



Search for a Vector Like Quark T' decaying into quark top and Higgs boson in a dileptonic same sign final state with the CMS experiment for Run 2 at LHC

Top LHC France - 9 April 2024 Benjamin Blancon¹ on behalf of the CMS collaboration

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Motivation



- Vector-Like Quark (VLQ) T':
 - Present in many BSM models (Little Higgs models, Extra dimension models...).
 - Electroweak and strong interactions with SM particles.
 - Interaction with the Higgs boson solves the hierarchy problem.
 - Mass $M_{T'}$ predicted in many BSM models to be <u>below or around 1 TeV</u> for a Higgs boson mass $m_{H} \approx 125$ GeV (13 TeV in the center of mass of the LHC for 2016-2018).
- No evidence for an excess using full Run 2 data in the T' → tH <u>all-hadronic resolved</u> <u>final state</u> (see <u>Stéphanie's presentation</u>) and <u>diphoton final state</u>.
 - Needs to be confirmed in other decays!

Signal process: final state



- Final state:
 - Two leptons same sign (SS).
 - Three jets with one b-jet.
 - Two neutrinos.
 - Three channels:
 - ο μμ.
 - ο eμ.
 - o ee.
- Nominal masses M_{T'} range: [600 1200 GeV].
- Analysis performed with the full Run 2 (2016-2018) data.



iP 2i

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- Searching for a resonance in the transverse mass $M_{TT'}$
- Three Control regions implemented.
- Background estimated with data-driven technique.
- Combined fit of Signal region and Control regions.
- Optimized for $M_{T'} = 700$ GeV.

PV tt dileptonic (tt): 1 or 2 leptons opposite sign (OS) and 2 b-jets. m W W

tt \overline{W} (t \overline{X}): 2 leptons SS and \ge 4 jets with 2 b-jets.

WZ (Diboson): \geq 2 leptons.



Object identification



Muon	Pt > 30 GeV, $ \eta < 2.4$, tight ID, optimized selection on isolation, distance to Primary Vertex (PV), 3D Impact parameter significance (SIP _{3D}) and charge misreconstruction veto.
Electron	Pt > 40 GeV, $ \eta < 2.5$, tight ID, optimized selection on isolation, distance to PV, SIP _{3D} , number of hits, photon conversion veto and charge misreconstruction veto.
Jet	Pt > 30 GeV, $ \eta < 2.4$, tight ID and removed overlap between the jets and the leptons in a cone of $\Delta R < 0.4$.
B-jet	Pt > 30 GeV, $ \eta $ < 2.4, tight ID and medium DeepJet WP. Identical overlap condition as the jets.

• Recommended CMS corrections applied (Pileup and b-tag weights, JEC, muon and electron efficiencies).







- Selection criteria:
 - The two leptons must be back-to-back.
 - The T' has a large mass so we expect the 2 leptons and the b-jet to have high Pt.
 - The top quark must have a non-hadronic decay.
- Falling M_{T,T} distribution needed to estimate the background.
- Background efficiency in each M_{T,T} bin should be the same after each cut to keep the same shape!
- Solution: cut optimization using quantiles of the background yield!





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Signal region (2018)

- All channels (μμ/eμ/ee) with 2018 simulation considered.
- Signal visible above the background (S/B = 1.83%).



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dibosons = WW + WW Deep Scattering + WWW + WH + ZH + WZ + ZZ ttX = ttW + ttH + ttZ Signal region (2018) splitted by channel ⁸

CMS



• Higher signal over background discrimination for muonic channels (S/B = 2.06%, 1,87% and 1,28% for $\mu\mu$, μ e and ee channels respectively).



• Same conclusion for 2016 (S/B = 1.57%) and 2017 (S/B = 1.84%).

Benjamin Blancon Control regions - tt2l (2018) Top LHC France 04.09.24

- CR tt2l: two leptons with opposite sign.
- Discriminant variable in this Region: invariant with a sport of the lepton and the b-iet comine for th top M_{μ} (the neutrino is not included). Lepton and b-jet selected as the closest each other (correct identification in 80% of cases).
- Data/MC agreement within 1σ for all the studied variables.







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Nuisance pools - CR tt2l (2018)

- Impact of nuisance parameters:
 - $\circ~$ All channels (µµ/eµ/ee) with 2018 simulation considered.
 - Signal injection test.
 - Systematic uncertainties: electron and ¹⁰/₁₁ muon efficiencies, b-tagging, rate on ¹²/₁₃ processes, luminosity, pileup and prefiring. ¹⁴/₁₆
 - Statistical uncertainties implemented with the Barlow-Beeston-lite approach.
- Main constraints are single top and tt rate.





0.5

Min(M(3j)) (GeV)





Nuisance pools - CR tt1l (2018)



-	Como naro co duno co naroviou o CD	Private work (CM	AS Simulation)			$\hat{\mathbf{r}} = 1.0^{+19.0}_{-1.0}$
•	Same procedure as previous CR.	1	rtt	· · · · · · · · · · · · · · · · · · ·	···[····	
		2	prop_binch3_bin1			
		3	prop_binch1_bin2	× *		
		4	syst_b_correlated			
	Main uncertainty is thrate.	5	rsingletop	× · · · · ·		
		6	lumi_cor_2016_2018			
		7	prop_binch2_bin1	• • • • • • • • • • • • • • • • • • •		
		8	syst_pu	• • • • • • • • • • • • • • • • • • •		
		9	lumi_uncor_2018	• • • • • • • • • • • • • • • • • • •		
		10	syst_elec_id			
		11	rttx	• • • • • • • • • • • • • • • • • • •		
		12	syst_elec_reco			
		13	syst_b_uncorrelated_2018			
		14	prop_binch1_bin0			
		15	prop_binch1_bin1	↓ ↓ ↓ ↓		
		16	syst_l_correlated			
		17	lumi_cor_2017_2018			
		18	prop_binch3_bin0			
		19	syst uncorrelated 2018		1	1 1

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prop_binch1_bin4





Nuisance pools - CR ttX ((2018)
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		Private work (CMS Simulation)					$\hat{r} = 1.0^{+14.6}$	
•	Same procedure as previous CRs.	1	rttx	····	×		-1.0	
		2	lumi_cor_2016_2018		×			
		4	prop_binch3_bin3		• • • • • • • • • • • • • • • • • • •			
	Major uncertainty is ttX rate (by far)	5	lumi_uncor_2018					
-	Major ancertainty is thirde (by far).	6	prop_binch1_bin1					
		7	prop_binch2_bin1		×			
	· · · · · · · · · · · · · · · · · · ·	9	prop_binch1_bin0		×			
	Strong anti-correlation between signal and ttX	10	prop_binch3_bin0		<u> </u>			
		11	syst_l_correlated					
	is observed.	12	syst_b_uncorrelated_2018					
		13	rsingletop		×			
	► New optimization needed.	14	syst_elec_id		×			
		16	prop_binch2_bin0					
		17	rdibosons		*			
		18	syst_l_uncorrelated_2018					
		19	prop_binch3_bin1					
		20	lumi_cor_2017_2018		×			
				Correlatio	on matrix of fit p	arameters		
			r 1	-0.0166428	-0.0277781	-0.085852	-0.650929	
		rdibos	sons -0.0166428	1	5.74209e-05	-0.000712093	-0.0068865	
		rsingl	etop -0.0277781	5.74209e-05	1	-4.90835e-05	0.00159033	
			rtt -0.085852	-0.000712093	-4.90835e-05	1	-0.0454508	
			rttx -0.650929	-0.0068865	0.00159033	-0.0454508	1	
			r	rdibosons	rsingletop	rtt	rttx	



Nuisance pools - All regions (2018)

- Impact plots with all channels and all regions for 2018 simulation considered.
- Major constraint and uncertainty still on ttX rate.
- → Most urgent issue to resolve.

	Pı	rivate work (CMS Simulation)	$\hat{r} = 1.0^{+4.7}$
S	1	rttx	-1.0
	2	syst_b_correlated	
	3	prop_binch1_bin5	
	4	prop_binch2_bin5	
	5	lumi_cor_2016_2018	
	6	lumi_uncor_2018	
7	7	prop_binch2_bin4	
7	8	prop_binch3_bin5	
	9	prop_binch1_bin4	
	10	syst_b_uncorrelated_2018	
	11	prop_binch12_bin3	
	12	rdibosons	
	13	prop_binch11_bin0	
	14	prop_binch7_bin2	
	15	prop_binch9_bin1	
	16	rdy	
	17	prop_binch2_bin6	
	18	prop_binch6_bin0	
	19	syst_elec_id	
	20	rsingletop	





Nuisance pools - All regions (Run 2)

- Impact plots with all channels and all regions for Run 2 simulation considered.
- Major constraint and uncertainty still on ttX rate.
- --> Confirmation of the behavior in 2018.
- Several constraints to be looked at in more details.
- 95% upper limit on the cross-section: $\sigma = 587^{+241}_{-170}$ fb at M_T = 700 GeV.

Private w	vork (CMS Simulation)		$\hat{r} = 1.0^{+3.3}_{-1.0}$
1	rttx	····i····i·····	-1.0
2	syst_b_correlated		
3	prop_binch25_bin5		
4	prop_binch26_bin5		
5	prop_binch1_bin5		
0	rdibosons		
7	prop_binch1_bin4		
8	lumi_cor_2016_2018		
9	prop_binch14_bin5		
10	prop_binch2_bin5		
11	prop_binch13_bin5		
12	prop_binch13_bin4		
13	prop_binch26_bin4		
14	prop_binch27_bin5		
15	prop_binch25_bin4		
16	prop_binch36_bin3		
17	syst_prefiring		
18	syst_b_uncorrelated_2018		
19	prop_binch35_bin0		
20	rdy		
21	lumi_uncor_2018		
22	lumi_uncor_2017		
23	syst_pu		
24	syst_l_correlated		
25	rtt		
26	prop_binch11_bin0		
27	prop_binch33_bin1		
28	prop_binch31_bin2		
29	prop_binch14_bin4		
30	prop_binch2_bin4		
🗕 Fit	+1σ Impact	-2 -1 0 1 2 -2 -1 0	1 2
× Pu	II -1o Impact	$(\hat{\theta} - \theta_i) / \sigma_i (\hat{\theta} - \theta_i) / \sqrt{\sigma_i^2} - \sigma^2$	Δr̂





Summary



- Focus on T' → top+H dileptonic SS final state using Run 2 samples.
- Analysis strategy settled: object identification, selection criteria and definition of the discriminant variables.
- Definition of the Control Regions, reasonable data/MC agreement.
- First impact of nuisances examined for full Run 2.
- Perspectives:
 - Apply remaining recommended CMS corrections to the simulated events.
 - Exclusion limits at 95% CL in the [600 GeV, 1200 GeV] range.







Back-up



VLQ production



Several extensions of the Standard Model (SM) predict the	
existence of VLQs:	

 \circ Spin $\frac{1}{2}$ fermions.

Slides from Francesco

- Left-handed and right-handed components behave in the same way under the SM symmetry group.
- Vector current couplings to the weak gauge bosons.
- Non-Yukawa coupling mass-terms for VLQs are allowed.

Туре	Charge
Х	+5/3
Т	+2/3
В	-1/3
Y	-4/3

SU(2) Multiplets					
Singlets	T,B				
Doublets	(T,B),(X,T),(B,Y)				
Triplets	(X,T,B),(T,B,Y)				



VLQ production



- VLQs could be produced both singly and in pair:
 - Pair production:
 - Strong interaction processes.
 - Model independent cross section, suppressed for large VLQ mass.
 - Single production:
 - Electroweak processes.
 - Cross section depending on VLQ mass and coupling to SM particles.
 - Models foresee preferential mixing with 3rd generation SM quarks.







Туре	Decay channel
Х	tW
Т	tZ, <mark>tH</mark> ,tA,bW
В	bZ,bH,tW
Y	bW



Higgs boson branching ratio decay







T' production





• Single T' produced via electroweak process.











- List of corrections already applied:
 - Generator weights.
 - Pileup weights.
 - B-tag weights.
 - Jet energy corrections (to be updated).
 - Muon SFs (Trigger/Reco/ID/Isolation/Rochester) (to be updated).
 - Electron SFs (Trigger/Reco/ID) (to be updated).
- List of corrections to apply in the future:
 - Jet energy resolution.
- Filters applied:
 - Flag_goodVertices
 - $\circ \quad Flag_globalSuperTightHalo2016Filter$
 - Flag_HBHENoiseFilter
 - Flag_HBHENoiseIsoFilter
 - Flag_EcalDeadCellTriggerPrimitiveFilter

- Flag_BadPFMuonFilter
- Flag_BadPFMuonDzFilter
- Flag_hfNoisyHitsFilter
- Flag_eeBadScFilter
- Flag_ecalBadCalibFilter (2017/2018)



Discriminant variable

 $M_{T,T'}$ is defined as follows.

$$\begin{split} M_{T,T'}^{2} &= \left(\sum_{particles} E_{T}\right)^{2} - \left(\sum_{particles} \overrightarrow{p_{T}}\right)^{2} \\ &= \left(E_{T,lep,Higgs} + E_{T,\nu,Higgs} + E_{T,j1,Higgs} + E_{T,j2,Higgs} + E_{T,lep,top} + E_{T,\nu,top} + E_{T,b,top}\right)^{2} \\ &- \left(\overrightarrow{p_{T,lep,Higgs}} + \overrightarrow{p_{T,\nu,Higgs}} + \overrightarrow{p_{T,\nu,Higgs}} + \overrightarrow{p_{T,j2,Higgs}} + \overrightarrow{p_{T,lep,top}} + \overrightarrow{p_{T,\nu,top}} + \overrightarrow{p_{T,\nu,top}}\right)^{2} \\ &= \left(\overrightarrow{p_{T,\nu,Higgs}} + E_{T,\nu,top} = \sqrt{\overrightarrow{p_{T,\nu,Higgs}^{2}} + M_{T,\nu,thiggs}^{2}} + \sqrt{\overrightarrow{p_{T,\nu,top}^{2}} + M_{T,\nu,top}^{2}} + M_{T,\nu,top}^{2}\right)^{2} \\ &= \left(\overrightarrow{p_{T,\nu,Higgs}} + E_{T,\nu,top} = \sqrt{\overrightarrow{p_{T,\nu,Higgs}^{2}} + M_{T,\nu,top}^{2}}\right)^{2} \\ &= \sqrt{\left(|\overrightarrow{p_{T,\nu,Higgs}}| + |\overrightarrow{p_{T,\nu,top}}|\right)^{2}} \\ &= \sqrt{\left(|\overrightarrow{p_{T,\nu,Higgs}}|^{2} + |\overrightarrow{p_{T,\nu,top}}|^{2} + 2|\overrightarrow{p_{T,\nu,top}}|^{2} + 2|\overrightarrow{p_{T,\nu,Higgs}}||\overrightarrow{p_{T,\nu,top}}|}. \end{split}$$
Hypothesis 1: the two neutrinos are anticolinear (cos (ν_{H}, ν_{t})) = -1).
 $\Rightarrow E_{T,\nu,Higgs} + E_{T,\nu,top} = \sqrt{\overrightarrow{p_{T,\nu,Higgs}^{2}} + 4 \times |\overrightarrow{p_{T,\nu,Higgs}^{2}}||\overrightarrow{p_{T,\nu,top}}|}. \end{aligned}$



Benjamin Blancon Top LHC France 04.09.24 Discriminant variable

Hypothesis 2: $|\overrightarrow{p_{T,\nu,Higgs}}|$ is taken from the GEN information per mass point value. We have two cases.

• If $|\overrightarrow{p_{T,\nu,Higgs}}| > |\overrightarrow{p_{T,\nu,top}}|$, $|\overrightarrow{p_{T,\nu,top}}| = |\overrightarrow{p_{T,\nu,Higgs}}| - |\overrightarrow{p_{T,\nu,top}}|$. $\Leftrightarrow |\overrightarrow{p_{T,\nu,top}}| = |\overrightarrow{p_{T,\nu,Higgs}}| - |\overrightarrow{p_{T,\nu,top}}|$. As $|\overrightarrow{p_{T,\nu,top}}| > 0$, this case occurs when $|\overrightarrow{p_{T,\nu,Higgs}}| > |\overrightarrow{p_{T,MET}}|$. • If $|\overrightarrow{p_{T,\nu,Higgs}}| < |\overrightarrow{p_{T,\nu,top}}|$, $|\overrightarrow{p_{T,\nu,top}}| = |\overrightarrow{p_{T,\nu,top}}| - |\overrightarrow{p_{T,\nu,Higgs}}|$. $\Leftrightarrow |\overrightarrow{p_{T,\nu,top}}| = |\overrightarrow{p_{T,\nu,top}}| - |\overrightarrow{p_{T,\nu,Higgs}}|$. As $|\overrightarrow{p_{T,\nu,top}}| > 0$, this case occurs when $|\overrightarrow{p_{T,\nu,Higgs}}| < |\overrightarrow{p_{T,MET}}|$.

 $\Rightarrow M_{T,T'} = \sqrt{\left(E_{T,lep,Higgs} + E_{T,j1,Higgs} + E_{T,j2,Higgs} + E_{T,lep,lop} + E_{T,b,lop} + \sqrt{\overrightarrow{p_{T,MET}}^2 + 4 \times \left|\overrightarrow{p_{T,\nu,Higgs}}\right| \times \left||\overrightarrow{p_{T,\nu,Higgs}}| \pm |\overrightarrow{p_{T,MET}}|\right|}\right)^2 - \left(\overrightarrow{p_{T,Jjlb}} + \overrightarrow{p_{T,MET}}\right)^2.$

- Figure of merit: Significance defined as S = sqrt(2*lnQ) where $lnQ = \sum_{bins} (s+b)*ln(1+s/b) s$.
- Run 2, All channels ($\mu\mu/e\mu/ee$):
 - Strategy 1: $S = 0.467 \sigma$.
 - $\circ \quad Strategy 2: S = 0.307 \ \sigma.$



Top LHC France Signal selection - Optimization

- First 'naive' cut to have the best S/B ratio for the target Cut variable (example: signal bump at $M_{TT} = 685$ GeV for Cut variable > 160 GeV).
- Cut variable (y-axis) vs M_{T,T} (x-axis) is plotted in a 2D histogram for the background.
- Percentage of the background yield kept in each bin to plot the related 1D graph. The percentage is chosen so that the signal will be not modified, i.e. the 'naive' cut is still valid. 2
- Fit of the 1D graph.

 \rightarrow New Cut that preserves the background shape while keeping the signal strength! (3)

Cut variable f(M___).



Private work (CMS Simulation)

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Signal region (2016) splitted by channel³⁰

P²i

CMS



Signal region (2017) splitted by channel³¹

P²i







Uncertainties



- Theoretical cross sections:
 - tt: 6%.
 - \circ Single top: 30%.
 - $\circ \quad t\bar{t}X{:}\ 20\%.$
 - Dibosons: 10%.
 - Drell-Yan: 25%.
- Leptons:
 - Electron (Reco/ID) (systematics).
 - Muon (ID/Isolation) (systematics+statistics per year).
- Jets:
 - Heavy jets b-tagging (correlated/uncorrelated per year) (systematics).
 - Light jets b-tagging (correlated/uncorrelated per year) (systematics).
- Pileup (systematics).
- Prefiring (systematics).
- Luminosity (systematics):
 - \circ Uncorrelated per year.
 - Correlated for 2016-2018 and 2017-2018.

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Private work (CMS Simulation)

P2i

 $\hat{\mathbf{r}} = \mathbf{1.0}_{-1.0}^{+5.1}$ rttx 2 rtt 3 syst b correlated lumi cor 2016 2018 4 5 prop binch1 bin5 6 lumi_uncor_2018 7 prop_binch2_bin5 8 syst b uncorrelated 2018 9 prop_binch3_bin5 10 prop_binch1_bin4 11 prop binch2 bin4 12 rdibosons 13 syst_l_correlated 14 syst_elec_id 15 syst elec reco 16 rsingletop 17 syst I uncorrelated 2018 18 prop binch2 bin6 19 prop_binch2_bin7 20 prop binch3 bin6





Control regions (2016)







Nuisance pools (2016)



Private work (CMS Simulation)			$\hat{\mathbf{r}} = 1.0_{-1.0}^{+5.8}$	Private work (CMS Simulation)	1	$\hat{\mathbf{r}} = 1.0^{+19.0}_{-1.0}$
1	rttx	· · · · · · · · · · · · · · · · · · ·		1 ""	· · · · · · · · · · · · · · · · · · ·	
2	rtt	• • • • • • • • • • • • • • • • • • •		2 syst_b_correlated	••••••••••	
3	prop_binch1_bin5			3 rsingletop	••••••••••••••••••••••••••••••••••••••	
4	prop_binch1_bin4	• • • • • • • • • • • • • • • • • • •		4 prop_binch2_bin9		
5	syst_prefiring	• • • • • • • • • • • • • • • • • • •		5 prop_binch3_bin7	▶ →	
6	prop_binch2_bin5			6 syst_pu		
7	lumi_uncor_2016	• • • • • • • • • • • • • • • • • • •		7 prop_binch1_bin4		
8	syst_pu	• • • • • • • • • • • • • • • • • • •		8 rdy		
9	rsingletop	↓ ★ • 1		9 prop_binch2_bin5	••••••••••••••••••••••••••••••••••••••	
10	prop_binch2_bin4			10 syst_prefiring		
11	prop_binch1_bin7	••••••••••••••••••••••••••••••••••••••		11 prop_binch1_bin7	▶ →	
12	lumi_cor_2016_2018			12 prop_binch2_bin1		
13	syst_l_correlated	• • • • •		13 prop_binch2_bin8		
14	syst_elec_reco			14 prop_binch1_bin5	••••••••••••••••••••••••••••••••••••••	
15	prop_binch2_bin6	• • • • • • • • • • • • • • • • • • •		15 prop_binch3_bin5	••••••••••••••••••••••••••••••••••••••	
16	prop_binch3_bin6	••••••••••		16 syst_elec_reco		
17	syst_elec_id	••••••••••••••••••••••••••••••••••••••		17 prop_binch3_bin4	*****	
18	rdibosons	↓ ↓ ↓		18 prop_binch3_bin8		
19	syst_l_uncorrelated_2016	• • • • •		19 prop_binch1_bin8	••••••••••••••••••••••••••••••••••••••	
20	prop_binch3_bin4			20 prop_binch1_bin6		

SR

CR tt2l



Nuisance pools (2016)





CR tt1l

CR ttX

P2i

Nuisance pools (2016)





All regions



Control regions (2017)







Nuisance pools (2017)



Private work (CMS Simulation)		$\hat{\mathbf{r}} = 1.0^{+6.1}_{-1.0}$	Private work (CMS Simulation)		$\hat{\mathbf{r}} = 1.0_{-1.0}^{+19.0}$
1 rttx	· · · · · · · · · · · · · · · · · · ·		1 prop_binch3_bin8	· · · · · · · · • · · · · • • ! · · · · ! · ·	
2 rtt	× • • • • • • • • • • • • • • • • • • •		2 rtt	•••••	
3 lumi_uncor_2017	*		3 rsingletop	••••••••••••••••••••••••••••••••••••••	
4 syst_b_correlated			4 prop_binch3_bin7	••••••••••••••••••••••••••••••••••••••	
5 prop_binch2_bin5	***		5 prop_binch1_bin1	••••••••••••••••••••••••••••••••••••••	
6 prop_binch1_bin4			6 prop_binch2_bin7		
7 prop_binch1_bin5			7 prop_binch1_bin4	• • • • •	
8 syst_prefiring	•••••••••••		8 prop_binch1_bin8	► *	
9 lumi_cor_2016_2018			9 prop_binch2_bin5	••••••••••••••••••••••••••••••••••••••	
10 syst_b_uncorrelated_2017			10 rdy	••••••••••••••••••••••••••••••••••••••	
11 prop_binch2_bin4	•••••••••		11 prop_binch3_bin6	••••••••••••••••••••••••••••••••••••••	
12 rdibosons			12 lumi_uncor_2017		
13 syst_pu	••••••••••••••••••••••••••••••••••••••		13 syst_b_correlated	• • •••••	
14 syst_l_correlated	••••••••••••••••••••••••••••••••••••••		14 prop_binch2_bin6		
15 syst_elec_id			15 prop_binch3_bin2	••••••••••••••••••••••••••••••••••••••	
16 lumi_cor_2017_2018			16 syst_prefiring		
17 prop_binch3_bin5	••••••••••••••••••••••••••••••••••••••		17 syst_l_correlated	*	
18 prop_binch1_bin6			18 prop_binch1_bin9		
19 syst_elec_reco	••••••••••••••••••••••••••••••••••••••		19 prop_binch1_bin6		
20 syst_l_uncorrelated_2017			20 prop_binch2_bin8	••••••••••••••••••••••••••••••••••••••	

CR tt2l

SR



Nuisance pools (2017)





CR ttX

CR tt1l



Nuisance pools (2017)



Private work (CMS Simulation)

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All regions