

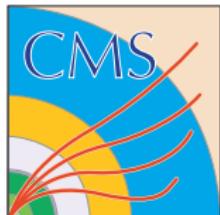
Search for $t\bar{t}$ resonances in CMS

Top LHC France 2016, 19-20 May 2016

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On Behalf of the CMS collaboration

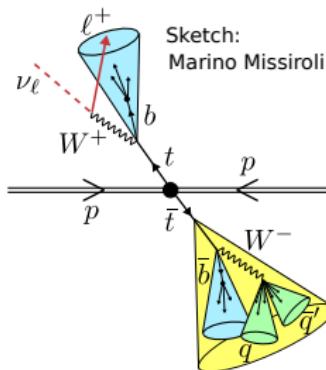
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May 19th, 2016



Introduction

- Numerous BSM models predict new particles with enhanced couplings to the top quark
- Massive new particles could manifest as resonances in the $t\bar{t}$ pairs production, visible in the $t\bar{t}$ mass spectrum
 - ▶ Leptophobic topcolor Z' bosons
 - ▶ Kaluza–Klein (KK) excitations of a gluon predicted in various extensions of the Randall–Sundrum (RS) model (model with extra-dimensions)
- We present here a model-independent search for the production of spin-1 heavy resonances decaying into $t\bar{t}$ in boosted semileptonic final state at $\sqrt{s} = 13$ TeV



$$t\bar{t} \rightarrow (W^+ b)(W^- \bar{b}) \rightarrow (q_1 \bar{q}_2 b)(l^- \bar{\nu}_l \bar{b}) + \text{charge conjugate}$$

Datasets

■ Data samples

- ▶ 2015 data recorded by CMS (2.6 fb^{-1})
- ▶ $\sqrt{s} = 13 \text{ TeV}$

■ MC samples

- ▶ $t\bar{t}$
- ▶ $W + \text{jets}$
- ▶ $Z + \text{jets}$
- ▶ Diboson (WW, WZ, ZZ)
- ▶ Single top (s- and t-channel)
- ▶ Z' boson with same LH and RH couplings to fermions as the SM Z boson
 - Masses ranging from 500 GeV to 4 TeV
 - Resonances width Γ/M of (narrow hypothesis) 1% and (wide hypothesis) 10% and 30% (only for mass points of 1, 2, 3 and 4 TeV)
- ▶ KK gluon excitations
 - Masses ranging from 500 GeV to 4 TeV
 - Width is mass dependent

Background

Signal

Event reconstruction

- Events are reconstructed using Particle Flow (PF) algorithm
- PU mitigation: using PU Charged Hadrons Subtraction (CHS) *i.e.* removes charged hadrons not associated with leading primary vertex
- Jets: reconstructed using anti- k_T algorithm with 2 different cone parameter choices:
 - ▶ $R = 0.4$: AK4 jets or small-radius jets
 - ▶ $R = 0.8$: AK8 jets or large-radius jets
- Identify small-radius jets coming from b quarks using CMS b-tagging algorithm (CSV) with WP corresponding to $\sim 65\%$ efficiency and mis-identification rate of $\sim 0.1\%$
- Final state objects can overlap due to high Lorentz boost of t quark's decay products: identify large-radius jets coming from hadronically-decaying top using t-tagging algorithm
 - ▶ Based on jet soft-drop mass M_{SD} and N-subjettiness ratio τ_{32}
 - ▶ $110 < M_{SD} < 210 \text{ GeV}$
 - ▶ $\tau_{32} = \tau_3 / \tau_2 < 0.69$
$$\left. \begin{array}{l} \\ \end{array} \right\} \sim 50\% \text{ efficiency and } \sim 3\% \text{ misidentification rate}$$
- Corrections on JES and JER propagated to MET $\sum_{\text{PF particle}} \vec{p}_T$

Selection

Muon channel

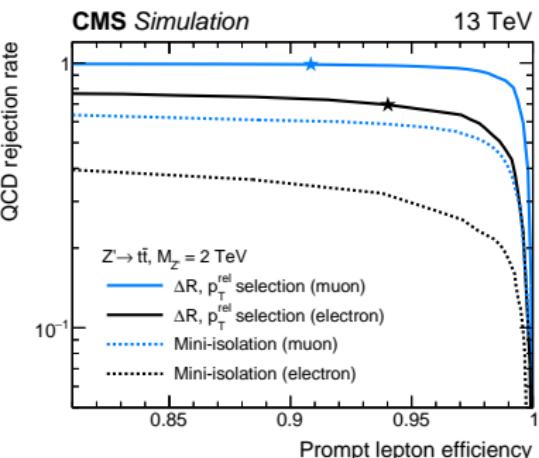
- HLT_Mu45_eta2p1
- Exactly one muon
- $p_T^\mu > 50$ and $|\eta| < 2.1$
- ≥ 2 jets with $|\eta| < 2.4$, $p_T^{\text{jet}1} > 150$ GeV, $p_T^{\text{jet}2} > 50$ GeV
- MET > 50 GeV
- $H_T = \text{MET} + p_T^{\text{lep}} > 150$ GeV

Electron channel

- HLT_Ele45_PFJet200_PFJet50
- Exactly one electron
- $p_T^e > 50$ and $|\eta| < 2.5$
- ≥ 2 jets with $|\eta| < 2.4$, $p_T^{\text{jet}1} > 250$ GeV, $p_T^{\text{jet}2} > 70$ GeV
- MET > 120 GeV
- No H_T cut

- Tighter selection in electron channel:
 - ▶ Increased p_T cut due to HLT requirements
 - ▶ Increased MET cut to suppress QCD multijet bkg
- No lepton isolation requirement at trigger or offline level but 2D-cut :

$$\Delta R_{\min}(l, j) > 0.4 \text{ or } p_T^{\text{rel}}(l, j) > 20 \text{ GeV}$$
- Veto on 2nd lepton and 2nd t-tagged jet to avoid overlap with dilepton and all hadronic channel (ensures exclusive selection)



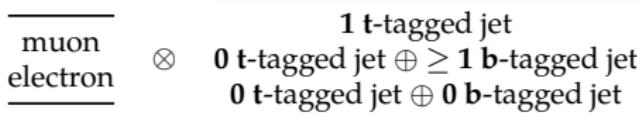
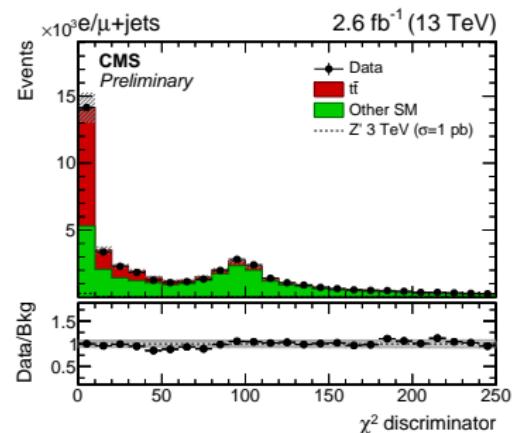
Kinematical reconstruction of $t\bar{t}$ system

■ Kinematical reconstruction of $t\bar{t}$ system

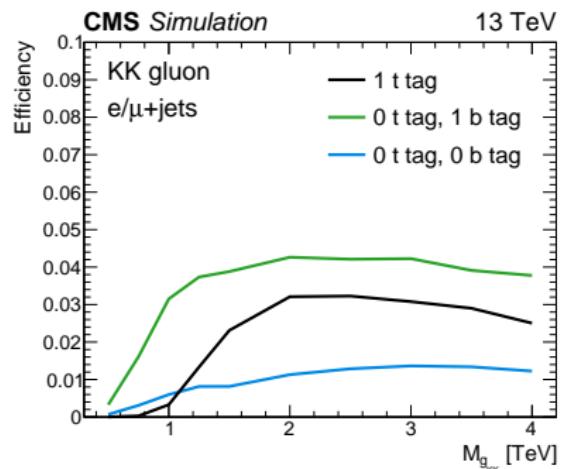
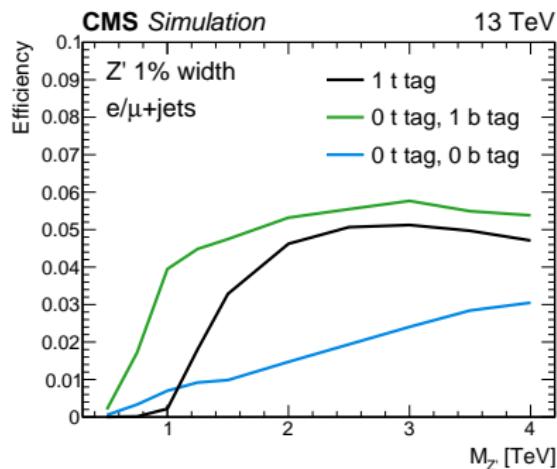
- ▶ MET (\equiv neutrino's p_T) and lepton assigned to leptonic side
- ▶ Neutrino's p_z determined from W-mass constraint
- ▶ Quantify compatibility of each $t\bar{t}$ hypothesis with $t\bar{t}$ decay using a χ^2 discriminator

$$\chi^2 = \left(\frac{M_t^{\text{lep}} - \bar{M}_t^{\text{lep}}}{\sigma_{M_t^{\text{lep}}}} \right)^2 + \left(\frac{M_t^{\text{had}} - \bar{M}_t^{\text{had}}}{\sigma_{M_t^{\text{had}}}} \right)^2$$

- ▶ The hypothesis with smallest χ^2 chosen as reconstructed $t\bar{t}$
- Signal region (SR) defined by $\chi^2_{\min} < 30$ (cut optimized to maximize expected sensitivity of the analysis)
- Final categorization based on lepton flavor, number of b-tagged jets and number of t-tagged jets



Signal efficiency



- Signal efficiency defined by the fraction of events selected, considering all decay channels
- 1 t-tag: rise in efficiency between 1 and 2 TeV due to p_T dependent turn-on of t-tagging algorithm ; reach a plateau (3-4%) at ~ 2 TeV
- 0 t-tag, 1 b-tag: plateau (4-5%) reached earlier
- 0 t-tag, 0 b-tag: continuous increase of efficiency due to p_T requirements on jets and leptons
- Smaller efficiency for KK gluon than Z' originating from a larger fraction of off-shell production resulting in a softer top quark p_T on average



Background estimation

- 2 main backgrounds: $t\bar{t}$ ($1t \oplus 0t+1b$) and $W+jets$ ($0t+0b$)
- $Z+jets$, single top and diboson: constitute small backgrounds overall
- Final background yields determined by a binned ML fit of bkg-only model to data
- Fit strategy:
 - ▶ Several observables (used simultaneously in the binned ML fit):
 - $M_{t\bar{t}}$ spectrum for low $M_{t\bar{t}}$ SR ($1l \oplus \chi^2 < 30 \oplus M_{t\bar{t}} < 2 \text{ TeV}$)
 - $M_{t\bar{t}}$ spectrum for $W+jets$ CR ($1l \oplus \chi^2 > 30$)
 - M_{ll} spectrum for $Z+jets$ CR ($2l \oplus \chi^2 < 30 \oplus 71 < M_{ll} < 111 \text{ GeV}$) where $2l$ means removing lepton veto
 - ▶ Shapes taken from MC distributions (template-based statistical evaluation)
 - ▶ 4 parameters are left unconstrained in the fit: $\sigma_{t\bar{t}}^{\text{SM}}$, $\sigma_{W+jets}^{\text{SM}}$, $\sigma_{Z+jets}^{\text{SM}}$, SF for t-tagging efficiency
 - ▶ Their uncertainties are derived from the fit
 - ▶ All other systematics included as nuisance parameters, using log-normal prior
 - ▶ Best fit values are used to correct the distributions of bkg and signal processes

Systematic uncertainties

Source of syst. uncert.	Uncertainty
t̄ cross section	8%
W + jets cross section	6%
Single top cross section	20%
Z + jets cross section	20%
Di-bosons cross section	20%
Luminosity	2.7%
Pile-up reweighting	$\pm 1\sigma$
Muon ID	$\pm 1\sigma(p_t, \eta)$
Muon trigger	$\pm 1\sigma(p_t, \eta)$
Electron ID	$\pm 1\sigma(p_t, \eta)$
Electron trigger	2%
Jet Energy Scale	$\pm 1\sigma(p_t, \eta)$
Jet Energy Resolution	$\pm 1\sigma(\eta)$
b-tagging	$\pm 1\sigma(p_t, \eta)$
b-tagging mistag rate	$\pm 1\sigma(p_t, \eta)$
t-tagging	unconstrained
t-tagging mistag rate	$\pm 19\%$
ME Q^2 -scale (t̄, W+jets)	$2\mu - \frac{1}{2}\mu$
PS scale (t̄)	$2\mu - \frac{1}{2}\mu$
PDFs	NNPDF 3.0

- We quantify effect of each systematic on the measurement of reconstructed $M_{t\bar{t}}$
- Prior uncertainties of $\sigma_{t\bar{t}}$, $\sigma_{W+\text{jets}}$, $\sigma_{Z+\text{jets}}$ taken from bkg-only fit
- t-tagging efficiency SF left unconstrained during limit setting, whereas other syst are modelled with log-normal distribution
- t-tagging mistag rate SF directly measured in CR dominated with W+jets (main non-top bkg) with an uncertainty of 19%

Systematic uncertainties causing the largest effect

- Dominant experimental systematic uncertainties:
 - ▶ t-tagging efficiency and t-tagging mistag rate in 1 t-tag signal category
 - ▶ b-tagging efficiency and b-tagging mistag rate in categories with no t-tagged jet
- Dominant theoretical uncertainties:
 - ▶ Missing higher orders (scale)
 - ▶ Uncertainties on PDFs
- Impact of the other systematics (pileup, trigger, lepton ID, JEC/JER) at the level of 2% or less
- Table below:
 - ▶ Posterior values
 - ▶ Z' with mass of 2 TeV and width of 1%

	1 t tag			0 t tag, 1 b tag			0 t tag, 0 b tag		
	$t\bar{t}$	W + jets	Z'	$t\bar{t}$	W + jets	Z'	$t\bar{t}$	W + jets	Z'
t- and b-tagging	6.7%	17.0%	7.3%	1.7%	3.6%	5.8%	6.1%	1.1%	12.1%
Scale uncertainty	4.1%	9.9%	–	5.3%	6.1%	–	5.7%	5.8%	–
PDF	2.7%	4.8%	4.2%	1.5%	3.6%	4.2%	1.8%	3.2%	4.8%

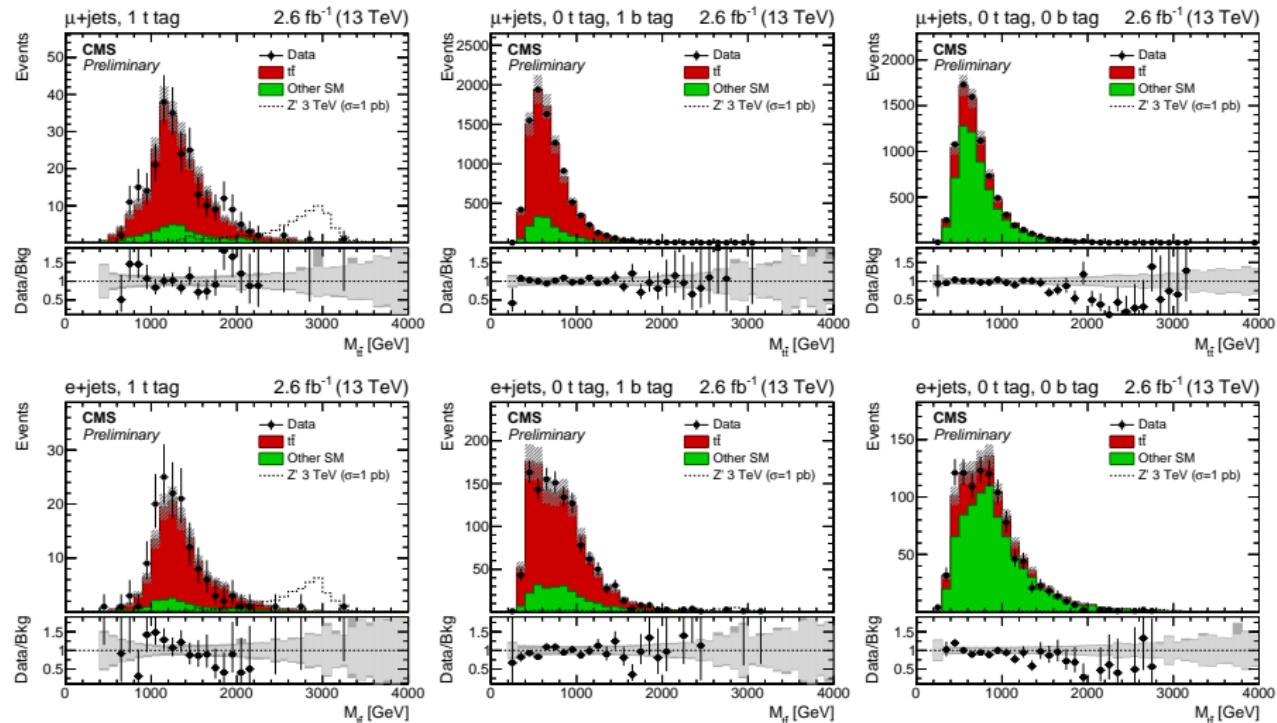
Number of expected and observed events

- Expected yields for SM bkg obtained from the ML fit to data
- Total expected bkg includes MC statistical uncert. and all posterior syst. uncert.

$\mu + \text{jets}$ signal region			
	1 t tag	0 t tag, 1 b tag	0 t tag, 0 b tag
$t\bar{t}$	218 ± 28	7602 ± 826	1965 ± 229
$W + \text{jets}$ (light-f)	27 ± 4	547 ± 54	4675 ± 377
$W + \text{jets}$ (heavy-f)	4 ± 1	333 ± 30	780 ± 65
single-top + DY + VV	9 ± 2	682 ± 111	635 ± 85
Total Background	258 ± 29	9164 ± 856	8055 ± 541
DATA	252	9230	7966

$e + \text{jets}$ signal region			
	1 t tag	0 t tag, 1 b tag	0 t tag, 0 b tag
$t\bar{t}$	119 ± 15	1016 ± 124	248 ± 32
$W + \text{jets}$ (light-f)	13 ± 2	97 ± 10	684 ± 58
$W + \text{jets}$ (heavy-f)	2 ± 1	44 ± 4	84 ± 8
single-top + DY + VV	4 ± 1	103 ± 18	74 ± 10
Total Background	138 ± 16	1260 ± 129	1090 ± 78
DATA	142	1217	1005

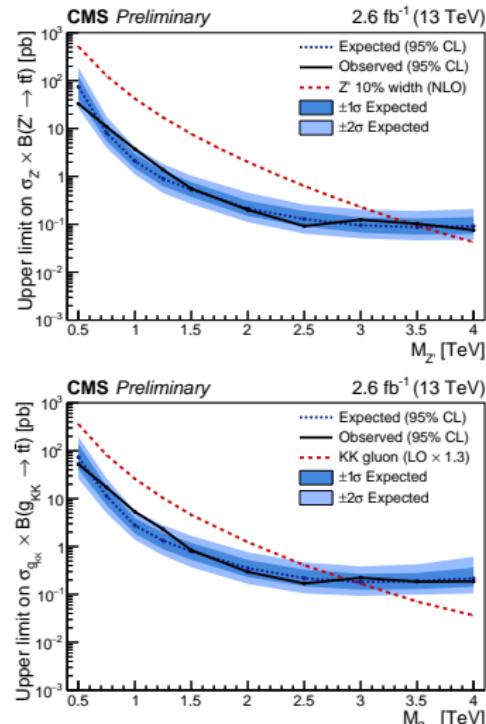
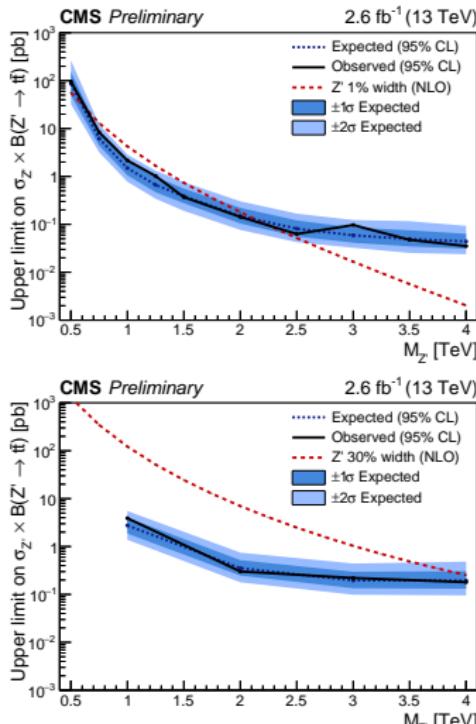
$t\bar{t}$ mass spectrum



- Good agreement between data and bkg prediction
- No significant deviation from expected SM bkg observed in data: we proceed to set limits

Limits setting

- Bayesian method used to extract 95% CL upper limits on $\sigma(pp \rightarrow X) \times BR(X \rightarrow t\bar{t})$
- Performing a template-based statistical evaluation using the reconstructed $M_{t\bar{t}}$ distribution
- 4 benchmark scenarios



Limits setting

- Bayesian method used to extract 95% CL upper limits on $\sigma(\text{pp} \rightarrow X) \times \text{BR}(X \rightarrow t\bar{t})$
- Performing a template-based statistical evaluation using the reconstructed $M_{t\bar{t}}$ distribution
- 4 benchmark scenarios
- Combining muon and electron channels enhances analysis sensitivity

signal	excluded mass regions [TeV]		
	$\mu + \text{jets}$ observed (expected)	$e + \text{jets}$ observed (expected)	combination observed (expected)
Z' (1% width)	0.5 – 1.8 (0.6 – 1.9)	1.0 – 1.1, 1.3 – 2.2 (0.9 – 1.7)	0.6 – 2.3 (0.6 – 2.1)
Z' (10% width)	0.5 – 3.2 (0.5 – 3.3)	0.5 – 3.2 (0.5 – 3.2)	0.5 – 3.4 (0.5 – 3.5)
Z' (30% width)	0.5 – 3.9 (0.5 – 4.0)	0.5 – 3.8 (0.5 – 3.8)	0.5 – 4.0 (0.5 – 4.0)
KK gluon	0.5 – 2.7 (0.5 – 2.8)	0.6 – 2.7 (0.6 – 2.5)	0.5 – 2.9 (0.5 – 2.9)

Conclusion

- A model-independent search for the production of heavy resonances decaying into $t\bar{t}$ has been presented
- Using 2015 data corresponding to an integrated luminosity of 2.6 fb^{-1} recorded by CMS detector in pp collisions at $\sqrt{s} = 13 \text{ TeV}$
- Analysis designed for boosted topologies where hadronically-decaying top is highly boosted and its decay product can overlap
- Non-observation of $t\bar{t}$ resonances at 8 TeV confirmed here (more details on 8 TeV combination in slide [33](#) and next backup slides)

Signal	Expected (observed) 95% CL M(signal) exclusion limit (TeV)	13 TeV ($l+jets$)	8 TeV (comb.)
$Z', \Gamma_{Z'}/M_{Z'} = 1\%$	2.1 (2.3)	2.4 (2.4)	
$Z', \Gamma_{Z'}/M_{Z'} = 10\%$	3.5 (3.4)	2.8 (2.9)	
$Z', \Gamma_{Z'}/M_{Z'} = 30\% (M_{Z'} > 1 \text{ TeV})$	4.0 (4.0)	-	
RS KK gluon	2.9 (2.9)	2.7 (2.8)	

- The analysis of resolved topologies in semileptonic final states at 13 TeV performed in Lyon is ongoing
- Other resonances could show up in $M_{t\bar{t}}$: search for spin 0 resonances decaying to $t\bar{t}$ is also performed in Lyon in collaboration with physicists from Belgium and Germany
- More challenging analysis as spin 0 production interferes with main SM $t\bar{t}$ production

Thanks for your attention!

Links

- Search for $t\bar{t}$ resonances in boosted semileptonic final states in pp collisions at $\sqrt{s} = 13$ TeV:
[CMS-PAS-B2G-15-002](#)
- Search for resonant $t\bar{t}$ production in proton-proton collisions at $\sqrt{s} = 8$ TeV resonances:
[B2G-13-008](#)

Backup

Search for $t\bar{t}$ resonances in boosted semileptonic final state



- Many BSM models predict heavy resonances with enhanced coupling to the top

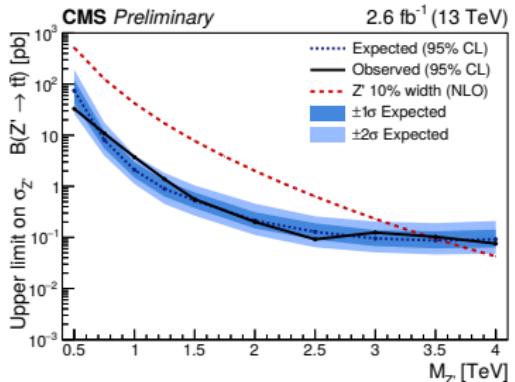
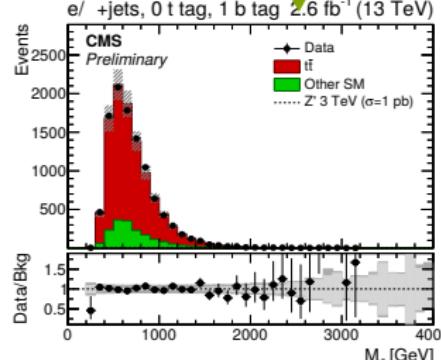
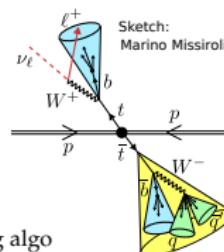
- Leptophobic topcolor Z' bosons
- KK excitations of a gluon in RS model

- Model-independent search for heavy res. decaying to $t\bar{t} \rightarrow (W^+ b)(W^- \bar{b}) \rightarrow (q_1 \bar{q}_2 b)(l^- \bar{\nu}_l \bar{b})$

- Boosted topologies:

- Hadronic t reconstructed as a single jet: top-tagging algo
- No isolation requirement for lepton

- Reconstruct $M_{t\bar{t}}$ using a χ^2 : no signal observed



- Set 95% CL upper limits on $\sigma_{sig} \times \mathcal{B}(sig \rightarrow t\bar{t})$ using Bayesian method
- Non-observation of $t\bar{t}$ resonances at 8 TeV confirmed here

Signal	Expected (observed) 95% CL M(signal) exclusion limit (TeV)	13 TeV ($l+jets$)	8 TeV (comb.)
$Z', \Gamma_{Z'} / M_{Z'} = 1\%$		2.1 (2.3)	2.4 (2.4)
$Z', \Gamma_{Z'} / M_{Z'} = 10\%$		3.5 (3.4)	2.8 (2.9)
$Z', \Gamma_{Z'} / M_{Z'} = 30\% (M_{Z'} > 1 \text{ TeV})$		4.0 (4.0)	-
RS KK gluon		2.9 (2.9)	2.7 (2.8)

Search for resonant $t\bar{t}$ production in boosted semileptonic final states at 13 TeV

Selection

- 1 muon (electron) with $p_T > 50$ (50) GeV and $|\eta| < 2.1$ (2.5)
- ≥ 2 jets with $|\eta| < 2.4$
 - ▶ $p_T^{jet1} > 150$ (250) GeV for muon (electron) channel
 - ▶ $p_T^{jet2} > 50$ (70) GeV for muon (electron) channel
- No isolation for leptons but 2D requirement instead:
 - ▶ $\Delta R(l, j) > 0.4$ or $p_T^{rel}(l, j) > 20$ GeV (j : small-radius jet with minimum angular separation to the lepton ;
 p_T^{rel} : magnitude of p_T lepton orthogonal to jet axis)
 - ▶ measurement of lepton 2D-cut efficiency in data using $Z \rightarrow ll$ (tag-and-probe method) CR
- $H_T^{lep} = E_T^{miss} + p_T^{lep} > 150$ GeV (muon channel)
- $E_T^{miss} > 50$ (120) GeV for muon (electron) channel
- Veto on additional lepton

$M_{t\bar{t}}$ reconstruction

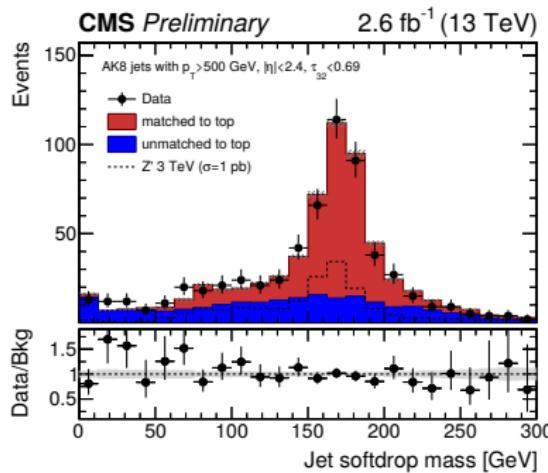
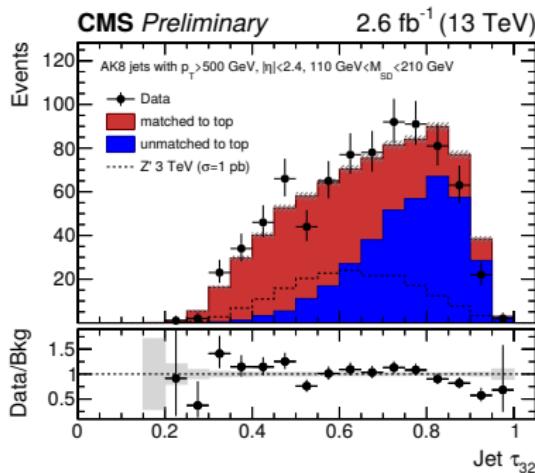
- 2 collections of jets:
 - ▶ Small-radius jets (AK4 jets)
 - ▶ Large-radius jets (AK8 jets)
- Use small-radius jets for b-tagging
- Use large-radius jets for top tagging
 - ▶ Soft-drop mass: $110 < M_{SD} < 210$ GeV
 - ▶ $\tau_{32} < 0.69$
- Events without top-tagged jet: only small-radius jets are used for both hadronic and leptonic top reconstruction
- Events with top-tagged jet: top-tagged jet assigned to hadronic top and only small-radius jets with $\Delta R > 1.2$ from t-tagged jet are used to reconstruct leptonic top decay

$$\chi^2 = \left(\frac{M_{lep} - \bar{M}_{lep}}{\sigma_{M_{lep}}} \right)^2 + \left(\frac{M_{had} - \bar{M}_{had}}{\sigma_{M_{had}}} \right)^2$$

- Take hypothesis with smallest χ^2 (χ^2_{min})
- Signal region: events are required to have $\chi^2_{min} < 30$

Validation of t-tagging variables distributions

- $\chi^2_{min} < 30$: events dominated by $t\bar{t}$ background (plots)
- $\chi^2_{min} > 30$: events dominated by W+jets background
- Good agreement between data and simulation



Categorization

- 6 categories based on lepton flavour, number of b-tagged and t-tagged jets:
 - ▶ 1 t-tag, 0 t-tag + 1 b-tag, 0 t-tag + 0 b-tag

Background model and normalization

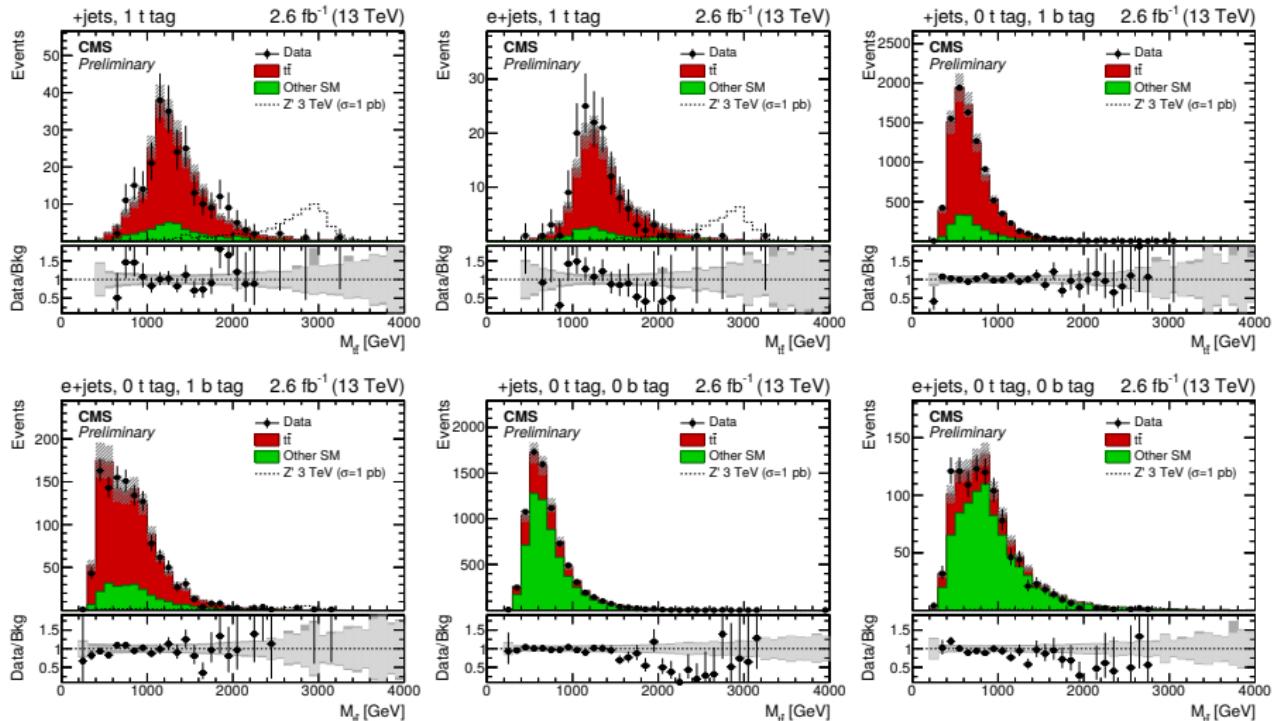
- Final background estimates determined by fitting background-only hypothesis to the data
- Several observables used simultaneously in a binned maximum likelihood fit to constraint different uncertainties of bkg model using the data
- Different observables:
 - ▶ $M_{t\bar{t}}$ in low-mass $l+jets$ SR ($M_{t\bar{t}} < 2$ TeV, $\chi^2_{min} < 30$):
 - ▶ $M_{t\bar{t}}$ in high- χ^2 CR ($\chi^2_{min} > 30$):
 - ▶ M_{ll} in dilepton CR (remove lepton veto, Z-mass window $71 < M_{ll} < 111$ GeV):
- $\sigma_{t\bar{t}}$, σ_{W+jets} , σ_{Z+jets} and t-tag SF left unconstrained in the fit
 - ▶ Derived from MLFit

Main systematics

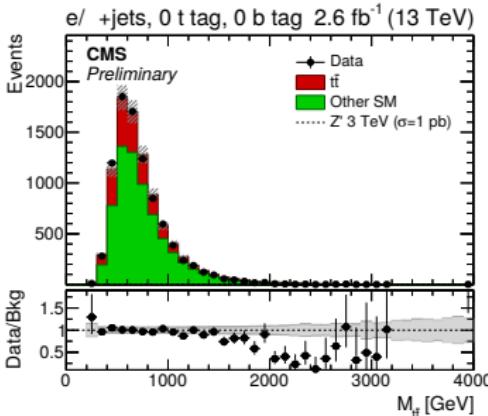
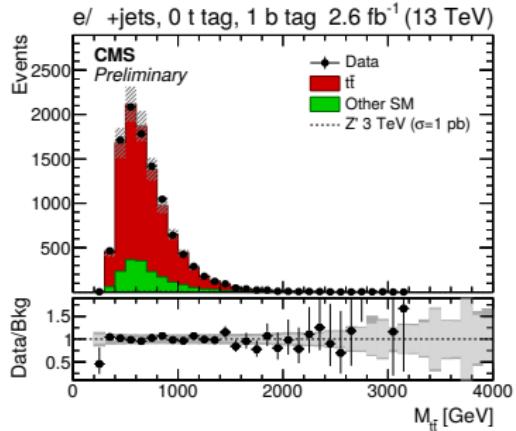
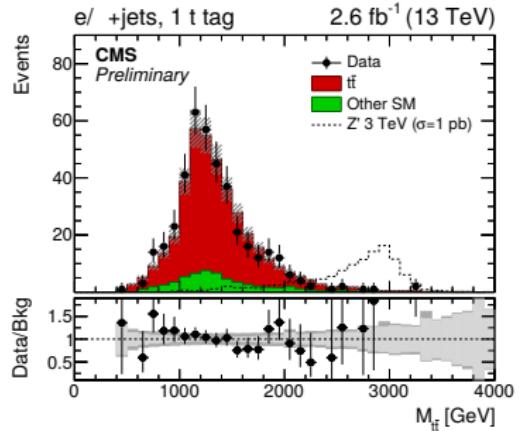
Table 1: Summary of largest systematic uncertainties for the $t\bar{t}$ and $W + \text{jets}$ backgrounds and a Z' signal with mass of 2 TeV and relative width of 1%. Shown are the posterior values. Uncertainties affecting all categories equally originate from the luminosity measurement (2.7%), the trigger efficiency (1.3%) and the lepton identification (1.2%). The posterior uncertainties on the cross sections are 6% for both, $t\bar{t}$ and $W + \text{jets}$ production.

	1-toptag			0-toptag, 1-btag			0-toptag, 0-btag		
	$t\bar{t}$	$W + \text{jets}$	Z'	$t\bar{t}$	$W + \text{jets}$	Z'	$t\bar{t}$	$W + \text{jets}$	Z'
t- and b-tagging	6.7%	17.0%	7.3%	1.7%	3.6%	5.8%	6.1%	1.1%	12.1%
Scale uncertainty	4.1%	9.9%	–	5.3%	6.1%	–	5.7%	5.8%	–
PDF	2.7%	4.8%	4.2%	1.5%	3.6%	4.2%	1.8%	3.2%	4.8%

$M_{t\bar{t}}$ distributions after maximum likelihood fit



$M_{t\bar{t}}$ distributions after maximum likelihood fit: summing e and μ



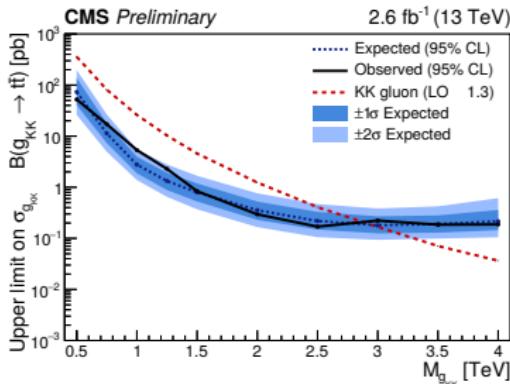
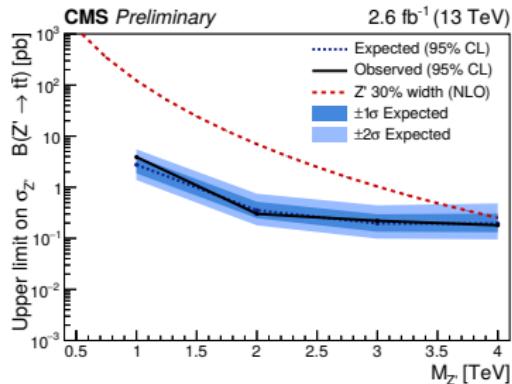
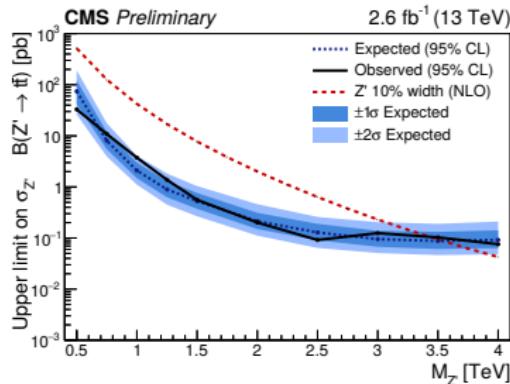
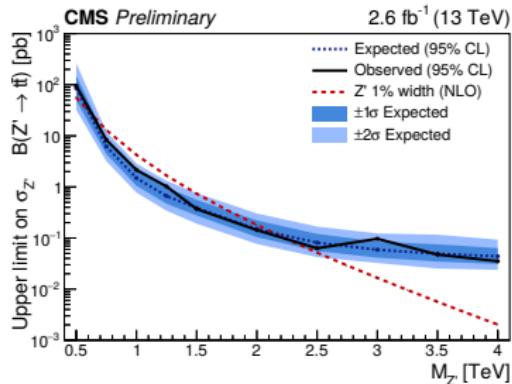
Number of events in signal region

Table 2: Number of events in the signal region. The expected yields for SM backgrounds are obtained from the maximum-likelihood fit to the data described in the text. The uncertainties reported for the background processes include the MC statistical uncertainties and the posterior systematic uncertainties on the SM cross sections.

$\mu + \text{jets}$ signal region			
	1-toptag	0-toptag, 1-btag	0-toptag, 0-btag
$t\bar{t}$	218 ± 36	7599 ± 1252	1964 ± 324
$W + \text{jets}$ (light-f)	26 ± 2	546 ± 42	4665 ± 353
$W + \text{jets}$ (heavy-f)	4 ± 1	332 ± 27	779 ± 61
single-top + DY + VV	10 ± 2	683 ± 118	635 ± 80
Total Background	258 ± 36	9160 ± 1258	8043 ± 489
DATA	252	9230	7966

$e + \text{jets}$ signal region			
	1-toptag	0-toptag, 1-btag	0-toptag, 0-btag
$t\bar{t}$	119 ± 20	1015 ± 167	247 ± 41
$W + \text{jets}$ (light-f)	13 ± 1	97 ± 8	680 ± 52
$W + \text{jets}$ (heavy-f)	2 ± 0	44 ± 4	84 ± 7
single-top + DY + VV	4 ± 1	103 ± 19	75 ± 10
Total Background	138 ± 20	1259 ± 168	1086 ± 67
DATA	142	1217	1005

Limits



Limits summary

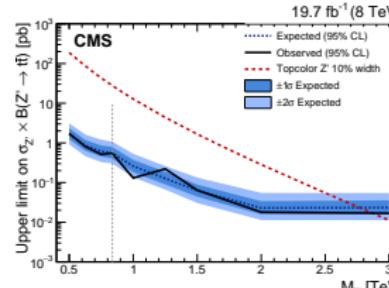
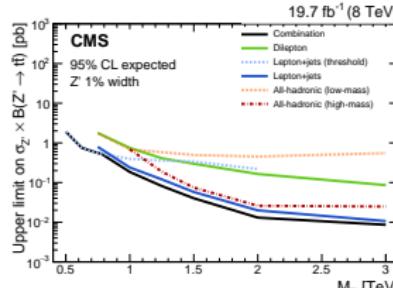
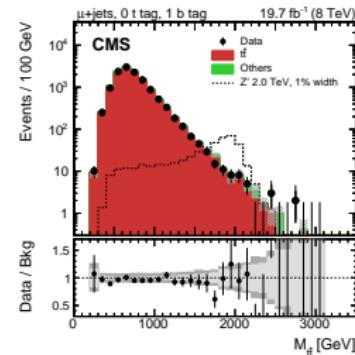
Table 3: Observed and expected excluded mass ranges for the BSM models considered in the statistical analysis. Mass limits are given for the $\mu + \text{jets}$ and $e + \text{jets}$ channels separately and for their combination.

signal	excluded mass regions [TeV]		
	$\mu + \text{jets}$ observed (expected)	$e + \text{jets}$ observed (expected)	combination observed (expected)
Z' (1% width)	0.5 – 1.8 (0.6 – 1.9)	1.0 – 1.1, 1.3 – 2.2 (0.9 – 1.7)	0.6 – 2.3 (0.6 – 2.1)
Z' (10% width)	0.5 – 3.2 (0.5 – 3.3)	0.5 – 3.2 (0.5 – 3.2)	0.5 – 3.4 (0.5 – 3.5)
Z' (30% width)	0.5 – 3.9 (0.5 – 4.0)	0.5 – 3.8 (0.5 – 3.8)	0.5 – 4.0 (0.5 – 4.0)
KK gluon	0.5 – 2.7 (0.5 – 2.8)	0.6 – 2.7 (0.6 – 2.5)	0.5 – 2.9 (0.5 – 2.9)

Search for resonant $t\bar{t}$ production at 8 TeV

Search for $t\bar{t}$ resonances at 8 TeV: summary

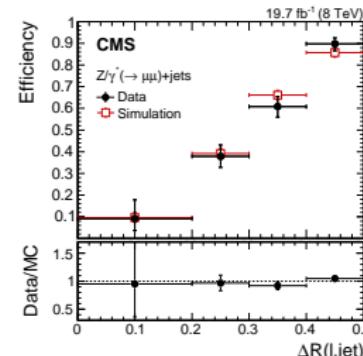
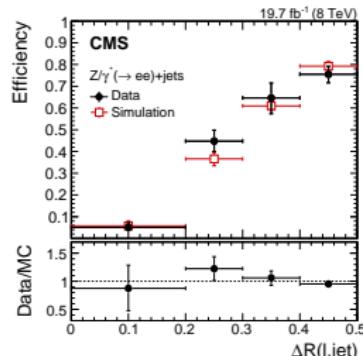
- Many BSM models predict heavy resonances with enhanced coupling to the top
 - ▶ Leptophobic topcolor Z' bosons
 - ▶ Kaluza–Klein excitations of a gluon in the Randall–Sundrum model
- Model-independent search for the production of heavy resonance decaying into top pair
- Dedicated analyses depending on W decay mode:
 - ▶ Dilepton
 - ▶ Lepton+jets: one analysis optimized for boosted topologies, one for threshold production of $t\bar{t}$ (best sensitivity for resonance masses below 0.75 TeV)
 - ▶ All-hadronic: 2 different selections, one optimized for higher resonance masses, one for lower resonance masses (decay products still collimated)
- $M_{t\bar{t}}$ distributions show no evidence of signal
- Combining analyses (lepton+jets threshold result below 0.75 TeV, combination of boosted analysis above) to set 95% CL upper limits on $\sigma_{sig} \times \mathcal{B}(sig \rightarrow t\bar{t})$ using Bayesian method (likelihood: product of Poisson laws in each bin for each cat. in each channel)



Signal	Expected	Observed
$Z', \Gamma', / M_{Z'} = 1.2\%$	2.4	2.4
$Z', \Gamma', / M_{Z'} = 10\%$	2.8	2.9
RS KK gluon	2.7	2.8

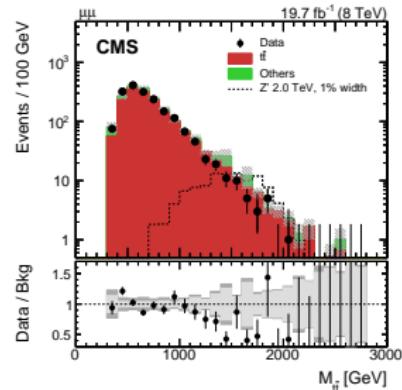
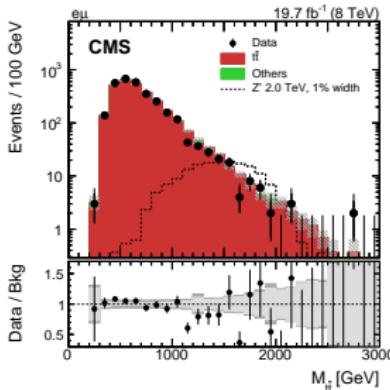
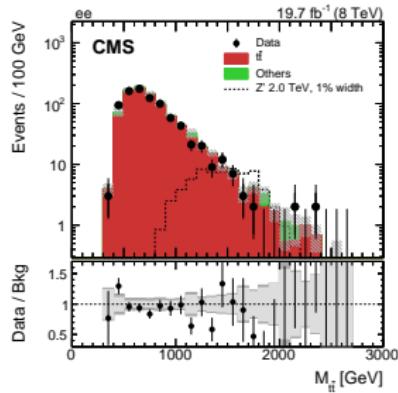
Selection: dilepton channel

- 2 leptons of opposite charges (from highly Lorentz-boosted top: non isolated lepton that partially or fully overlaps with the b jet)
 - ▶ ee channel: 2 electrons with $p_T > 85/20$ GeV, $|\eta| < 2.5$
 - ▶ e μ channel: 1 muon with $p_T > 45$ GeV and $|\eta| < 2.1$, and 1 electron with $p_T > 20$ GeV, $|\eta| < 2.5$
 - ▶ $\mu\mu$ channel: 2 muons with $p_T > 45/20$ GeV and $|\eta| < 2.1/2.4$
- $M_{ll} > 12$ GeV and outside $76 < M_{ll} < 106$ GeV (ee and $\mu\mu$ channels)
- At least 2 jets with $p_T > 100/50$ GeV and $|\eta| < 2.5$
- 2D isolation variable: $\Delta R(l, jet) > 0.5$ or $p_{T,rel}(l, jet) > 15$ GeV ($p_T(l)$ wrt the axis of the closest jet) (using only jets with $p_T > 30$ GeV)
- $E_T^{miss} > 30$ GeV (ee and $\mu\mu$ channels)
- At least 1 of the 2 leading jets required to be b-tagged (CSVM) OR both b-tagged (CVSL)
- $\Delta R(l_1, jet) < 1.2$ and $\Delta R(l_2, jet) < 1.5$



Dilepton channel: mass reconstruction

- $M(p_{l_1} + p_{l_2} + p_{j_1} + p_{j_2} + p_{\nu_1} + p_{\nu_2}) \sim M(t\bar{t})$
- Use \vec{p}_T^{miss} x and y components as p_x and p_y of the pair of neutrinos, p_z components of each neutrino is set to 0

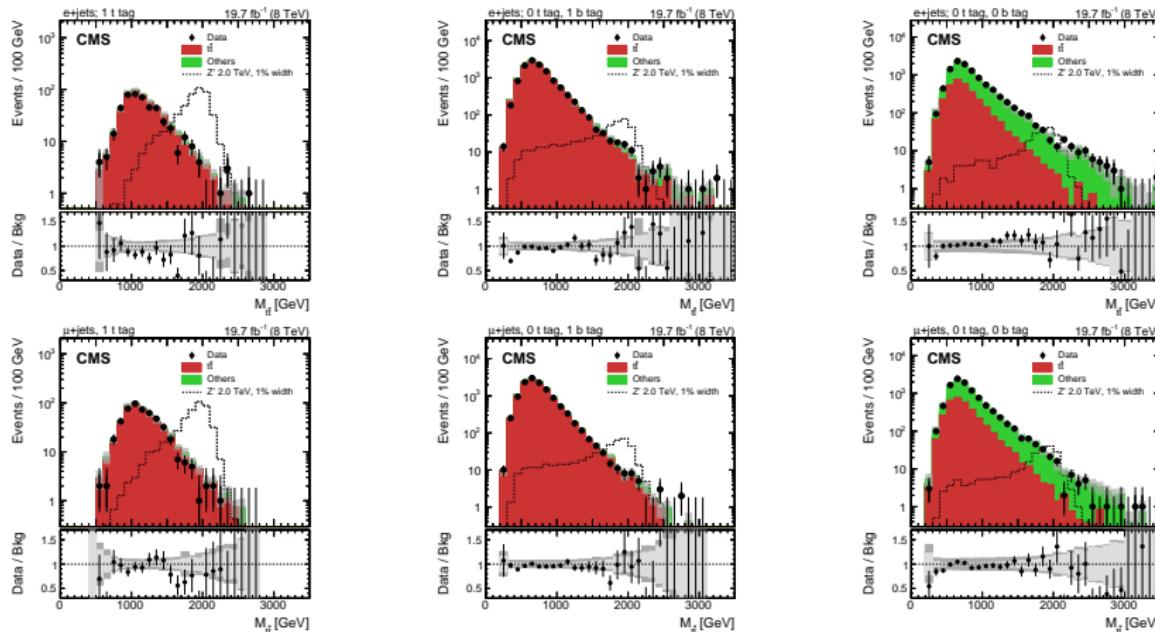


Selection: lepton+jets channel (boosted analysis)

- Exactly 1 electron with $p_T > 35$ GeV and $|\eta| < 2.5$ or 1 muon with $p_T > 45$ GeV and $|\eta| < 2.1$
- Veto on a second reconstructed lepton (avoid overlap with dilepton channel)
- At least 2 jets with $p_T > 150/50$ GeV and $|\eta| < 2.4$
- Reject event with ≥ 2 CA8 t-tagged jets (avoid overlap with all-hadronic channel)
- $E_T^{\text{miss}} > 50$ GeV
- $p_T^l + E_T^{\text{miss}} > 150$ GeV
- 2D isolation criteria: $\Delta R(l, \text{jet}) > 0.5$ or $p_{T,\text{rel}}(l, \text{jet}) > 25$ GeV (using only jets with $p_T > 25$ GeV)
- Ensure \vec{p}_T^{miss} not pointing along transverse direction of electron or leading jet:
 $|\Delta(e \text{ or } \text{jet}, \vec{p}_T^{\text{miss}}) - 1.5| < E_T^{\text{miss}}/50$ GeV

Lepton+jets: mass reconstruction

- $\chi^2 = \chi^2_{m_t^{Lep}} + \chi^2_{m_t^{Hadr}} < 50$, choosing jets combination with smallest χ^2
- In case a CA8 t-tagged jet found: all jets with $\Delta R < 1.3$ from the t-tagged jet removed from list of possible hypotheses
- Electron channel: $p_T^{t,Lep} > 140$ GeV (multijet bkg suppression)



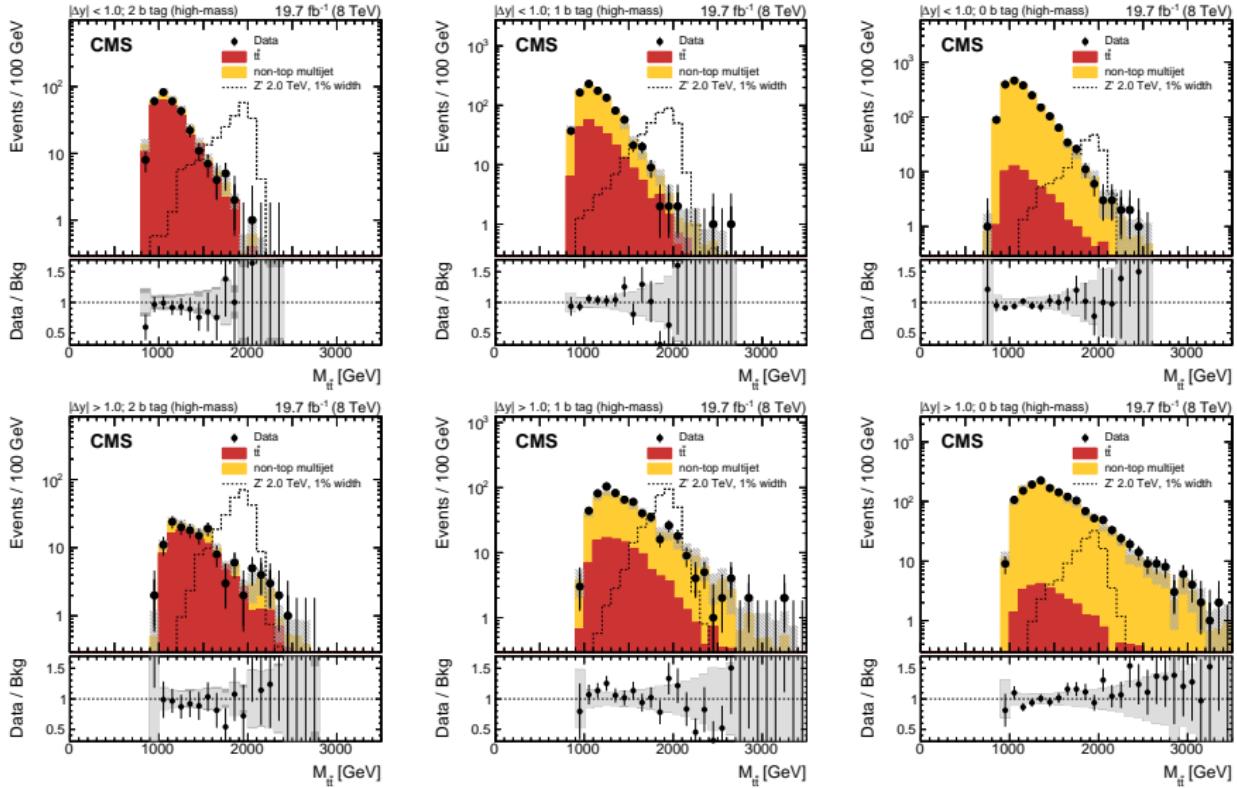
Selection: all-hadronic channel

Two exclusive selection:

- One optimized for higher resonance masses:
 - ▶ 2 CA8 t-tagged jets with $p_T > 400$ GeV and $|y| < 2.4$
 - ▶ $|\Delta\phi| > 2.1$ radians between jets (separated in azimuthal angle)
 - ▶ Rapidity difference between the 2 jets used to divide events in 2 categories : $|\Delta y| < 1.0$ and $|\Delta y| > 1.0$ (QCD multijet bkg with light-quark and gluon FS dominantly populating this region), Z' signal with $m = 2$ TeV equally split
 - ▶ Subdivided again, depending on number of CA8 t-tagged jets containing b-tagged subjet (0, 1, 2) \rightarrow 6 exclusive search regions with highest sensitivity in the categories with 2 b-tagged CA8 jets
- One optimized for lower resonance masses (decay products still somewhat collimated):
 - ▶ Applied to events that failed high mass selection
 - ▶ Decay product less collimated
 - ▶ 2 CA15 t-tagged jets with $p_T > 200$ GeV and $|y| < 2.4$
 - ▶ Sample split: $H_T < 800$ GeV or $H_T > 800$ GeV ($H_T = \sum p_T^{jet}$, using $p_T^{jet} > 50$ GeV)
 - ▶ Subdivided again wrt number of b-tagged CA15 jets

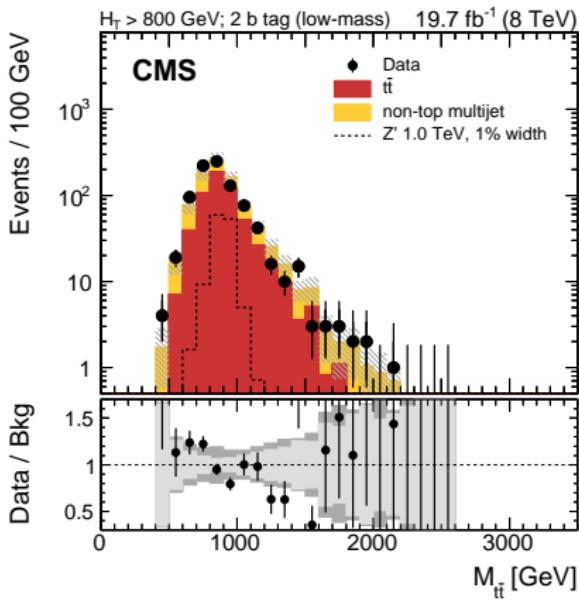
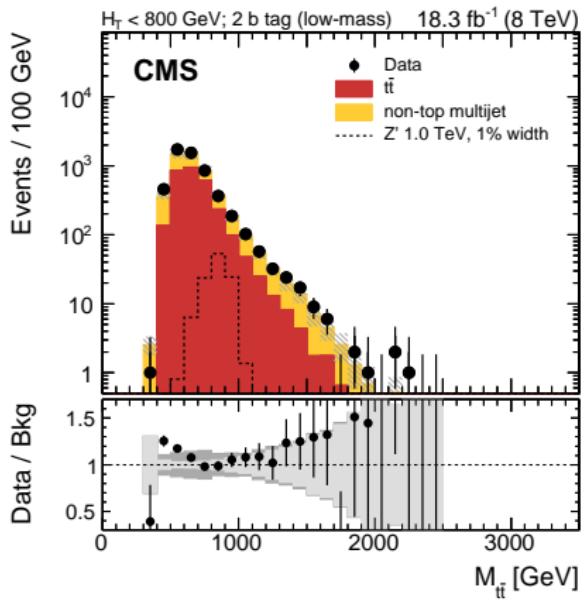
All-hadronic: mass reconstruction

High mass selection



All-hadronic: mass reconstruction

Low mass selection



Background normalization

Boosted analyses:

- Main source of irreducible background in all channels arises from SM $t\bar{t}$ production
- In the lepton+jets channels, W+jets production contributes to events without a CA8 t-tagged jet
- Single top quark, Z+jets, and diboson production constitute small backgrounds overall (dilepton and lepton+jets channels)
- Except for the non-top-quark multijet backgrounds in the all-hadronic channels, the shapes of all SM backgrounds are estimated from simulation
- The total yield of the simulated samples is obtained with a maximum likelihood fit to the $M_{t\bar{t}}$ distributions
 - ▶ Nuisance parameters are included in the fit to take into account the effect of systematic uncertainties
 - ▶ The parameters are constrained using log-normal probability density functions and are fitted simultaneously with the parameters corresponding to the background normalization

Threshold analysis (lepton+jets channel):

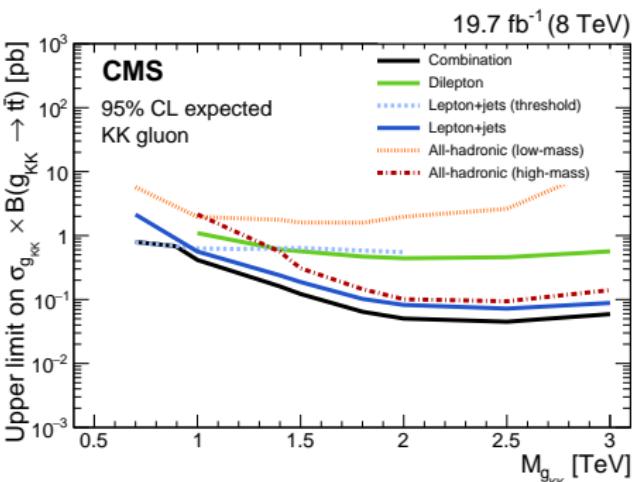
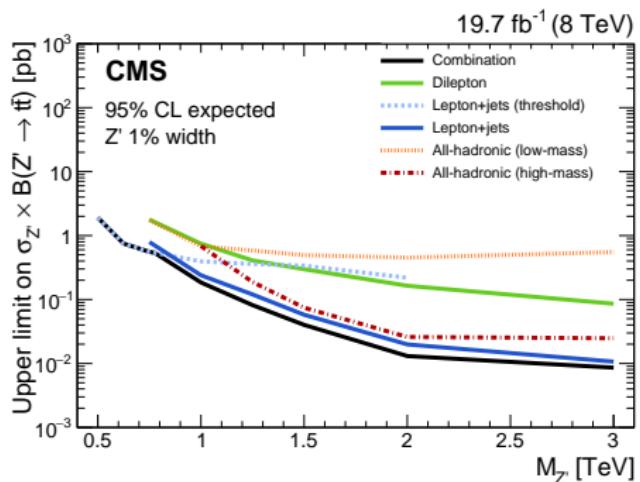
- Background estimated using data-driven technique

- ⊕: uncorrelated uncertainties that apply to a given channel
- ⊕: uncertainties correlated between channel

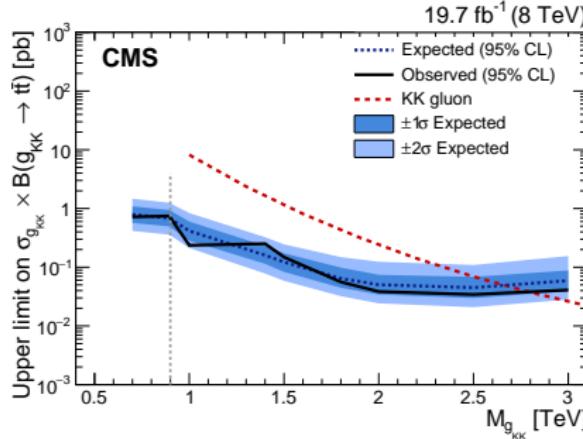
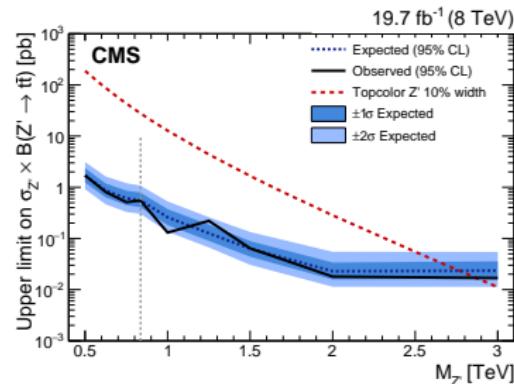
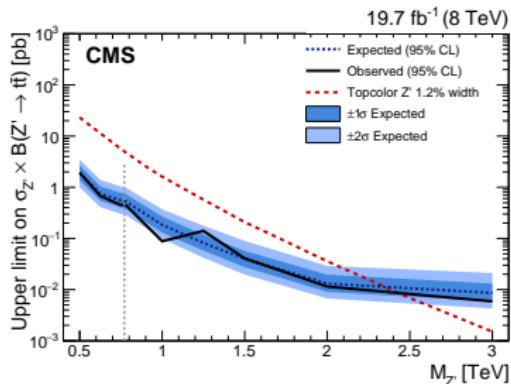
Source of uncertainty	Prior uncertainty	2ℓ	$\ell+\text{jets}$	Had. channel high-mass	Had. channel low-mass
Integrated luminosity	2.6%	⊕	⊕	⊕	⊕
$t\bar{t}$ cross section	15%	⊕	⊕	⊕	⊕
Single top quark cross section	23%	⊕	⊕		
Diboson cross section	20%	⊕	⊕		
Z+jets cross section	50%	⊕	⊕		
W+jets (light flavor) cross section	9%		⊕		
W+jets (heavy flavor) cross section	23%		⊕		
Electron+jet trigger	1%		⊕		
H_T trigger	2%			⊕	⊕
Four-jet trigger	$\pm 1\sigma(p_T)$				⊕
Single-electron trigger	$\pm 1\sigma(p_T, \eta)$	⊕			
Single-muon trigger and id	$\pm 1\sigma(p_T, \eta)$	⊕	⊕		
Electron ID	$\pm 1\sigma(p_T, \eta)$	⊕	⊕		
Jet energy scale	$\pm 1\sigma(p_T, \eta)$	⊕	⊕	⊕	⊕
Jet energy resolution	$\pm 1\sigma(\eta)$	⊕	⊕	⊕	⊕
Pileup uncertainty	$\pm 1\sigma$	⊕	⊕	⊕	⊕
b tagging efficiency ^(†)	$\pm 1\sigma(p_T, \eta)$	⊕	⊕		
b tagging mistag rate ^(†)	$\pm 1\sigma(p_T, \eta)$	⊕	⊕		
CA8 subjet b tagging	unconstrained			⊕	
CA8 t tagged jet efficiency	unconstrained		⊕	⊕	
CA8 t-tagged jet mistag	$\pm 25\%$		⊕		
CA15 t-tagged jet efficiency	$\pm 1\sigma(p_T, \eta)$				⊕
QCD multijet background	sideband			⊕	⊕
PDF uncertainty	$\pm 1\sigma$	⊕	⊕	⊕	⊕
$t\bar{t}$ ren. and fact. scales	$4Q^2$ and $0.25Q^2$	⊕	⊕	⊕	⊕
W+jets ren. and fact. scales	$4Q^2$ and $0.25Q^2$		⊕		
W+jets matching scale μ	2μ and 0.5μ		⊕		
MC statistical uncertainty		⊕	⊕	⊕	⊕

(†) AK5 and CA15 subjets

Limits combination



Limits results



Lower mass limits

	Mass limit [TeV]							
	Dilepton channel		Lepton+jets channel		All-hadronic channels		Combined	
	Exp.	Obs.	Exp.	Obs.	Exp.	Obs.	Exp.	Obs.
$Z', \Gamma_{Z'}/M_{Z'} = 1.2\%$	1.4	1.5	2.2	2.3	2.1	2.1	2.4	2.4
$Z', \Gamma_{Z'}/M_{Z'} = 10\%$	2.1	2.2	2.7	2.8	2.5	2.5	2.8	2.9
RS KK gluon	1.8	2.0	2.5	2.5	2.4	2.3	2.7	2.8

Observed and expected limits

$Z', \Gamma_{Z'} / M_{Z'} = 1\%$						
$M_{Z'} (\text{TeV})$	Expected (pb)	Expected range ($\pm 1\sigma$) (pb)	Expected range ($\pm 2\sigma$) (pb)		Observed (pb)	
0.75	0.61	0.89 — 0.43	1.3	— 0.32	0.86	
1.0	0.18	0.27 — 0.13	0.37	— 0.099	0.088	
1.25	0.082	0.12 — 0.058	0.18	— 0.042	0.14	
1.5	0.04	0.057 — 0.028	0.089	— 0.02	0.041	
2.0	0.013	0.02 — 0.009	0.029	— 0.0067	0.011	
3.0	0.0086	0.013 — 0.0059	0.021	— 0.0043	0.0059	
$Z', \Gamma_{Z'} / M_{Z'} = 10\%$						
$M_{Z'} (\text{TeV})$	Expected (pb)	Expected range ($\pm 1\sigma$) (pb)	Expected range ($\pm 2\sigma$) (pb)		Observed (pb)	
0.75	0.83	1.2 — 0.57	1.8	— 0.42	0.89	
1.0	0.26	0.37 — 0.18	0.53	— 0.14	0.13	
1.25	0.13	0.19 — 0.09	0.26	— 0.067	0.22	
1.5	0.063	0.089 — 0.044	0.13	— 0.03	0.064	
2.0	0.023	0.034 — 0.016	0.055	— 0.011	0.018	
3.0	0.023	0.036 — 0.016	0.055	— 0.011	0.017	
RS KK gluon						
$M_{gKK} (\text{TeV})$	Expected (pb)	Expected range ($\pm 1\sigma$) (pb)	Expected range ($\pm 2\sigma$) (pb)		Observed (pb)	
0.7	1.7	2.5 — 1.2	3.8	— 0.84	3.5	
1.0	0.42	0.6 — 0.28	0.84	— 0.21	0.24	
1.4	0.16	0.23 — 0.11	0.32	— 0.078	0.25	
1.5	0.12	0.17 — 0.083	0.24	— 0.059	0.15	
1.8	0.064	0.098 — 0.045	0.15	— 0.032	0.056	
2.0	0.05	0.074 — 0.034	0.12	— 0.024	0.038	
2.5	0.045	0.068 — 0.03	0.11	— 0.021	0.034	
3.0	0.059	0.088 — 0.039	0.15	— 0.028	0.041	