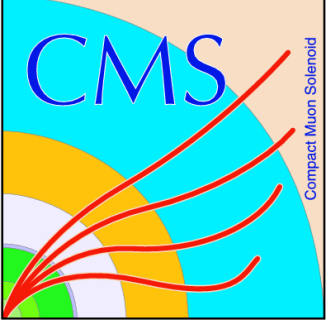
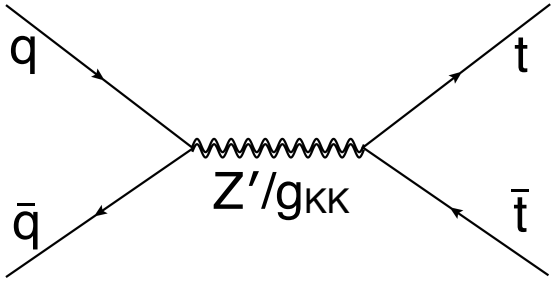


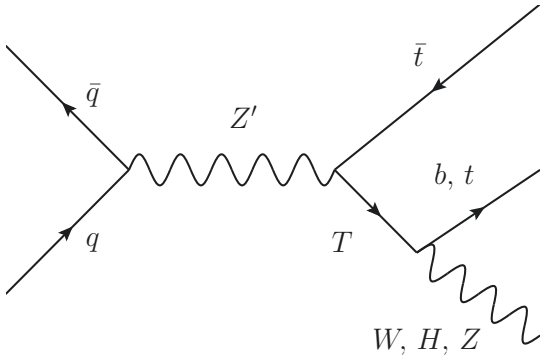
Searches for new resonances coupling to third generation quarks at CMS

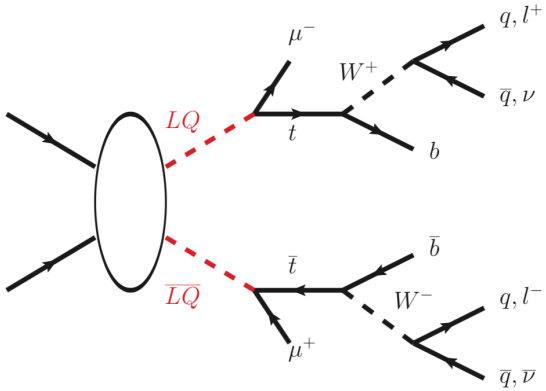
Kevin Nash
for the CMS Collaboration

Introduction

- Analyses use third generation quarks as a probe for new physics
- Heavy resonance decaying to third generation quarks
  - $Z' \rightarrow t\bar{t}$
  - $W' \rightarrow tb$
- With an intermediate VLQ
  - $Z' \rightarrow tT$
- Leptoquark pair production
  - $LQ \rightarrow \tau t$
  - $LQ \rightarrow \mu t$







Introduction

- Searches generally involve tagging heavy boosted objects (ex. top,W,H) merged into a single jet
- Softdrop mass
  - Decluster until softdrop condition is met
  - Groomed mass variable and subjets identified
- N-subjettiness
  - Identify subjet axes, and extract τ_N variables
  - τ_3/τ_2 - "three-prong" like
  - τ_2/τ_1 - "two-prong" like
- Subjet b tagging
  - Attempt to b tag softdrop subjets
  - Identify one or two subjets

Softdrop condition

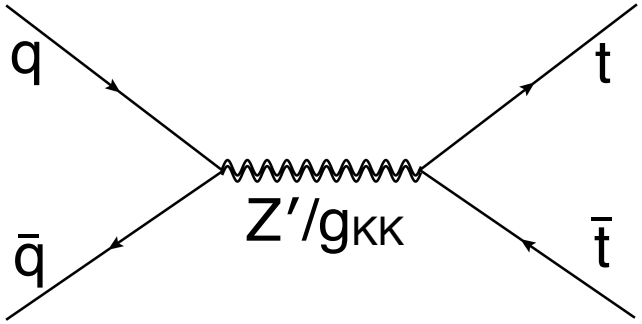
$$\frac{min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z(\Delta R_{12}/R_0)^{\beta}$$

N-subjettiness

$$\tau_N = \frac{1}{d}\sum_i p_{T_i} \min\{\Delta R_{1,i}, \Delta R_{2,i}, \ldots, \Delta R_{N,i}\}$$

$Z' \rightarrow t\bar{t}$

- Search for a heavy Z' resonance decaying to a top quark pair
- Search in multiple channels
  - Two hadronic tops (all hadronic)
  - One hadronic top and one semileptonic top (semileptonic)
  - Two semileptonic tops (dileptonic)
- Consider two signal hypotheses
  - Heavy Z' and RSgluon
- Heavy resonance leads to merged objects
  - Use boosted hadronic top identification
  - Lepton isolation starts to break down

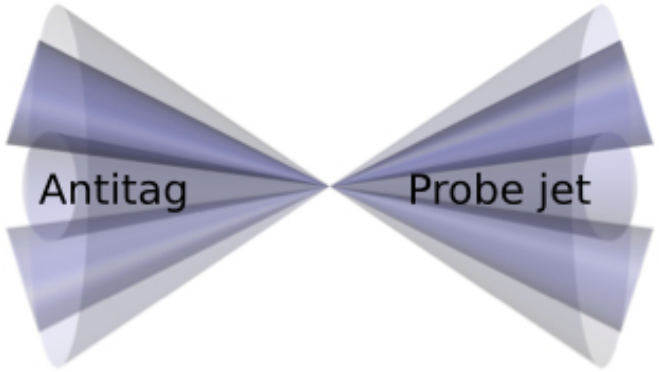


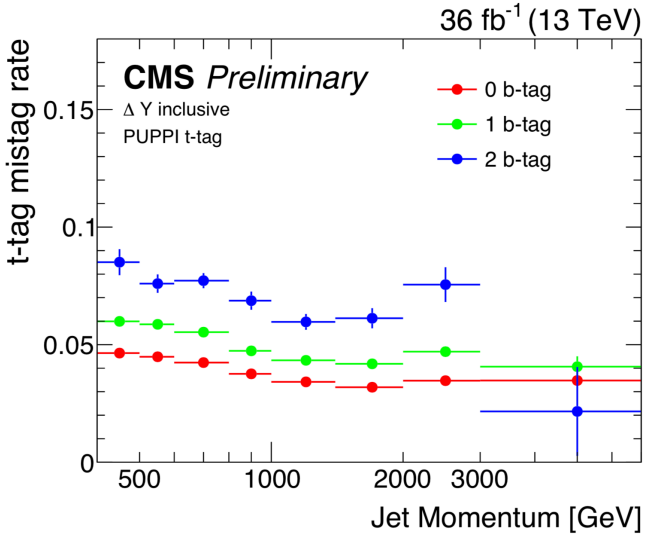
Link: CMS-PAS-B2G-17-017

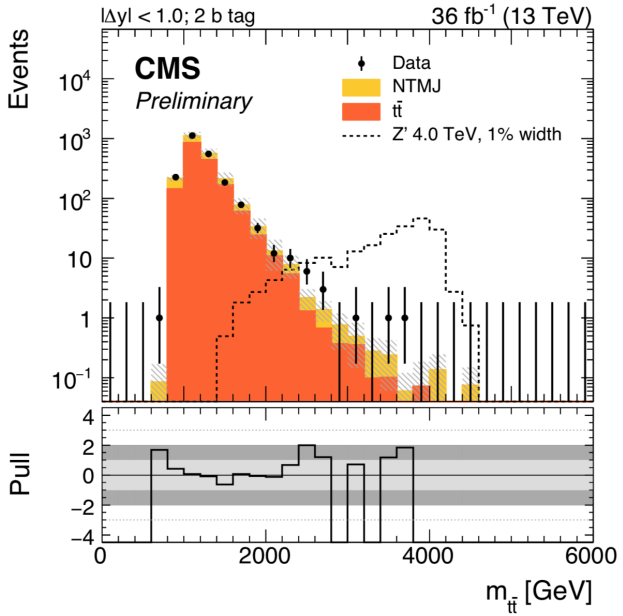
All hadronic

$Z' \rightarrow t\bar{t}$

- Require two top tagged jets
  - τ_3/τ_2, Softdrop mass, Subjet b tag (0,1, or 2)
- Select on rapidity difference
  - $\Delta R < 1.0, \Delta R > 1.0$
- Estimate QCD background using anti tag and probe
  - Invert Nsubjettiness selection





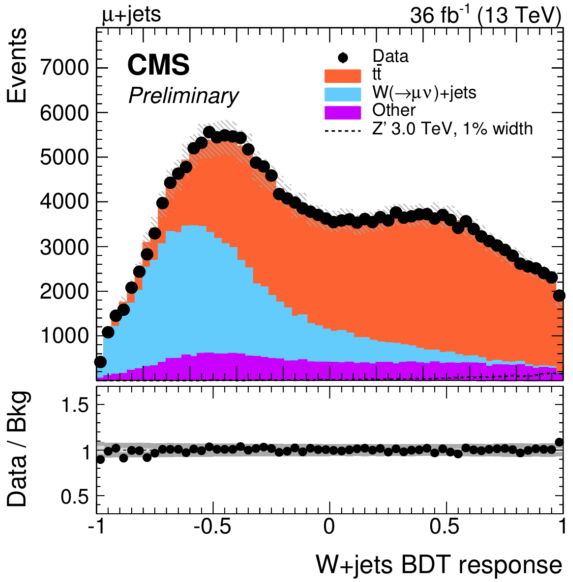


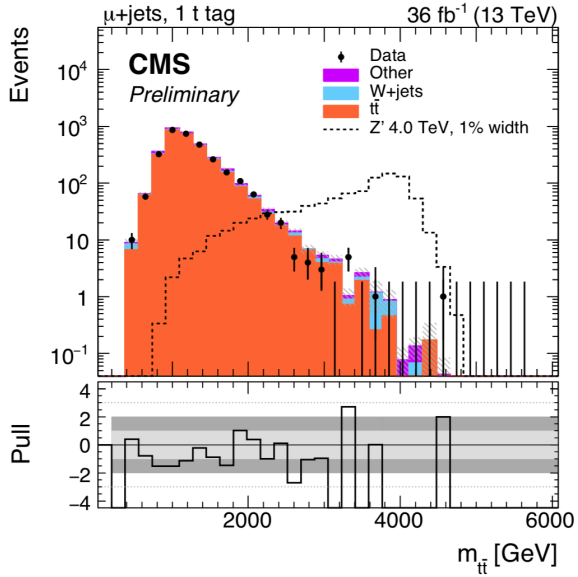
Semileptonic

$Z' \rightarrow t\bar{t}$

- Selection
  - One lepton (e or μ)
  - Two jets, one with high p_T
  - Hadronic top tag categories (0 or 1)
  - High p_T^{miss}
  - No lepton isolation cut
- Use BDT selection to separate W+jets
  - 10 inputs
- Reconstruct $t\bar{t}$ system using χ^2

$$\chi^2 = \left[\frac{M_{lep} - \overline{M}_{lep}}{\sigma_{M_{lep}}}\right]^2 + \left[\frac{M_{had} - \overline{M}_{had}}{\sigma_{M_{had}}}\right]^2$$

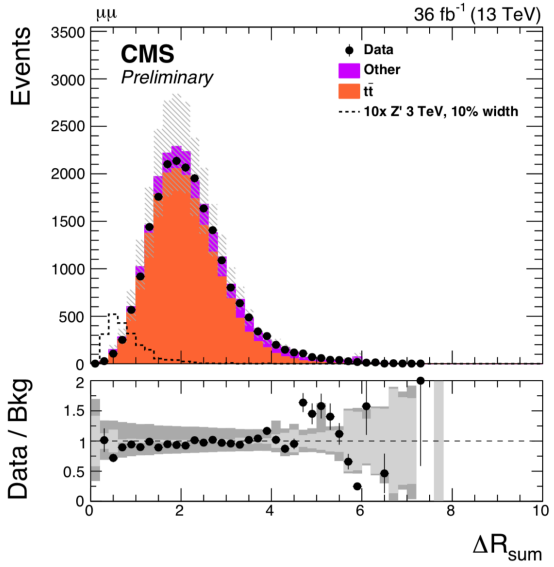


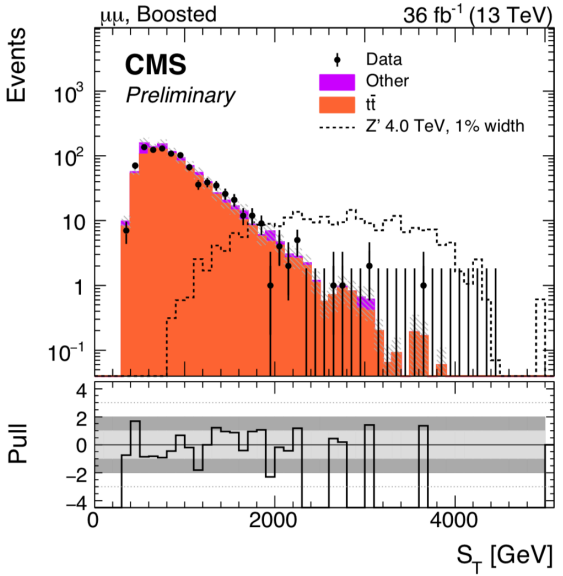


$Z' \rightarrow t\bar{t}$

- Selection
  - Two opposite sign leptons (e or μ)
  - Two jets, one with high p_T
  - At least one b tag
  - High p_T^{miss}
  - No lepton isolation cut
- Use $\Delta R_{sum} \equiv \Delta R_{j,l1} + \Delta R_{j,l2}$ to categorize events
  - Boosted: $\Delta R_{sum} < 1$
  - Resolved: $1 < \Delta R_{sum} < 2$
  - Background CR: $\Delta R_{sum} > 2$
- Set limits using S_T distribution

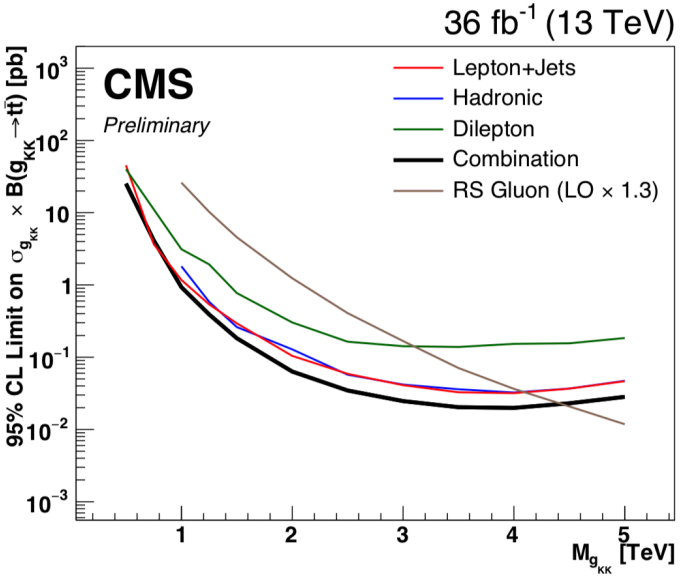
$$S_T \equiv \sum_{i=1}^{N_{\text{jet}}} p_{T_i} + \sum_{i=1}^{2} p_{T_i} + \vec{p}_T^{\,\text{miss}}$$

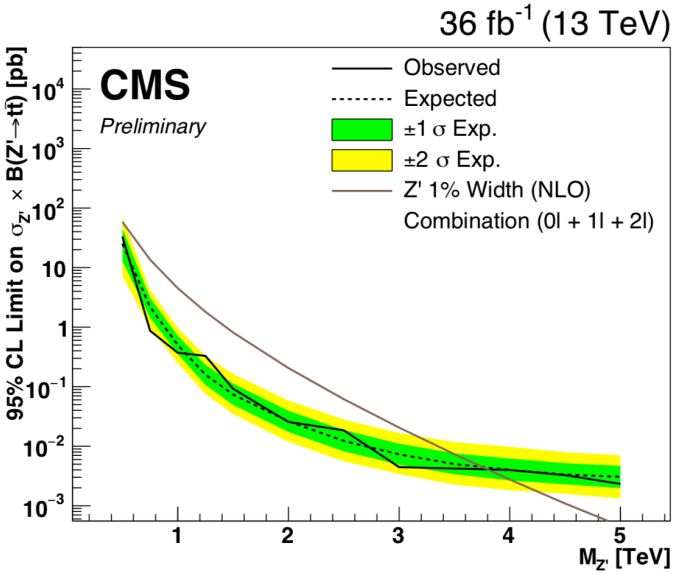




$Z' \rightarrow t\bar{t}$

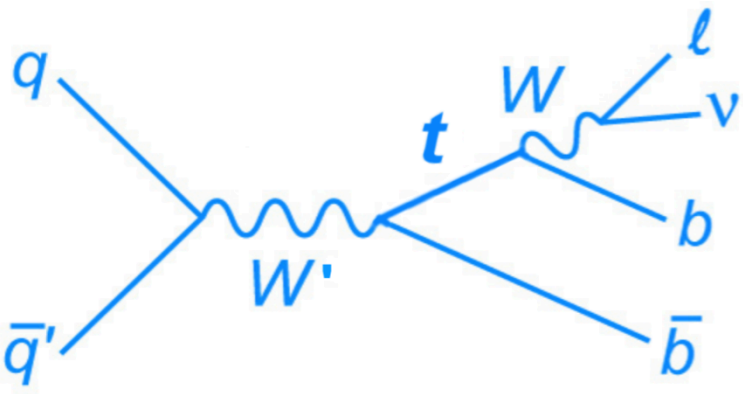
- Limits set using RSGluon and Z' signal hypotheses
- Limits extended
  - 3.8 TeV for the narrow Z' hypothesis
  - 4.6 TeV for the RSGluon hypothesis





$W' \rightarrow tb$

- Search for a heavy W' resonance decaying to a top quark and bottom quark
  - Semileptonic final state
- Set generic limits of left- and right-handed W' couplings



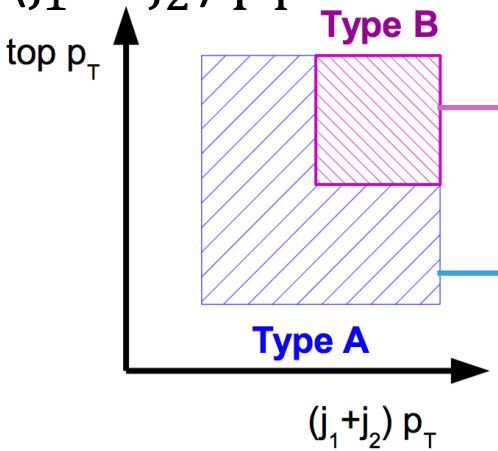
$$\mathcal{L} = \frac{V_{f_i f_j}}{2\sqrt{2}} g_w \bar{f}_i \gamma_\mu \left[a_R^{f_i f_j} (1+\gamma^5) + a_L^{f_i f_j} (1-\gamma^5) \right] \mathrm{W}'^{\mu} f_j + \mathrm{h.c.}$$

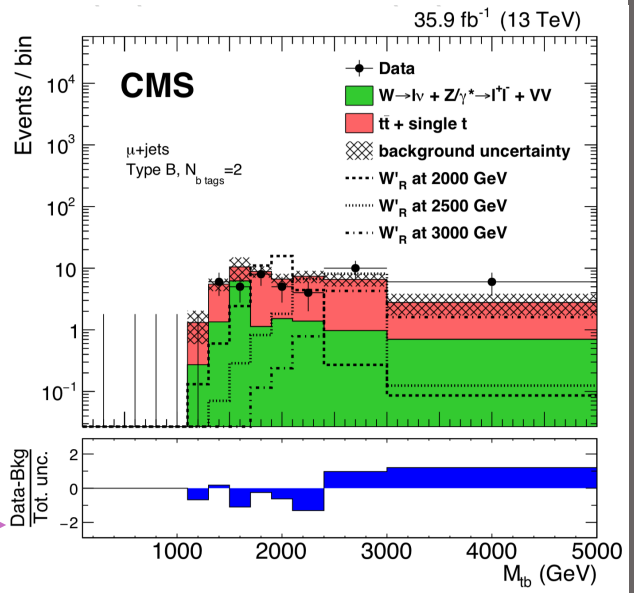
Link:physletb.2017.12.006

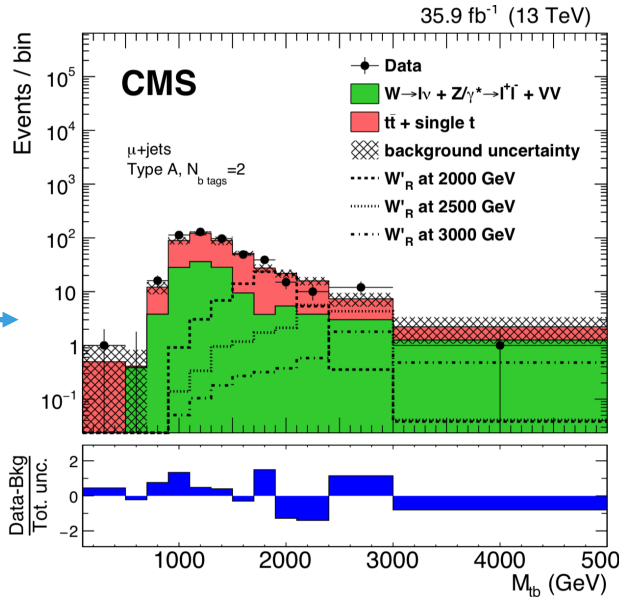
"Search for heavy resonances decaying to a top quark and a bottom quark in the lepton+jets final state in proton-proton collisions at 13TeV", *Phys. Lett. B* **777** (2018) 39

$W' \rightarrow tb$

- Selection
  - One lepton (e or μ)
  - Two jets, one with high p_T
  - B tag categories (1,2)
  - High p_T^{miss}
  - No lepton isolation cut
- Use kinematic categorization for limit setting
  - Top p_T , $(j_1 + j_2)\ p_T$

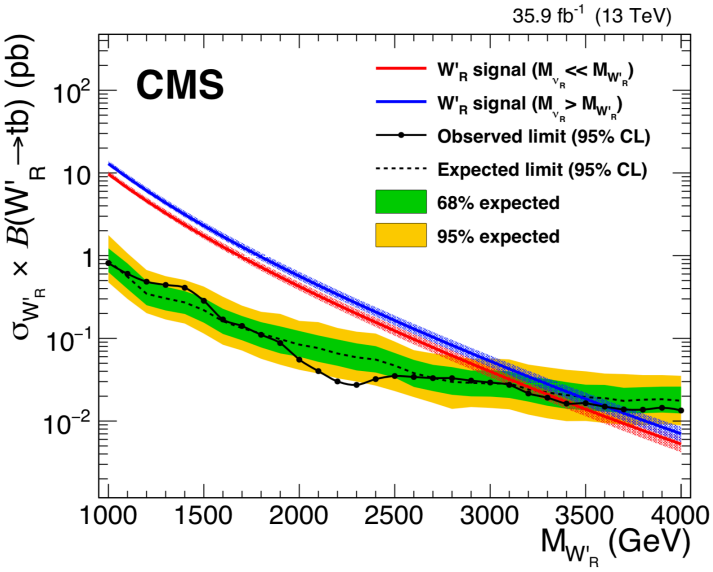


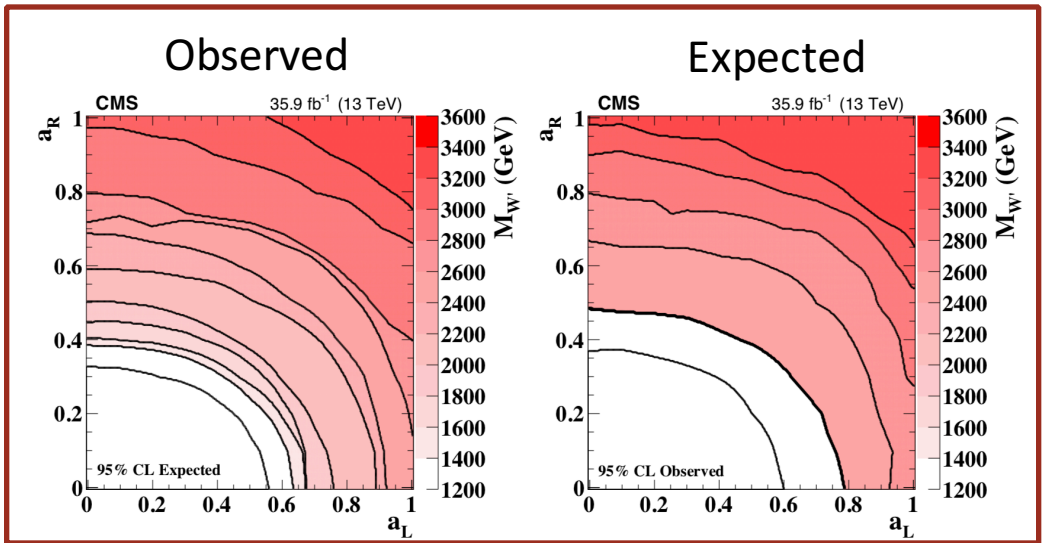




$W' \rightarrow tb$

- Backgrounds from Monte Carlo with data control regions
  - Investigate dilepton $t\bar{t}$ to check top p_T spectrum
  - Use 0 b tag region to investigate W+jets shape and normalization
- Limits set on W'_R hypothesis
  - $M_{W'_R} >> M_{\upsilon_R}$ -- Exclude $M_{W'_R} < 3.4$ TeV
  - $M_{W'_R} < M_{\upsilon_R}$ -- Exclude $M_{W'_R} < 3.6$ TeV
- Limits set in a_L, a_R plane
  - Left- and right-handed W' couplings



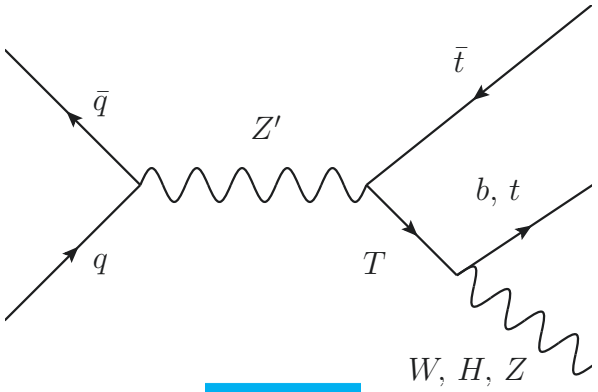


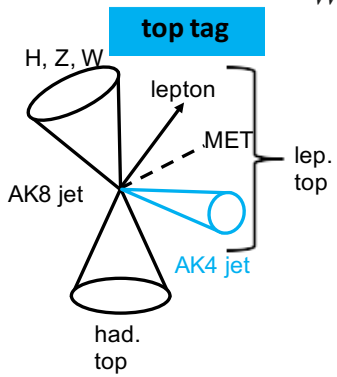
$Z' \rightarrow tT$

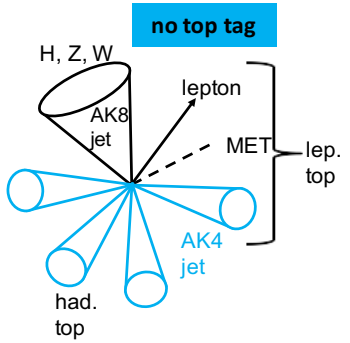
New!

- Search for a heavy Z' resonance decaying to a top and a T VLQ in the lepton+jets channel
  - T decays in to bW,tH,tZ analyzed
  - Use multiple boosted jet categories
    - H_{1b}, H_{2b}, Z, W
- Reconstruct Z' based on presence of a hadronic top tag
  - Event contains hadronic top tag
    - Leptonic top from lepton, MET, and AK4 jet
  - Event does not contain hadronic top tag
    - AK4 jets are assigned to either leptonic or hadronic top
  - Construct χ^2 to assign AK4 jets

$$\chi^2 = \left[\frac{M_{\text{lep}} - \overline{M}_{\text{lep}}}{\sigma_{M_{\text{lep}}}}\right]^2 + \left[\frac{M_{\text{had}} - \overline{M}_{\text{had}}}{\sigma_{M_{\text{had}}}}\right]^2$$





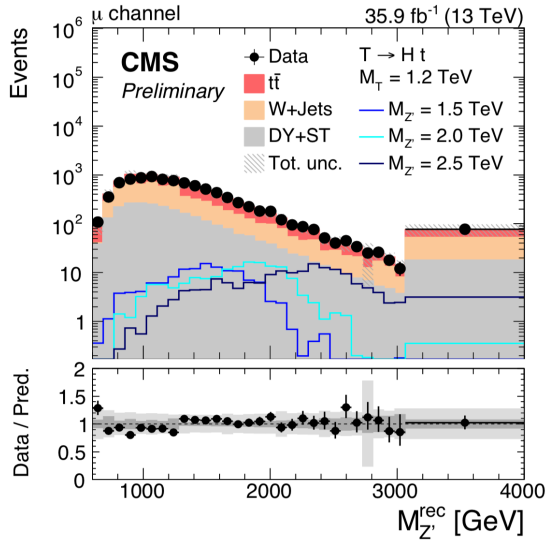


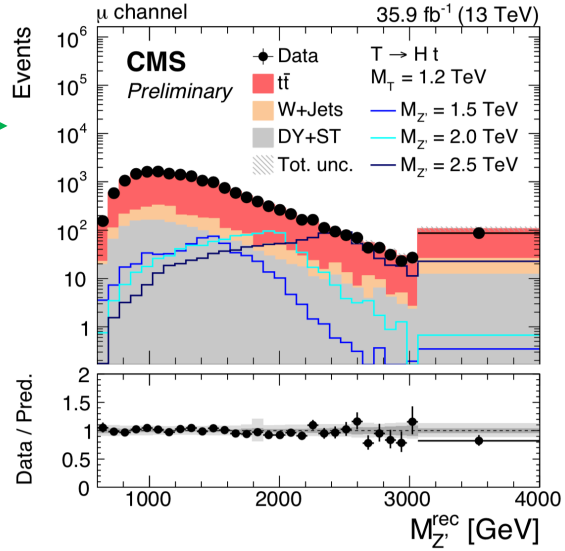
Link: CMS-PAS-B2G-17-015

$Z' \rightarrow tT$

New!

- Primary backgrounds $t\bar{t}$ and W+jets
  - Invert boson mass selection to simultaneously constrain
    - W+jets sideband from 0 b jets category
    - $t\bar{t}$ sideband from $\geq$1 b jet category
  - Shape taken from simulation

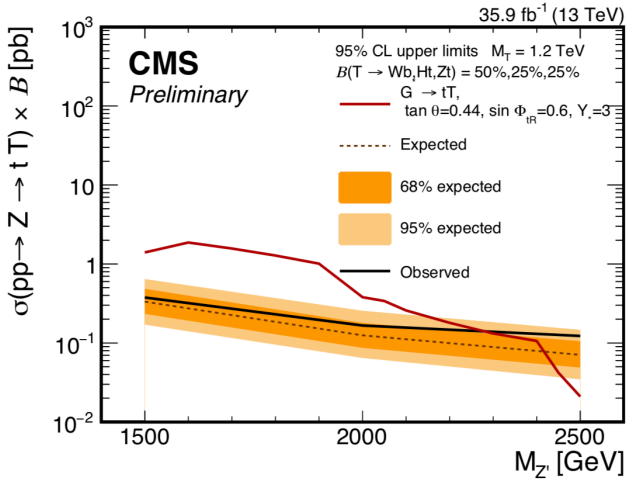


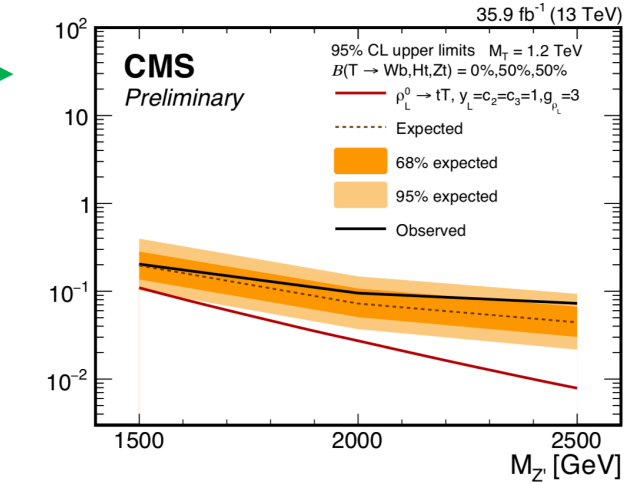


$Z' \rightarrow tT$

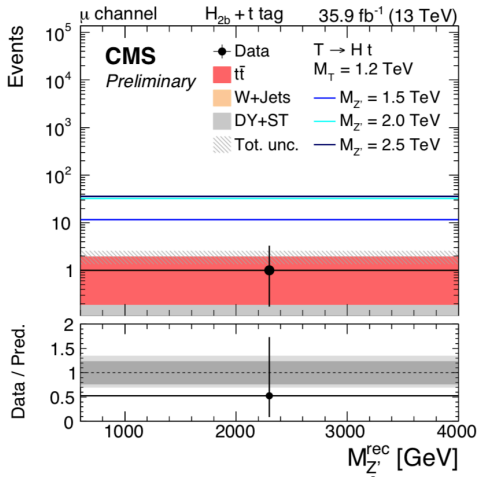
New!

- Set limits using two benchmark models
  - Extra dimension model
  - Composite model
- best sensitivity for $T \rightarrow tH$

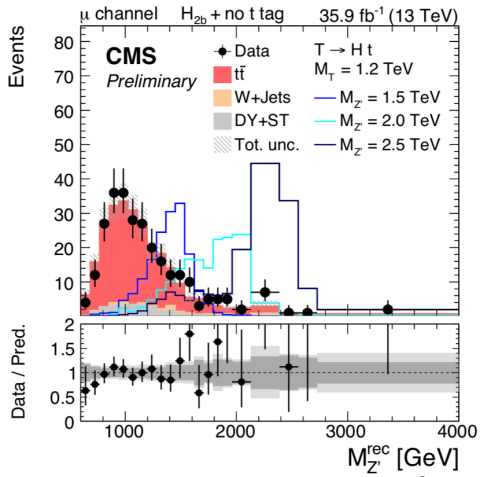




Higgs 2b muon channel



Top tagged

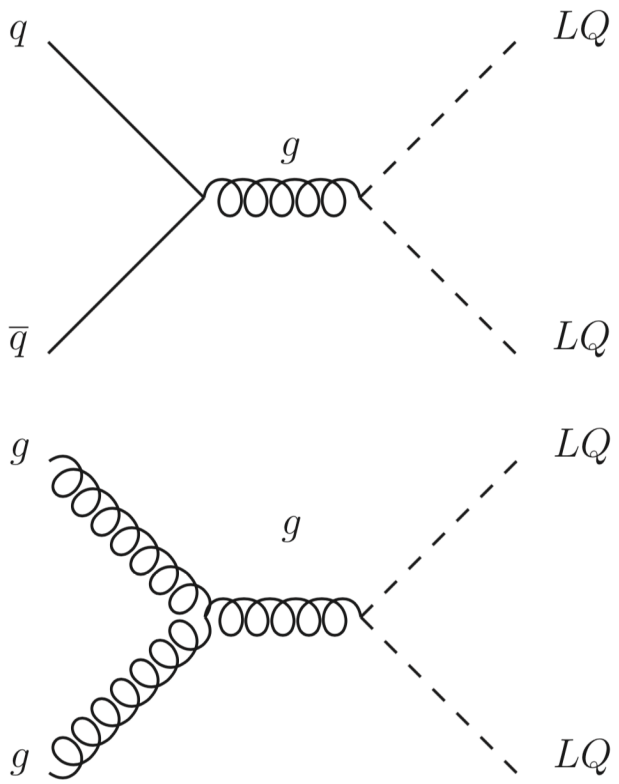


Not top tagged

T → bW and T → tZ also covered by:
B2G-16-013 (JHEP 09 (2017) 053)
and
B2G-17-007 (Phys. Lett. B 781 (2018) 574)

$LQ \rightarrow \ell t$

- Searches for third generation scalar leptoquarks
  - Non-zero lepton and baryon numbers
- Decay to third generation quark and lepton
  - top+τ
  - top+μ

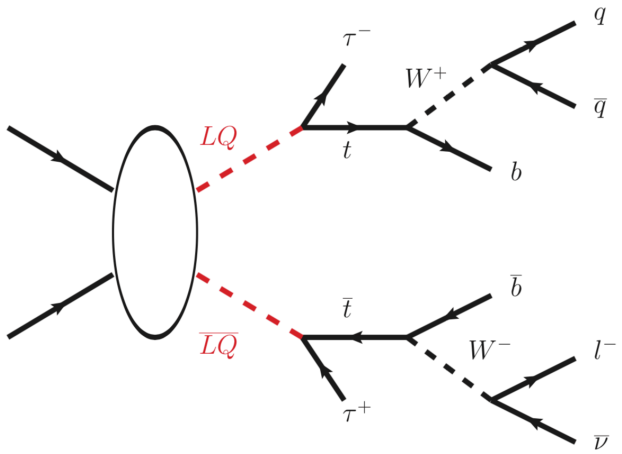


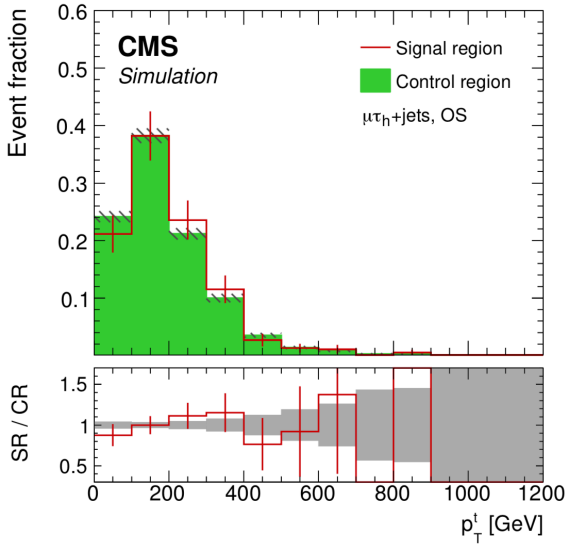
Link:CMS-PAS-B2G-16-027,arxiv:1803.02864

CMS Collaboration, "Search for third-generation scalar leptoquarks decaying to a top quark and a τ lepton at $\sqrt{s} = 13$ TeV"

LQ → τt

- Selection
  - One lepton (e or μ)
  - Three jets
  - τ tag categories (1 or ≥ 2)
    - $N_\tau = 1$
      - Limits set using the hadronic top p_T^{top} variable in bins of S_T
    - $N_\tau \geq 2$
      - Counting experiment
- Background estimation
  - Invert τ isolation to extract misidentified τ background
    - Extrapolate to signal region using ratio from MC
  - Prompt τ background from simulation

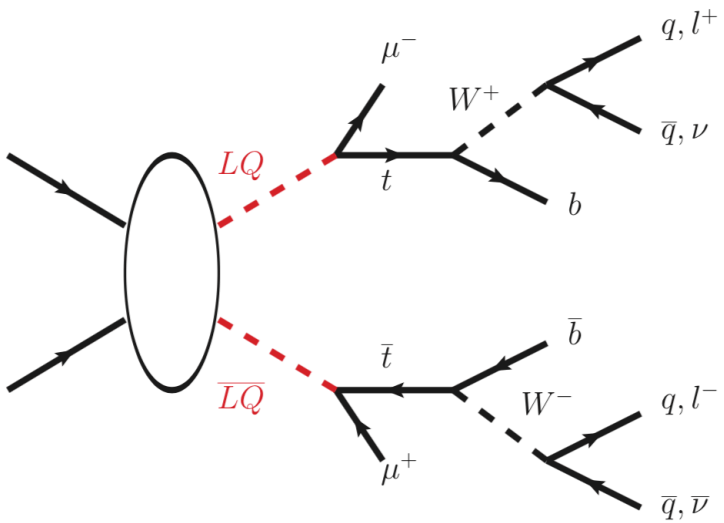




$$N_{SR}^{t\bar{t},\,data} = \left(N_{CR}^{data} - N_{CR}^{other,\,MC}\right) \frac{N_{SR}^{t\bar{t},\,MC}}{N_{CR}^{t\bar{t},\,MC}}$$

LQ → μt

- Selection
  - Two oppositely charged muons
  - At least two jets, one b tagged
  - High S_T
  - High $M_{\mu\mu}$
- Additional lepton categories
  - One additional electron or muon
    - Set limits using $M_{LQ} \equiv {}^1/_2\,(M_{LQ}^{lep} + M_{LQ}^{had})$
    - Reconstruct using χ^2
  - All remaining events
    - Set limits using S_T
    - Background estimate from data
      - Define zero muon control region
      - Extrapolate from control region using MC ratio as a function of S_T

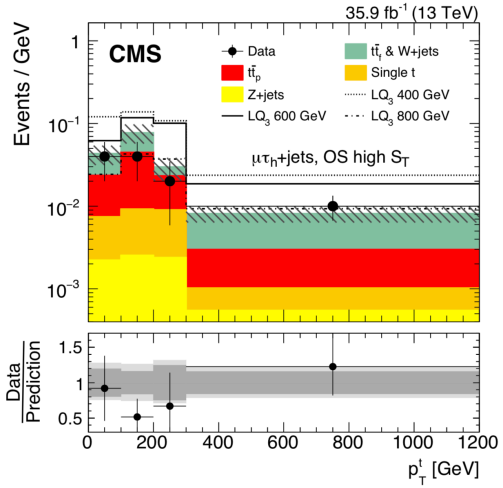


$$\chi^2 = \left(\frac{M_t - \overline{M}_t}{\sigma_M}\right)^2_{lep} + \left(\frac{M_t - \overline{M}_t}{\sigma_M}\right)^2_{had} + \left(\frac{\Delta M_{LQ}^{rel} - \overline{\Delta M}_{LQ}^{rel}}{\sigma_{\Delta M}}\right)^2$$

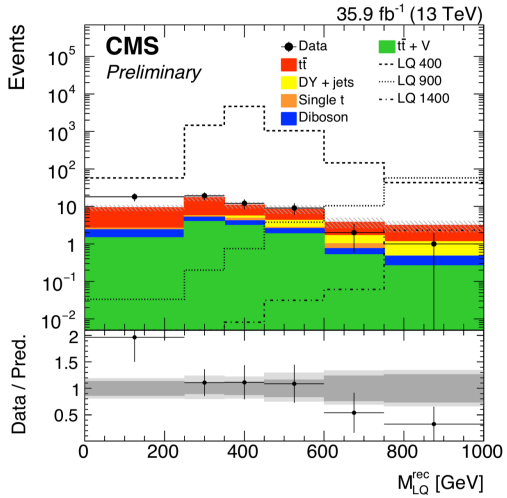
$LQ \rightarrow \ell t$

- Limit combination

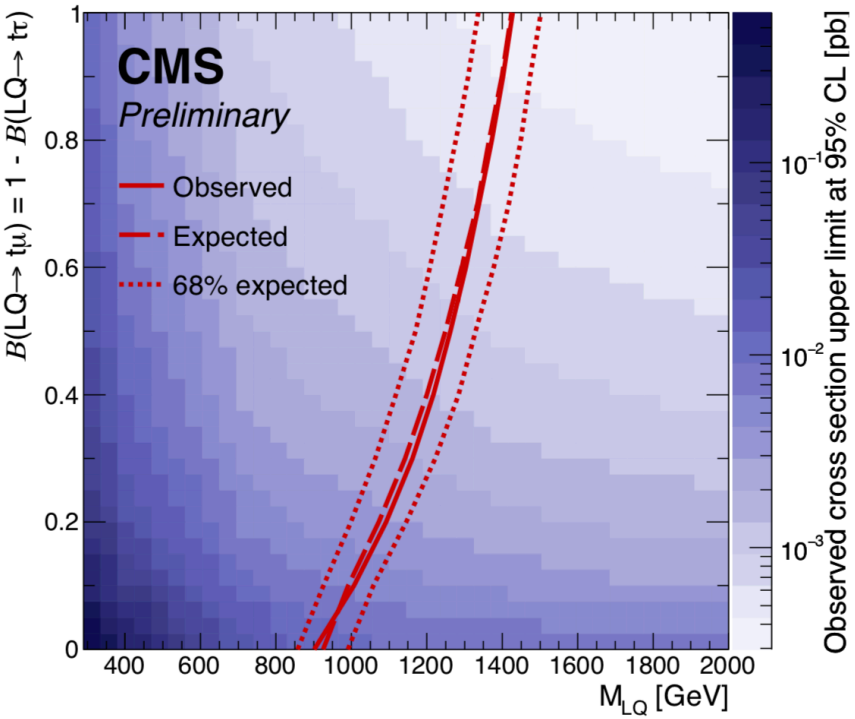
$LQ \rightarrow \tau t$

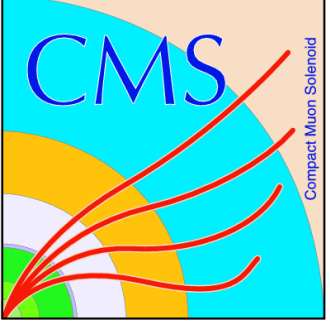


$LQ \rightarrow \mu t$



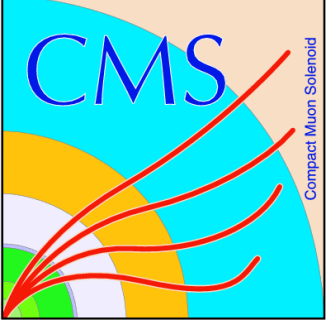
Combined limits





Summary

- Exciting new results from CMS
  - Heavy bosons to 3rd generation quarks
    - $Z' \rightarrow t\bar{t}$, $W' \rightarrow tb$
  - Including an internal VLQ
    - $Z' \rightarrow tT$
  - Leptoquark pair production
    - $LQ \rightarrow \tau t$, $LQ \rightarrow \mu t$
  - New methods push sensitivity beyond expected improvement
- Looking forward to new results using 2017 and 2018 data



Backup