Search for VLQ and 4 tops in **ATLAS** and **CMS** (SS+b signature)

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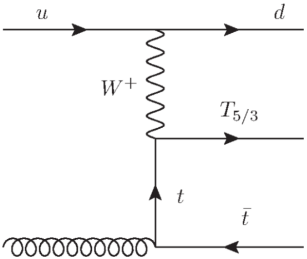
Vector-Like-Quarks (VLQ)

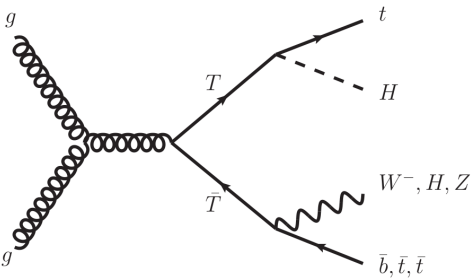
- 4^{th} generation of chiral quarks excluded by discovery of SM-like Higgs
- But there is still room for **Vector-Like Quarks**.
- Mass not from Yukawa coupling to the Higgs

- **Mix with 3^{rd} generation quarks** because of their mass

- B, T VLQs: charges -1/3, +2/3 (same as b and t)
- Y, X VLQs: charges -4/3, +5/3 (sometimes called $B_{-4/3}$ and $T_{5/3}$)

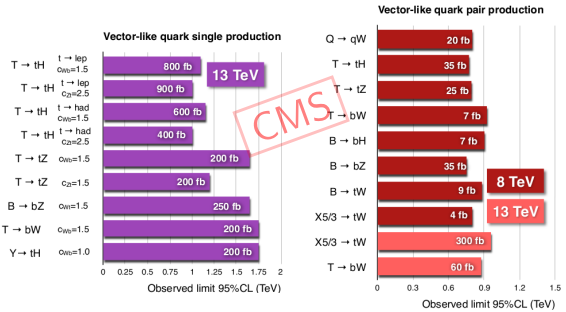
- Appear in **several models** such as extra dimensions, composite models





VLQ final states

- Single and/or pair production
- VLQ possible decays:
  - $T \to Wb$, Zt, Ht
  - $B \to Wt$, Zb, Hb
  - $Y \to Wb$
  - $X \to Wt$
- Lots of different analyses!



- Final states with several b-jets, light jets and leptons
  $\longrightarrow$ **single lepton** and **same-sign dilepton** channels

▸ CMS Public Results

- VLQs typically excluded at masses below ~ 1 TeV
  $\longrightarrow$ analyses target very high mass VLQs > 1 TeV

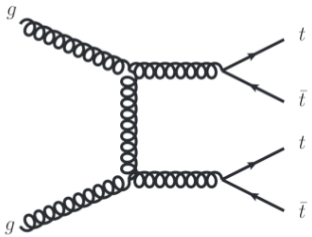
▸ ATLAS Public Results

Four top quarks production

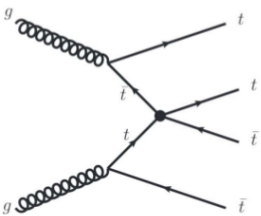
- The top quark plays a key role in many BSM scenarios

$\Longrightarrow$ Some of which predict an **enhancement of the $t\bar{t}t\bar{t}$ cross-section**

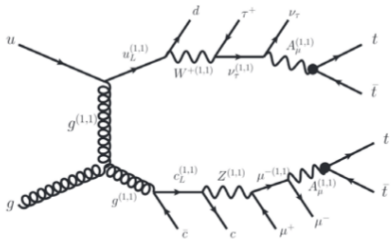
  - Contact Interaction model (CI)
  - Universal Extra Dimensions (UED)
  - 2HDM



Standard Model



CI



UED

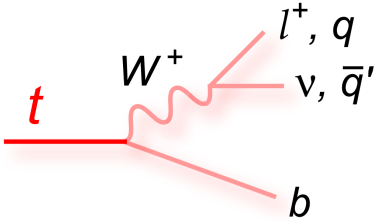
- $\sigma^{SM}_{t\bar{t}t\bar{t}}$ **not yet measured** experimentally

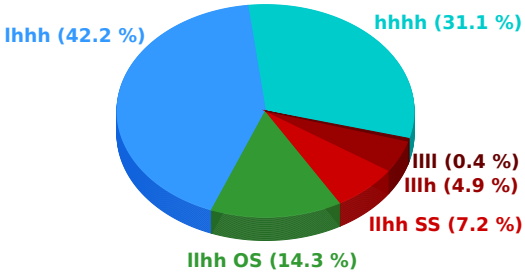
  $\rightarrow$ theory (NLO): **$9.2\,\text{fb}^{+30.8\,\%\ +5.5\,\%}_{-25.6\,\%\ -5.9\,\%}$ @ 13 TeV** [1] (was ~ 1 fb @ 8 TeV)

[1] J. Alwall et al., 10.1007/JHEP07(2014)079

The $t\bar{t}t\bar{t}$ final state

- 4t $\rightarrow$ 4W + 4b
- Analysis channels
  - **single lepton** channel
  - **same-sign dilepton** channel (including trilepton)





Analyses considered in this talk

- I will present 3 analyses using the same-sign leptons + b-jets final state

ATLAS

- Search for new physics in SS/multilepton events
  - $3.2\,\text{fb}^{-1}$
  - SM and BSM 4top + T, B and $T_{5/3}$ VLQ pair production

ATLAS-CONF-2016-032

CMS

- Search for SM 4top with SS/multilepton final states
  - $35.9\,\text{fb}^{-1}$
  - SM 4top

arXiv:1710.1061

- Search for VLQ T and B (single lepton, SS dilepton and trilepton channels)
  - $35.9\,\text{fb}^{-1}$
  - T and B VLQ pair production

arXiv:1805.04758

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Selections

ATLAS 4top/VLQ search

- 8 signal regions
- SS dilepton + trilepton flavours mixed
- split in H_T, N_b, E_T^{miss}
- low mass + Z veto for ee events
- regions similar to 8 TeV analysis to check modest excess

Definition			Name
$e^{\pm}e^{\pm} + e^{\pm}\mu^{\pm} + \mu^{\pm}\mu^{\pm} + eee + ee\mu + e\mu\mu + \mu\mu\mu$, $N_{\text{jets}} \geq 2$			
$400 < H_{\text{T}} < 700$ GeV	$N_b = 1$	$E_{\text{T}}^{\text{miss}} > 40$ GeV	SR0
	$N_b = 2$		SR1
	$N_b \geq 3$		SR2
$H_{\text{T}} \geq 700$ GeV	$N_b = 1$	$40 < E_{\text{T}}^{\text{miss}} < 100$ GeV	SR3
		$E_{\text{T}}^{\text{miss}} \geq 100$ GeV	SR4
	$N_b = 2$	$40 < E_{\text{T}}^{\text{miss}} < 100$ GeV	SR5
		$E_{\text{T}}^{\text{miss}} \geq 100$ GeV	SR6
	$N_b \geq 3$	$E_{\text{T}}^{\text{miss}} > 40$ GeV	SR7

CMS 4top SM search

- 8 SR, 2 CR (ttW, ttZ)
- $H_T > 300$ GeV
- $p_T^{\text{miss}} > 50$ GeV
- low $m_{e^{\pm}e^{\pm}}$ veto
- low mass + Z veto for OS pair with 3rd lepton

N_ℓ	N_{b}	N_{jets}	Region
2	2	≤ 5	CRW
		6	SR1
		7	SR2
		≥ 8	SR3
	3	5, 6	SR4
		≥ 7	SR5
	≥ 4	≥ 5	SR6
≥ 3	2	≥ 5	SR7
	≥ 3	≥ 4	SR8
Inverted Z veto			CRZ

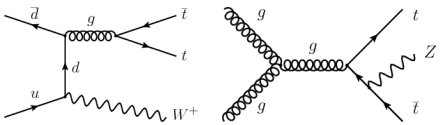
CMS VLQ search

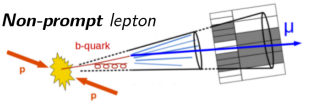
- SS dilepton channel
  - splitted in flavours ee, $e\mu$, $\mu\mu$
  - low m_{ll} veto, Z veto (ee, $e\mu$)
  - $N_j \geq 4$, $H_T > 1200$ GeV
- trilepton channel
  - splitted in eee, $ee\mu$, $e\mu\mu$, $\mu\mu\mu$
  - low $m_{ll,OS}$ veto
  - $N_j \geq 3$, $N_b \geq 1$, $p_T^{\text{miss}} > 20$ GeV

Backgrounds

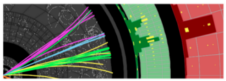
Irreducible backgrounds

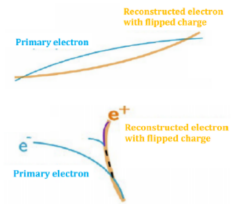
- SM processes producing same-sign leptons and b-jets
- Dominant backgrounds: ttW, ttZ
- Estimated using Monte-Carlo
- Normalization of ttW/Z constrained in CR during the final fit for CMS 4top search





***Fake** lepton* - jet wrongly reconstructed as a lepton





Reducible backgrounds

- Fake/Non-prompt leptons
  - Lepton from hadron decay
  - Jet misidentified as reconstructed lepton (mostly electrons)
- Electron charge mis-identification
  - High p_T electron
  - Electron from photon conversion
- Estimated using data-driven methods

Fake/non-prompt background

- Introduce new lepton definition: "loose": **relaxed ID and/or isolation**
- Regular leptons are called "tight" (tight $\subset$ loose)

$$\textbf{Real efficiency: } r = \frac{N_{\text{real}}^{\text{tight}}}{N_{\text{real}}^{\text{loose}}} \qquad \textbf{Fake efficiency: } f = \frac{N_{\text{fake}}^{\text{tight}}}{N_{\text{fake}}^{\text{loose}}}$$

Matrix Method (used by ATLAS 4top/VLQ search)

$$\begin{pmatrix} N_t \\ N_{\bar{t}} \end{pmatrix} = \begin{pmatrix} r & f \\ 1-r & 1-f \end{pmatrix} \begin{pmatrix} N_{\text{real}}^{\text{loose}} \\ N_{\text{fake}}^{\text{loose}} \end{pmatrix}$$

t: tight
$\bar{t}$: loose and not tight

- Fake bkg yield $= \frac{f}{r-f}(r\,N_{\bar{t}} + (r-1)N_t) \Rightarrow$ weight events $\begin{cases} w = \frac{f}{r-f}(r-1) & \text{if tight} \\ w = \frac{f}{r-f} r & \text{otherwise} \end{cases}$
- Can be generalized to 2 or 3 leptons

Tight-to-loose method (used by CMS 4top/VLQ searches)

- Define ϵ_{TL}, equivalent to Matrix Method f
- Weight strictly loose events with $\epsilon_{TL}/(1-\epsilon_{TL})$
- Same as Matrix Method assuming $r \simeq 1$

Fake/non-prompt background - efficiencies and systematics

- **Real efficiency r** from real-enriched CR
  - High E_T^{miss}, high $m_T(W)$: $W \to l\nu$ CR
  - Z mass window: $Z \to ll$ CR
- **Fake efficiency** = (data - MC_{real})$_{\text{tight}}$ / (data - MC_{real})$_{\text{loose}}$ in fake-enriched CR
  - Low E_T^{miss}, low $m_T(W)$: reject $W \to l\nu$ CR
  - Exactly 1 loose lepton, Z veto CR
- Efficiencies usually parametrized in p_T and η.
- Other variables can be crucial, like N_b
- Systematics uncertainties around 20 to 60 %
- **Extrapolation of efficiencies** from CR to SR is difficult
  - $\rightarrow$ Different distributions of critical variables in CR and SR
  - $\rightarrow$ Different composition fake/non-prompt in CR and SR
- Need a loose sample with **large difference between real and fake efficiencies**

Electron charge mis-identification background

- Define probability that an electron's charge is mis-identified: **charge flip rate ε**
- Calculate ε using Z $\rightarrow$ ee events (Poisson likelihood maximization)
- Charge flip rates binned in $|\eta|$ and p_T

- Define opposite-sign CR for each same-sign SR, and we have:

$$N_{SS}^{reco} = N_{OS}^{true}(\varepsilon_i(1-\varepsilon_j) + \varepsilon_j(1-\varepsilon_i))$$
$$N_{OS}^{reco} = N_{OS}^{true}((1-\varepsilon_i)(1-\varepsilon_j) + \varepsilon_i\varepsilon_j)$$

ε_i: first electron
ε_j: second electron

- Can get N_{SS}^{reco} from weighting N_{OS}^{reco} in CR

$$\text{weight} = \frac{\varepsilon_i + \varepsilon_j - 2\varepsilon_i\varepsilon_j}{(1-\varepsilon_i)(1-\varepsilon_j) + \varepsilon_i\varepsilon_j}$$

- Fake/Non-prompt background removal needed to avoid double counting

- 10 - 30 % systematic uncertainties

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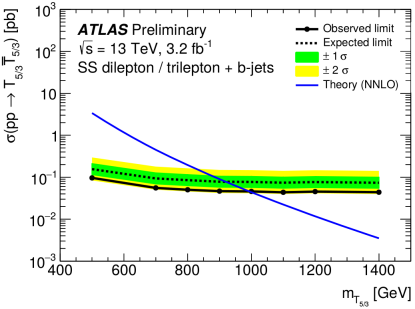
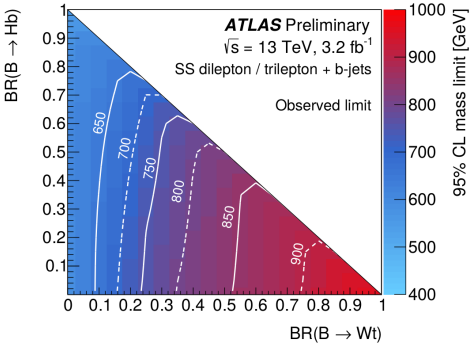
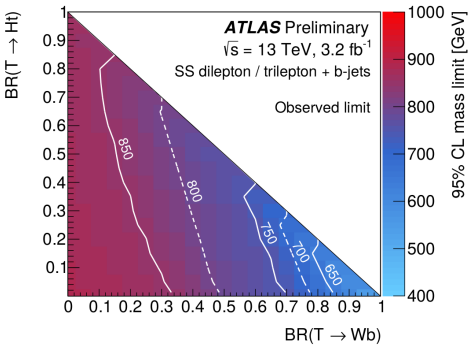
Results - **ATLAS** 4top/VLQ search

ATLAS-CONF-2016-032

- **Signal extraction**: simultaneous fit of the 8 signal regions
- 95 % CL limits: observed (expected)
  - $\sigma^{SM}_{t\bar{t}t\bar{t}} < 95$ (107) fb
  - $m_B > 0.83$ (0.75) TeV (singlet)
  - $m_T > 0.78$ (0.73) TeV (singlet)
  - $m_{T_{5/3}} > 0.99$ (0.92) TeV







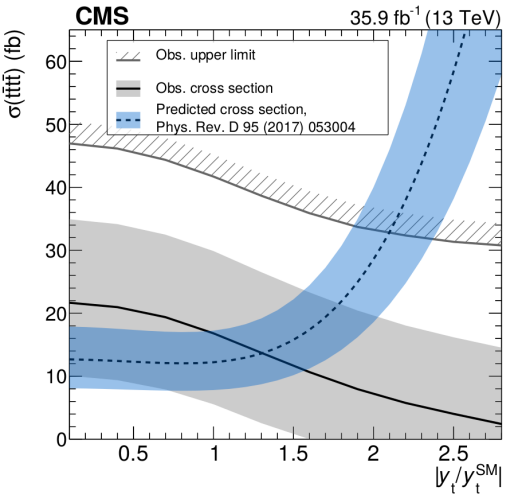
arXiv:1710.1061

- **Signal extraction**: simultaneous fit of the 8 SR + 2 CR
  - Signal strength μ
  - Normalization factor for ttW: 1.2 ± 0.3
  - Normalization factor for ttZ: 1.3 ± 0.3

- 95 % CL limit on $\sigma^{SM}_{t\bar{t}t\bar{t}}$
  $\longrightarrow$ 41.7 $(20.8^{+11.2}_{-6.9})$ fb

- Fit result (measurement of $\sigma^{SM}_{t\bar{t}t\bar{t}}$)
  $\longrightarrow$ $16.9^{+13.8}_{-11.4}$ fb

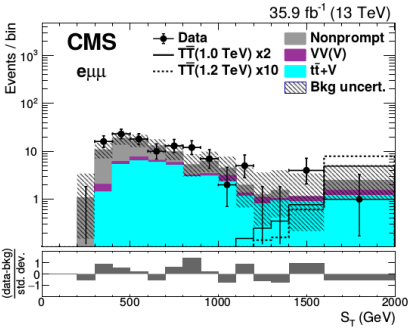
- 95 % CL limit on top quark Yukawa coupling
  $\longrightarrow$ $|y_t/y_t^{\mathrm{SM}}| < 2.1$

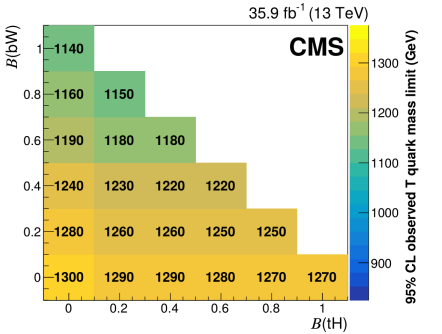


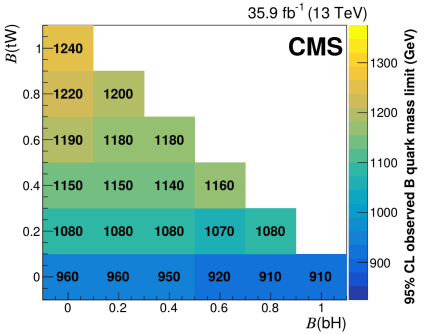
Results - CMS VLQ search

arXiv:1805.04758

- Use event yields in SS dilepton SR
- Use S_T distributions in trilepton SR (sum of leptons and jets $p_T + p_T^{\text{miss}}$)
- **Combination** between single lepton (not presented), SS dilepton and trilepton channels
- $m_B > 1170$ (1130) GeV (singlet)
- $m_T > 1200$ (1160) GeV (singlet)







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Conclusion

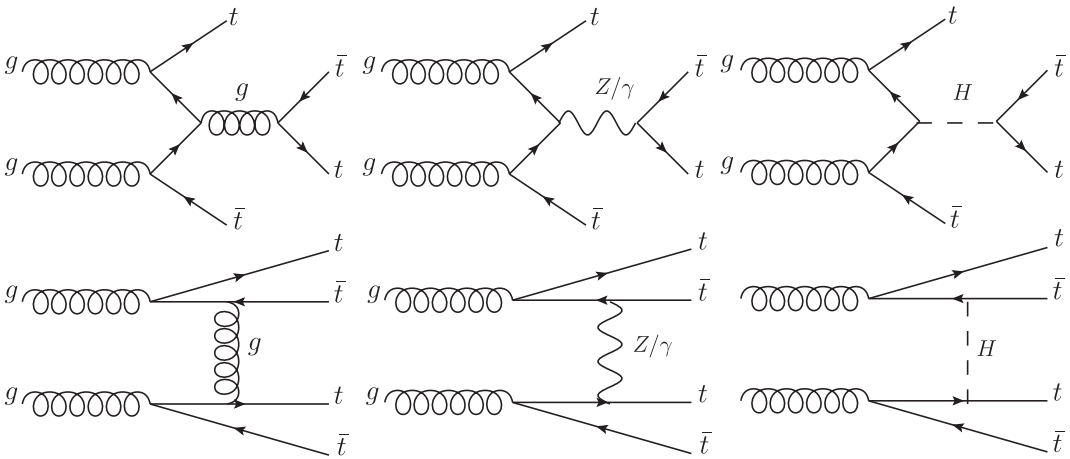
- **SS dilepton/multilepton** is a very interesting signature for 4top/VLQ searches
- Data driven techniques to estimate the **fake/non-prompt background**
- No excess found yet $\rightarrow$ limits set on a variety of models
- Best sensitivity to **SM 4top** from **CMS** SS/multilepton search
  $\longrightarrow$ Expected limit of 20.8 fb, or **2.3 times the SM cross-section**

$\Longrightarrow$ Looking forward to see **ATLAS** 4top results with 2016 data published!

- **Interesting full Run 2 analyses ahead**, since sensitivity to SM 4top will be very close to the SM cross-section

BACKUP

4top Feynman diagrams



- Phys. Rev. D 95, 053004

4top cross-section details

	8 TeV	13 TeV	14 TeV
$\sigma^{\mathrm{SM}}(t\bar{t}t\bar{t})_{g+Z/\gamma}$:	1.344 fb,	9.997 fb,	13.140 fb,
$\sigma^{\mathrm{SM}}(t\bar{t}t\bar{t})_{H}$:	0.171 fb,	1.168 fb,	1.515 fb,
$\sigma^{\mathrm{SM}}(t\bar{t}t\bar{t})_{\mathrm{int}}$:	−0.224 fb,	−1.547 fb,	−2.007 fb.

▸ Phys. Rev. D 95, 053004

ATLAS SSbjets objects selection

	Electrons	Muons	Jets
Trigger	1 electron, $p_{\mathrm{T}} > 24$ GeV	1 isolated muon, $p_{\mathrm{T}} > 20$ GeV or 1 muon, $p_{\mathrm{T}} > 50$ GeV	
p_{T}	> 25 GeV	> 25 GeV	> 25 GeV
$\lvert\eta\rvert$	< 1.37 or $1.52 < \lvert\eta\rvert < 2.47$	< 2.5	< 2.5
Object ID	tight	medium	–
Vertex match	$\lvert d_0\rvert/\sigma(d_0) < 5$ $\lvert\Delta z_0 \sin\theta\rvert < 0.5$ mm	$\lvert d_0\rvert/\sigma(d_0) < 3$ $\lvert\Delta z_0 \sin\theta\rvert < 0.5$ mm	JVT requirement (if $\lvert\eta\rvert < 2.4$ and $p_{\mathrm{T}} < 50$ GeV)
Isolation	track and calorimeter	track	–
Multiplicity	2 same-charge leptons or ≥ 3 leptons		–

CMS 4top SSbjets objects selection

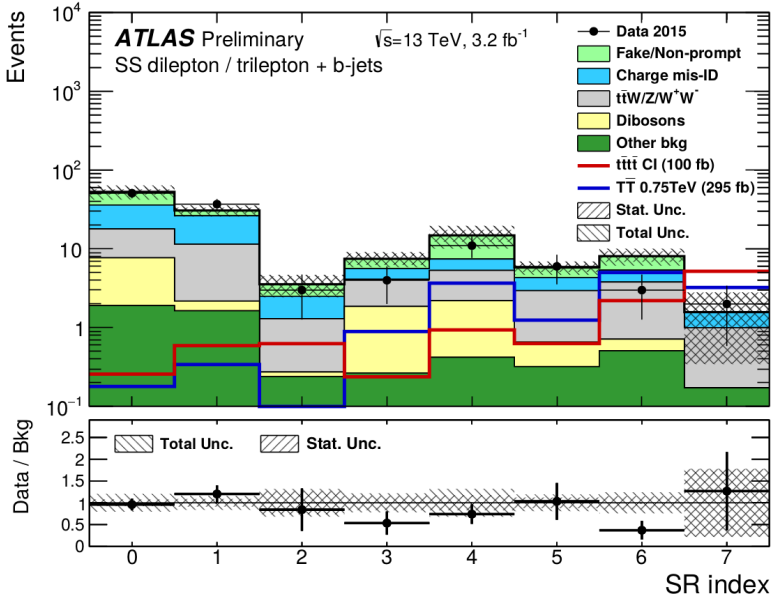
Object	p_{T} (GeV)	$\lvert\eta\rvert$
Electrons	>20	<2.5
Muons	>20	<2.4
Jets	>40	<2.4
b-tagged jets	>25	<2.4

ATLAS 4top/VLQ search SR yields

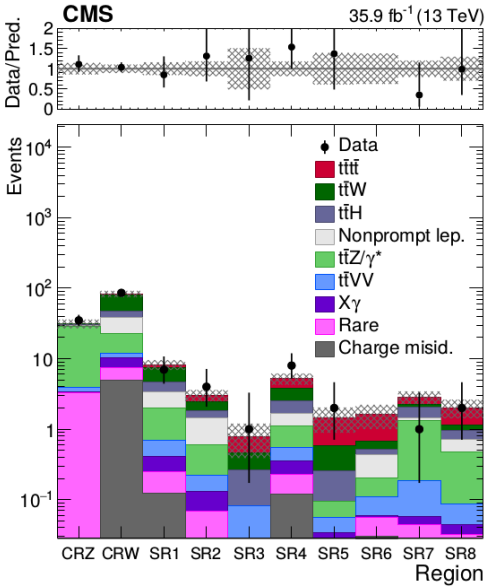
	SR0	SR1	SR2	SR3	SR4
Fake/Non-prompt	16.3± 9.5	4.2 ±3.3	1.0 ± 0.9	1.8 ± 1.4	7.1±4.5
Charge mis-ID	18.1± 4.1	14.9±3.5	1.2 ± 0.3	1.5 ± 0.4	2.1±0.5
$t\bar{t}W/Z/W^+W^-$	10.1± 1.4	9.2 ±1.3	1.0 ± 0.3	2.2 ± 0.3	3.1±0.5
Dibosons	5.8 ± 1.0	0.5 ±0.2	0.03±0.07	1.6 ± 0.4	1.8±0.4
Other bkg.	2.0 ± 1.0	1.7 ±0.9	0.3 ± 0.2	0.3 ± 0.2	0.5±0.3
Total bkg.	52 ± 11	31 ± 5	3.6 ± 1.0	7.4 ± 1.5	15 ± 5
$t\bar{t}t\bar{t}$ (SM)	0.5 ± 0.1	0.8 ±0.1	0.9 ± 0.1	0.2 ± 0.1	0.5±0.1
$t\bar{t}t\bar{t}$ (CI)	0.26±0.04	0.6 ±0.1	0.6 ± 0.1	0.24±0.05	0.9±0.1
UED 1.2 TeV	<0.01	<0.01	<0.01	0.3 ± 0.1	3.8±0.8
$T\bar{T}$ 0.75 TeV	0.2 ± 0.1	0.31±0.1	0.04±0.04	0.9 ± 0.2	3.7±0.4
Data	51	37	3	4	11

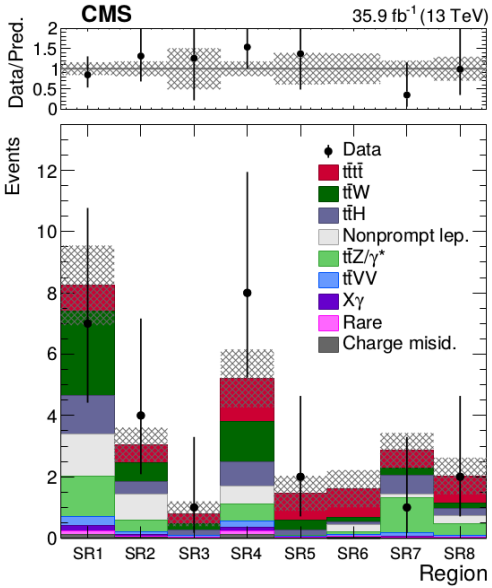
	SR5	SR6	SR7
Fake/Non-prompt	1.4±0.9	2.6±1.8	0.0 ±0.6
Charge mis-ID	1.4±0.4	1.6±0.5	0.6 ±0.2
$t\bar{t}W/Z/W^+W^-$	2.3±0.6	3.0±0.7	0.8 ±0.4
Dibosons	0.3±0.1	0.2±0.1	0.0 ±0.1
Other bkg.	0.4±0.2	0.7±0.4	0.5 ±0.3
Total bkg.	5.8±1.2	8.1±2.0	1.9 ±0.8
$t\bar{t}t\bar{t}$ (SM)	0.7±0.1	1.8±0.2	3.6 ±0.4
$t\bar{t}t\bar{t}$ (CI)	0.6±0.1	2.2±0.2	5.2 ±0.4
UED 1.2 TeV	0.6±0.1	6.6±0.7	10.1±0.8
$T\bar{T}$ 0.75 TeV	1.3±0.2	5.0±0.5	3.2 ±0.4
Data	6	3	2

ATLAS 4top/VLQ search SR yields



CMS SM 4top search SR yields





CMS SM 4top search SR yields

	SM background	$t\bar{t}t\bar{t}$	Total	Observed
CRZ	31.7 ± 4.6	0.4 ± 0.3	32.1 ± 4.6	35
CRW	83.7 ± 8.8	1.9 ± 1.2	85.6 ± 8.6	86
SR1	7.7 ± 1.2	0.9 ± 0.6	8.6 ± 1.2	7
SR2	2.6 ± 0.5	0.6 ± 0.4	3.2 ± 0.6	4
SR3	0.5 ± 0.3	0.4 ± 0.2	0.8 ± 0.4	1
SR4	4.0 ± 0.7	1.4 ± 0.9	5.4 ± 0.9	8
SR5	0.7 ± 0.2	0.9 ± 0.6	1.6 ± 0.6	2
SR6	0.7 ± 0.2	1.0 ± 0.6	1.7 ± 0.6	0
SR7	2.3 ± 0.5	0.6 ± 0.4	2.9 ± 0.6	1
SR8	1.2 ± 0.3	0.9 ± 0.6	2.1 ± 0.6	2

CMS SM VLQ search SR yields

Table 6: Numbers of predicted and observed events for lepton flavor categories in the same-sign dilepton channel before the fit to data. Uncertainties include both statistical and systematic components.

Sample	ee	eμ	$\mu\mu$
$T\bar{T}$ (1.0 TeV)	1.34 ± 0.08	3.11 ± 0.18	2.12 ± 0.12
$T\bar{T}$ (1.2 TeV)	0.42 ± 0.02	1.00 ± 0.06	0.66 ± 0.04
Prompt SS	4.03 ± 0.57	10.2 ± 1.4	5.79 ± 0.82
Nonprompt	4.6 ± 2.6	10.6 ± 5.6	5.4 ± 3.0
Charge misid.	4.1 ± 1.3	2.61 ± 0.81	—
Total bkg	12.8 ± 3.0	23.4 ± 5.8	11.2 ± 3.1
Data	12	31	9
Data/bkg	0.94 ± 0.35	1.33 ± 0.41	0.80 ± 0.35

Table 7: Numbers of predicted and observed events for lepton flavor categories in the trilepton channel before the fit to data. Uncertainties include both statistical and systematic components.

Sample	eee	eeμ	e$\mu\mu$	$\mu\mu\mu$
$T\bar{T}$ (1.0 TeV)	1.60 ± 0.14	2.54 ± 0.18	3.32 ± 0.23	2.79 ± 0.23
$T\bar{T}$ (1.2 TeV)	0.40 ± 0.03	0.71 ± 0.05	0.90 ± 0.06	0.78 ± 0.06
VV(V)	4.32 ± 0.77	5.44 ± 0.78	6.52 ± 0.93	5.89 ± 0.89
$t\bar{t}$ +V	20.9 ± 2.9	31.9 ± 4.1	37.0 ± 4.7	35.8 ± 5.0
Nonprompt	19 ± 11	41 ± 18	51 ± 15	20.0 ± 8.4
Total bkg	44 ± 11	78 ± 19	94 ± 15	61.7 ± 9.8
Data	54	102	111	71
Data/bkg	1.22 ± 0.35	1.31 ± 0.34	1.18 ± 0.22	1.15 ± 0.23

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