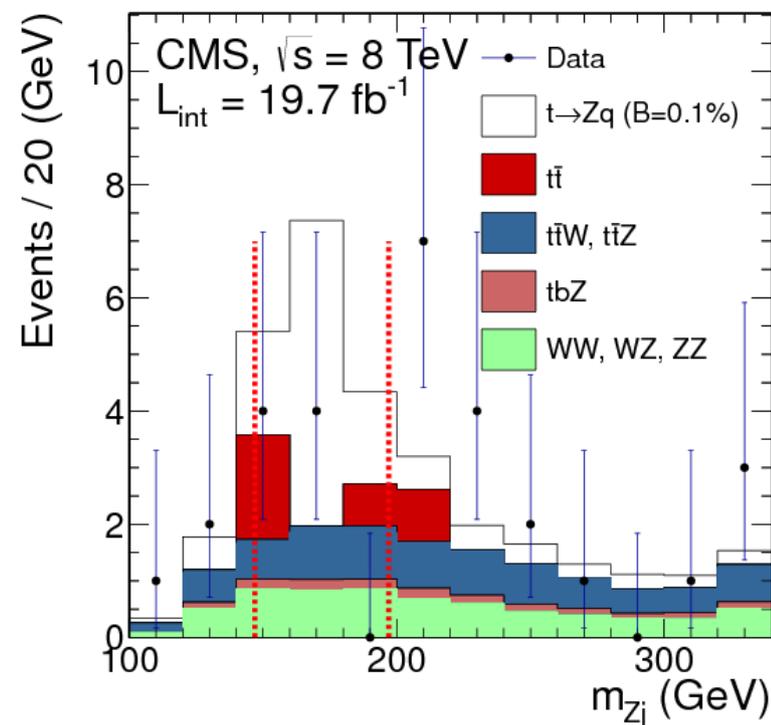
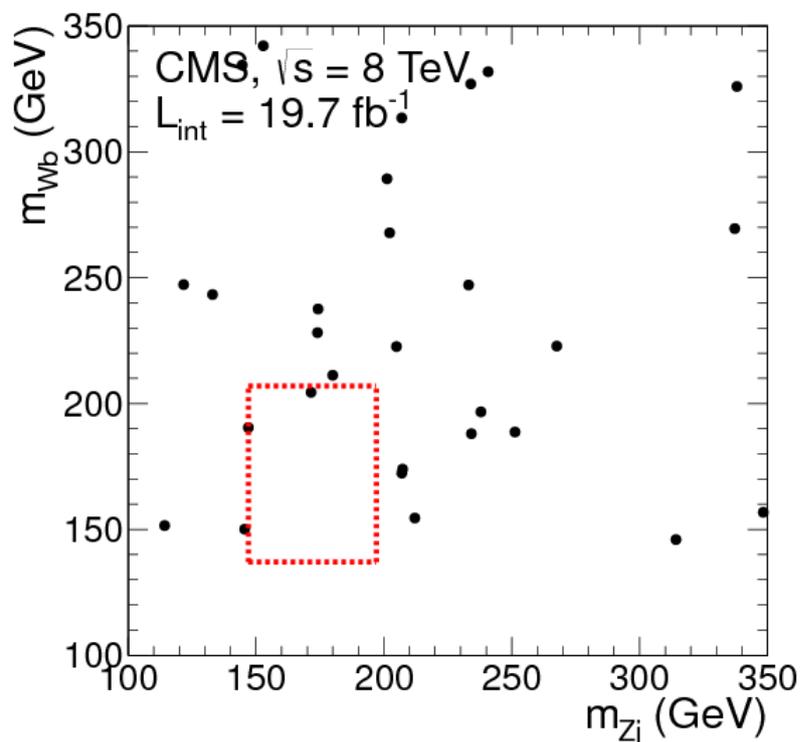


Search for flavor-changing neutral currents in top-quark decays $t \rightarrow Zq$ in pp collisions at $\sqrt{s} = 8 \text{ TeV}$

CMS PAS
TOP-12-037

$t\bar{t} \rightarrow Zq + Wb$ – No excess in number of events

In combination with 7 TeV: $Br(t \rightarrow Zq) < 0.5 \times 10^{-3}$ at 95% CL



2D scatter distribution and comparison between Data and MC after the event selection. Top mass requirements are shown with dotted box (left) and lines (right).

Conclusion

- LHC is currently the main place for top physics, many analysis are published
- LHC demonstrates a good agreement with SM in top sector. There are no any evidence of deviation from SM in top physics.
- Details are available in the dedicated [CMS publications](#)