VII CPAN days

search for resonant $t\bar{t}$ production at $\sqrt{s} = 8$ TeV with the CMS detector

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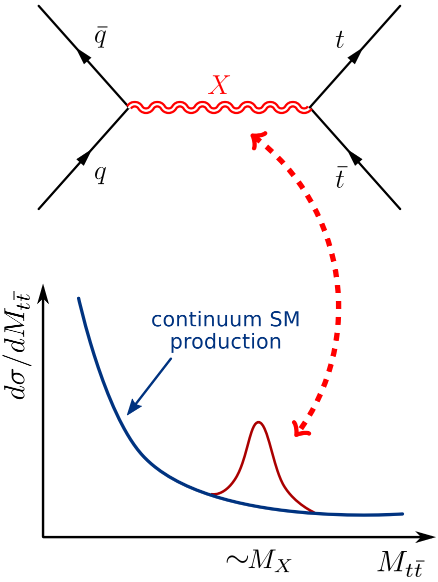
introduction

- several models of BSM physics predict new elementary particles which preferentially decay to a $t\bar{t}$ pair
  - heavy Z' bosons in models with extended gauge sectors
  - Kaluza-Klein resonances in models with extra-dimensions

model-independent search for a high-mass resonance in the $M_{t\bar{t}}$ spectrum



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- "Search for resonant $t\bar{t}$ production in proton-proton collisions at $\sqrt{s} = 8$ TeV"
  - CMS-B2G-13-008 paper accepted for publication in PRD
  - combination of several analyses with full Run1 luminosity ($L = 19.7$ fb^{-1})

    - dilepton
    - $\ell +$ jets
    - all-hadronic

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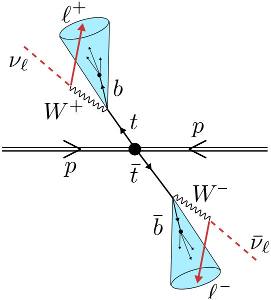

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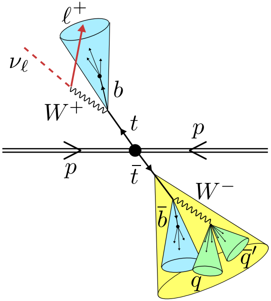

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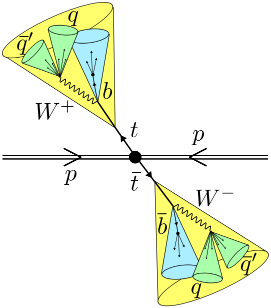

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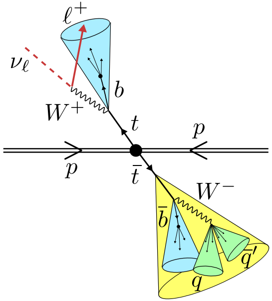


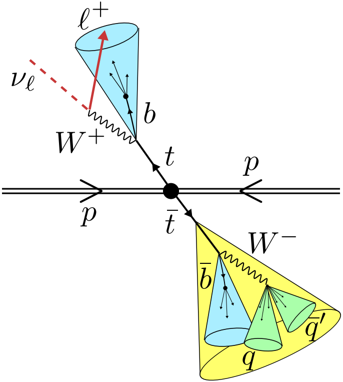
- in this talk, focus on the boosted $t\bar{t} \to \ell +$ jets analysis
  - one of the most sensitive sub-channels in the high-$M_{t\bar{t}}$ region

introduction / $\ell + $ jets

high-mass $t\bar{t}$ resonances ($M_X \gtrsim 1$ TeV) $\Longrightarrow$ top quarks with increasingly high-p_T

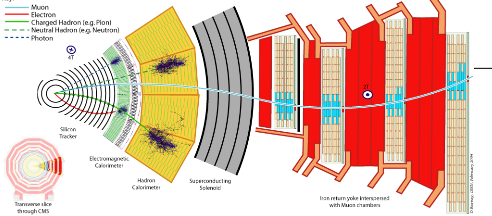
$\boxed{\text{boosted } \ell(= e, \mu) + \text{jets final state}}$

- signature:
  - exactly 1 high-p_T lepton
  - at least 2 high-p_T jets
  - missing transverse energy (MET)

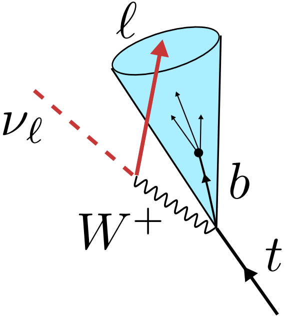


- key features:
  - no isolation requirement on the lepton
  - use of jet top-tagging to identify large-radius jets from top decay

object reconstruction

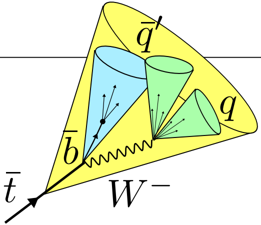


- event reconstruction based on Particle Flow (PF) algorithm:
  - combines information coming from all CMS subdetectors

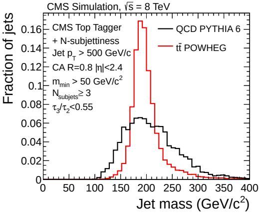


- charged leptons (e/μ):
  - no requirements on isolation
    - leptons from boosted top decays are not expected to be isolated
- missing E_T: reconstructed from 4-momenta of all PF candidates in the event
- small-radius hadronic jets (cone $R = 0.5$):
  - jet-lepton cleaning:
    - no minimum ΔR requirement between lepton and jet candidates
    - if a lepton is inside the jet, lepton-$p4$ subtracted from jet-$p4$
- b-tagging: used to identify jets from b quark decays

object reconstruction / jet top-tagging

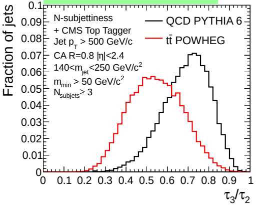


- hadronic decays of high-p_T tops can be reconstructed as a single jet with specific substructure properties
  - jet substructure techniques recently developed and tested for the first time at the LHC
  - jet top-tagging crucial for $t\bar{t}$ searches at high masses ($M_X \geqslant 1$ TeV)



- large-radius hadronic jets (cone $R = 0.8$):
  - CMS Top-Tagging algorithm used to reconstruct subjets
    - $N_{\text{subjets}} \geqslant 3$
    - jet mass: 140 GeV $< m_{\text{jet}} < 250$ GeV
    - minimum subjet pair-wise mass: $m_{\text{min}} > 50$ GeV
    - N-subjettiness ratio: $\tau_{32} \equiv \tau_3/\tau_2 < 0.7$

CMS-PAS-JME-13-007



event selection

signature: 1 lepton, al least 2 high-p_T jets and MET

- Trigger requirements:

$\mu+$jets : single-muon trigger

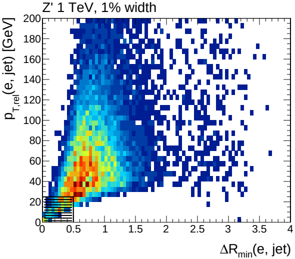
$e+$jets : logical OR of "$e+2$ jets" and single-jet triggers

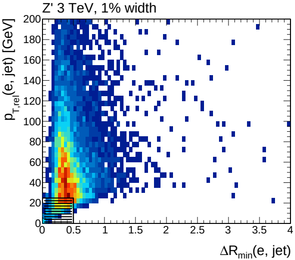
- $==1$ muon (electron) w/o isolation cuts
- $>=1(2)$ jets with $p_T > 150(50)$ GeV, $|\eta| < 2.4$
- $\not{E}_T > 50$ GeV and $H_T^{\text{lep}} \equiv \not{E}_T + p_T^{\ell} > 150$ GeV

- lepton "2D-cut":

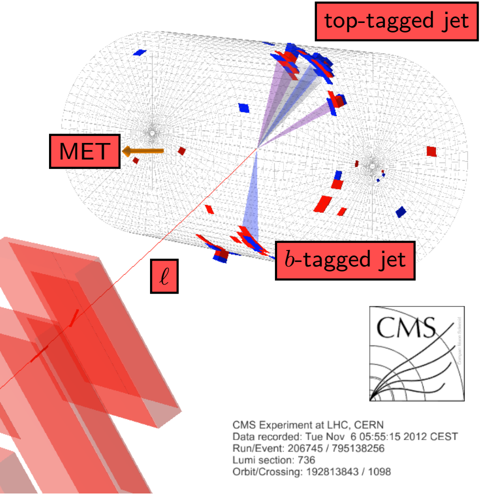
$\Delta R_{\text{min}}(\ell, j) > 0.5$ OR $p_{T,\text{rel}}(\ell, j) > 25$ GeV

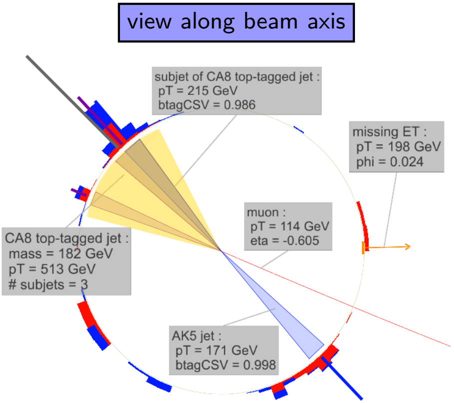
  - replaces standard isolation
  - suppresses QCD multijet bkg





event display from CMS data





$t\bar{t}$ kinematical reconstruction and final selection

- in the $\ell +$ jets channel, it is possible to perform the reconstruction of the $t\bar{t}$ system
  - reconstruct the kinematics of the $t\bar{t}$ pair based on detector-level objects
    - neutrino p_z estimated based on W-mass constraint
    - multiple $t\bar{t}$ hypotheses due to jet assignments and # of solutions for p_z^ν
    - if the event contains a top-tagged jet: hadronic top $\equiv$ top-tagged jet
  - keep only the $t\bar{t}$ hypothesis with minimum χ^2 discriminator

$$\chi^2 = \left[\frac{M_{\text{top}}^{\text{lep}} - \bar{m}_{\text{top}}^{\text{lep}}}{\sigma_M^{\text{lep}}}\right]^2 + \left[\frac{M_{\text{top}}^{\text{had}} - \bar{m}_{\text{top}}^{\text{had}}}{\sigma_M^{\text{had}}}\right]^2$$

- final event selection for the $\ell +$ jets SR:
  - upper cut on $t\bar{t}$ discriminator ($\chi^2_{\text{min}} < 50$) to reduce non-$t\bar{t}$ backgrounds
  - events split in 3 exclusive categories, based on # of t-tag and b-tag jets

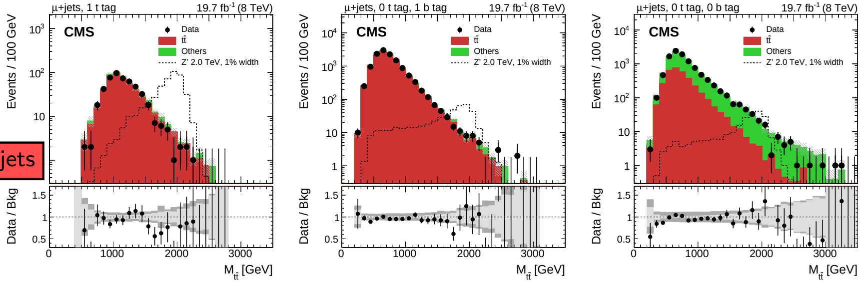
$M_{t\bar{t}}$ distributions in the $\ell +$ jets channel

- background model:
  - main background given by SM $t\bar{t}$ production
  - sizeable contribution from $W +$ jets only for events with 0 b-tagged jets
  - other backgrounds (single top, $Z +$ jets, diboson) are very small

➤ no significant excess observed in data with respect to the expected background

1 t-tag | 0 t-tag $+$ 1 b-tag | 0 t-tag $+$ 0 b-tag

$\mu +$ jets



[signal templates normalized to a cross section of $\sigma = 1$ pb]

systematic uncertainties

source of uncertainty	uncertainty
luminosity	2.6%
$t\bar{t}$ cross section	15%
$W+$jets (light) cross section	9%
$W+$jets (heavy) cross section	23%
single top cross section	23%
$Z+$jets cross section	50%
diboson cross section	20%
pileup reweighting	$\pm 1\sigma$
muon trigger and ID	$\pm 1\sigma(p_T, \eta)$
electron + jet trigger	1%
electron ID	$\pm 1\sigma(p_T, \eta)$
jet energy scale	$\pm 1\sigma(p_T, \eta)$
jet energy resolution	$\pm 1\sigma(\eta)$
jet b-tagging efficiency	$\pm 1\sigma(p_T, \eta)$
jet b-mistag rate	$\pm 1\sigma(p_T, \eta)$
jet top-tagging efficiency	unconstrained
jet top-mistag rate	$\pm 25\%$
Parton Distribution Functions	$\pm 1\sigma$
$t\bar{t}$ Q^2 scale	$Q^2/4$ and $4Q^2$
$W+$jets Q^2 scale	$Q^2/4$ and $4Q^2$
$W+$jets matching scale	$\mu/2$ and 2μ

- most uncertainties affect the $M_{t\bar{t}}$ distributions in terms of both normalization and shape
- cross sections of SM backgrounds: prior uncertainties taken from theory or from CMS measurements
- theory uncertainties on MCs include
  - PDF parameterization
  - choice of renormalization and ME-PS matching scales ($t\bar{t}$, $W+$jets)
- Data/MC SFs on CA8 jet top-tagging:
  - t-tag eff: no assumptions on prior unc.
  - t-mistag: measured in $W+$jets CR

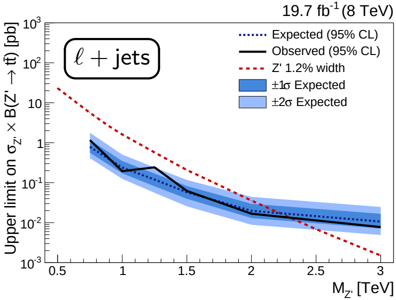
95% CL limits on $\sigma \times$ BR in the $\ell +$ jets channel

- proceed to set upper limits on $\sigma(pp \to X) \times \text{BR}(X \to t\bar{t})$ for 3 BSM models:
  - Z' boson with 1% and 10% width, and KK gluon resonance

- exclusion limits for the $\ell +$ jets channel:
  - $t\bar{t}$ resonances excluded up to $2.3 - 2.8$ TeV (depending on the BSM model)
  - limits on $\sigma \times$ BR improved up to 40% wrt preceeding version of $\ell +$ jets analysis

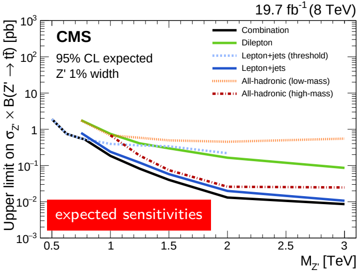
$\ell +$ jets analysis : mass limits [TeV]

signal model	expected	observed
Z' (1% width)	2.2	2.3
Z' (10% width)	2.7	2.8
KK gluon	2.5	2.5



combination of $t\bar{t}$ searches   CMS-B2G-13-008

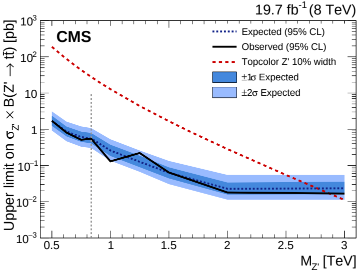
- outlook on the full combination of $t\bar{t}$ searches in CMS:
  - dilepton channel
  - $\ell +$ jets channel: 2 analyses
    - optimized for boosted and non-boosted $t\bar{t}$
  - all-hadronic channel: 2 analyses
    - exploiting different top-tagging techniques



- exclusion limits on resonant $t\bar{t}$ production for 3 BSM models:

lower mass limits [TeV]

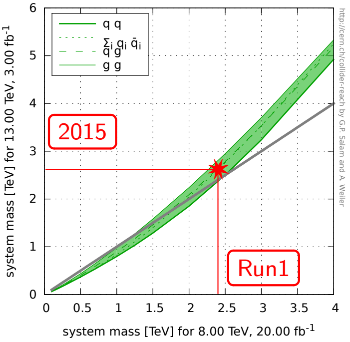
signal model	dilepton obs (exp)	lepton+jets obs (exp)	all-hadronic obs (exp)	**combination** obs (exp)
Z' (1.2% width)	1.5 (1.4)	2.3 (2.2)	2.1 (2.1)	**2.4** (**2.4**)
Z' (10% width)	2.2 (2.1)	2.8 (2.7)	2.5 (2.5)	**2.9** (**2.8**)
KK gluon	2.0 (1.8)	2.5 (2.5)	2.3 (2.4)	**2.8** (**2.7**)



developments and prospects for Run2

- several improvements under development for the Run2 analysis:
  - new HLT selection optimized for the boosted $t\bar{t} \to \ell +$ jets final state
  - enhanced performance (and new methods) for jet substructure
  - BSM signal models:
    - test Z' resonances with generic chirality couplings to top quarks
    - include interference effects with $t\bar{t}$ SM production (KK gluon)

- Run1 mass limits on $t\bar{t}$ resonances expected to be reached with $L \simeq 3$ fb^{-1} at $\sqrt{s} = 13$ TeV



conclusions

CMS-B2G-13-008

- combination of searches for resonant $t\bar{t}$ production at 8 TeV with the CMS detector
  - combination of all final states: dilepton, $\ell +$ jets and all-hadronic
  - $\ell +$ jets analysis is the most sensitive sub-channel in the combination
  - Z' resonance with 1% (10%) width excluded for masses up to 2.4 (2.9) TeV
- best exclusion limits on the production of $t\bar{t}$ resonances at $\sqrt{s} = 8$ TeV up to date

- in 2015, the LHC has delivered the first data at $\sqrt{s} = 13$ TeV
  - searches for $t\bar{t}$ resonances at 13 TeV underway in CMS
  - same sensitivity of Run1 searches (mass limits) expected with $L \simeq 3$ fb^{-1}

BACK-UP

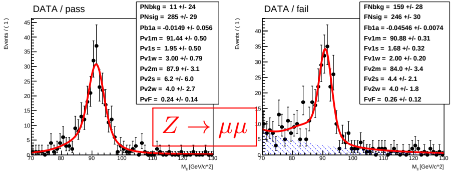
$\ell + $ jets / lepton 2D-cut efficiency in $Z \to \ell\ell$ sample

- lepton 2D-cut $\equiv \Delta R(\ell, j) > 0.5$ OR $p_{T,\text{rel}}(\ell, j) > 25$ GeV
- efficiency measured with Tag-n-Probe method in $Z \to \ell\ell$ control region:

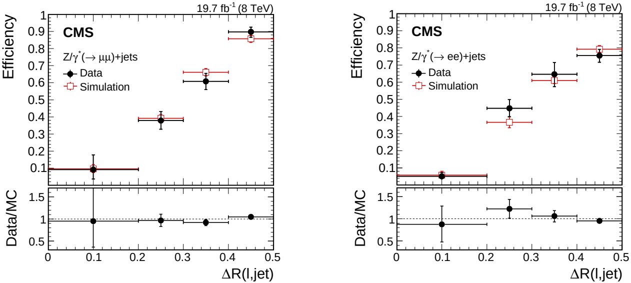
➤ 2 OSSF leptons in the Z mass peak

➤ same jet kinematics of $\ell +$ jets channel

➤ efficiency measured for Data and MC in low-ΔR region ($\Delta R < 0.5$)



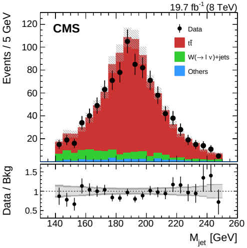
➤ good agreement between Data and MC efficiencies

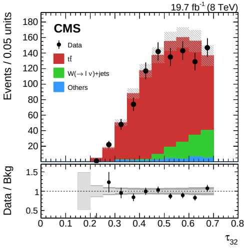


$\ell +$ jets / jet top-tagging efficiencies

➤ Data/MC SF for top-tagging efficiency (for real tops):

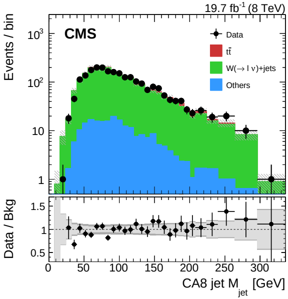
- measurements in CMS of this SF performed in the $\ell +$ jets SR, thus not used for this search
- SF introduced as a free parameter in the statistical analysis
- no assumptions on its uncertainty (*in situ* measurement)





➤ Data/MC SF for top-mistag efficiency:

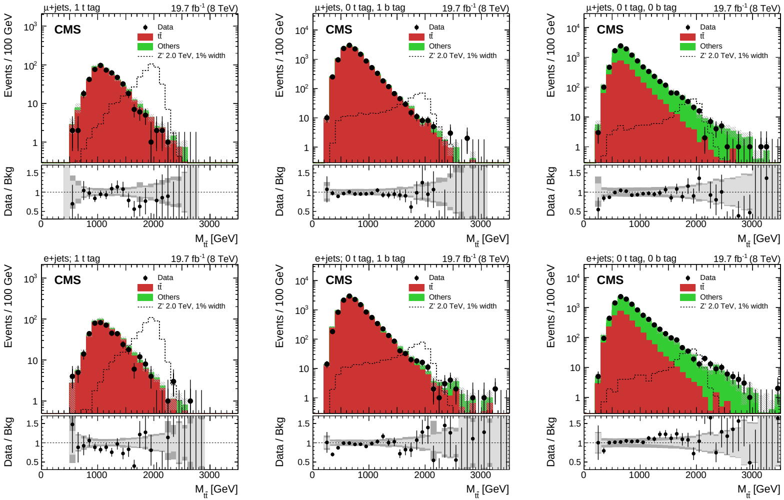
- measured in a sideband dominated by $W +$ jets
- control sample selection:
  - same kinematics of the $\ell +$ jets channel
  - inverted χ^2 cut ($\chi^2_{\text{lep}} > 50$)
  - b-tag veto (to suppress $t\bar{t}$ bkg)
- Data/MC SF measured with an uncertainty of 25%



$\ell + \text{jets}$ / $M_{t\bar{t}}$ distributions

$\mu + \text{jets}$

$e + \text{jets}$



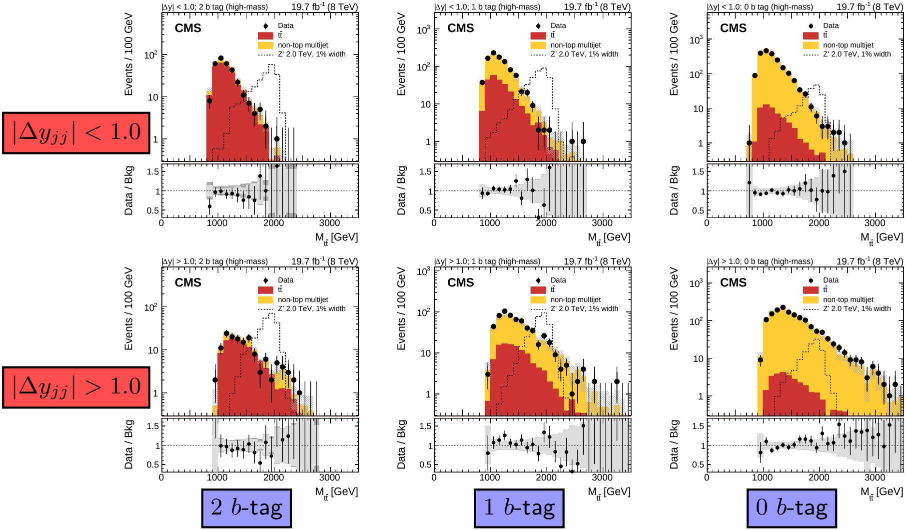
1 t-tag

0 t-tag + 1 b-tag

0 t-tag + 0 b-tag

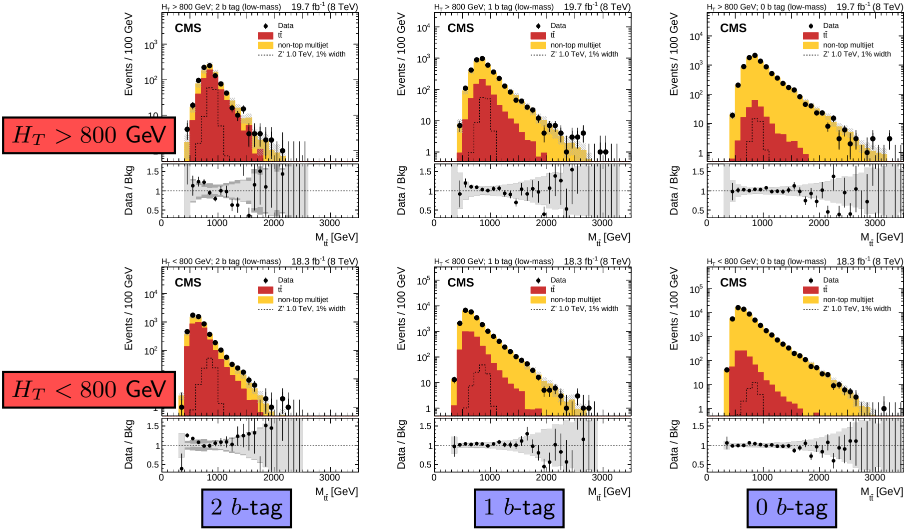
[signal templates normalized to a cross section of $\sigma = 1$ pb]

all-hadronic (high-mass) / $M_{t\bar{t}}$ distributions



[signal templates normalized to a cross section of $\sigma = 1$ pb]

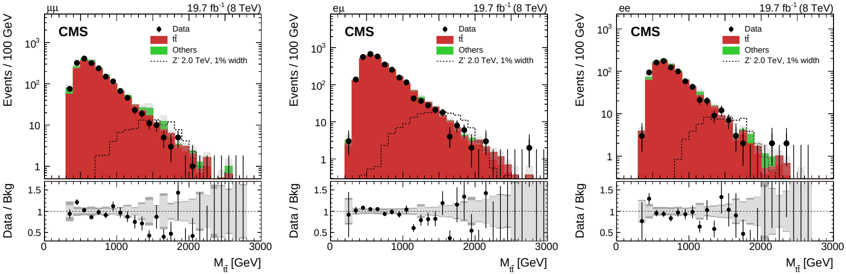
all-hadronic (low-mass) / $M_{t\bar{t}}$ distributions



[signal templates normalized to a cross section of $\sigma = 1$ pb]

dilepton / $M_{t\bar{t}}$ distributions

$\mu\mu$ $e\mu$ ee



[signal templates normalized to a cross section of $\sigma = 1$ pb]