# Searches for New Resonances Decaying to Top Quarks

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### TOP2016
### Olomouc, Czech Republic
### September 19-23, 2016

# Outline

➤ Two sets of searches will be presented

- Neutral gauge bosons $Z' \to t\bar{t}$
- Charged gauge bosons $W' \to tb$

➤ Common elements of these searches include

- Their existence is predicted by various Beyond the Standard Model (BSM) theories
- The assumption that the new particles decay predominantly into top quarks or top quark pairs

➤ Most of the presented results use 2-13 fb$^{-1}$ of 13 TeV data collected in 2015/16

# Searches for $t\bar{t}$ Resonances

➢ Some BSM theories predict new heavy bosons that decay preferentially into t$\bar{t}$ pairs

▪ Spin 0 color singlet (H/A in 2-Higgs-Doublet Model (2HDM))

- Branco, Ferreira et al., NP B690 (2004) 81

▪ Spin 1 color singlet (topcolor leptophobic Z')

- Harris and Jain, EPJC 72 (2012) 2072

▪ Spin 1 color octet (Kaluza-Klein (KK) excitations of gluon)

- Lille, Randall and Wang, JHEP 09 (2007) 074

▪ Spin 2 color singlet (KK excitation of the graviton)

- Agashe, Davoudiasl, Perez and Soni, PRD (2007) 036006
- Fitzpatrick, Kaplan, Randall and Wang, JHEP 09 (2007) 013

# Searches for $t\bar{t}$ Resonances

➤ Two different decay topologies can be exploited in the lepton plus jets decay channel

➤ Resolved (low mass)
- At least four well separated small-radius jets
- Well isolated lepton

➤ Boosted (high mass)
- One large-radius jet with and $m_{jet} \sim m_t$ and substructure selection
- Lepton close to/inside the b-jet



Resolved topology

Merged topology due to boosted tops
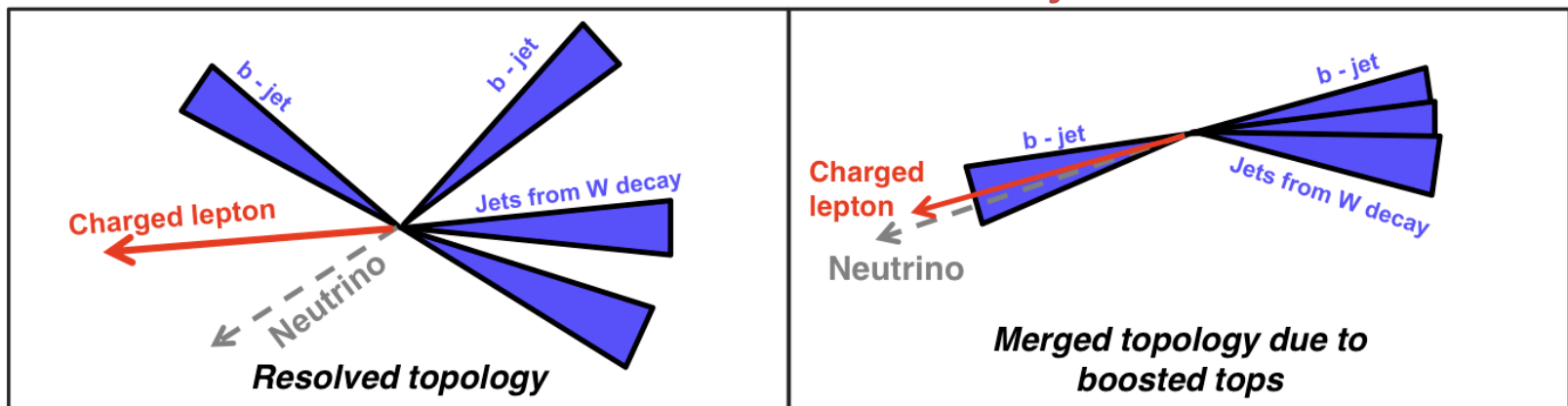
# Searches for $t\bar{t}$ Resonances (Lepton + Jets) at ATLAS

➢ Experimental signature in the boosted decay channel is a top-tagged, large-radius jet and a high $p_T$ lepton with nearby small-radius jet and missing $E_T$

➢ Event selection includes

- ≥ 1 anti-kt R=1.0 (AK10) jets with $p_T$ > 300 GeV that has been trimmed and top-tagged using N-subjettiness ratio $\tau_{32}$ and jet mass criteria (80% efficient WP)

- Exactly one electron (muon) with $p_T$ > 30 (25) GeV and isolated using a requirement on the surrounding track $p_T$

- One AK4 jet with $p_T$ > 25 GeV and $\Delta R(jet, lep) < 1.5$

- ≥ 1 b-tagged track jet (70% efficient WP)

- $E_T^{miss} > 20$ GeV and $E_T^{miss} + m_T^W > 60$ GeV

➢ $m_{t\bar{t}}^{reco}$ is reconstructed from the semileptonic top candidate and hadronic top candidate

➢ Backgrounds are determined from MC simulation and data-driven methods
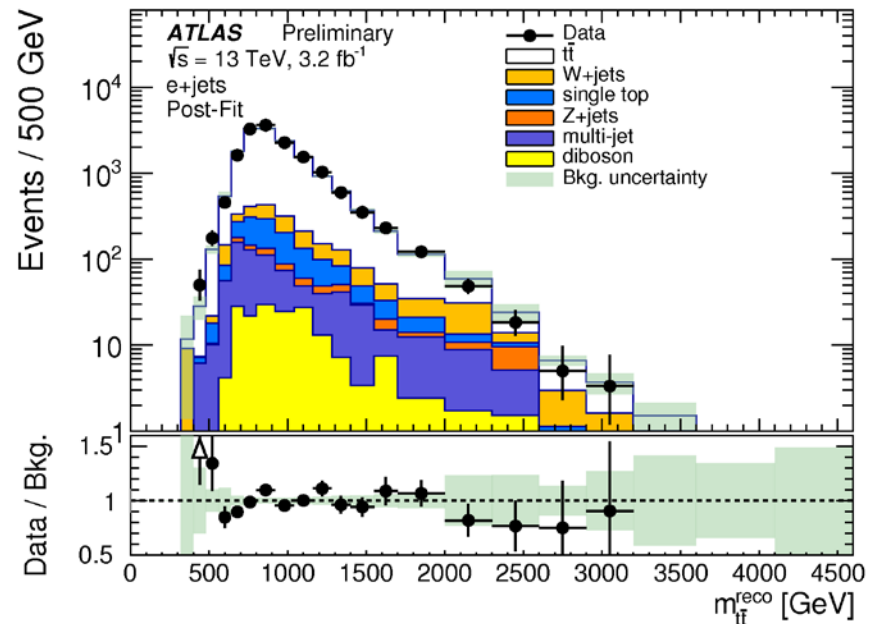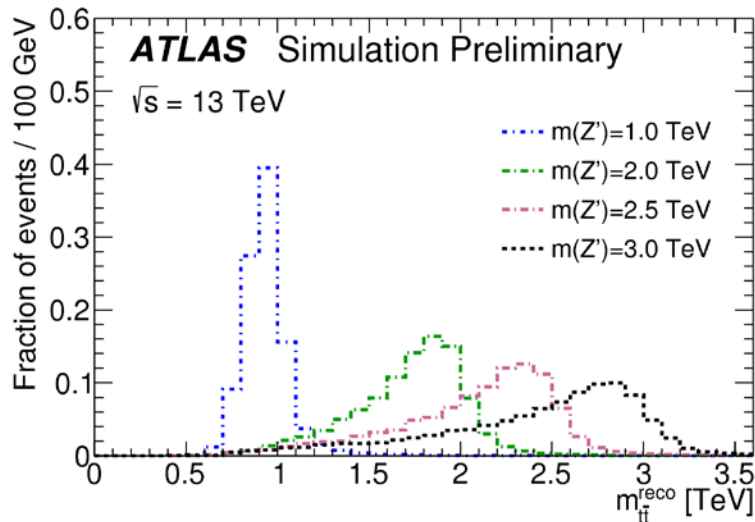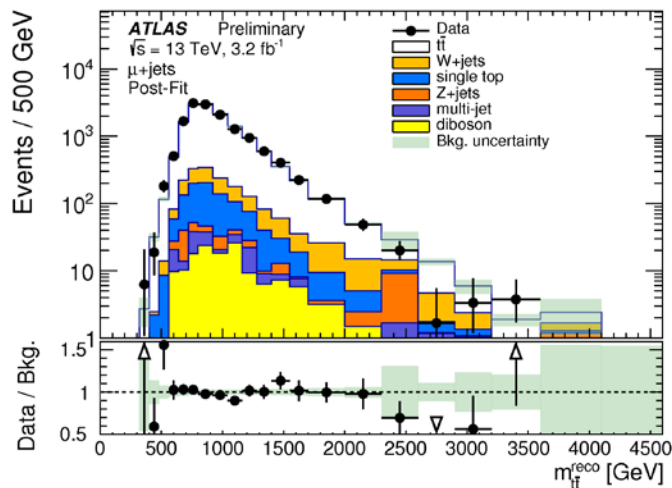
# Searches for $t\bar{t}$ Resonances (lepton + jets) at ATLAS
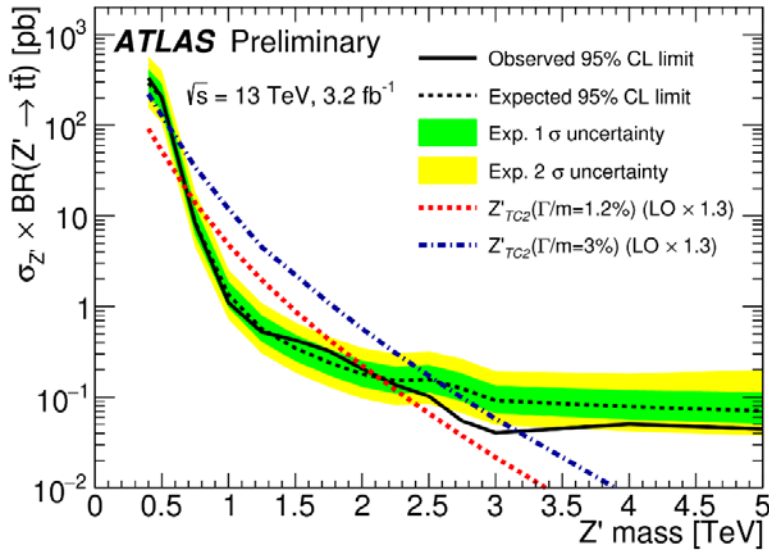




➢ The $m_{t\bar{t}}$ distributions in the two signal regions ($e/\mu$) are used in a profile likelihood ratio method

➢ 95% CL exclusion limits are set excluding
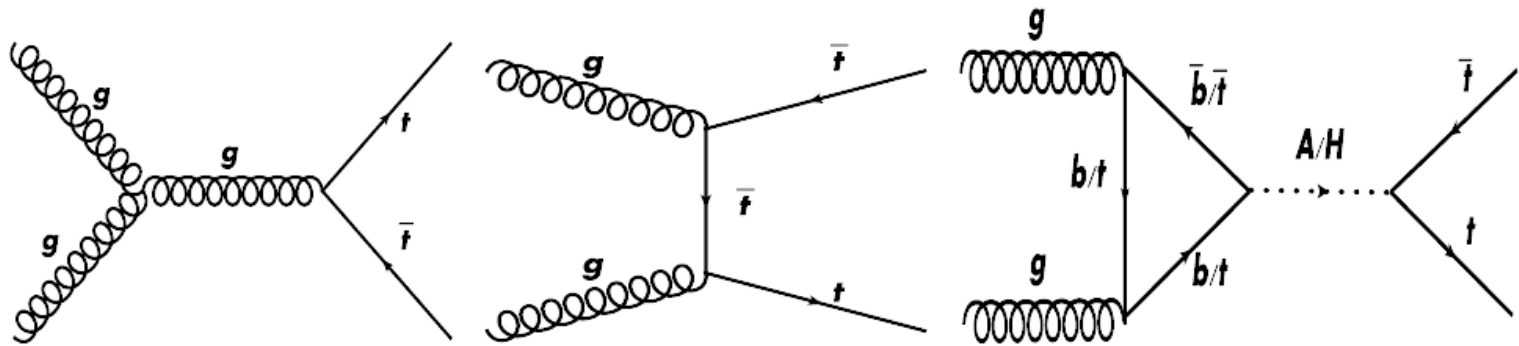
$0.7 < m_{Z'} < 2.0$ TeV (1.2% width)
$0.7 < m_{Z'} < 3.2$ TeV (3% width)

ATLAS-CONF-2016-014

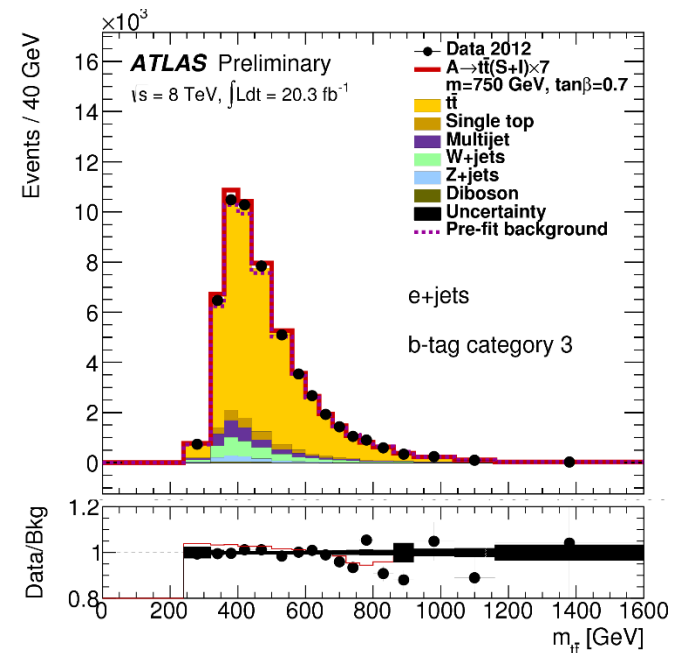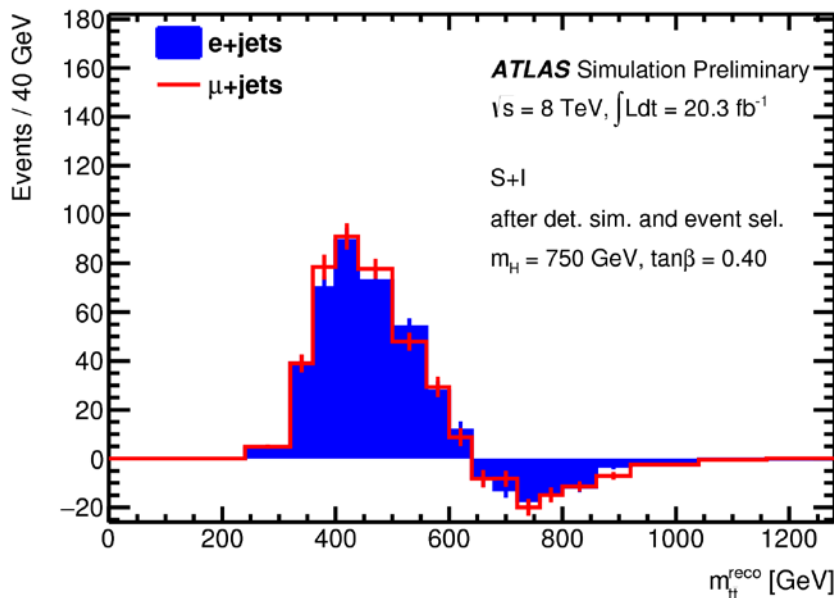# Search for Scalar tt̄ Resonances (Lepton + Jets) at ATLAS

➤ A re-interpretation of the 8 TeV resonance search result using 20.3 fb$^{-1}$ of data



➤ Analysis targets resonance masses between 400 and 800 GeV

- Hence only data satisfying the resolved topology reconstruction are used (independent of boosted topology)

- Same selection criteria and mass reconstruction algorithm are used as for the resolved topology result

# Search for Scalar t$\bar{\text{t}}$ Resonances (Lepton + Jets) at ATLAS

➢ MadGraph5_aMC@NLO is modified to generate only pure A/H signal (S) plus interference (I) events for $m_{A/H} = 500$ and 750 GeV at a few low tan $\beta$ values

  ▪ Difference between this approach and an approach where Background (B) MC samples are subtracted from S + I + B samples is taken as a systematic uncertainty for the signal
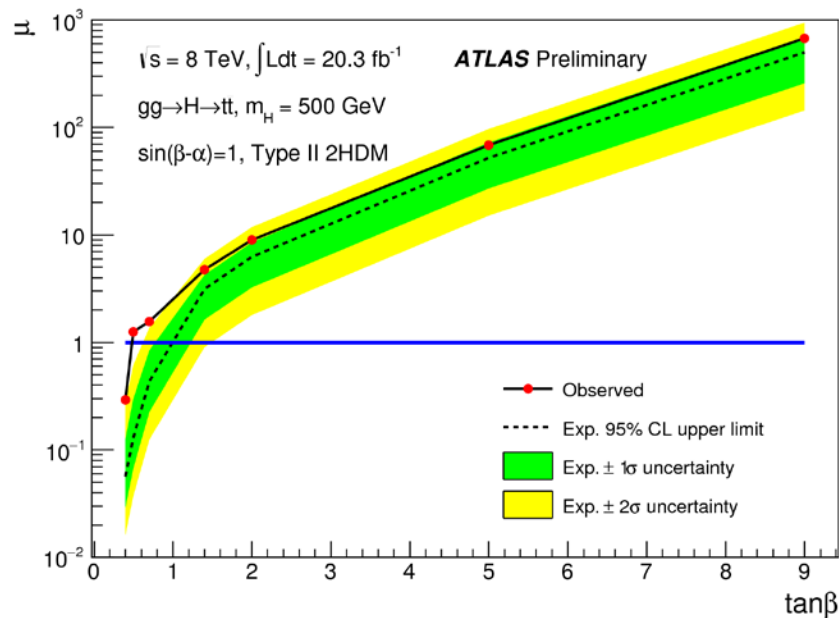
# Search for Scalar $t\bar{t}$ Resonances (Lepton + Jets) at ATLAS

➤ Limits are set by utilizing six signal regions and parameterizing $m_{t\bar{t}}^{reco}$ as $\mu S + \sqrt{\mu} I + B$



➤ 95% confidence levels are set on $\mu$ for a pure type-II 2HDM model and exclude

$\tan\beta < 0.85$ for 500 GeV $A$
$\tan\beta < 0.45$ for 500 GeV $H$
No values of $\tan\beta$ are excluded for a mass of 750 GeV

ATLAS-CONF-2016-073

# Search for $t\bar{t}$ Resonances (Lepton + Jets) at CMS

➢ Optimized for high mass (> 1 TeV) resonances

➢ Event selection includes

- Optionally one AK8 jet that has been top-tagged using criteria on $M_{soft-drop}$ and $\tau_{32}$ (3% mistag WP)

- ≥ 2 AK4 jets with leading $p_T$ > 250 (150) GeV in the electron (muon) channel

- Exactly one electron or muon with $p_T$ > 50 GeV and isolated using $\Delta R(lep, jet) > 0.4$ **or** $p_T^{rel}(lep, jet) > 20$ GeV

- ≥ 0 b-tagged AK4 jets (65% efficient WP)

- $E_T^{miss}\left(H_T^{lep}\right) > 120$ (150) GeV in the electron (muon) channel

- $\chi^2 = \left(\dfrac{M_{lep}-\bar{M}_{lep}}{\sigma_{M_{lep}}}\right)^2 + \left(\dfrac{M_{had}-\bar{M}_{had}}{\sigma_{M_{had}}}\right)^2 < 30$

# Searches for t$\bar{t}$ Resonances (Lepton+Jets) at CMS

➢ 6 signal regions (e/$\mu$ x (1 t-tag or 0 t-tag, 1 b-tag or 0 t-tag, 0 b-tag)) are used in limit setting

➢ Simultaneous background-only fit is carried out in the signal region and three control regions ($t\bar{t}, W + jets, Z + jets$) to estimate background contributions
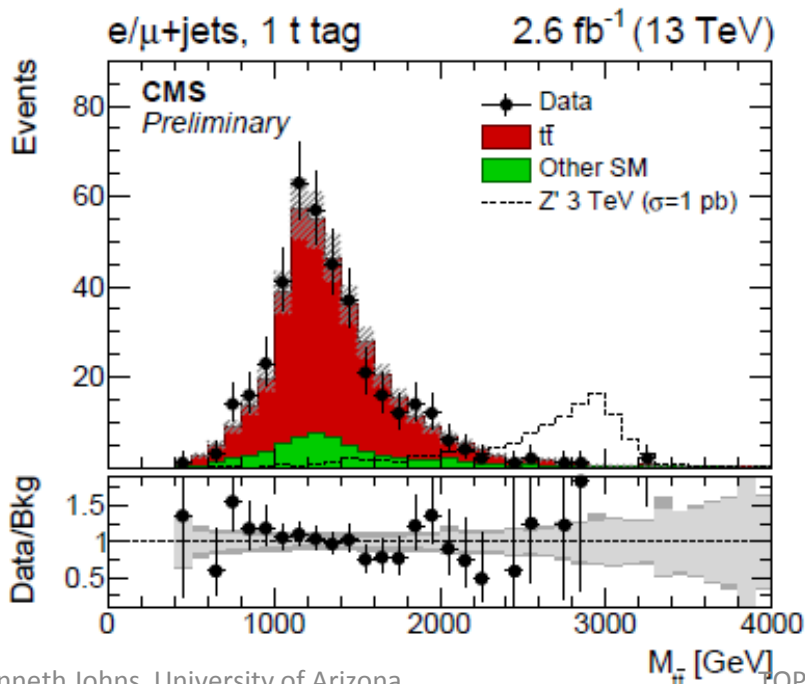


➢ 95% CL Bayesian limits are set excluding

$0.6 < m_{Z'} < 2.3$ TeV (1% width)
$0.5 < m_{Z'} < 3.4$ TeV (10% width)
$0.5 < m_{Z'} < 4.0$ TeV (30% width)
$0.5 < m_{g_{KK}} < 2.9$ TeV

CMS-PAS-B2G-15-002

# Searches for t$\bar{\text{t}}$ Resonances (All-hadronic) at CMS

➤ Focuses on high mass $t\bar{t}$ resonances by identifying two boosted top quark decays as two large-radius jets that are top-tagged

➤ Event selection includes

- Two AK8 jets with p$_T$ > 400 GeV and $|\Delta\varphi| > 2.1$ that are top-tagged using $M_{soft\ drop}$ and $\tau_{32}$ criteria (3% mistag WP)

- Optionally, at least 1 b-tagged subjet within a top-tagged jet (1% mistag WP)

- H$_T$ > 1000 GeV

➤ Six signal regions are used in the search: 3 b-tag conditions x 2 $\Delta y(jet_1, jet_2)$ regions

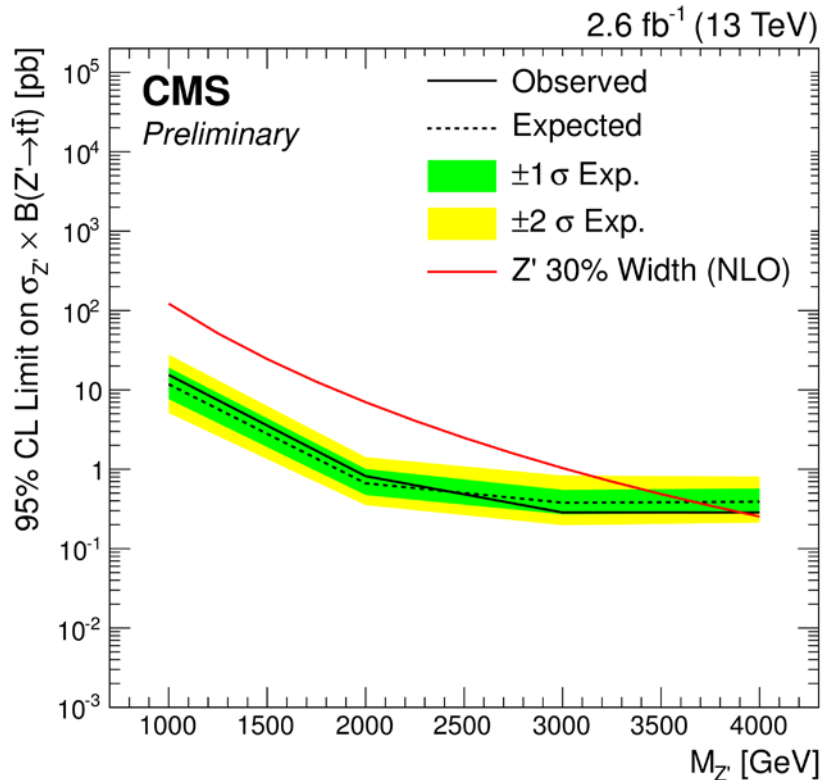# Searches for $t\bar{t}$ Resonances (All-hadronic) at CMS

➤ SM $t\bar{t}$ background shape is taken from MC simulation and normalization from theory

➤ QCD multijet background is estimated using a data-driven anti-t-tag and probe method to measure t-tag mistag rates
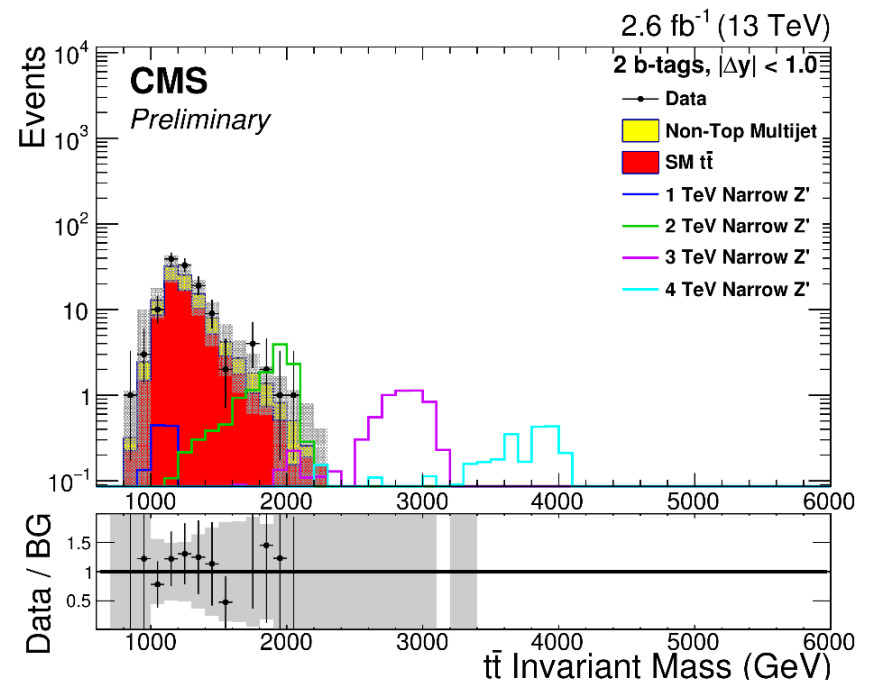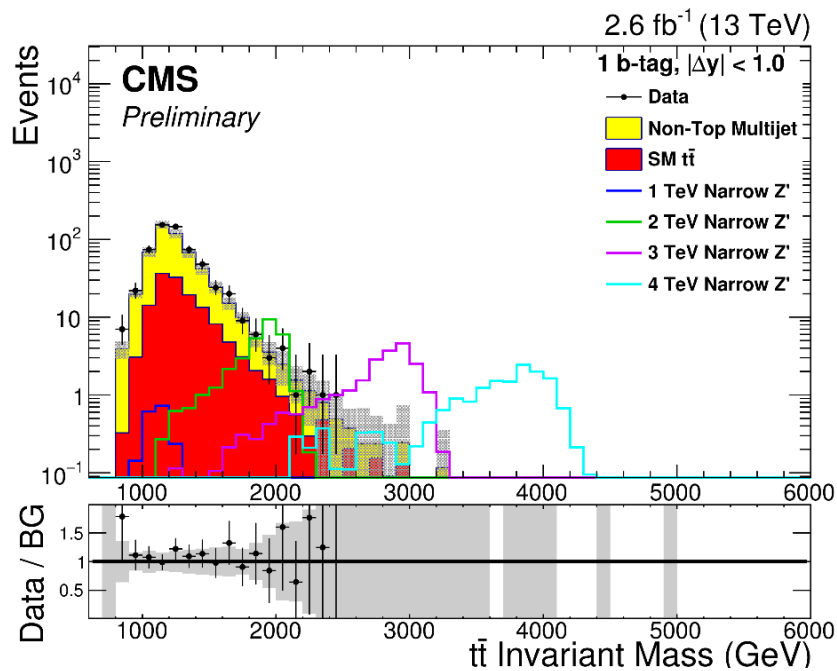
# Searches for $t\bar{t}$ Resonances (All-hadronic) at CMS

➤ Template-based shape analysis is performed using the $m_{t\bar{t}}$ distributions with binned likelihood method with Bayesian statistics



2.6 fb$^{-1}$ (13 TeV)

CMS Preliminary

95% CL Limit on $\sigma_{Z'} \times B(Z' \rightarrow t\bar{t})$ [pb]

— Observed
···· Expected
■ ±1 σ Exp.
■ ±2 σ Exp.
— Z' 30% Width (NLO)

$M_{Z'}$ [GeV]

➤ 95% CL limits are set excluding

$1.4 < m_{Z'} < 1.6$ TeV (1% width)
$1.0 < m_{Z'} < 3.3$ TeV (10% width)
$1.0 < m_{Z'} < 3.8$ TeV (30% width)
$1.0 < m_{g_{KK}} < 2.4$ TeV

CMS-PAS-B2G-15-003

# Search for $W'_R \to tb$ (Semileptonic) at CMS

➤ Signature is a high $p_T$ lepton, significant $E_T^{miss}$ and two high-$p_T$ b-jets

➤ Event selection includes

- Exactly one lepton with $p_T$ > 180 GeV
- $\Delta R(lep, jet) > 0.4$ **or** $p_T^{rel}(lep, jet) > 60 \, (50)$ GeV for e $(\mu)$ channel
- $\geq$ 2 high $p_T$ AK4 jets (leading jet $p_T$ > 350 (450) GeV)
- $\geq$ 1 b-tagged high $p_T$ jets

➤ Top quark jet is reconstructed from the W and one of the two leading jets.  The W' mass is reconstructed from the top jet and b jet
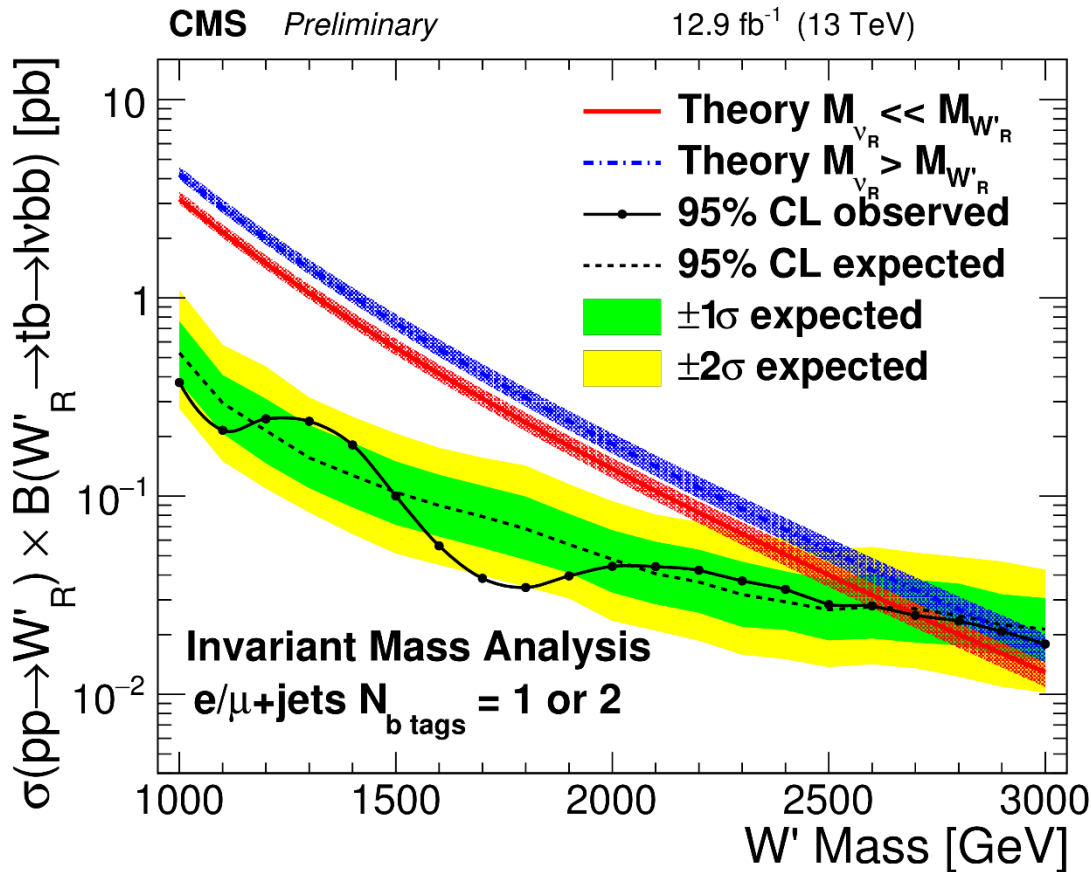
# Search for $W'_R \rightarrow tb$ (Semileptonic) at CMS

➢ Search is carried out in 4 regions ($e/\mu$ x 1,2 *b-jets*) using the reconstructed invariant mass $M_{tb}$

➢ W+jet and $t\bar{t}$ backgrounds are estimated from MC simulation and cross-checked with data in control regions
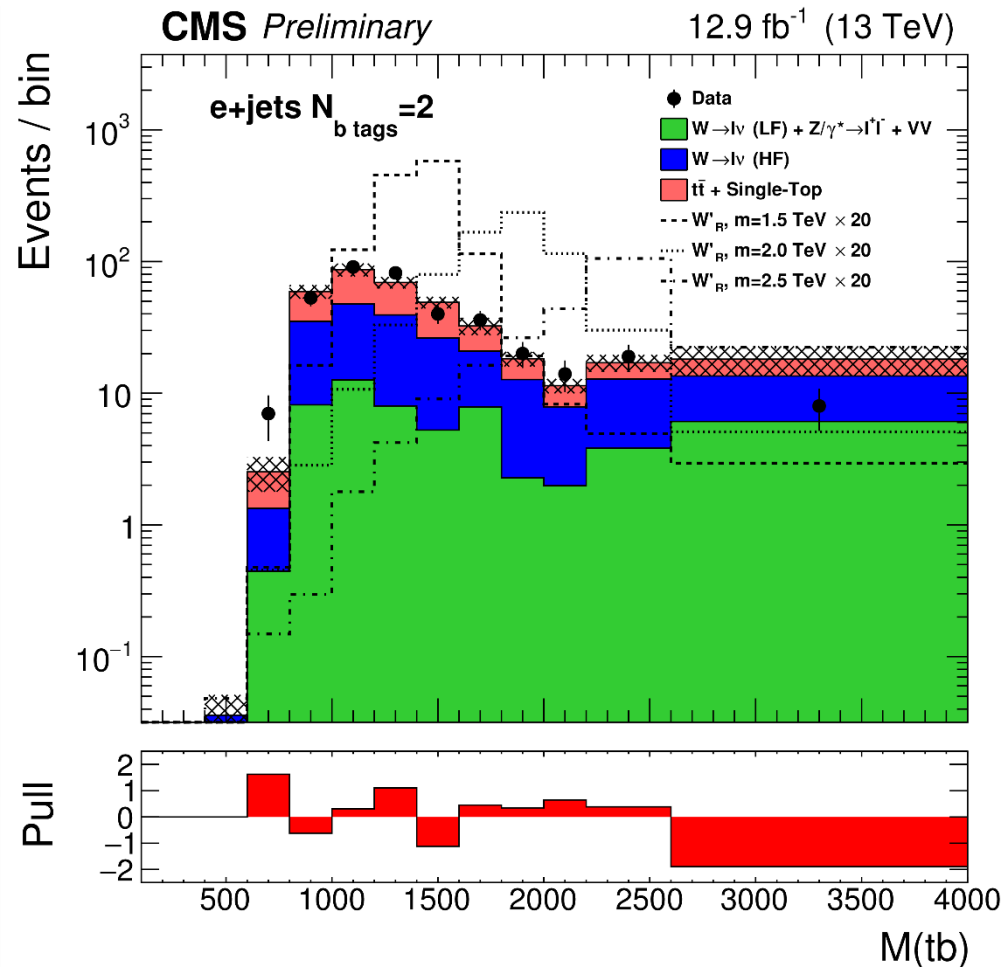
# Search for $W_R' \rightarrow tb$ (Semileptonic) at CMS

➤ Limits are set using the $M_{tb}$ distribution in a binned likelihood fit with Bayesian statistics



➤ 95% CL limits are set excluding

$$1.0 < M_{W'} < 2.67 \text{ TeV}$$

CMS-PAS-B2G-16-017

➤ Presently these are the most stringent limits in this decay channel

# Search for $W'_R \to tb$ (Hadronic) at CMS

➢ Signature is a top-tagged large-radius jet recoiling against a high $p_T$ b-jet

➢ Event selection includes

■ One AK8 jet with $p_T$ > 350 GeV and top-tagged (3% mistag WP)

- Additionally, at least one subjet must be b-tagged

■ One AK8 jet with $p_T$ > 350 GeV, b-tagged with a loose (10% mistag) WP and $M_{soft-drop} < 70$ GeV

■ $|\Delta\varphi(jet_1, jet_2)| > \frac{\pi}{2}$

■ $|\Delta y(jet_1, jet_2)| < 1.3$

# Search for $W_R' \to tb$ (Hadronic) at CMS

➢ Limit setting is carried out with the $M_{tb}$ distribution in a binned likelihood fit using Bayesian statistics
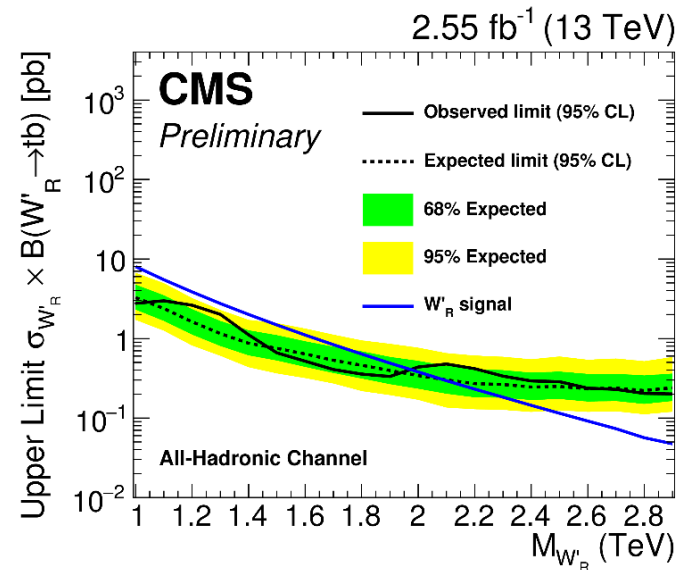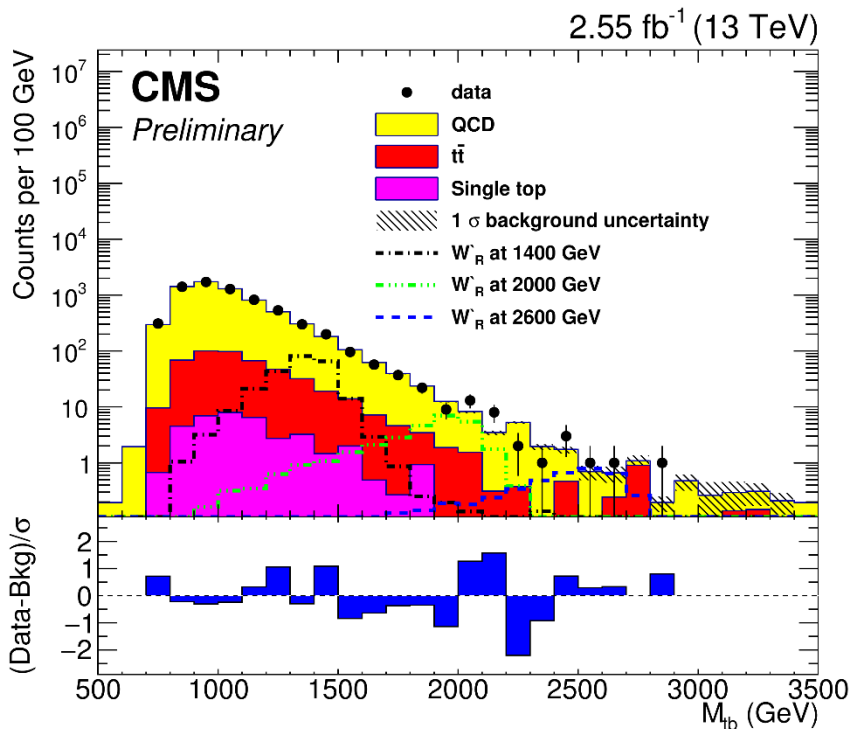


$m_{W_R'} < 2.0$ TeV is excluded in this first measurement at $\sqrt{s} = 13$ TeV

CMS-PAS-B2G-16-009

# Search for $Z' \to Tt$ at CMS

➢ Some models predicting heavy $Z'$ bosons also include a fourth generation of Vector-like Quarks (VLQ's)

- $T' \to Ht, Zt, Wb$ are dominant decay modes in some models

➢ This analysis searches for $Z' \to T't \to Wbt$ where the $W$ and $t$ decay hadronically

- Experimental signature is a boosted W jet, a boosted top jet and a b jet
- Composite Higgs effective model is used as a benchmark
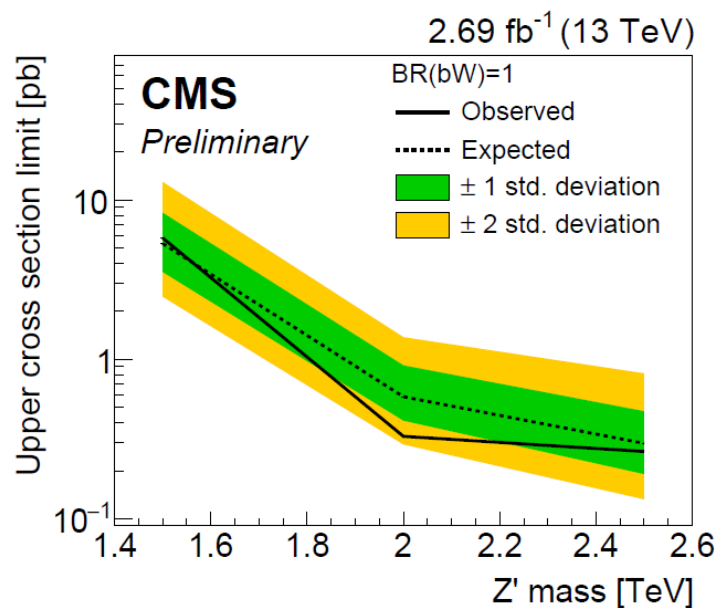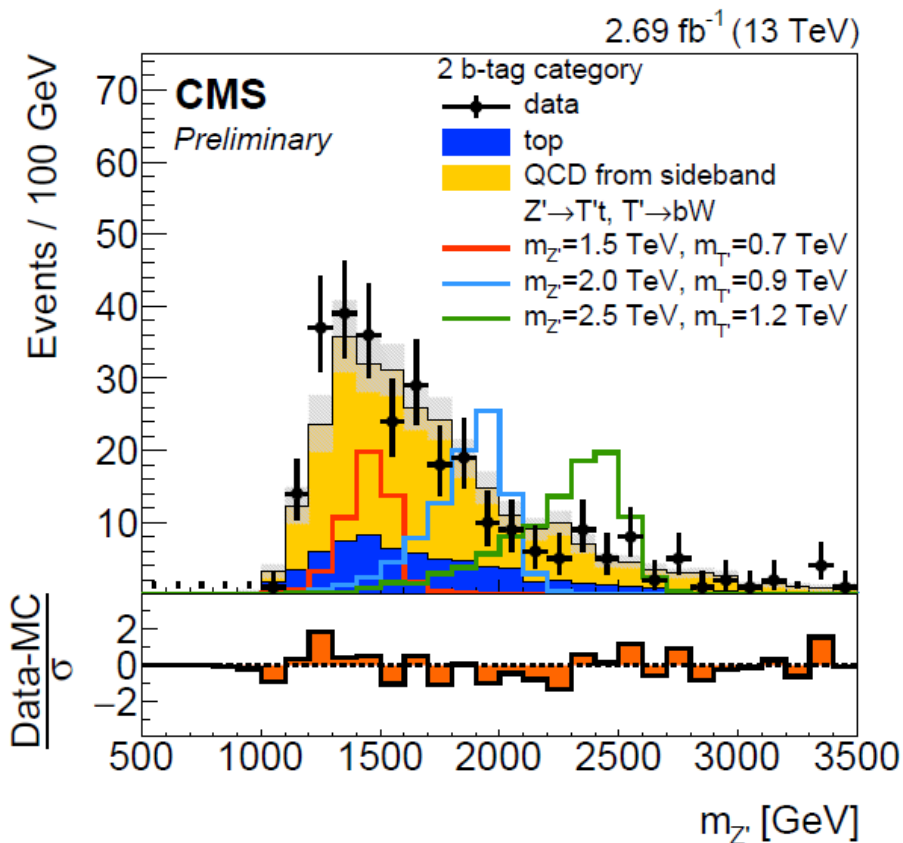
# Search for $Z' \rightarrow Tt$ at CMS

➤ Event selection includes

- One AK8 jet with $p_T > 400$ GeV that is top-tagged using soft-drop mass and $\tau_{32}$ criteria
  - Optionally b-tagged subjets are identified

- One AK8 jet with $p_T > 200$ GeV that is W-tagged using soft-drop mass and $\tau_{21}$ criteria

- One AK4 jet with $p_T > 100$ GeV that is b-tagged with a medium WP
  - $\Delta R > 0.8$ separation between the AK4 jets and AK8 jets

➤ Z' is defined using the 4-vector sum of the three jets

# Search for $Z' \to Tt$ at CMS

➢ Z' invariant mass is in limit-setting and the dominant QCD multijet background is estimated using data-driven methods



$Z'$ cross section exclusion limits range from 0.13 to 11 pb

CMS-PAS-B2G-16-013

# Conclusions

➢ Results of ATLAS and CMS searches for Z' and W' that decay into top quarks were presented

  ▪ New is a search for $Z' \to Tt$ where T is a VLQ

➢ No evidence was found for exotic physics

  ▪ The exclusion limits set are already competitive with or exceed Run 1 limits

➢ A search for scalar $t\bar{t}$ resonances at $\sqrt{s} = 8$ TeV was also shown

➢ We eagerly look forward to updated results for resonances decaying into top quarks using the full 2015-2016 data set

# Backup Slides

# Searches for $t\bar{t}$ Resonances (Lepton+Jets) at CMS

➤ Top tagger utilizes $\tau_{32}$ and $M_{soft\ drop}$ with a 50% efficiency and 3% mistag WP
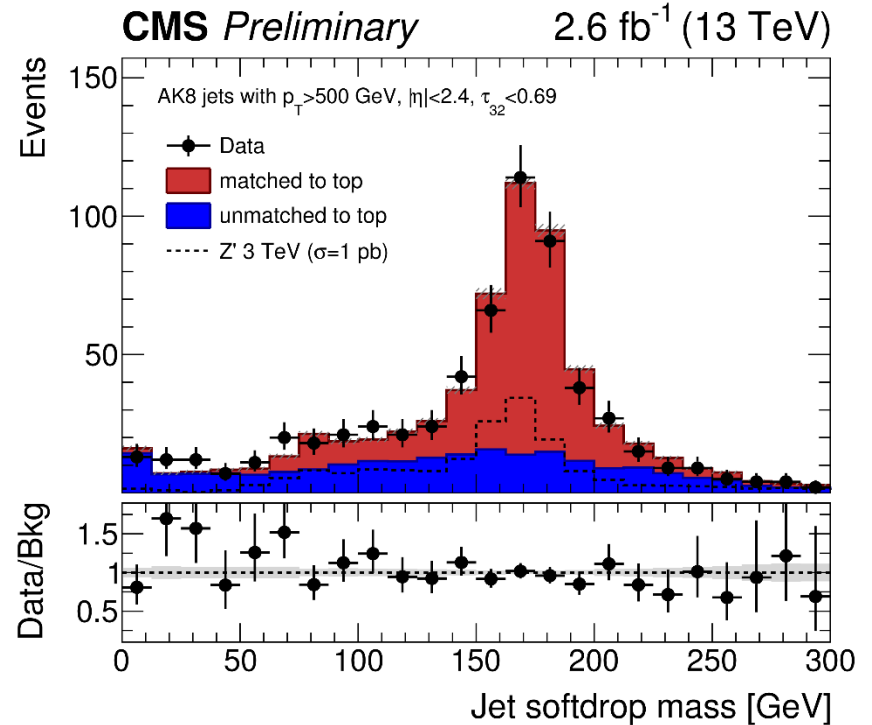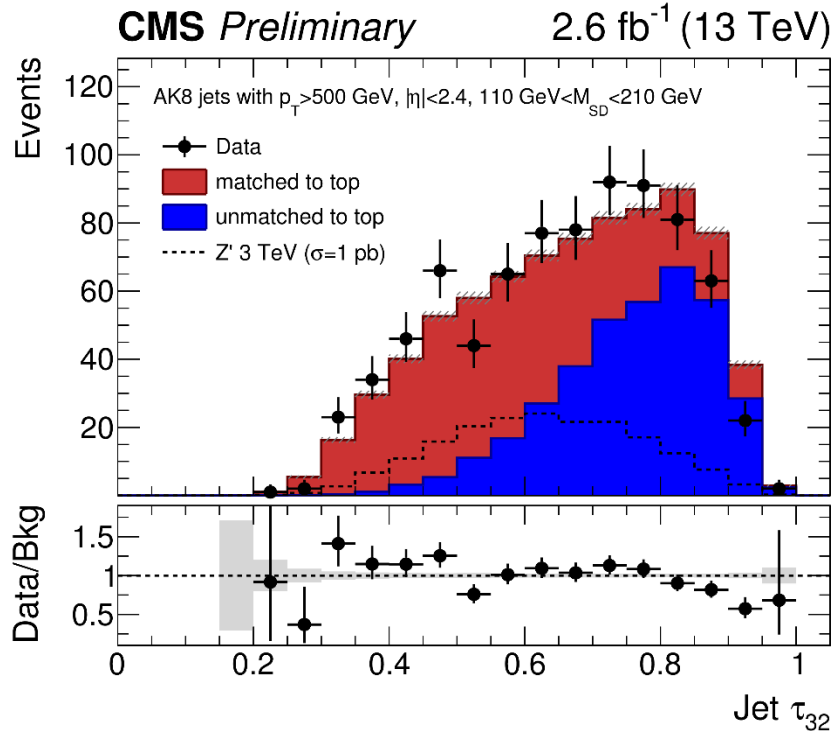
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➤ Event selection includes

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- $\geq 2$ high $p_T$ AK4 jets (leading jet $p_T$ > 350 (450) GeV)

- $\geq 1$ b-tagged high $p_T$ jets

- $E_T^{miss}$ > 120 (50) GeV for e ($\mu$) channel

- $p_T^{top}(reco) > 250$ GeV and $p_T^{jet_1 + jet_2} > 350$ GeV

# Search for $W'_R \to tb$ (Hadronic) at CMS

➤ Primary sources of background are SM QCD multi-jet and $t\bar{t}$ production

➤ A data-driven method is used to estimate the QCD multi-jet contribution and cross-checked in appropriate control regions
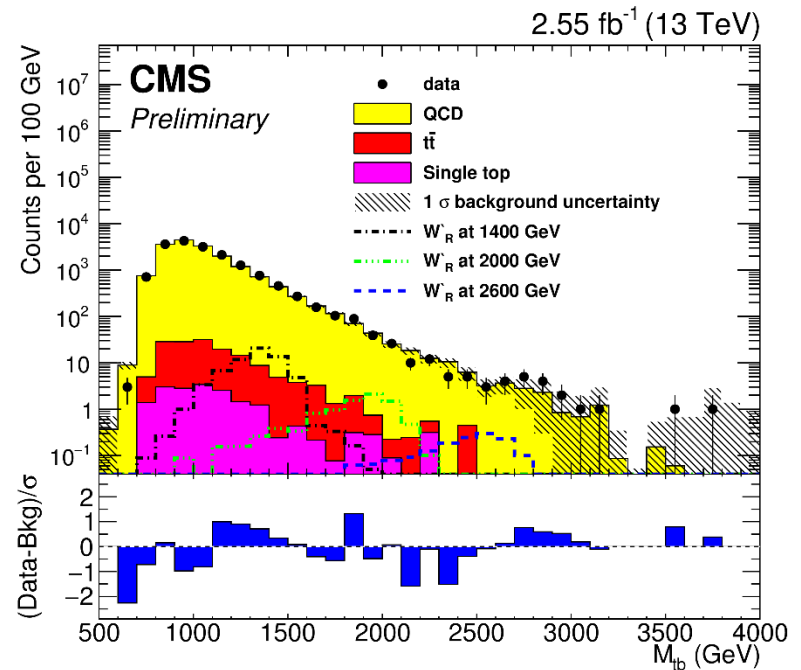


Control region with the subjet b-tag requirement inverted

# Searches for t$\bar{\text{t}}$ Resonances

➢ m(t$\bar{\text{t}}$) = 2.5 TeV candidate event